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MURRAY–DARLING BASIN AUTHORITY

# A Case Study for Compliance Monitoring using Satellite Imagery

## The Northern Connectivity Event

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**Acknowledgement of the Traditional Owners of the Murray–Darling Basin**
The Murray−Darling Basin Authority pays respect to the Traditional Owners and their Nations of the Murray−Darling Basin. We acknowledge their deep cultural, social, environmental, spiritual and economic connection to their lands and waters.

The guidance and support received from the Murray Lower Darling Rivers Indigenous Nations, the Northern Basin Aboriginal Nations and our many Traditional Owner friends and colleagues is very much valued and appreciated.

Aboriginal people should be aware that this publication may contain images, names or quotations of deceased persons.

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# Executive Summary

In July 2017 the ABC aired an episode of *Four Corners* which made allegations of the misuse of Commonwealth-owned environmental water in the Northern Murray–Darling Basin, including direct allegations of theft. In response several reviews into Basin-wide compliance and water management were triggered at both the State and Commonwealth level. These highlighted the need for a more proactive approach to environmental water protection and a tightening of rules and policies through future water sharing arrangements. These improved arrangements will help ensure environmental flows are protected in the future to the degree that they can deliver the ecological outcomes desired and as prescribed in the Basin Plan.

An important part of strengthened compliance investment is the testing and trialing of the use of remote sensing, particularly the use of satellite imagery, to assist with future compliance checking and investigation. Satellite imagery provides an important method for consistently measuring water use and water presence over spatial scales as large as the Murray-Darling Basin.

Remote sensing alone cannot ensure compliance. It is a necessary part of an effective compliance framework, but it must be combined with other data (such as accurate metering and a robust hydrometric network), and with a compliance culture that is supported by the community and enforced by Basin governments. The purpose of this report is to demonstrate the use of remote sensing as a rapid 'first filter' compliance check.

In June 2018 the Commonwealth Environmental Water Holder approved a large-scale environmental flow in the Northern Basin, known as the Northern Connectivity Event, to be released from headwater storages in the Border Rivers and Gwydir catchments and subsequently flow through the Barwon–Darling for specifically prescribed environmental and socio-economic benefit during a very dry time. To ensure the flow achieved the desired outcomes, NSW initiated a temporary restriction on consumptive extraction in the Barwon–Darling, providing an excellent opportunity to test and trial a pilot of the use of satellite imagery for compliance purposes, with the MDBA working closely with the Commonwealth Environmental Water Office to do so. A review of the governance, management, processes and procedures applied to this temporary water restriction is also currently being undertaken by the MDBA.

This report presents the results of this trial which used free, open and publicly available "Sentinel 2" satellite imagery (provided by Geoscience Australia) to track and measure the flow as it progressed through the Northern Basin, as a test into imagery usefulness for more broad scale application across the Basin into the future for compliance purposes. The trial was also an excellent opportunity to test the use of such imagery for measuring ecological outcomes.

Sentinel 2 is an excellent choice for work of this nature, as it has a high return period (imaging the same part of the ground every 3-5 days) and can resolve features down to 10m in size. It also has well understood technical parameters for application.

The overall aim was to use the imagery to measure the degree to which water was present in farm dams and storages during the event, and how the total area of water present changed over time, the overall premise being that as a temporary limit was placed on consumptive extraction, no sudden and significant increases to water present in storages would be expected to occur. Coupled with this was an analysis of properties of the flow itself, taken from publicly available river gauge data. Again, no sudden or significant changes to the flow properties would be expected to occur other than those originating from natural attenuation processes.

One hundred and thirty four Sentinel 2 images were provided to the MDBA by Geoscience Australia from April to the end of July 2018 (which includes partial coverage images), covering seventy individual dates and more than a third of the Basin, taken every five days and allowing features down to 10m in size to be seen on the ground. No significant or enduring changes were seen to either farm dam and storage water areas across the region, or any unusual properties of the flow itself seen during the course of the event, which indicates a low probability that any significant compliance issues occurred. The imagery used in this study will be made publicly available on the MDBA website, and was used to supplement Commonwealth Environmental Water Office external stakeholder information.

A large amount of satellite imagery is available and continues to be taken every day, much of it free and openly available for anyone to use. It provides an important line of evidence for compliance studies, to support other compliance activities carried out by partner agencies. This work highlights the significant utility of satellite imagery to support compliance activities, and forms an important first step in plans to use such technologies for both compliance and ecological monitoring across the Basin into the future.

# Introduction

Satellite imagery provides an extremely powerful tool for studies into landscape change and monitoring across spatial scales as large as the Murray-Darling Basin. It allows investigation not only into historical changes, but also current conditions and future changes using upcoming imagery, new satellites, and tailored application of new and emerging technologies. By developing and applying specific analysis methods, satellite imagery coupled with observed river flow provides an extremely useful resource for decision making, water policy development and water resource management. It is uniquely suited to hydrological and ecological monitoring across large areas that are difficult to monitor regularly and consistently from the ground.

Remote sensing using satellite imagery provides one line of evidence for supporting compliance activities. These tools and their associated data offer the opportunity to observe the behavior of water moving through the landscape, as well as water present in farm dams and storages and crop presence at a range of scales – from farm to catchment level and in close to real-time. These observations provide Basin water agencies with a line of information, which may be used to trigger further investigation or other compliance responses as appropriate under certain circumstances.

The July 2017 ABC *Four Corners* program made allegations of water theft in the Murray–Darling Basin, triggering several reviews into Basin-wide compliance and water management. In particular, the *Murray–Darling Basin Water Compliance Review*, the Matthews' *Investigation into NSW Water Management and Compliance*, and more recently, the *Independent Audit of Queensland Non-urban Water Measurement and Compliance*, have highlighted the importance and opportunities the use of innovative technologies, such as remote sensing through satellite imagery, present in improving water compliance activities. This was further emphasised by subsequent commitments agreed by Commonwealth and Basin governments through the Basin Compliance Compact at the Murray–Darling Basin Ministerial Council meeting on 8th June 2018, and the creation of the NSW Natural Resource Access Regulator (NRAR).

In part resulting from these commitments and to ensure that upcoming environmental flow releases (described below) were adequately protected from consumptive extraction, the NSW Minister for Regional Water made an Order imposing a Temporary Water Restriction on water licence holders in the Barwon–Darling system between 29 April and 22 June 2018, applied to the prescribed Barwon–Darling Unregulated River Water Source (between the Queensland border and Menindee Lakes) in all circumstances other than the taking of water under a local water utility access licence, domestic and stock access or town water supply access.

A review of the governance, management, processes and procedures applied to this Temporary Water Restriction is currently being undertaken by the MDBA. The findings of this review will be published soon. Objectives of this review include to identify lessons learnt and opportunities available to improve protection of environmental water through upcoming state water sharing arrangements. Specifically, the review will consider:

- governance and management arrangements that were in place between NSW agencies,
- compliance activities implemented by the NSW Natural Resources Access Regulator to monitor water access licence holders during the embargo,

- processes and procedures for investigating and addressing unauthorised take, and
- mechanisms used to educate and create awareness of the embargo.

A significant amount of historical satellite imagery is available freely and publicly and is currently available for Basin-scale studies, including those for compliance. This includes imagery from satellites such as Landsat, which images the whole world with a 16-day revisit time at 30m resolution. Landsat (operated by the United States Geological Survey, USGS) has an archive going back to 1984, providing a very useful long historical archive. Landsat 9 is planned and due for launch in 2020, which will continue to add to the archive into the future. Additionally, Sentinel 2 (operated by the European Space Agency, ESA), images the whole world every 5 days, at 10m resolution, providing very significant supplementary imagery to the longer-term Landsat archive. When used together, Landsat and Sentinel provide a very powerful resource for Basin scale application.

Both Landsat and Sentinel 2observe the Earth at multiple wavelengths (bands) simultaneously, with the way in which these bands are combined for specific monitoring purposes being progressively tested and understood by researchers. Weather permitting, a combination of Landsat and Sentinel 2 can provide whole of Murray-Darling Basin coverage on average every 3 days, at resolutions of up to 10m, all provided openly and freely.

In addition, commercial satellite imagery is available at higher resolution and with a more frequent return period, for example companies such as Planet Labs[1]. While wholesale application of commercial data to large spatial scales would be unwieldy in terms of sheer data volume, size and associated resourcing, it is envisaged commercial data could be useful as an option to supplement the free and open imagery, for areas and times of interest as required.

# The Northern Connectivity Event (NCE)

In early 2018 the MDBA assisted the Commonwealth Environmental Water Office (CEWO) in planning a "Northern Basin Connectivity Event", an environmental watering action (to occur in early-to-mid 2018) where environmental water releases of up to 23.8 GL and 7.2 GL were proposed from both the CEWO and NSW Office of Environment and Heritage (OEH) respectively, originating from headwater storage in the Border Rivers (Glenlyon Dam) and Gwydir catchments (Copeton Dam) to produce a coordinated flow into the Barwon–Darling. The flow would help address dry conditions whereby more than 1,000 km of the Barwon–Darling had ceased to flow with significant ecological and socio-economic implications. Flows were planned to begin as releases from headwater storage in April, with the flow expected to take until mid-June to reach Wilcannia and possibly beyond. The flow would be protected by the flow extraction embargo in the Barwon–Darling described above.

The flow would represent the first time a coordinated environmental water delivery has been attempted in the northern Basin since the Basin Plan was legislated in 2012 and is closely aligned with the intended ecological outcomes to result from the Basin Plan, providing longitudinal connectivity and wholesale replenishing of drought refuges and food sources for native fish across the Northern Basin. This would improve the condition of the inland river system and help build resilience for the longer term if dry conditions persist. As well as strong ecological outcomes, the

[1] https://www.planet.com/

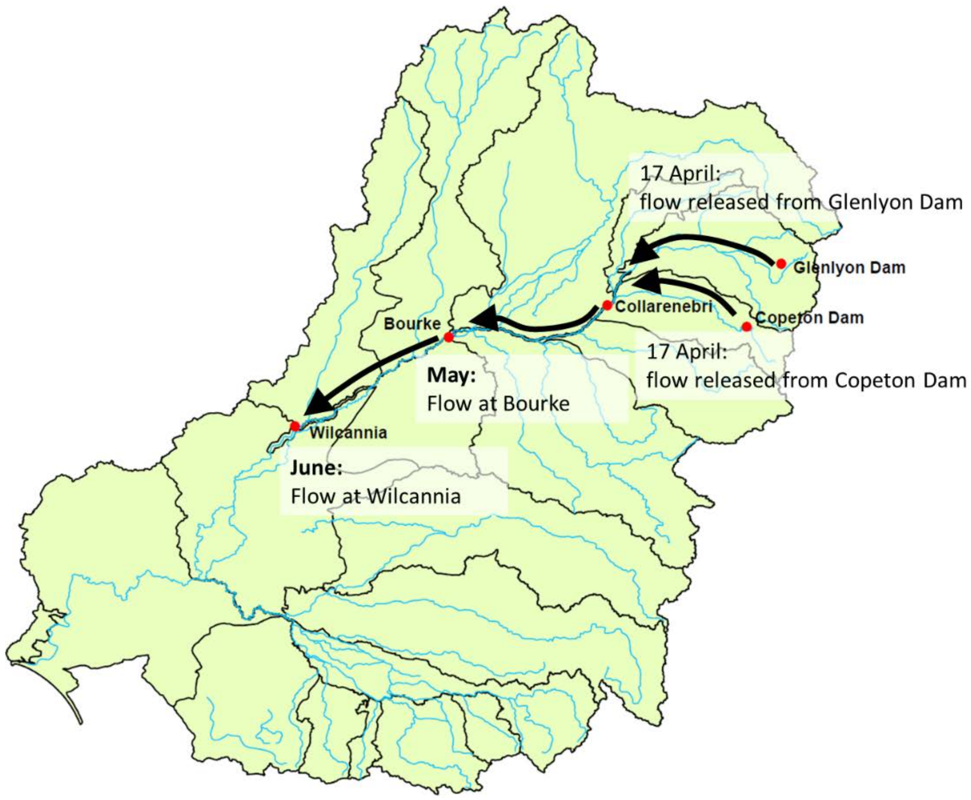
flow would also help alleviate pressures on local communities who had been living with dry conditions in the Northern Basin for a significant period, with the river having ceased to flow in January 2018, with adverse water quality issues as a result.

This event was consistent with the environmental watering plan included in the Basin Plan, which encourages cross-border and cross-agency cooperation to achieve environmental flows.

A large program of on-ground ecological monitoring activities was planned, including monitoring of the flow itself, as well as habitat monitoring and the response of native fish to the flow, to increase understanding of flow behaviour and ecological response to inform future watering events. Community events were also planned in towns along the length of the Barwon–Darling, to further inform stakeholders of the objectives and purpose of such large-scale environmental watering, with associated media releases, factsheets and social media posts to provide information as to the benefits and purpose of environmental watering.

The locations and timing of planned water releases for the Northern Connectivity Event as well the spatial scale of the event are presented in Figure 1, with water releases beginning in mid-April from headwater storage and taking until late-June to arrive in Wilcannia, highlighting the large travel times required for flows to progress through such a large fraction of the Basin.

Figure 1: The spatial extent, key dates and locations of the Northern Connectivity Event.



# Monitoring the Northern Connectivity Event using Satellite Imagery

The MDBA has been developing and building capability for the application of satellite imagery for Basin Plan implementation-related activities and reporting requirements, as well as for compliance. As a result, the MDBA was requested by the CEWO to undertake monitoring of the Northern Connectivity Event using satellite imagery, covering the Barwon–Darling, the Gwydir and Border Rivers catchments.

Importantly, satellite imagery alone is not enough to broadly understand changes seen in the landscape. The addition of gauge flow data as measured in the river daily is critical, providing additional information for flow behaviour, as well as informing where and when the flow is on any particular date and flagging if the flow does not reach the next gauge, or if the volume of flow has been significantly altered, hence requiring follow up investigation.

The satellite imagery results, when coupled with gauge data, provide very valuable information to support the extensive on-ground monitoring activities managed by the CEWO and NSW OEH, and the NSW Natural Access Regulator provide additional information for operational, ecological, compliance and public communication-related outcomes. In summary, these aim to include:

- A better understanding of how the flow behaves spatially and correlates to measured gauge flows over a large area.
- Additional information and understanding of how individual flow events propagate downstream through the respective catchments, by adding this event to the historical record (MDBA 2018).
- An investigation into whether the imagery can provide evidence of river and billabong/waterhole reconnection occurring because of an in-channel flow event.
- Provision of a broad scale information base with which to compare on-ground ecological monitoring and results (for example information on the presence of algae or general water discolouration).
- A trial of the ability of freely available satellite imagery to observe the presence or absence of water in irrigation channels, on-farm storages, ring tanks and irrigation bays, as a function of time throughout the temporal and spatial extent of the event.
- A trial of the ability of freely available satellite imagery to observe crop presence and change over time during the extent of the event, and
- Producing data for detailed maps and other products showing the landscape as observed during the event for stakeholder communications purposes.

The remainder of this report details the application of the satellite imagery as well as the availability of river gauge data and its application for monitoring the Northern Connectivity Event. Results are presented showing how this data was used to track the flow, to test monitoring ecological benefit as well as monitor the presence and change of water in the landscape (particularly within farm dams and storages) as the event progresses downstream. Recommendations are then made as to the effectiveness of freely available satellite imagery for more wholesale use for compliance and ecological monitoring activities across the Basin.

# Data

## Landsat & Sentinel 2 Imagery

There are many thousands of satellites orbiting the Earth, collecting data for a multitude of uses, including for Earth observation, communications, navigation, weather monitoring and for astronomical purposes. Two satellites from the Sentinel constellation were used for monitoring the Northern Connectivity Event, specifically Sentinel-2A and Sentinel-2B. These particular satellites were used for reasons such as the ease of data access, spatial coverage, spatial resolution, a high return frequency and the data being provided freely and openly with known specifications, properties and associated data governance. Sentinel also has upcoming further launches, which will increase the utility of the data yet further. Building and developing capacity to apply these data now will pay additional dividends into the future.

Satellite imagery, as for any source of information carries certain caveats and risks which can limit its usefulness for wholesale application. These need to be considered when planning how to use imagery for any specific purpose. These comprise:

- **Cloud Cover:** The quality of a satellite image is largely dependent on the weather. Cloud presence can restrict the usefulness of an image as visible light satellite sensors (such as those present on Sentinel-2A, 2B) are unable to penetrate cloud. Radar satellites that penetrate cloud do exist, such as Sentinel-1A, and 1B (using C-band synthetic-aperture radar). The use of such data is being considered for application to compliance activities but is beyond the scope of this current work.
- **Cloud Composition:** Clouds are made of water vapour, hence are also highlighted in any attempt to detect water in the landscape. Cloud shadows can also hide features and skew the results of water detection methods. Useful imagery is always limited to cloud-free or near cloud-free scenes, with cloud masks typically used to remove cloud-related artefacts.
- **Image Frequency and Image Extent:** The return interval of Sentinel 2 cannot provide an image every day for the areas of interest for the Northern Connectivity Event. Nor does it cover the entire spatial extent of the event on the same day, rather a part of it, due to the intricacies of orbital mechanics.
- **Image Resolution:** The inherent resolution of the imagery limits the details that can be seen clearly on the ground. While the Landsat pixel width is limited to 30m, for Sentinel 2 it is limited to 10m. Any features smaller than this pixel size, such as more narrow river channels, or individual small trees, cannot typically be directly detected in isolation, but rely on the supplementary application of higher resolution imagery.
- **Forest Canopy:** The satellite sensors cannot penetrate dense forest canopy. This makes it difficult to detect water presence under large groups of dense trees and limits the usefulness of such data in heavily forested areas, without the application of supplementary information.

These caveats become very limiting if only a single image for a region is available for study, but with additional data increasing the usefulness of the imagery by “filling in the gaps” in both frequency and resolution, the caveats can be effectively reduced.

The caveats also depend on where in the Basin the imagery is to be applied. Application to the mountains of Victoria, or the central parts of the Barmah–Millewa Forest for example, is a very different prospect to application in very arid and open regions of the Northern Basin (such as the Barwon–Darling). The combination of images from multiple satellites, associated with tailored and specifically designed analysis techniques, helps reduce these caveats but they cannot be entirely eliminated.

For this work, only Sentinel 2 imagery was used as a test to its usefulness for compliance and ecological monitoring. Future plans for the use of satellite imagery includes combining Sentinel 2 with Landsat, a second system of satellites with great utility for Basin-wide studies. The following table outlines the resolution, image frequency, and spatial width of image, date of launch and expected lifespan of the Sentinel satellites used, as well as for Landsat for completeness.

Table 1: Specifications of Sentinel-2A, Sentinel-2B, Landsat-7 and Landsat-8 satellite systems.

| | Sentinel 2A | Sentinel 2B | Landsat 7 | Landsat 8 |
|---|---|---|---|---|
| **Image Resolution (RGB, NIR)** | 10 m [1] | 10 m [1] | 30 m [3] | 30m [4] |
| **Image Frequency** | 10 days [1] | 10 days [1] | 16 days [3] | 16 days [4] |
| **Return Period (at equator)** | 5 days | | 8 days | |
| **Combined Return period** | 3 days | | | |
| **Swath Width** | 290 km [1] | 290 km [1] | 170 km [3] | 170 km [4] |
| **Launch Date** | 23/06/2015 [2] | 7/03/2017 [2] | 15/04/1999 [3] | 11/02/2013 [4] |
| **Lifespan** | 7.25 years [2] | 7.25 years [2] | 5+ years [3] | 5+ years [4] |

1. https://sentinel.esa.int/web/sentinel/missions/sentinel-2/overview
2. https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/sentinel-2
3. https://landsat.usgs.gov/landsat-7-history
4. https://landsat.usgs.gov/landsat-8-mission

Sentinel 2 imagery is obtained from a multispectral imager, which covers thirteen spectral bands (443 – 2190 nm) with a spatial resolution of 10m for the visible and NIR bands, 20m for six red-edge and shortwave infrared bands and 60m for three atmospheric correction bands. The various bands for both the Sentinel and Landsat constellations are provided in Table 2 below.

Table 2: Band resolution and wavelength for both the Sentinel and Landsat systems.

| | Sentinel-2A & 2B | | Landsat 5,7,8 | Landsat 5 (1984 -) | Landsat 7 (1999 -) | Landsat 8 (2013 -) |
|---|---|---|---|---|---|---|
| | MSI | | | TM | ETM+ | OLI |
| | Spatial Resolution (m) | Wavelength (nm & band) | Spatial Resolution (m) | Wavelength (nm & band) | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Blue** | 60 | 430 – 457 (1) | 30 | | | 435 - 451 (1) |
| | 10 | 447 – 545 (2) | 30 | 450 - 520 (1) | 450 - 520 (1) | 452 - 512 (2) |
| **Green** | 10 | 537 – 582 (3) | 30 | 520 - 600 (2) | 520 - 600 (2) | 533 - 590 (3) |
| **Red** | 10 | 645 – 683 (4) | 30 | 630 - 690 (3) | 630 - 690 (3) | 636 - 673 (4) |
| | 20 | 694 – 713 (5) | | | | |
| | 20 | 731 – 749 (6) | | | | |
| **Near Infra-Red** | 10 | 762 – 907 (7) | 30 | 760 - 900 (4) | 770 - 900 (4) | 851 - 879 (5) |
| | 20 | 768 – 796 (8) | | | | |
| | 20 | 848 – 881 (9) | | | | |
| **Short Wave Infra-Red** | 60 | 935 – 955 (10) | | | | |
| | 60 | 1363 – 1384 (11) | 30 | | | 1363 - 1384 (9) |
| **Short Wave Infra-Red 1** | 20 | 1542 – 1685 (12) | 30 | 1550 - 1750 (5) | 1550 - 1750 (5) | 1566 - 1651 (6) |
| **Short Wave Infra-Red 2** | 20 | 2081 – 2323 (13) | 30 | 2080 - 2350 (7) | 2080 - 2350 (7) | 2107 - 2294 (7) |

Imagery tailored for any purpose is produced by a combination of a subset of these bands in a specific way, as described further below.

Application of the imagery was made by splitting the river system into four broad geographic sections, to align with Sentinel 2 orbit paths. Using the planned release dates of the Northern Connectivity Event from headwater storage (as seen in Figure 1), and the expected travel times into, and through, the Barwon–Darling river system (MDBA 2018), the arrival time of the event was predicted at various locations and key gauges throughout the system. This was coupled with the

Sentinel[2] Acquisition Plan to predict the number of images and their associated acquisition dates for monitoring the event.

A total of 134 prospective images were determined from this process and are listed below in Table 3, covering 70 individual dates, highlighted in bold. Note that for upstream sections only dates where the flow was expected to be present were requested, imagery for Sections A and B end in early June when the flow was expected to have passed from that area. Also note that some dates occur less than 5 days since the previous pass by that satellite, due to partial coverage being gained for that part of the section, and there are some date overlaps as the same images can be used for Section B as were used for Section A, due to the spatial scale of the area of interest. Full coverage occurs every five days but partial coverage can occur at periods less than this, depending on the satellite orbit. These partial coverage images were included in the table for completeness.

Table 3: Predicted image dates and satellite name for each of the four broad geographic sections. Discrete image dates have been highlighted in bold.

| SECTION A U/S tributary reach | | SECTION B D/S tributary reach to Walgett | | SECTION C Walgett to D/S Bourke | | SECTION D D/S Bourke to Menindee | |
|---|---|---|---|---|---|---|---|
| Date | Satellite | Date | Satellite | Date | Satellite | Date | Satellite |
| **03/04/2018** | Sentinel 2A | 03/04/2018 | Sentinel 2A | **01/04/2018** | Sentinel 2B | 01/04/2018 | Sentinel 2B |
| **05/04/2018** | Sentinel 2B | 05/04/2018 | Sentinel 2B | 03/04/2018 | Sentinel 2A | **02/04/2018** | Sentinel 2A |
| **08/04/2018** | Sentinel 2B | 08/04/2018 | Sentinel 2B | **04/04/2018** | Sentinel 2B | 04/04/2018 | Sentinel 2B |
| **10/04/2018** | Sentinel 2A | 10/04/2018 | Sentinel 2A | **06/04/2018** | Sentinel 2A | 06/04/2018 | Sentinel 2A |
| **13/04/2018** | Sentinel 2A | 13/04/2018 | Sentinel 2A | 08/04/2018 | Sentinel 2B | **07/04/2018** | Sentinel 2B |
| **15/04/2018** | Sentinel 2B | 15/04/2018 | Sentinel 2B | **09/04/2018** | Sentinel 2A | 09/04/2018 | Sentinel 2A |
| **18/04/2018** | Sentinel 2B | 18/04/2018 | Sentinel 2B | **11/04/2018** | Sentinel 2B | 11/04/2018 | Sentinel 2B |
| **20/04/2018** | Sentinel 2A | 20/04/2018 | Sentinel 2A | 13/04/2018 | Sentinel 2A | **12/04/2018** | Sentinel 2A |
| **23/04/2018** | Sentinel 2A | 23/04/2018 | Sentinel 2A | **14/04/2018** | Sentinel 2B | 14/04/2018 | Sentinel 2B |
| **25/04/2018** | Sentinel 2B | 25/04/2018 | Sentinel 2B | **16/04/2018** | Sentinel 2A | 16/04/2018 | Sentinel 2A |
| **28/04/2018** | Sentinel 2B | 28/04/2018 | Sentinel 2B | 18/04/2018 | Sentinel 2B | **17/04/2018** | Sentinel 2B |
| **03/05/2018** | Sentinel 2A | 03/05/2018 | Sentinel 2A | **19/04/2018** | Sentinel 2A | 19/04/2018 | Sentinel 2A |
| **05/05/2018** | Sentinel 2B | 05/05/2018 | Sentinel 2B | **21/04/2018** | Sentinel 2B | 21/04/2018 | Sentinel 2B |
| **08/05/2018** | Sentinel 2B | 08/05/2018 | Sentinel 2B | 23/04/2018 | Sentinel 2A | **22/04/2018** | Sentinel 2A |
| **10/05/2018** | Sentinel 2A | 10/05/2018 | Sentinel 2A | **24/04/2018** | Sentinel 2B | 24/04/2018 | Sentinel 2B |
| **13/05/2018** | Sentinel 2A | 13/05/2018 | Sentinel 2A | **26/04/2018** | Sentinel 2A | 26/04/2018 | Sentinel 2A |
| **15/05/2018** | Sentinel 2B | 15/05/2018 | Sentinel 2B | 28/04/2018 | Sentinel 2B | **27/04/2018** | Sentinel 2B |
| **18/05/2018** | Sentinel 2B | 18/05/2018 | Sentinel 2B | **29/04/2018** | Sentinel 2A | 29/04/2018 | Sentinel 2A |
| **20/05/2018** | Sentinel 2A | 20/05/2018 | Sentinel 2A | 03/05/2018 | Sentinel 2A | **02/05/2018** | Sentinel 2A |
| **28/05/2018** | Sentinel 2B | 28/05/2018 | Sentinel 2B | **04/05/2018** | Sentinel 2B | 04/05/2018 | Sentinel 2B |
| **02/06/2018** | Sentinel 2A | 02/06/2018 | Sentinel 2A | **06/05/2018** | Sentinel 2A | 06/05/2018 | Sentinel 2A |

[2] https://sentinel.esa.int/web/sentinel/missions/sentinel-2/acquisition-plans

| SECTION A U/S tributary reach | | SECTION B D/S tributary reach to Walgett | | SECTION C Walgett to D/S Bourke | | SECTION D D/S Bourke to Menindee | |
|---|---|---|---|---|---|---|---|
| Date | Satellite | Date | Satellite | Date | Satellite | Date | Satellite |
| - | - | - | - | 08/05/2018 | Sentinel 2B | **07/05/2018** | Sentinel 2B |
| - | - | - | - | **09/05/2018** | Sentinel 2A | 09/05/2018 | Sentinel 2A |
| - | - | - | - | **11/05/2018** | Sentinel 2B | 11/05/2018 | Sentinel 2B |
| - | - | - | - | 13/05/2018 | Sentinel 2A | **12/05/2018** | Sentinel 2A |
| - | - | - | - | **14/05/2018** | Sentinel 2B | 14/05/2018 | Sentinel 2B |
| - | - | - | - | **16/05/2018** | Sentinel 2A | 16/05/2018 | Sentinel 2A |
| - | - | - | - | 18/05/2018 | Sentinel 2B | **17/05/2018** | Sentinel 2B |
| - | - | - | - | **19/05/2018** | Sentinel 2A | 19/05/2018 | Sentinel 2A |
| - | - | - | - | **26/05/2018** | Sentinel 2A | 26/05/2018 | Sentinel 2A |
| - | - | - | - | 28/05/2018 | Sentinel 2B | **29/05/2018** | Sentinel 2A |
| - | - | - | - | **29/05/2018** | Sentinel 2A | 31/05/2018 | Sentinel 2B |
| - | - | - | - | **31/05/2018** | Sentinel 2B | **01/06/2018** | Sentinel 2A |
| - | - | - | - | 02/06/2018 | Sentinel 2A | 03/06/2018 | Sentinel 2B |
| - | - | - | - | **03/06/2018** | Sentinel 2B | 05/06/2018 | Sentinel 2A |
| - | - | - | - | **05/06/2018** | Sentinel 2A | **06/06/2018** | Sentinel 2B |
| - | - | - | - | **08/06/2018** | Sentinel 2A | 08/06/2018 | Sentinel 2A |
| - | - | - | - | **10/06/2018** | Sentinel 2B | 10/06/2018 | Sentinel 2B |
| - | - | - | - | **13/06/2018** | Sentinel 2B | **11/06/2018** | Sentinel 2A |
| - | - | - | - | **15/06/2018** | Sentinel 2A | 13/06/2018 | Sentinel 2B |
| - | - | - | - | **18/06/2018** | Sentinel 2A | 15/06/2018 | Sentinel 2A |
| - | - | - | - | **20/06/2018** | Sentinel 2B | **16/06/2018** | Sentinel 2B |
| - | - | - | - | **23/06/2018** | Sentinel 2B | 18/06/2018 | Sentinel 2A |
| - | - | - | - | **25/06/2018** | Sentinel 2A | 20/06/2018 | Sentinel 2B |
| - | - | - | - | - | - | **21/06/2018** | Sentinel 2A |
| - | - | - | - | - | - | 23/06/2018 | Sentinel 2B |
| - | - | - | - | - | - | 25/06/2018 | Sentinel 2A |
| - | - | - | - | - | - | **26/06/2018** | Sentinel 2B |

## Image Acquisition & Processing

The Sentinel 2 satellites (operated by the European Space Agency) acquire raw images (Level 0 data) for each band individually and simultaneously and downlink them to tracking stations on the ground. This data is then processed to correct for co-registration, resampling, top-of-atmosphere corrections and converted to surface reflectance units, producing "Level 1" data which is applicable for most uses and is then made available by their operating management Agencies in an archived format within 24 hours after being taken by the satellite. The data is then disseminated to partner organisations and Agencies world-wide, which includes many local Agencies such as Geoscience Australia (GA) and the Bureau of Meteorology (BoM).

Additional further processing can then occur to produce “Level 2” data, involving bottom-of-atmosphere corrections for application to specific purposes requiring more scientific robustness and greater discrimination of more subtle on-ground features.

For this work, the MDBA has been in collaboration with the Geoscience Australia Digital Earth Australia (DEA) program[3], to readily and quickly access the Sentinel “Level 1” imagery, once it is received by GA from the operating management agencies, with some test “Level 2” data being provided to test vegetation condition and extent mapping (see later). Geoscience Australia is part of the cross-jurisdictional Copernicus Hub[4] with direct access to the Sentinel 2 archive and well regarded as an authority on the provision and processing of satellite imagery for application to specific purposes, being similarly regarded for this work as the first point of contact for imagery acquisition. For this work Level 1 data was regarded as sufficient for most of the work program, given timeframes involved in the production of Level 2 data and the purposes for which the imagery was to be applied (see later).

The Sentinel 2 data was provided by Geoscience Australia through an Amazon Web Service (AWS) cloud storage space from which the MDBA copied the data. Once received, the MDBA developed a python processing pipeline to:

- mosaic the imagery into a more manageable format (from individual tiles into date swath footprints, for each band, as ESRI format 6-band TIFF image files) for that date,
- include relevant metadata as present in the original data for that date,
- populate attribute fields in the resulting mosaics for analysis purposes, and
- combine all individual date mosaics into a master mosaic containing the whole dataset.

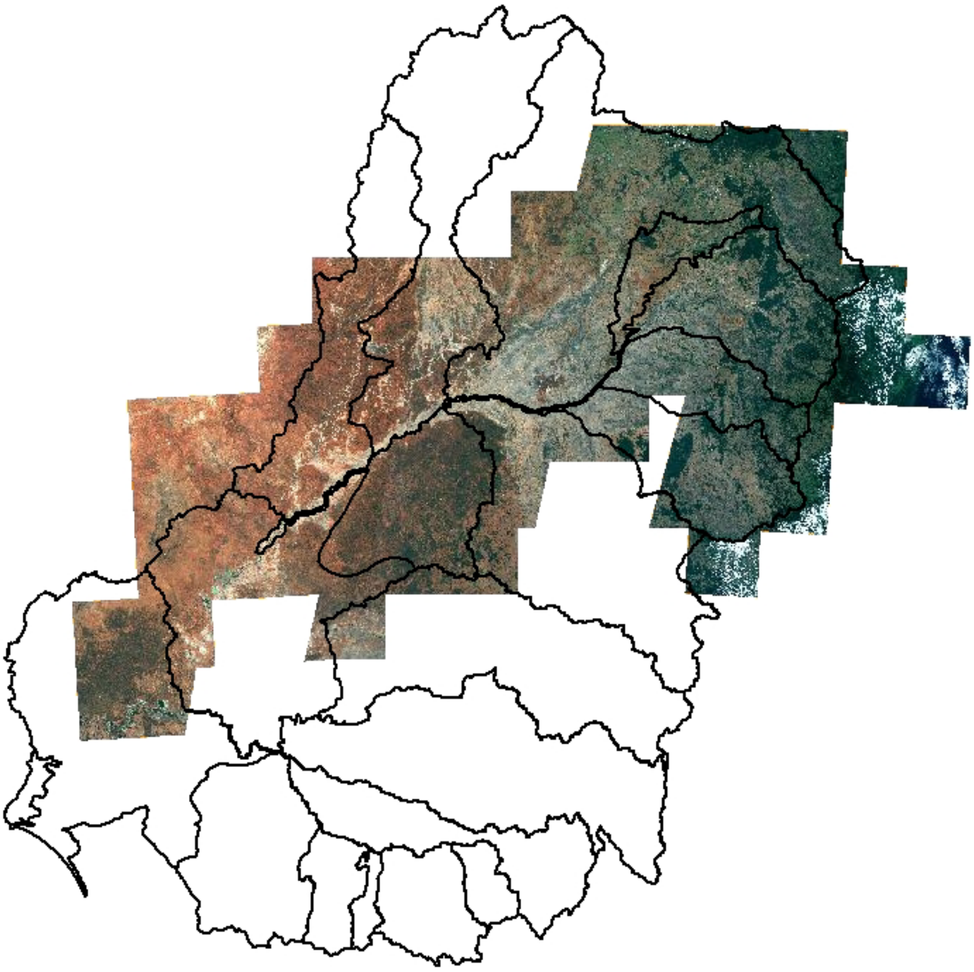
The master mosaic was then published as an ESRI GIS web service on the MDBA internal ArcGIS Enterprise Portal, making the imagery available for subsequent analysis through software such as ArcMap, and allowing subsequent publication from the internal portal to an external portal for data provision outside the MDBA using standard desktop tools, if required.

The method used to produce the image mosaics was coded using multithreading techniques which allows full processing of imagery from tile provision to mosaic production across the spatial extent of the Northern Connectivity Event in less than 5 hours.

Figure 2 shows an example mosaic of true colour (RGB) imagery as produced by the MDBA image processing pipeline and as captured by Sentinel-2A and 2B. The imagery is overlaid onto an outline of the Murray-Darling Basin, highlighting the spatial extent covered by the Northern Connectivity Event as well as the effectiveness of the mosaicking technique.

[3] http://www.ga.gov.au/about/projects/geographic/digital-earth-australia
[4] http://www.copernicus.gov.au/

Figure 2: Example colour imagery mosaic showing the spatial extent of the Northern Connectivity Event monitoring as seen from Sentinel-2A and 2B.



# Gauge Data

Observed flow data (or gauge data) provides another very important line of evidence when tracking flows through river systems. Flow data complements satellite imagery, they work hand in hand, indicating where and when the flow is physically present and hence where and for what date the imagery can be used to best advantage.

The MDBA has used gauge data as measured daily to monitor the Northern Connectivity Event to provide information on the location, timing and behavior of the flow event as it passes various gauges, through analysis of hydrological properties such as flow peak, duration, volume and timing. Event peaks and volumes at upstream and downstream gauges have been used to provide information about the attenuation of the event within river reaches, using the same methods as developed for MDBA 2018. Studying the way in which the flow event changes as it progresses provides one line of evidence for any possible compliance flag, if for example the flow was seen to undergo sudden and unexpected changes to its properties.

Observed flow data for gauges in the NSW Border Rivers, Gwydir and Barwon–Darling catchments is publicly available and was sourced for this work from the NSW RealTimeData website[1] with data for the QLD Border Rivers catchment being sourced from the QLD Water Monitoring Information Portal[2].

The MDBA has used data from 28 gauges throughout these catchments to ensure there was enough longitudinal coverage of the event. Data was available daily for each of these gauges, with no gap-filling required, although depending on the quality codes of the data these flow readings may be subject to small changes after subsequent data validation has been performed by relevant State measurement Agencies. The figures below outline the locations of these gauges for the Border Rivers (Figure 3), Gwydir (Figure 4) and Barwon–Darling (Figure 5).

Figure 3: Location of gauges used in the Border Rivers catchment.

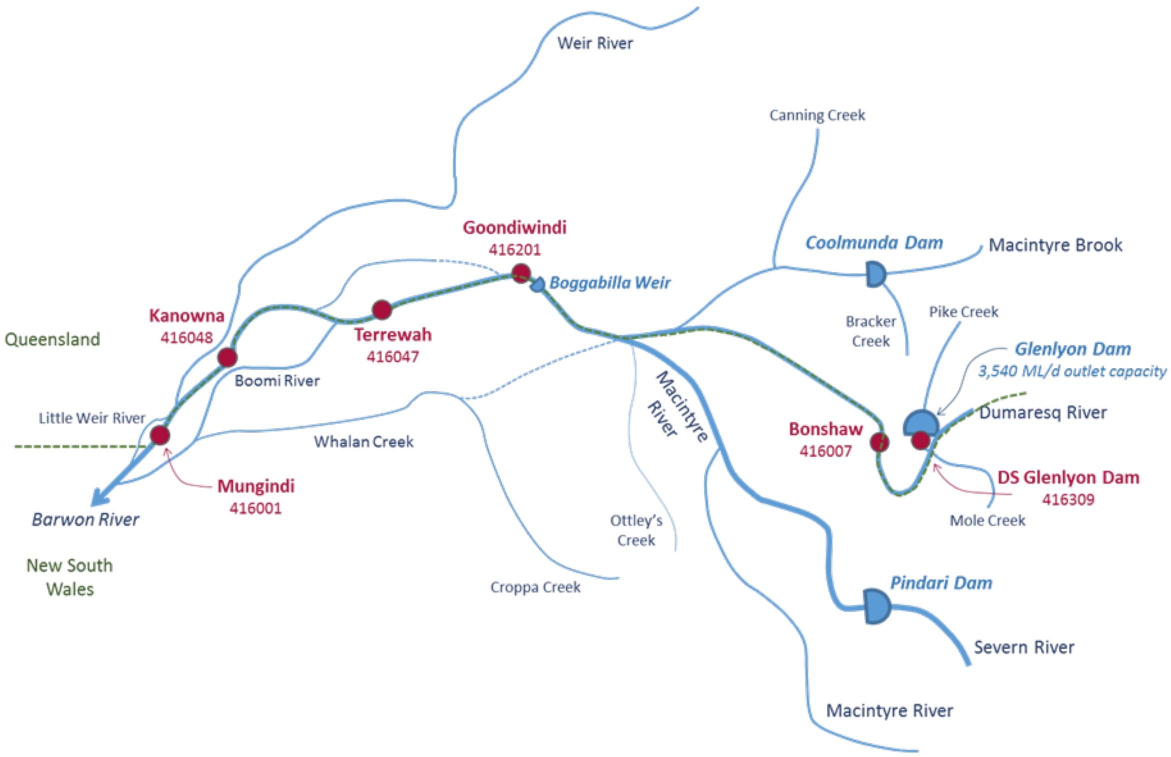


Figure 4: Location of gauges used in the Gwydir catchment.

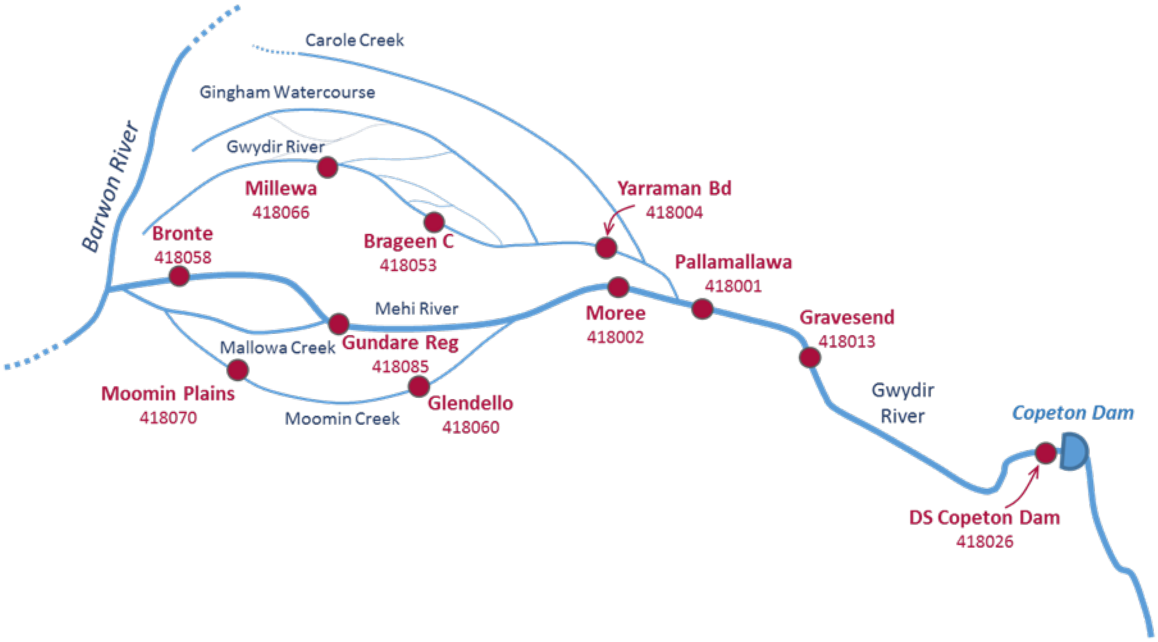
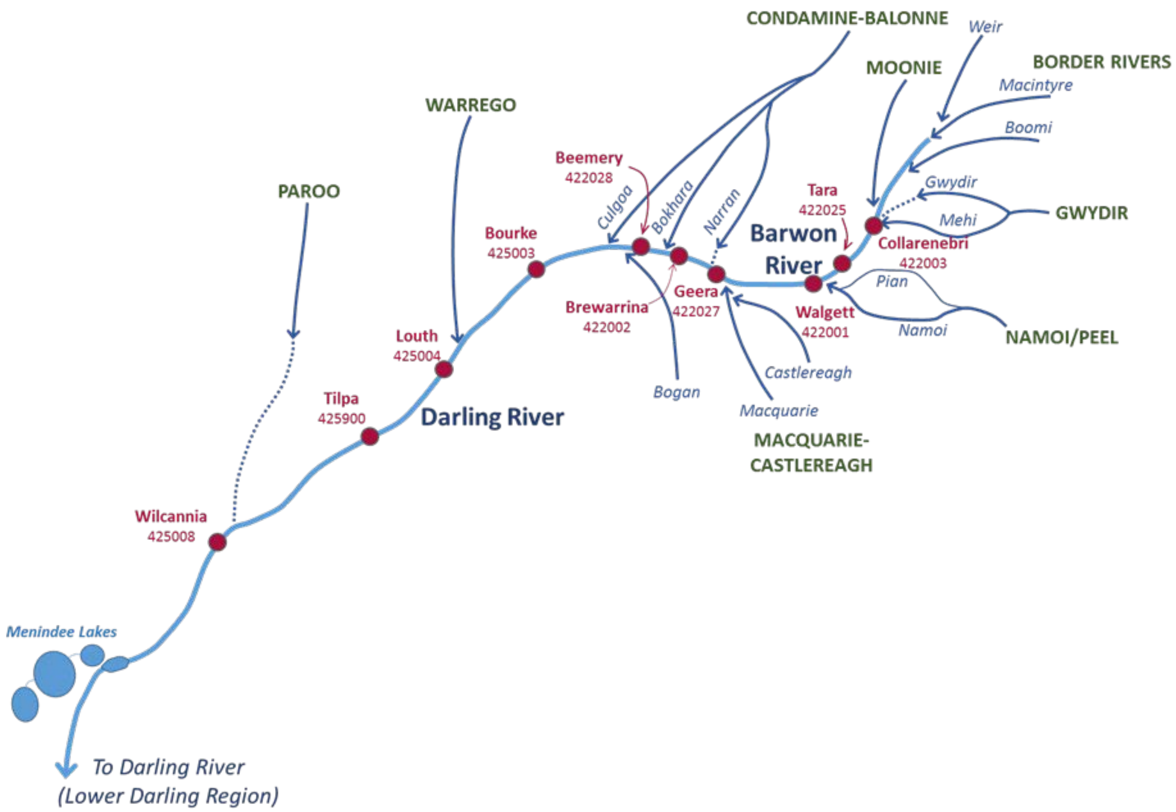



Figure 5: Location of gauges used in the Barwon–Darling catchment.



# Analysis Techniques

In summary, data as provided to the MDBA by Geoscience Australia for this work comprised individual images for each of the various Sentinel 2 bands (Table 2) and processed using the mosaicking method previously described. The imagery products described below were then derived via a specific combination of those individual bands for specific purposes, producing imagery which highlights certain features of the landscape. For the Northern Connectivity Event monitoring work, there were three data products derived, namely:

- Colour Imagery for visual mapping and communications purposes,
- Imagery derived to highlight the presence of water in the landscape, and
- Imagery derived to highlight the location and condition of vegetation in the landscape.

These three products were used in combination with the gauge data to meet the project aims and produce results and are described more fully below.

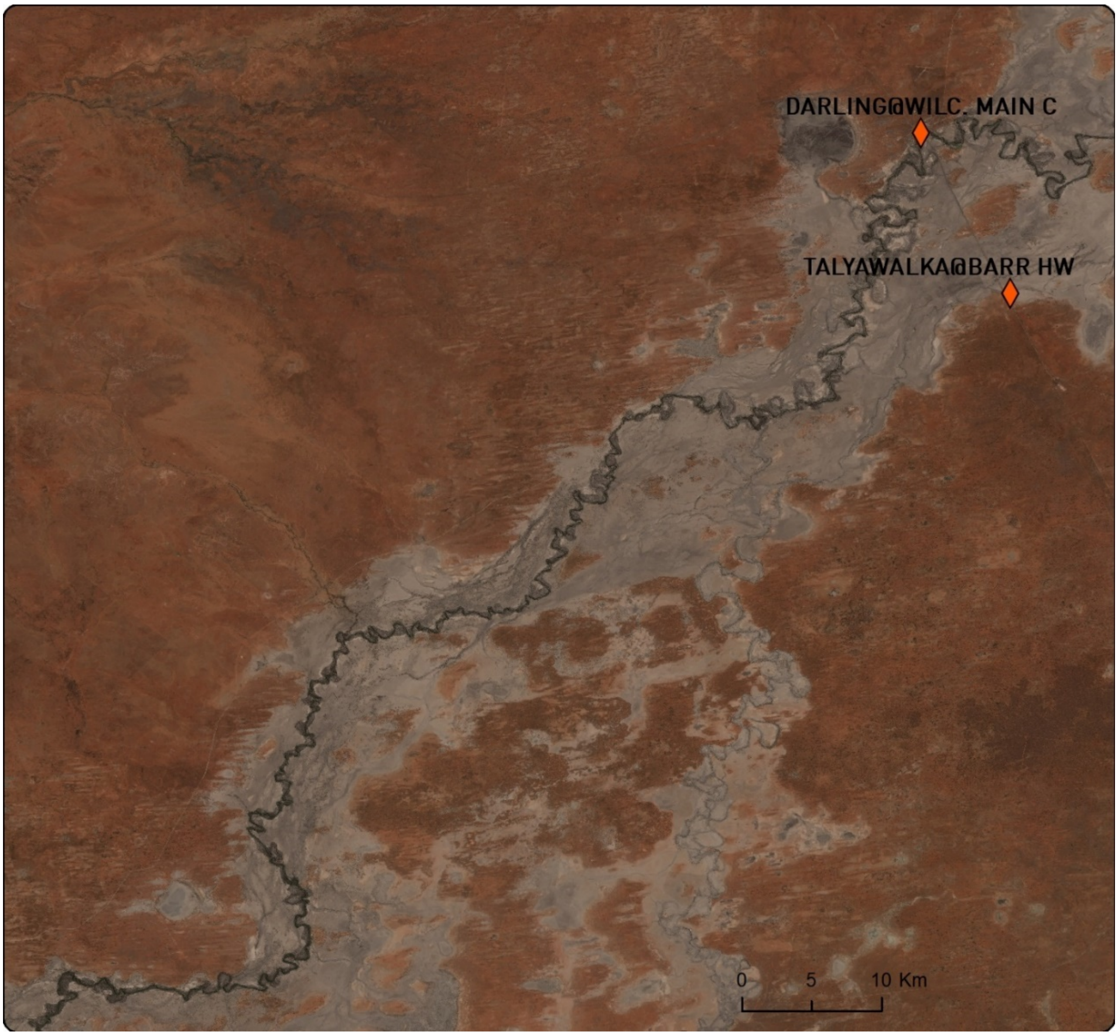
## Imagery for Mapping & Communications

The first data product was produced by combining the red (R), green (G) and blue (B) imagery bands to create a true colour (or RGB) image of the landscape. True colour imagery is very useful as a visual aid to provide broad-scale landscape information and reflects the view the human eye would have if present at the satellite looking down at the Earth.

In a colour image, the actual colours of the various components of the landscape become apparent. These include the different colours of various crops and native vegetation as well as the changes to water colour due to the presence of discolouration from algae or the differing sources of water in the river. The 10m resolution of Sentinel 2 is sufficient to discern relatively subtle changes to water colour as shown later in this report, which can be used to determine when fresh water enters a river or to deduce information on other water quality issues such as algal blooms. Colour imagery can also show exposed banks along a river bed when the flow is low, and the submersion of these banks as the flow increases. Cloud and associated cloud shadow are also clearly shown in true colour imagery.

The colours and features present in RGB imagery are in some cases very striking, and this, as well as being an extremely useful source of information into the general landscape make them very valuable for communications products and for informing stakeholders as to the current appearance of the landscape, wherever they happen to be in the Basin. Figure 6 shows an example of colour imagery covering the landscape near Wilcannia, as seen by Sentinel 2 on a clear day, the 4th April 2018.

Figure 6: Example colour imagery of the landscape surrounding Wilcannia, as seen by Sentinel 2 on the 4th April 2018.




# Imagery for Water Detection & Tracking

Application of remote sensing techniques to highlight the presence or absence of water in the landscape is a standard analysis method, for which there many options available and which has a long history of use. While there is no single method which is perfectly capable of detecting all kinds of water (IE clear water, muddy water etc) under all circumstances (under cloud shadow or under heavy canopy cover), an application of a relevant technique, applied carefully, can provide a very informative line of evidence into hydrological behaviour. Applying appropriate techniques on a long archive of imagery (IE that provided by Landsat) can permit knowledge of flow behaviour and change through time across large spatial scales, of great importance to hydrological studies including compliance related work and resulting water policy development.

Water detection algorithms are generally applied to the spatial data to determine which parts of the image should be classified as water and which should not, depending on thresholds applied, hence the results are very useful to study large waterbodies such as lakes, on-farm storages, irrigation bays and ring tanks as well as wide river channels and irrigation channels, given the limitations inherent to the resolution of the image.

For this work, application of water detection methods was made to the images outlined in Table 3, across the spatial scale shown in Figure 2 and combined with the gauge data outlined above to:

- provide an ability to track the Northern Connectivity Event as it progressed through the various river systems,
- to see if any flow moved into the surrounding landscape (i.e. filling of wetlands), and
- to measure the presence or absence of water in irrigation bays, storages, dams and channels during the event and measure any changes if they were seen to occur, during a time when no consumptive extraction was permitted.

There are many different methods which can be used to classify water, all based on the inherent properties of water. These properties reflect near infra-red radiation while absorbing visible wavelengths. For this work the MDBA has investigated the use of three water detection methods, namely:

- Normalized Difference Water Index (NDWI),
- Modified Normalized Difference Water Index (MNDWI), and
- Supervised Classification.

All three were tested and compared as to their suitability to the task at hand. The “NDWI” method is one of the most widely used remote sensing indices for water measurement, and is found from the difference between the green and near-infrared bands and normalizes this difference to give each pixel a value between -1 and 1, calculated using the McFeeters (1996) equation as follows:

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

An example of how the NDWI method can detect water in a stretch of Darling River channel between Tilpa and Wilcannia is seen in Figure 7, for a Sentinel 2 image taken on the 4$^{th}$ April and the 19$^{th}$ May 2018, superimposed on the colour image of that same day. The increase in water present in the channel as the flow increased is clear, which reconnects the previously disconnected river. This water originated in a rainfall event in Queensland, which preceeded the Northern Connectivity Event but illustrates the method well.

Figure 7: Example colour image of a reach of the Darling River between Tilpa and Wilcannia taken on the 4th April and the 19th May 2018 with water as detected by the NDWI method highlighted in blue. The water in this case originated in a rainfall event that preceeded the Northern Connectivity Event.

The "MNDWI" is a second method to apply for water detection which is very similar but instead of the Near Infrared band, a short-wave infrared (SWIR) band is used, calculated as follows:

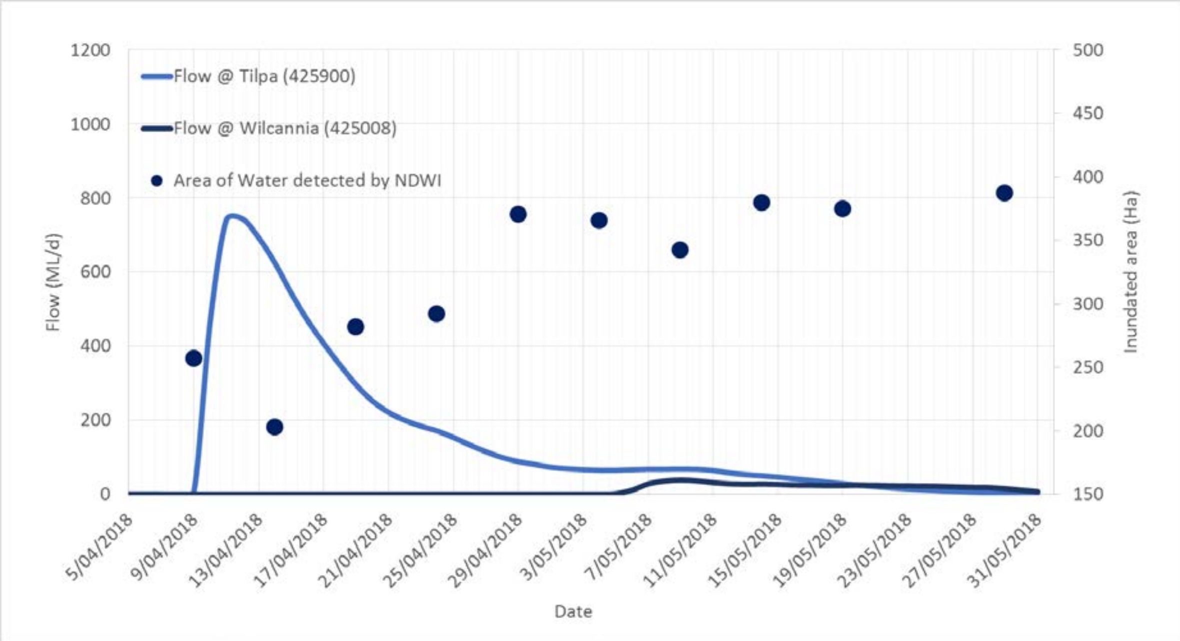
$$MNDWI = \frac{Green - SWIR1}{Green + SWIR1}$$

MNDWI is known to classify water in built-up areas with greater accuracy than the NDWI but is however considered more susceptible to contamination by cloud, with an increased chance of resulting commission errors (Du et al 2016). This was seen to occur during testing for this work.

"Supervised classification" is a third more user-driven method, whereby a user manually creates samples from a colour (or any) image which are known to be water bodies (IE open water bodies). The characteristics of these samples are then applied to determine which other parts of the image contain pixels of the same (or very similar) spectral properties and are hence also likely to be similarly classified as water bodies. For this work the NDWI method was chosen due to the ease of application and apparent robust nature of the results, with both MNDWI and Supervised Classification produces results with significant commission errors.

Figure 8 illustrates the choice to use NDWI further by an application of the method for all Sentinel 2 satellite images obtained for April and May 2018 covering the area between Tilpa and Wilcannia on the Darling River as an example. The total area of water detected in the river reach increases commensurate with the passage of the rainfall flow through the reach (a flow which preceded the Northern Connectivity Event), indicating the ability of the method to detect changes to the amount of water present in the river channel, consistent with increasing flow. The images for these dates were also checked visually with the NDWI method detecting the water consistently with that seen by eye.

Figure 8: Gauge flows measured at Tilpa and Wilcannia showing the passage of the flow, and the total area of water detected in the river channel for each satellite image covering the same period.




Further detailed work is needed to fully quantify the ability of each of these three methods under all circumstances, but it was found that for the purposes of a trial and pilot study, the ease of application, the success of detecting water when compared to that seen by eye and the long provenance of the NDWI method was enough reason for application in this case.

# Imagery for Crop Extent & Native Vegetation Condition

As per combining wavelengths to produce the NDWI results, combining wavelengths in a different way produces the standard Normalized Difference Vegetation Index (NDVI), which, instead of detecting water, can be used to measure the apparent "greenness" of pixels in the image. Greenness in this case is taken as a proxy for detecting different types of vegetation and its condition, and for compliance purposes the presence of crops.

NDVI is again a standard analysis technique with a long history of use and utilizes the difference between the near-infrared and red bands, which highlights the presence of chlorophyll (rather than water) and normalizes this difference to give each pixel a value between -1 and 1. This allows statistical studies into greenness distributions in the landscape. The higher the value the greater the "greenness", which is typically taken as a proxy for vegetation health and for crop presence. The NDVI value is calculated using the following formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

As crops display greenness values usually greater than that of native vegetation (depending on the crop type planted), NDVI images can reveal where crops are present in the landscape and how those crops change over time, which can be useful for studies into compliance issues.

Figure 9 shows an example of applying the NDVI algorithm to a Sentinel 2 image covering an area centered on the Terrewah gauge in the Border Rivers catchment, as taken on the 3rd April 2018. As displayed, the darker the green colour, the higher the NDVI value, hence that part of the image has a higher NDVI "greenness", which in this case is attributed to the presence of crops. The crops are presented as the dark green rectangles spread across the landscape. The bright areas in the image result from water in farm storages, which appears bright in NDVI.

Figure 9: Sentinel 2 NDVI image of an area in the Border Rivers catchment, taken on the 3rd April 2018.

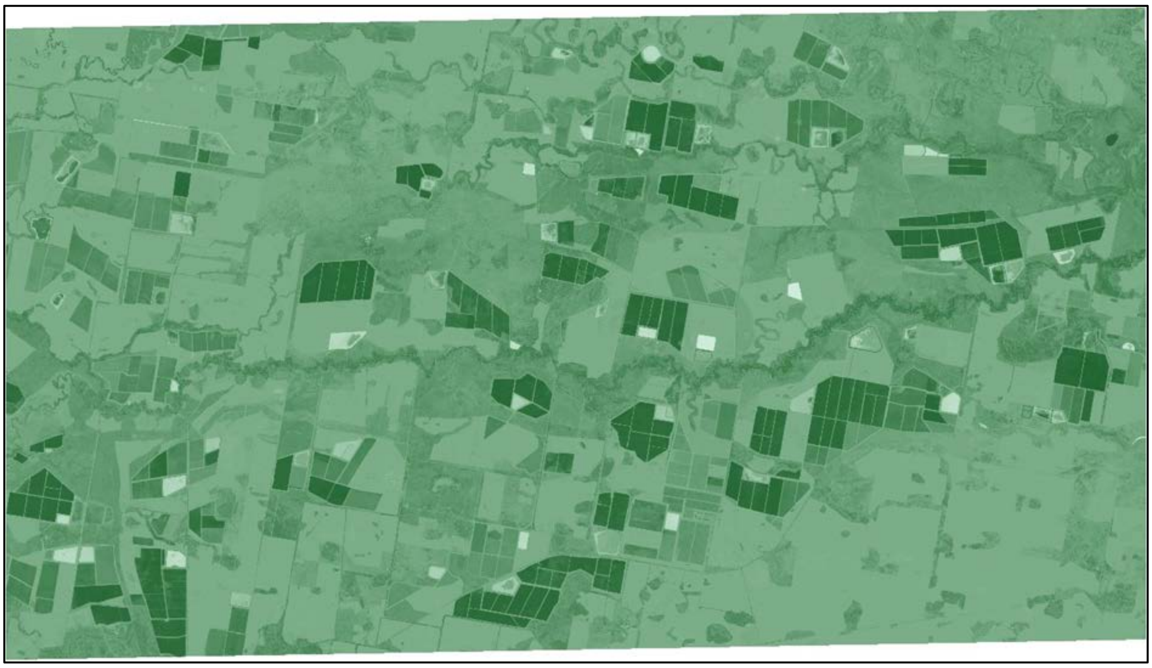
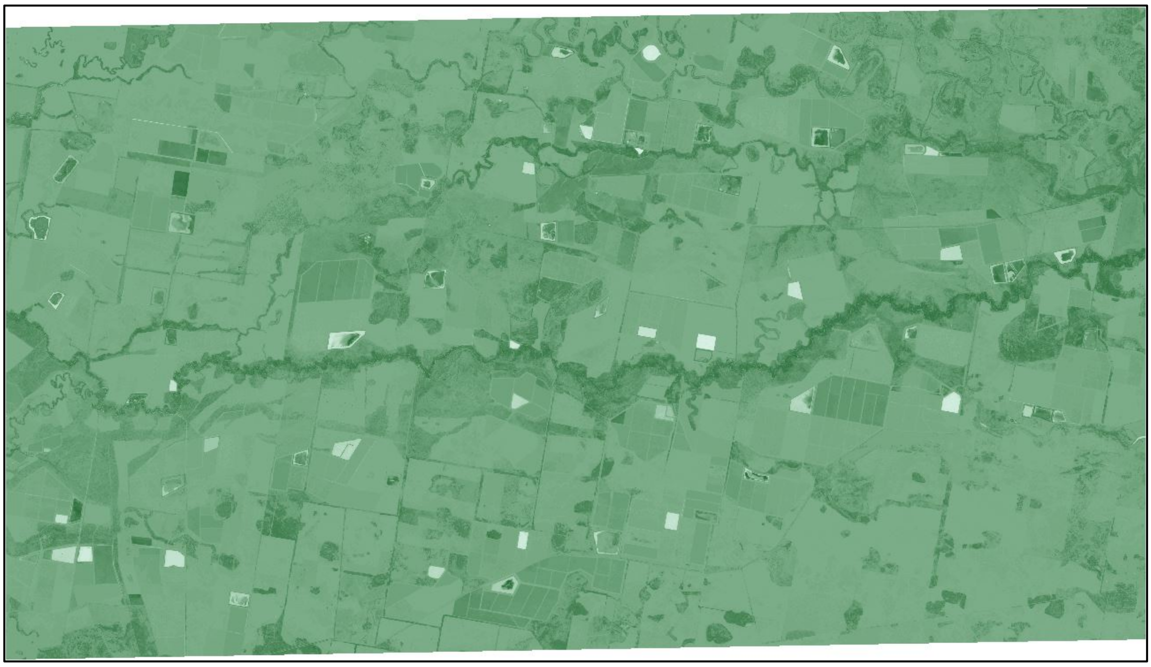


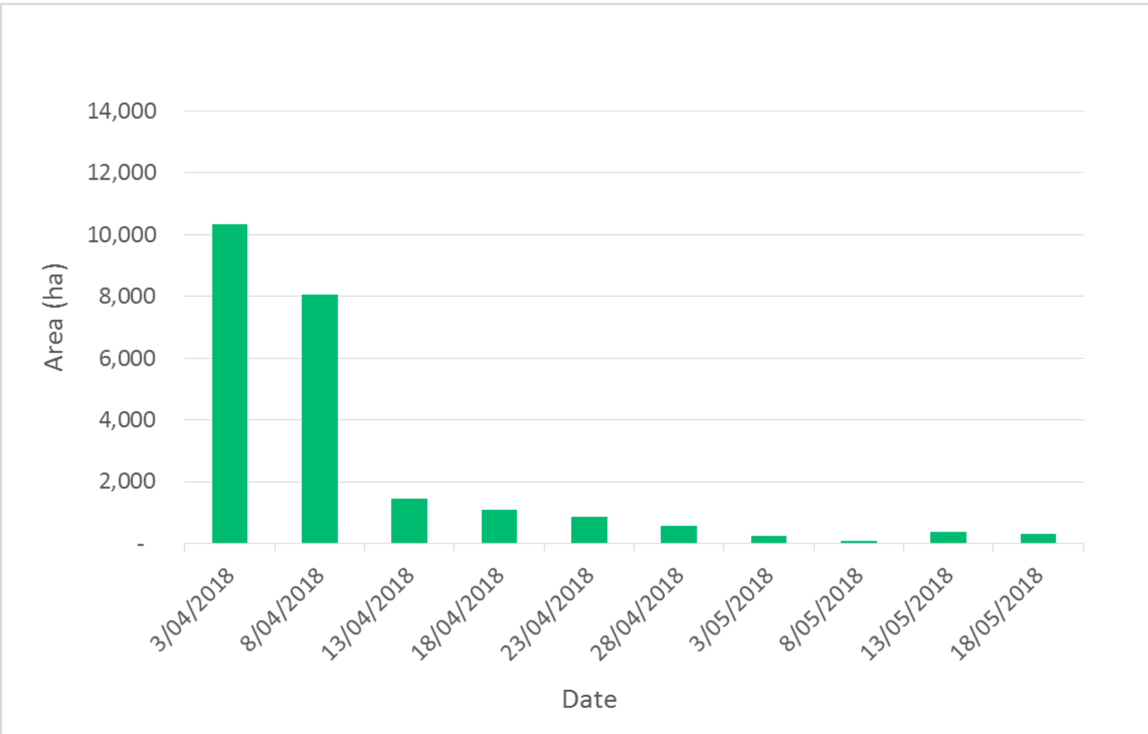
Figure 10 shows the same Terrewah location as above, but for an image taken just over 6 weeks later, on the 18th May 2018. Changes to the cropping area are clearly seen by a significant reduction in the number of "highly green" pixels what were present in Figure 9, indicating that the crops associated with that greenness are no longer as apparent, most likely they were harvested between those dates.

Figure 10: Sentinel 2 NDVI image of an area in the Border Rivers catchment, taken on the 18th May 2018.



This change is also shown in Figure 11, which shows how the total area of these highly green pixels varies as a function of time through April and May 2018. There was a large reduction in cropping between the 8th April and 13th April, which is attributed to the crop being harvested between those dates. The area of crop remains low for the remainder of the time sampled indicating little or no further planting or watering.

Figure 11: Total measured area of vegetation with greenness >0.6 for the region seen in Figure 9, as measured between 3/04/2018 and 18/05/2018.



By using information which includes NDVI greenness it is possible to measure the changes to crop area as a function of time, due to the fact most crops are typically inherently much greener (or more generally comprised of material with a very different spectral response) than the surrounding landscape. This is for use as one method available for compliance-related activities as required.

In addition to compliance uses, vegetation greenness changes can also be applied to areas of ecological significance, whereby the change in greenness could be attributed to a native vegetation response to a watering event. Such application for the Northern Connectivity Event is outlined later in this report.

## Accounting for Cloud

Satellite images are very limited in their usefulness if the day on which the image was captured was excessively cloudy. Images taken on partly cloudy days are, however, still useful if an effective cloud mask can be developed and applied, highlighting any parts of the image that are, statistically speaking, free of cloud and are available for use.

Clouds have inherent reflectance properties when observed in different wavelengths, as does water and vegetation and can, in the main, be identified by studying how brightly they appear in images taken in specific bands tailored for cloud detection, in this case the Sentinel 2 short-wave Infrared (band 10) as outlined in Table 2, which was specifically designed to detect cirrus cloud.

For this work most images were cloud free, but for future use when required a cloud mask was developed and is currently being tested which studies the statistical properties of the image as seen in the cirrus band 10. The work is based on the premise that the brighter the pixel as seen in this band, the more likely it is that the pixel contains cloud, with the likelihood of cloud being present based on a quantile analysis of the pixel distribution across the whole image. The first quantile is assumed to be cloud free, with increasing probability of cloud presence the higher the short-wave infrared reflectance. Images are always also visually inspected for cloud, and this cloud masking technique is currently being tested and modified for future use.

To illustrate the broad method, an example cloudy image as seen on the 9$^{th}$ May 2018 for an area surrounding Wilcannia is shown in Figure 12, covering the same spatial area as Figure 6 for comparison.

Figure 12: A cloudy image near Wilcannia taken on the 9th May 2018, covering the same spatial area as Figure 6.

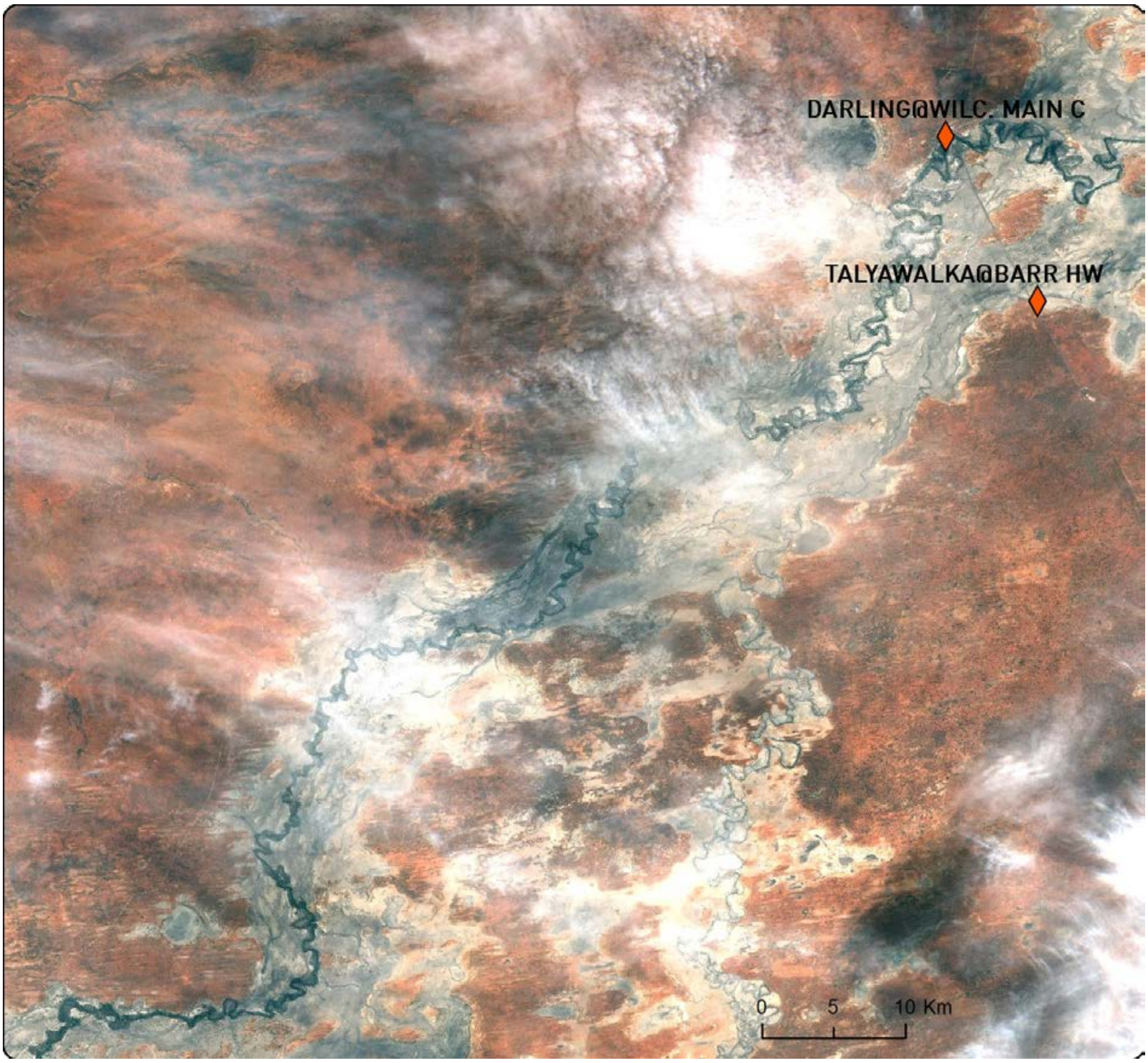
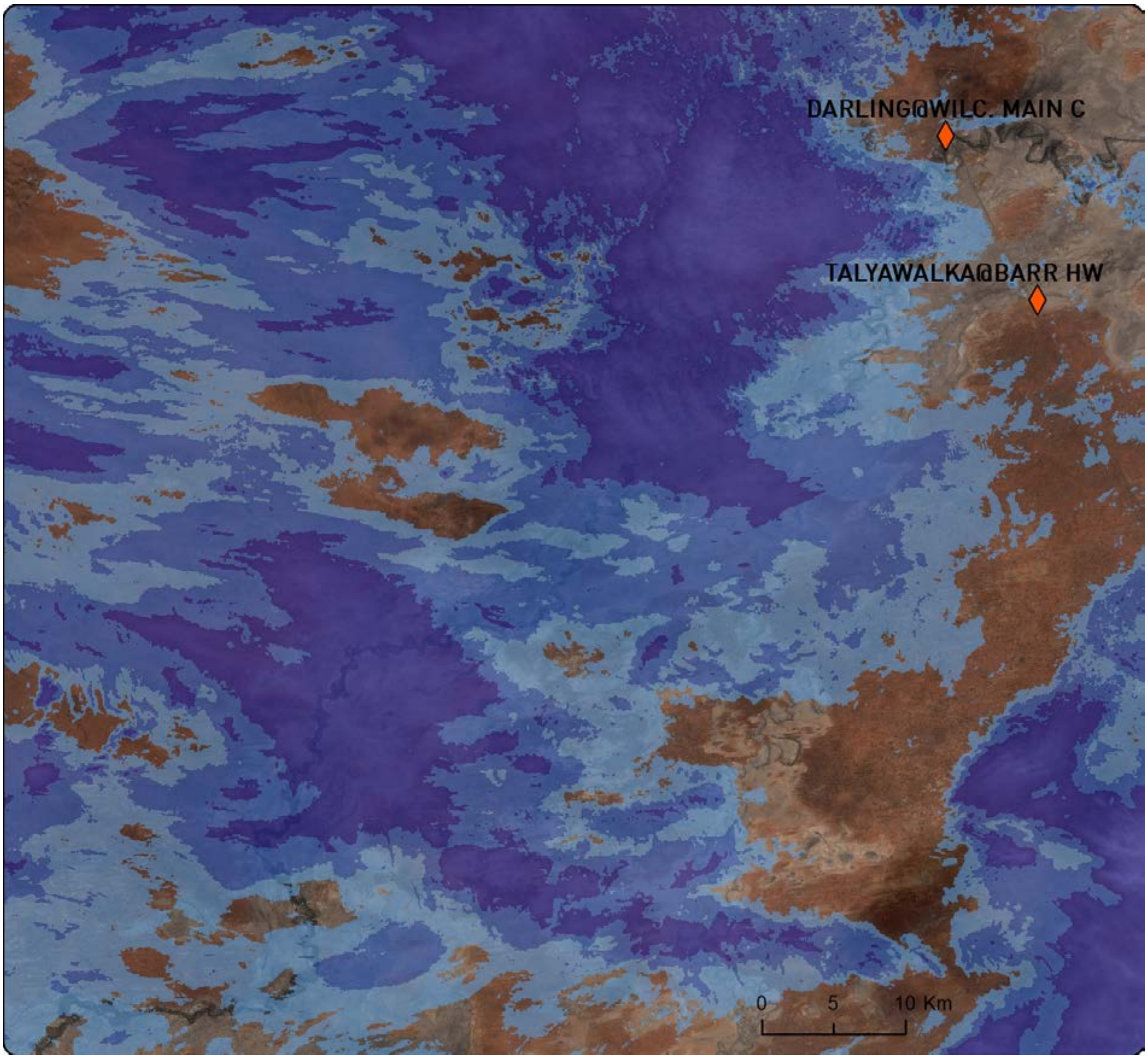



Figure 13 shows the results of applying the cloud detection technique to the image above, with the darker blue indicating the higher probability that cloud is present at that part of the image. Some parts of the image are classified as cloud-free and are hence still available for more detailed analysis. It can also be seen that cloud shadows are not fully accounted for, which require different masking techniques which are currently being developed.

Figure 13: The results of applying the cloud masking technique to the image seen above.




This cloud masking technique is a one example of how parts of the image can be effectively 'blocked out' if they are statistically classified as containing cloud, hence the results obtained when using the images for compliance purposes can be made more robust. No cloud mask technique is perfect and can therefore only be used as an indication of cloud presence. Visual inspection of the images will always be necessary, and for excessively cloudy days the image is simply discarded.

Future work includes investigating the inclusion of Sentinel 1 imagery, which uses synthetic aperture radar. Radar can see through the clouds, hence making the need for cloud masking less relevant and allowing for more continuous monitoring of the landscape, irrespective of cloud.

# Results

## Monitoring Flow Progress through the Landscape

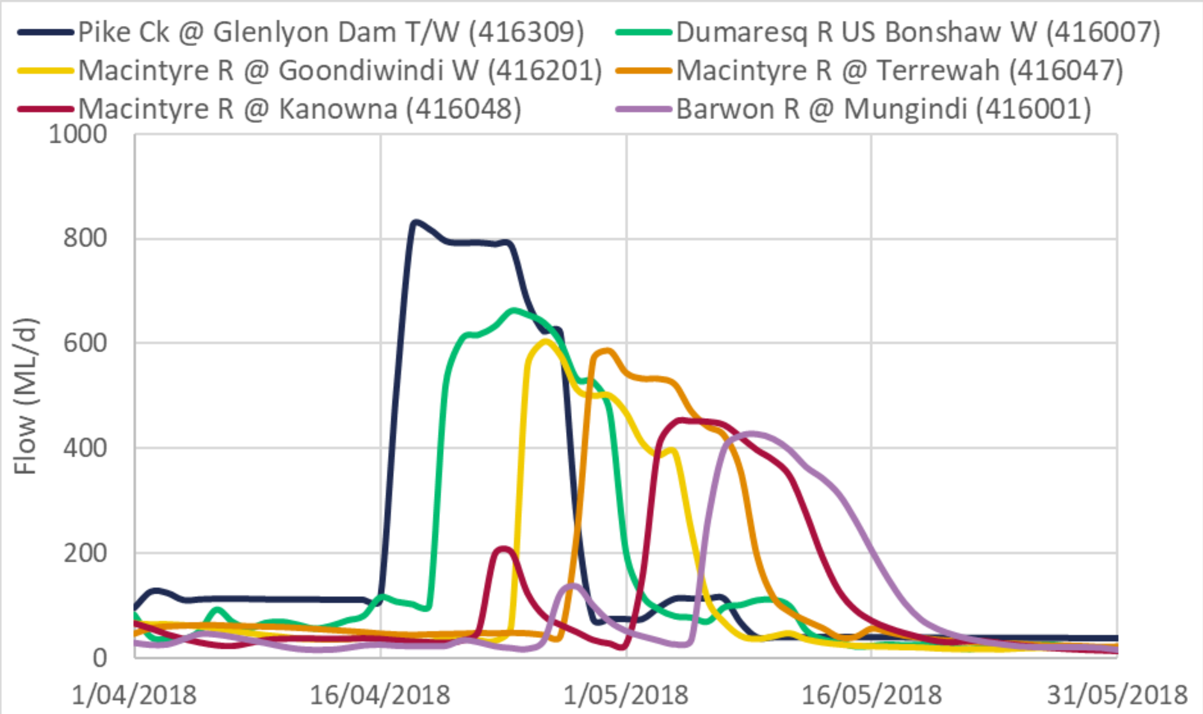
To analyse the Northern Connectivity Event, the MDBA used observed flow data recorded in April, May, June and July for 28 gauges throughout the Gwydir, Border Rivers and Barwon–Darling catchments, the locations of which are shown in Figure 3, Figure 4 and Figure 5 respectively. Observed flow data was used to inform where and when the flow was at any given time, which gave an indication of where and when satellite imagery could be used to best advantage. Observed flow data was also used to analyse the hydrological properties of the event as it travelled downstream. This includes the volume and duration of the event, the magnitude and timing of the peak of the event and the travel time of the event between upstream and downstream gauges.

Such information can be used to study how the overall flow properties behave as the flow progresses. If any unexpected changes occur, such as sudden significant decreases in flow volume or other properties (for example the anomalous event presented in MDBA 2018), it would raise a compliance flag and indicate the need for further investigation. For this work, the event was studied in this way specifically to see if any sudden significant changes occurred, rather than comparing the attenuation of the event to a catalogue of similar historical events, which forms part of a future work program.

### Border Rivers

Flow releases from Glenlyon Dam began on 17th April and continued for 12 days. The event then travelled through the Dumaresq River, into the Macintyre River and then entered the Barwon River. Figure 14 shows the hydrograph of the event at various gauges within the Border Rivers catchment, as seen from the publicly available gauge data, indicating the changes to the properties of the flow as it progressed downstream.

Figure 14: Hydrograph of the northern connectivity event in the Border Rivers catchment




The event is clearly shown on the hydrograph at each of the six gauges. Before the flow was released from Glenlyon dam, flows in the Border Rivers system were low at less than 100 ML/d gauged at the downstream sites. The northern connectivity event had a peak of around 800 ML/d at Glenlyon Dam. As it travelled through the system, the event peak gradually reduced as the event was attenuated.

From the flow data above, the hydrological properties of the event at each of the gauges were determined. These are shown in Table 4 below.

Table 4: Hydrologic properties of the event throught the Border Rivers catchment

| Site | Start Date | Duration (days) | Peak Flow (ML/d) | Peak Date | Event Volume (GL) | Travel Time from previous gauge (days) |
|---|---|---|---|---|---|---|
| **Pike Ck @ Glenlyon Dam T/W** | 17/04/2018 | 12 | 825 | 18/04/2018 | 8.3 | - |
| **Dumaresq R US Bonshaw W** | 20/04/2018 | 17 | 662 | 24/04/2018 | 7.1 | 6 |
| **Macintyre R @ Goondiwindi W** | 25/04/2018 | 15 | 604 | 26/04/2018 | 5.4 | 2 |
| **Macintyre R @ Terrewah** | 28/04/2018 | 17 | 585 | 30/04/2018 | 5.8 | 4 |
| **Macintyre R @ Kanowna** | 2/05/2018 | 20 | 451 | 5/05/2018 | 4.8 | 5 |

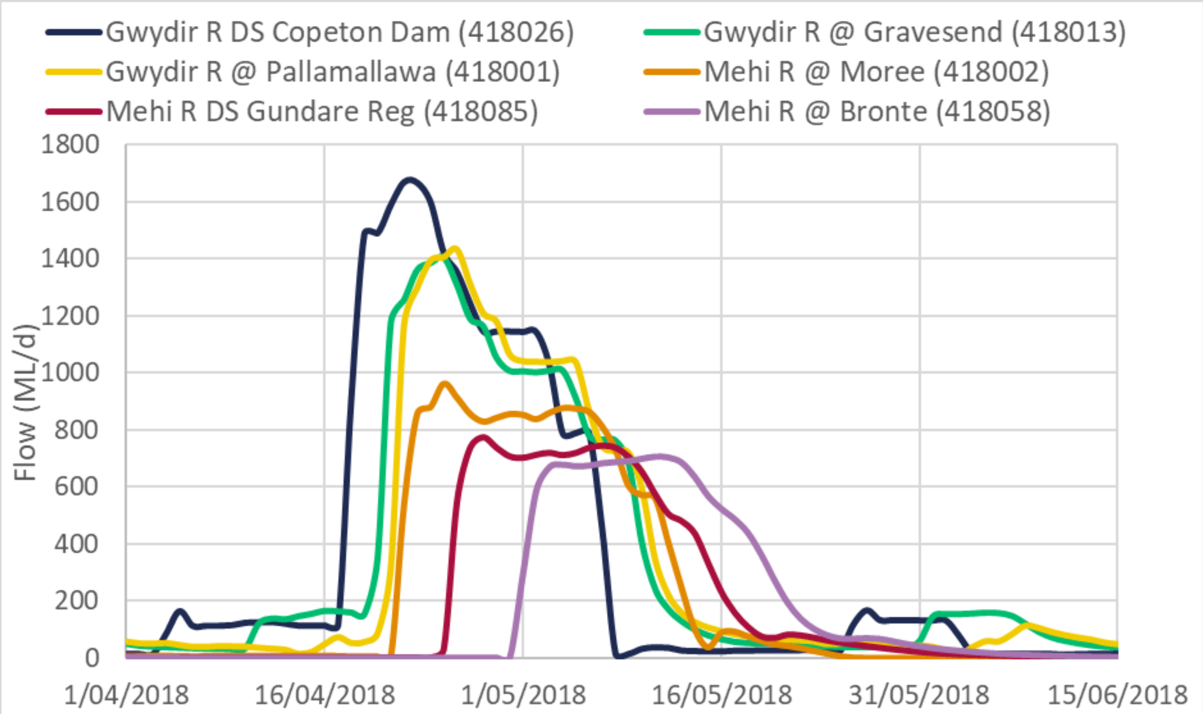
| Site | Start Date | Duration (days) | Peak Flow (ML/d) | Peak Date | Event Volume (GL) | Travel Time from previous gauge (days) |
| --- | --- | --- | --- | --- | --- | --- |
| **Barwon R @ Mungindi** | 6/05/2018 | 33 | 428 | 9/05/2018 | 4.5 | 4 |

Nineteen days after the release from Glenlyon Dam began, the front of the flow event reached Mungindi at the end of the Border Rivers system. As the event progressed, the flow peak reduced from 825 ML/d to 428 ML/d and the volume reduced from 8.3 GL to 4.5 GL as measured. The duration of the event increased from 12 days to 33 days. Reductions in volume and increases in duration of this nature are expected to result from natural attenuation as the flow event progresses through the system. For the flow in this case no sudden or significant changes were observed to the hydrograph properties indicating no significant flow extraction occurred.

## Gwydir

Flow releases from Copeton Dam began on 17th April and continued for 20 days. The event travelled down the Gwydir River to Pallamallawa, downstream of which the bulk of the event travelled through the Mehi River into the Barwon Darling. Small flows were present in the Moomin Creek, peaking at just over 50 ML/d. A portion of the flow also travelled through the lower Gwydir system, peaking at 120 ML/d at Yarraman Bridge and approximately 25 ML/d at Millewa. A significant portion of the flow also travelled from the Gwydir River and into the Carole Creek. It then flowed into Gil Gil Creek before entering the Barwon River. Figure 15 shows the hydrograph of the event at gauges along the Gwydir and Mehi rivers.

Figure 15: Hydrograph of the northern connectivity event in the Gwydir catchment




The event was released from Copeton Dam and peaked at around 1,700 ML/d. As it travelled through the Gwydir and Mehi systems, the flow peak gradually reduced, and the shape of the hydrograph attenuated.

The hydrological properties of the event in the Gwydir system as measured from this data are shown in Table 5 below.

Table 5: Hydrologic properties of the event throught the Gwydir catchment

| Site | Start Date | Duration (days) | Peak Flow (ML/d) | Peak Date | Event Volume (GL) | Travel Time from previous gauge (days) |
|---|---|---|---|---|---|---|
| **Gwydir R DS Copeton Dam** | 17/04/2018 | 20 | 1671 | 22/04/2018 | 24.0 | - |
| **Gwydir R @ Gravesend** | 20/04/2018 | 37 | 1402 | 25/04/2018 | 22.2 | 3 |
| **Gwydir R @ Pallamallawa** | 21/04/2018 | 44 | 1435 | 26/04/2018 | 22.7 | 1 |
| **Mehi R @ Moree** | 22/04/2018 | 24 | 964 | 25/04/2018 | 16.8 | - |
| **Mehi R DS Gundare Reg** | 25/04/2018 | 26 | 774 | 28/04/2018 | 13.6 | 3 |
| **Mehi R @ Bronte** | 1/05/2018 | 26 | 706 | 11/05/2018 | 12.4 | 13 |

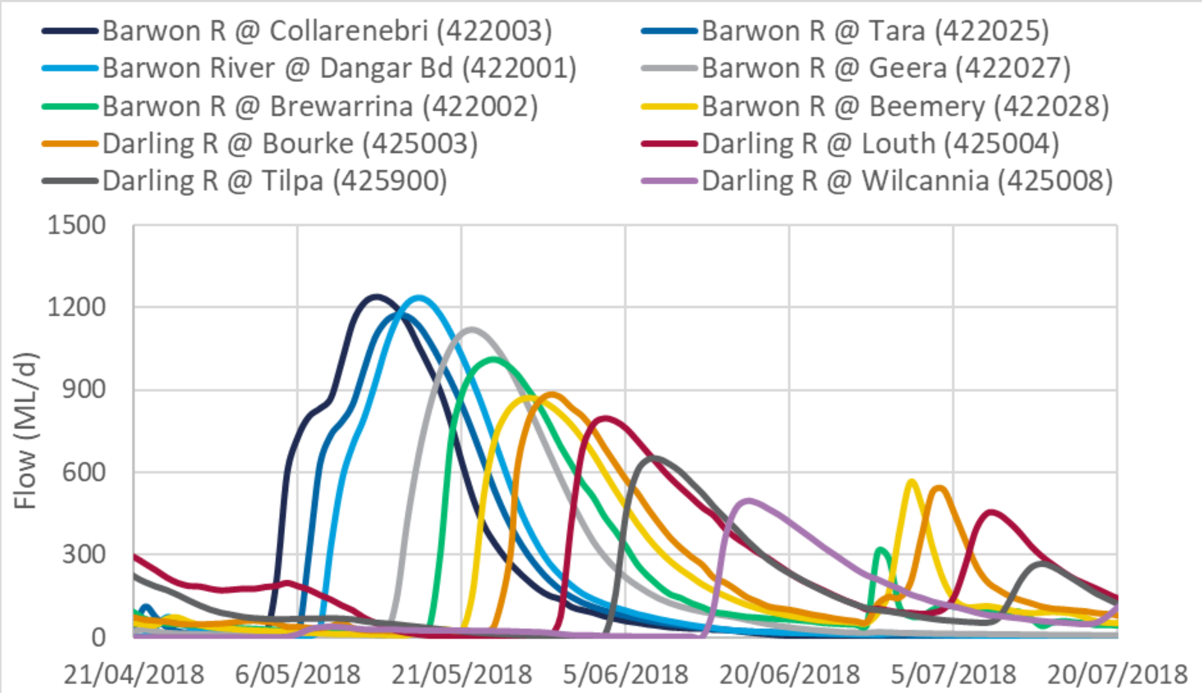
| Site | Start Date | Duration (days) | Peak Flow (ML/d) | Peak Date | Event Volume (GL) | Travel Time from previous gauge (days) |
|---|---|---|---|---|---|---|
| **Moomin Ck @ Glendello** | 27/04/2018 | 34 | 53 | 7/05/2018 | 1.0 | 12 |
| **Moomin Ck @ Moomin Plains** | 8/05/2018 | 36 | 54 | 13/05/2018 | 0.6 | 6 |
| **Gwydir R @ Yarraman Bd** | 2/05/2018 | 27 | 120 | 3/05/2018 | 0.7 | 7 |
| **Gwydir R @ Brageen Crossing** | 3/05/2018 | 17 | 96 | 4/05/2018 | 0.4 | 1 |
| **Gwydir R @ Millewa** | 8/05/2018 | 20 | 25 | 13/05/2018 | 0.2 | 9 |
| **Gil Gik Ck @ Galloway** | 30/04/2018 | 35 | 240 | 9/05/2018 | 4.3 | - |

Two weeks after the release from Copeton Dam began, the front of the flow event reached the Bronte gauge on the Mehi River at the end of the Gwydir system. As the event continued to travel, the flow peak reduced from 1,671 ML/d to 706 ML/d and the volume reduced from 24 GL to 12.4 GL. The duration of the event increased a small amount from 20 days to 26 days. As per the Border Rivers, reductions in volume and increases in duration of this nature are expected to result from natural attenuation as the flow event progresses through the system. For the flow in this case no sudden or significant changes were observed to the hydrograph properties, again indicating no significant extraction of the flow occurred.

## Barwon–Darling

After reaching Collarenebri on the 4th May, the Northern Connectivity Event travelled downstream within the Barwon and Darling rivers towards Menindee Lakes. The flow data was closely monitored as the event travelled through the Barwon–Darling system to ensure the event properties were not undergoing any sudden, unexpected and significant changes, as per the Border Rivers and Gwydir. Figure 16 presents the hydrograph of the event at key gauges as measured along the Barwon–Darling River.

Figure 16: Hydrograph of the northern connectivity event in the Barwon–Darling catchment




As seen above, the flow peak gradually reduced as it travelled along the Barwon–Darling due to attenuation. At Collarenebri, the peak was above 1,200 ML/d and at the most downstream gauge, Wilcannia, the flow peak was around 500 ML/d. A small rise in flow is seen for gauges downstream of Geera after the connectivity event passed through, which is attributed to rainfall at Brewarrina which occurred on the 27th and 28th June.

Earlier in the year a previous rain event occurred resulting in an unregulated flow event passing through the Barwon–Darling system which preceded the Northern Connectivity Event. This rainfall flow had a peak of around 1,700 ML/d as measured at Bourke and, by the time it reached Wilcannia, flows were as low as 40 ML/d. Losses of the unregulated event were significantly greater than the Northern Connectivity Event. This is because, as the unregulated event travelled through the system, much of the volume was used to fill the many weir pools along the river and wet the dry river bed. Later in the year, when the Northern Connectivity Event occurred, the river channel was hence wetter and weir pools were filled which resulted in the smaller reduction in the peak and volume of the event.

The hydrological properties of the event in the Barwon–Darling system are shown in Table 6.

Table 6: Hydrologic properties of the event throught the Barwon–Darling catchment

| Site | Start Date | Duration (days) | Peak Flow (ML/d) | Peak Date | Event Volume (GL) | Travel Time from previous gauge (days) |
|---|---|---|---|---|---|---|
| **Barwon R @ Collarenebri** | 4/05/2018 | 71 | 1238 | 13/05/2018 | 19.9 | - |
| **Barwon R @ Tara** | 7/05/2018 | 71 | 1174 | 15/05/2018 | 18.8 | 2 |

| Site | Start Date | Duration (days) | Peak Flow (ML/d) | Peak Date | Event Volume (GL) | Travel Time from previous gauge (days) |
|---|---|---|---|---|---|---|
| **Barwon River @ Dangar Bd** | 8/05/2018 | 76 | 1237 | 17/05/2018 | 18.9 | 2 |
| **Barwon R @ Geera** | 15/05/2018 | 70 | 1120 | 22/05/2018 | 17.1 | 5 |
| **Barwon R @ Brewarrina** | 19/05/2018 | 40 | 1009 | 24/05/2018 | 15.1 | 2 |
| **Barwon R @ Beemery** | 22/05/2018 | 37 | 873 | 27/05/2018 | 13.7 | 3 |
| **Darling R @ Bourke** | 24/05/2018 | 35 | 884 | 29/05/2018 | 13.0 | 2 |
| **Darling R @ Louth** | 30/05/2018 | 34 | 797 | 3/06/2018 | 12.6 | 5 |
| **Darling R @ Tilpa** | 4/06/2018 | 35 | 648 | 8/06/2018 | 9.4 | 5 |
| **Darling R @ Wilcannia** | 13/06/2018 | 35 | 495 | 16/06/2018 | 7.4 | 8 |

Twenty days after the event first reached Collarenebri, the front of the flow event arrived at Bourke, a further 20 days later the front of the flow event arrived at Wilcannia. As the event travelled through the Barwon–Darling system, the flow peak reduced from 1,238 ML/d to 495 ML/d and the volume reduced from 20 GL to 7.4 GL. Again, reductions in volume and increases in duration of this nature are expected to result from natural attenuation as the flow event progresses through the system. For the flow in this case no sudden or significant changes were observed to the hydrograph properties which again indicates no significant extraction of the flow occurred.

# Water Present in Farm Storages and Dams

For compliance purposes, the progress of the northern connectivity flow as measured through hydrograph analysis (previously described) was coupled with monitoring of the total area of water present in farm dams and storages throughout the Barwon–Darling catchment from Mungindi to the Menindee Lakes. This was to provide information on the area of water that was present in farm dams and storages across the region, and importantly how that area changed during the event, to couple with understanding the behaviour of the flow and for use if any significant changes were seen to the properties of the flow as it progressed.

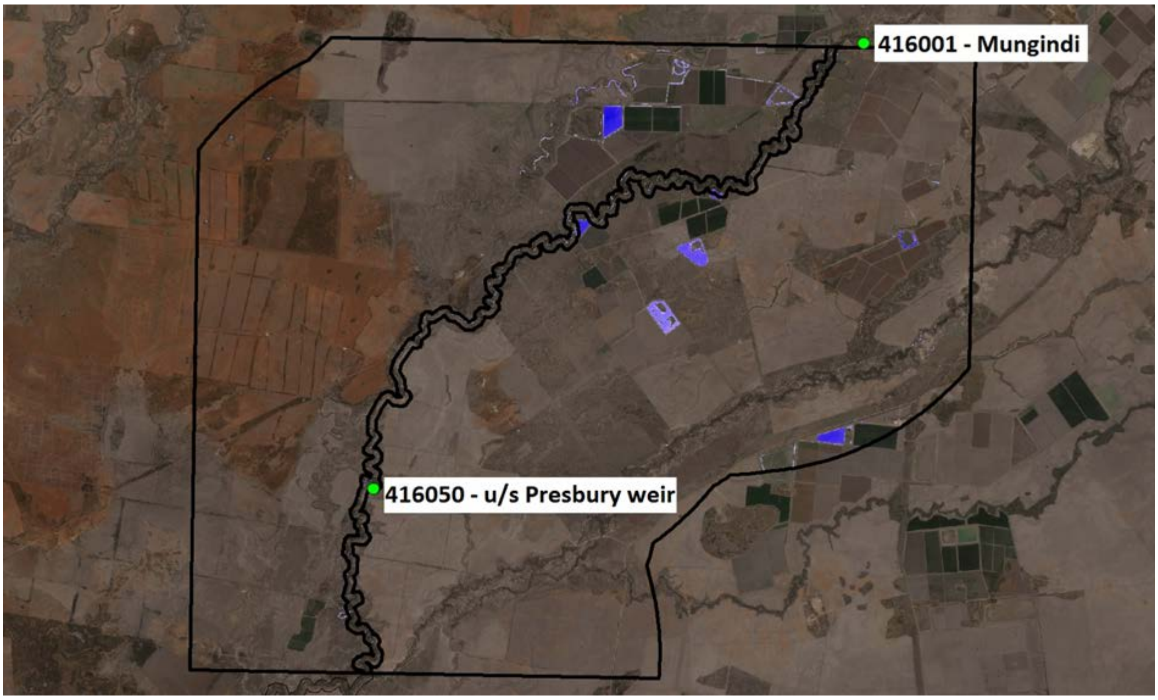
The overall premise was that if a storage is empty, and no extraction was permitted, then no increase in area of water in that storage would be reasonably expected to occur while the flow event was underway. Similarly, if a farm storage is full, no further increase in area would be expected to occur. If water was seen to enter a farm storage, it would indicate that a portion of the flow may have been extracted, which can be tested further by investigating the changing properties of the hydrograph. Hence remotely sensing water area in storages as seen by satellite images, when coupled with the hydrograph information, provides an extra line of evidence to indicate if a compliance issue has occurred.

For this work, the Barwon–Darling catchment was divided into the same zones as defined for the Barwon–Darling water sharing plan (NSW 2012). Each zone was further divided into a floodplain and river/riparian zone, which allowed for a more considered analysis of where water was detected in the landscape, and where major changes were located if seen.

The river/riparian zone was defined by applying a 150m buffer around the main channel of the river and to define the floodplain a 10km buffer was used, chosen arbitrarily. The total area of water as detected by the NDWI method within each of these two buffers was then found for each image within each zone and the changes measured during the course of the event.

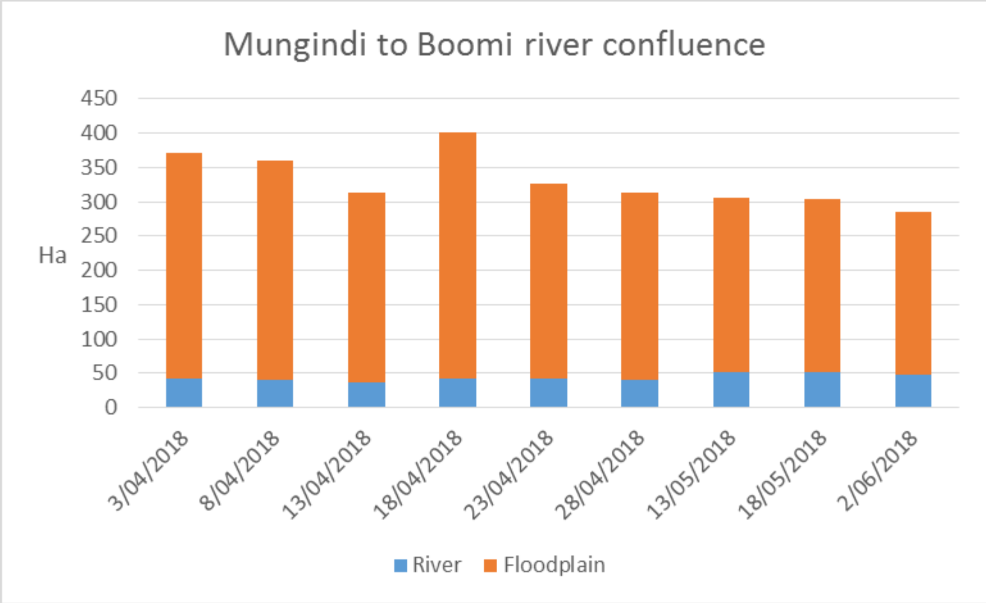
This is illustrated in Figure 17 below, which shows the Mungindi to U/S Presbury Weir zone as an example, as seen by Sentinel 2 on the 3rd April 2018, and with the gauge locations highlighted, the buffer to define the river and floodplain and the presence of water in farm dams and storages highlighted in blue for that zone. The total area of water present (highlighted in blue) was calculated for this image and repeated for each satellite image available, and the trends observed.

Figure 17: The Mungindi to U/S Presbury Weir zone as seen by Sentinel 2 on the 3rd April 2018 as an example of how total area of water in farm dams was analysed for this work. Trends over time were measured to check for possible compliance issues.




The degree to which water detected in this zone changed during the connection event is seen in Figure 18 below, for both water present within the river and floodplain buffer. As can be seen, no significant or enduring change in water area measured in farm dams and storages was seen during the event for this zone. This, when combined with a lack of sudden and significant changes to the event hydrograph for this zone, indicates a low probability for a significant compliance issue being present, based on this method. Results for the remaining zones as analysed are presented in Appendix A.

Figure 18: The degree to which the total area of water detected in the river and floodplain (which includes farm dams and storages) changed for the Mungindi to U/S Presbury Weir zone as an example during the course of the period when the limit on extraction occurred. By this method large changes to the area which endure would indicate a possible compliance issue requiring further investigation.




The method employed here can detect circumstances if water is not present in a farm dam or storage which is subsequently filled and can also detect storages that were full and subsequently empty. If, however a storage is already full, it cannot determine changes to the volume present in that storage, hence cannot be applied under all circumstances. For such cases where full storages are "topped up", the method would rely more on understanding the changed properties of the flow hydrograph.

For the northern connectivity event, the flow event was not seen to undergo significant and sudden changes to flow properties from the hydrograph analysis, nor was a significant, sudden and enduring increase seen to the total area of water present in farm dams and storages studied during the temporary limitation on consumptive extraction, indicating a low probability of a significant compliance issue being present based on this method.

# Changes Seen

Although no sudden and significant increases in farm storage water area were measured, changes were seen in the landscape during the course of the Northern Connectivity Event, involving the draining of large irrigation storages. Such changes **do not in this instance imply a compliance issue**, as the storages did not subsequently refill, but is described here as an example of the changes that were seen.

The most significant of these storages seen to drain was located downstream of Collarenebri and upstream of Walgett on the Barwon River and is shown in Figure 19 and Figure 20 below. This particular storage measures 1km on a side, and as seen below was observed to be filled with water on the 28th April 2018 (Figure 19, circled) and was subsequently drained by the 13th May (Figure 20, also circled). The water present in the storage as detected by the NDWI method has been highlighted in blue and superimposed on the colour image taken on that same day. Also note the smaller storage located to the bottom left of the image has also partly dried during these two dates.

Figure 19: NDWI water detection result superimposed on a colour image of a large irrigation storage (circled) located downstream of Collarenebri and upstream of Walgett that was seen to be filled with water on the 28th April 2018.

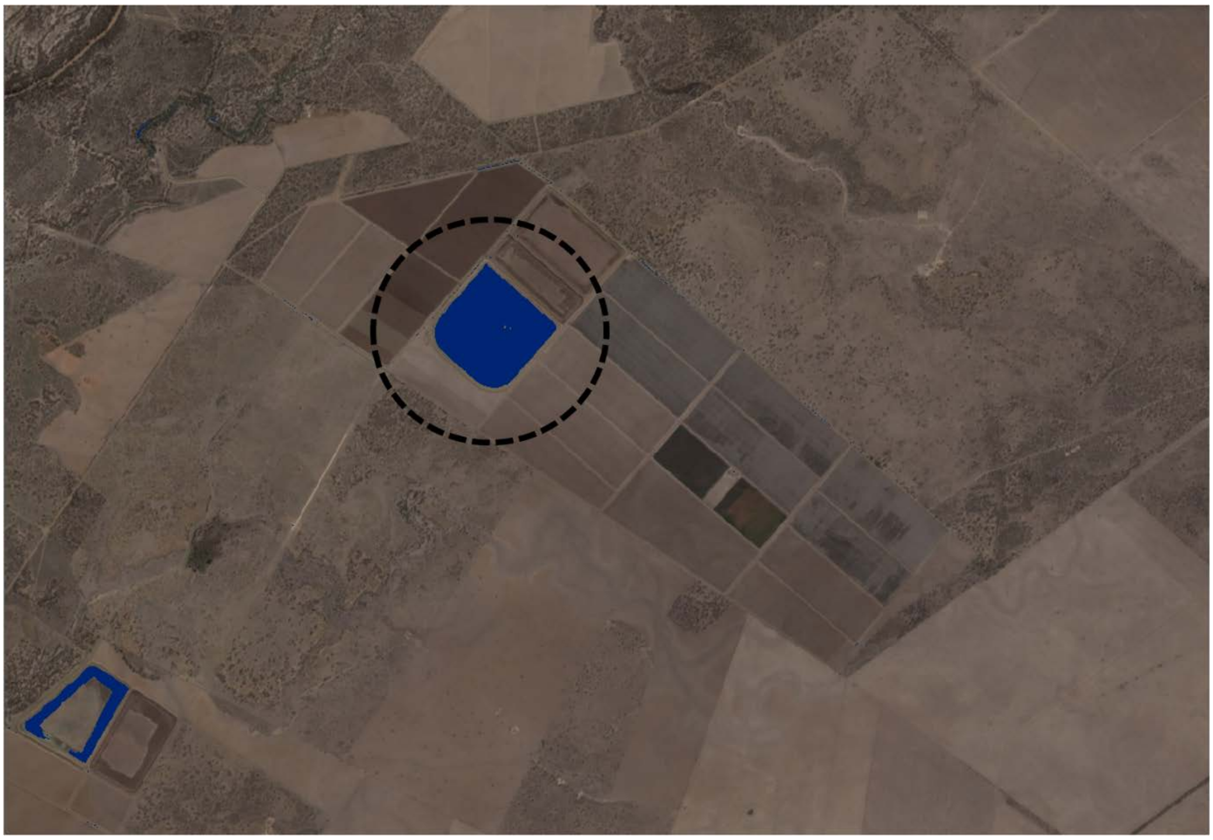
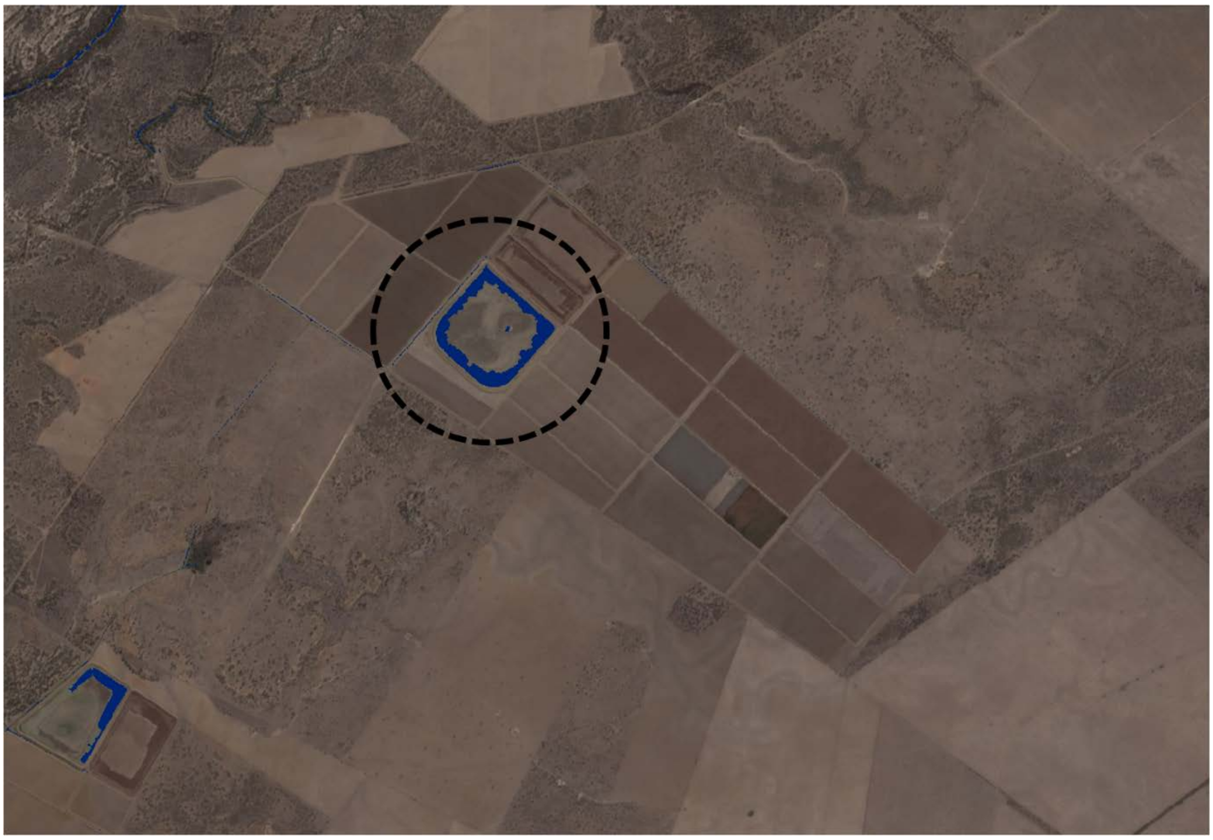


Figure 20: The same area as above as seen on the 3rd May 2018, with the large irrigation storage drained (also circled). Some drying of the second smaller stoarage in this region can also be seen to have occurred.



# Satellite Imagery as a Test Case for Ecological Monitoring

## Water Quality Changes

Water quality improvement is one of the key outcomes desired from environmental flow delivery in general, and is a major outcome sought from the Basin Plan, with water quality improvements being of great importance to communities across the Basin. Salinity improvements, the flushing of algal blooms and improvements to water composition and are three of many ways in which environmental water delivery can and does assist greatly.

In a true colour image water discolouration which results from the presence of algae can be seen, as does a difference in water colour due to differing water composition (for example the presence of lack of suspended clays). True colour imagery was used to observe changes to water colour in this way for the Northern Connectivity Event, hence inferring water quality improvements. This provides examples of how satellite imagery can be used for such monitoring remotely over large spatial scales.

## Gwydir (Mehi River)

In the Gwydir catchment, the bulk of the water released from Copeton Dam travelled to the Barwon River via the Mehi River. The flow arrived at Collarenebri, downstream of the confluence of the Mehi and Barwon rivers, around the 4th May. Prior to this the Barwon River experienced very low flows for more than a month and water quality as a result was very poor.

The change in water colour due to the different sources of water were seen in the Sentinel 2 images. Figure 19 shows a true colour image of the confluence of the Mehi and Barwon Rivers taken on the 28$^{th}$ April, prior to the arrival of the connection event. The Barwon River channel shows water which is light brown in colour (circled), considered to result from containing large amounts of suspended clays and other solids originating from further upstream.

Figure 21: True colour image produced from Sentinel 2 data of the confluence of the Mehi and Barwon Rivers taken on the 28th April 2018.

The Northern Connectivity Event brought fresher water through the Mehi River and into the Barwon River. This is evident in Figure 20 below, an image of the same location taken five days later on the 3rd May. The environmental water is darker in colour (also circled), seen entering the Barwon from the Mehi and moving towards the lower left of the image, as it does not contain the same degree of suspended clays, while the water originating from the Barwon River (upstream of the confluence) remains the same light brown colour. From this point a mixing of the two types of water would occur. Again, the impressive degree of detail in the landscape as seen from Sentinel 2 images is clearly shown.

Figure 22: True colour image produced from Sentinel 2 data of the confluence of the Mehi and Barwon Rivers taken on the 3rd May 2018, showing the connection event water flowing into the Barwon (circled).

## Barwon–Darling

As mentioned previously, the Barwon River had been experiencing very low flows prior to the connection event. When flows are low for a lengthy period, weir pools begin to empty and become stagnant. If temperature and other conditions are favourable, algae growth can occur along the river. Algae growth was observed in the Sentinel 2 true colour imagery at Collarenebri. This is shown in Figure 21 (circled areas) showing the Barwon River on the 23rd April, 10 days before the connection event reached Collarenebri. Algae is seen at several locations as a green discolouration along the river, particularly downstream of the bridge at Collarenebri, and in two bends of the river further upstream.

Figure 23: Image of Collarenebri on the Barwon River taken 23rd April 2018 showing algae present (circled).

Flows of up to 1,200 ML/d were recorded at Collarenebri over the next several days, with the flow peaking at 1,238 ML/d on 13th May. These flows flushed the algae from the channel, as seen below in the image taken again on the 13th May (Figure 22) with the green regions seen in Figure 21 no longer present (also circled).

Figure 24: Image of Collarenebri on the Barwon River taken 13th May 2018 showing the removal of the algae (same areas as above circled).

# Native Vegetation Condition

## Gwydir (Moomin Creek)

The monitoring of native vegetation condition and extent is another major piece of information that can be obtained from appropriate use of satellite imagery. Sentinel 2 imagery, with a resolution of

10m and with bands specifically designed for studies into vegetation detection and condition studies, (Table 2) is an excellent choice with which to undertake such work. For the connection event, NDVI analysis (described above) was also applied to test changes to the condition of native vegetation along a test site on the Moomin creek in the Gwydir catchment. This location was chosen as it provides a relatively dry location (a lengthy period since the last flow event passed through) with vegetation fringing the creek which has a good chance of showing an improvement to condition due to the environmental water passing though.

Given the low flow passing through the region (fully in channel) and the limited timeframe for which imagery was used for this work (given it takes a long time for vegetation to respond to watering), it was not expected that a significant increase in vegetation condition would be seen, however the connection event provided an excellent opportunity to test the ability of Sentinel 2 imagery for such purposes, with further work underway to further test its usefulness.

Figure 23 shows an image of the location chosen for testing if any change to vegetation condition could be discerned, taken on the 7th May 2018, centered on the Glendello gauge on the Moomin Creek. The location of vegetation fringing the creek as well as surrounding properties can be seen.

Figure 25: Colour image of the Glendello test site for monitoring native vegetation respose to the environmental flow, taken by Sentinel 2 on the 7th May 2018.

Analysis was made as to whether any change to the NDVI greenness of the vegetation could be seen which could be attributed to the passage of the environmental flow by comparing the greenness before, during and after the flow event passed through. Figure 24 presents the results, which splits the results up into discrete NDVI bins. Note only a small area of vegetation is present in this area fringing the river.

Figure 26: Comparison of NDVI greenness for a test site on the Moomin Creek to test improvements to native vegetation as a result of the environmental flow.

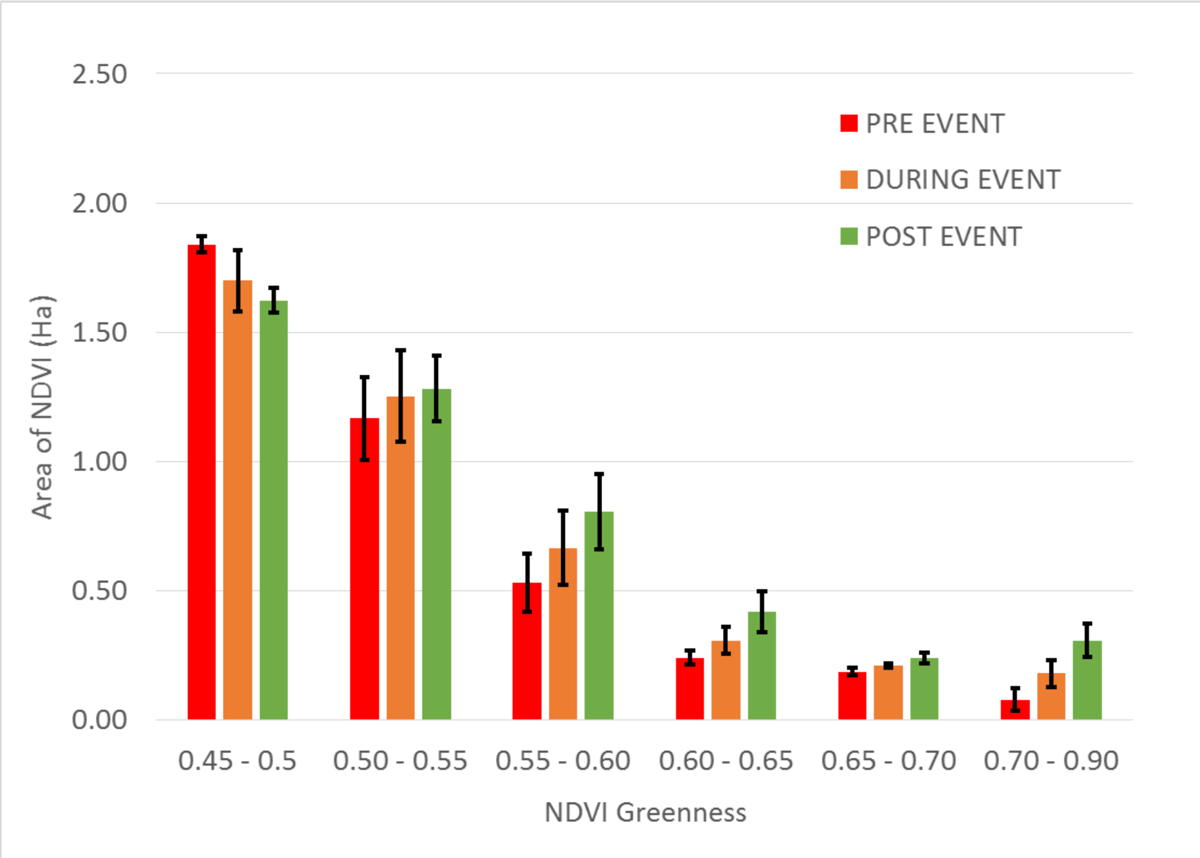



Figure 24 shows there are some indications of a systematic improvement in NDVI greenness when comparing average NDVI values before (red) to during (orange) and after (green) the passage of the environmental flow for the region shown in Figure 25. The error bars represent the standard deviation of the mean. Furthermore the spatial location of the areas showing an apparent increase lies along the edges of the creek itself, rather than in parts of the test region where no water reached. The result in this case is however not statistically significant, but is encouraging as a test into whether the data could be used to monitor ecological changes for further (or historic) flow events that were of a significant flow magnitude and cover areas with more significant vegetation cover.

This is an encouraging preliminary result for the use of Sentinel 2 for monitoring such ecological outcomes, however significantly more work is required to fully test the sensitivity of the technique, test different techniques, determine their associated uncertainties and the spatial scale over which statistically meaningful results can be obtained. There is also a need for some field validation of the results.

# Summary and Conclusions

This report presents the results of a trial of the use of free, open and publicly available satellite imagery for application to compliance activities in the northern part of the Murray-Darling Basin, using the Northern Connectivity Flow Event as a pilot and as a test as to its usefulness for more broad scale application across the Basin as a whole. More than a hundred images from the Sentinel 2 satellite system were provided to the MDBA by Geoscience Australia from April to the end of July 2018, covering 70 individual dates, taken every 3-5 days, with a resolution of 10m on the ground, including some imagery with partial coverage. The imagery as provided sampled more than a third of the Murray-Darling Basin.

The overall aims of the work were to test the ability of the imagery to successfully track the Northern Connectivity Event as it progressed through the river system, and to measure the degree to which water was present in farm dams and storages during the event, and how they changed over time. As a restriction was placed on extractions for consumptive use in the Barwon–Darling while this flow event was in effect, no significant change to the amount of water present in farm dams and storages would be reasonably expected to occur, and certainly no large increase in the presence of water in storages was expected to be seen.

The imagery was also used in conjunction with publicly available gauge data, which was used to observe the properties of the flow event itself, and to check whether any sudden and significant changes to the flow properties were seen to occur as it flowed downstream, again highlighting that an impact to the flow, and hence a possible compliance issue was present. No significant or enduring changes were seen to either farm dam and storage water areas across the region, or to the properties of the flow itself during the course of the event, which indicates no significant compliance issues occurred.

The flow event also provided an opportunity to test the use of Sentinel 2 satellite imagery for studies into water quality changes and into the condition and extent of native vegetation, with some encouraging results being obtained. Further work is underway to test the methods developed and understand the statistical properties of the results for application more broadly across the Basin. The imagery used in this study will be made publicly available on the MDBA website.

Satellite imagery is ubiquitous, with much of it free and openly available, and provides one important line of evidence for compliance activities; which can be used to support other activities underway by partner agencies. For the temporary restriction in consumptive extraction put in place during the Northern Connectivity Event, a review of the governance, management, processes and procedures applied is currently being undertaken by the MDBA. The review will include lessons learnt and further opportunities available to improve environmental water protection policies within upcoming state water sharing arrangements.

This work represents the first large-scale use of satellite imagery for tracking the progress of an environmental flow event covering a large fraction of the Basin along with associated hydrological changes yet attempted by the MDBA, and highlights its significant utility to monitor changes in the landscape during such an event. It provides a first step in a longer-term work program to use satellite imagery and gauge data for compliance studies across the Basin on a regular basis.

# References


Du, Y.; Zhang, Y.; Ling, F.; Wang, Q.; Li, W.; Li, X. Water bodies' mapping from Sentinel-2 imagery with modified normalized difference water index at 10-m spatial resolution produced by sharpening the SWIR band. *Remote Sens.* 2016, *8*, 354.

McFeeters, S. K. (1996). The use of the normalized difference water index (NDWI) in the delineation of open water features. International Journal of Remote Sensing, 17(7), 1425–1432. doi: 10.1080/01431169608948714

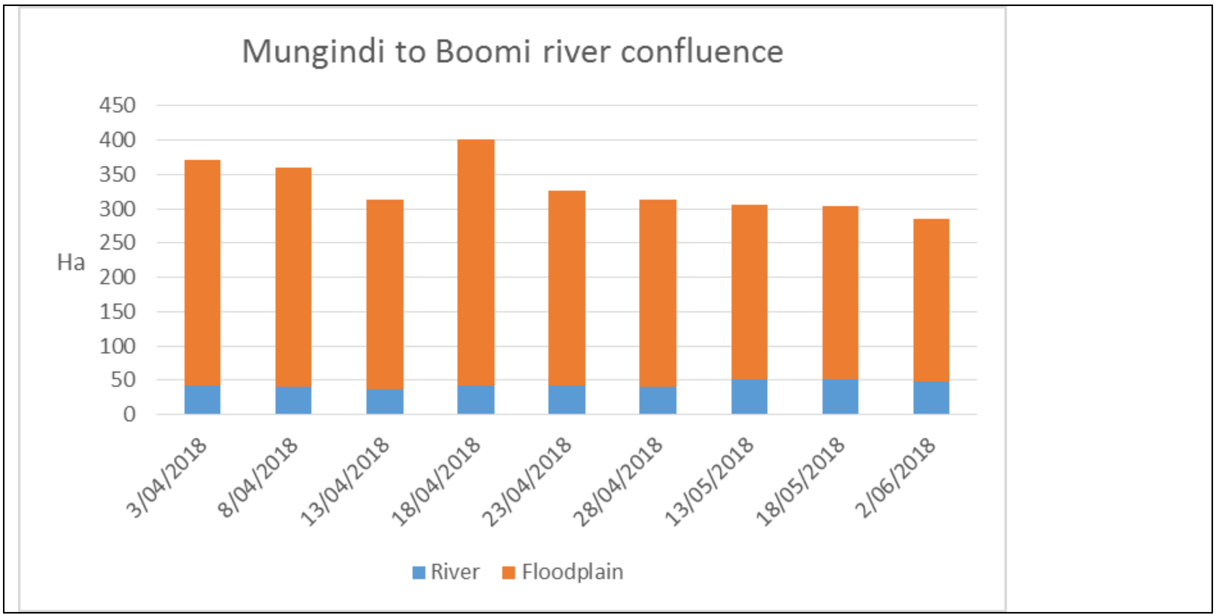
MDBA (2018), Observed Flows in the Barwon–Darling 1990-2017: A Hydrologic Investigation, Murray-Darling Basin Authority, Canberra.

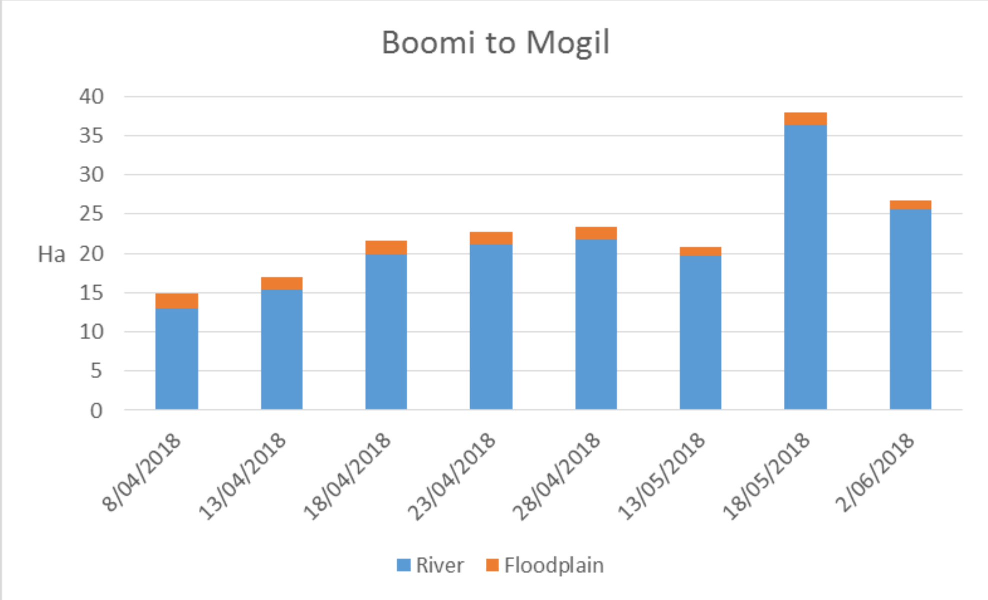
NSW (2012), Water Sharing Plan for the Barwon–Darling Unregulated and Alluvial Water Sources Background Document, NSW Department of Primary Industries.

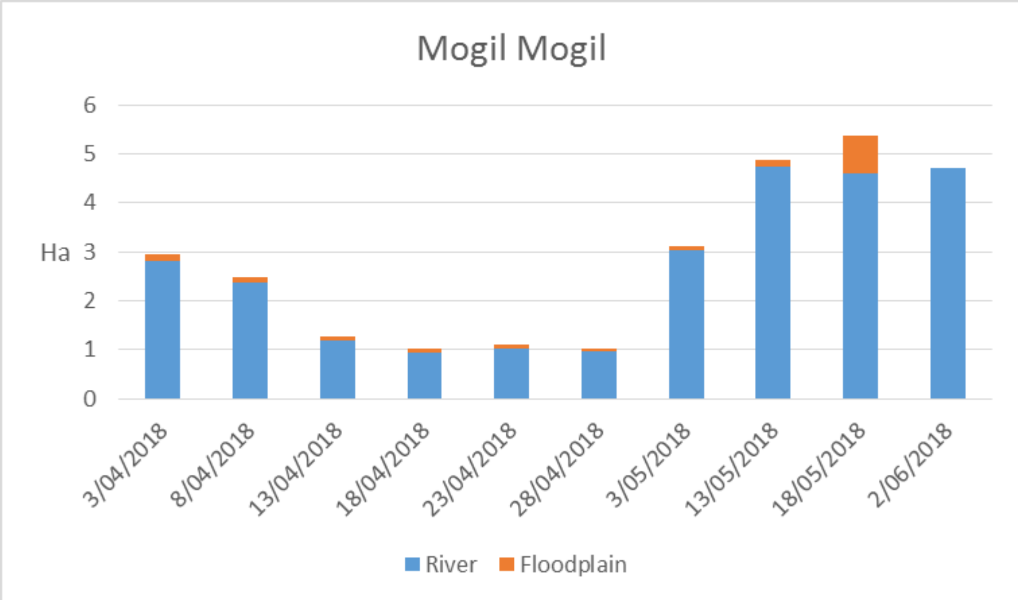

# Appendix A

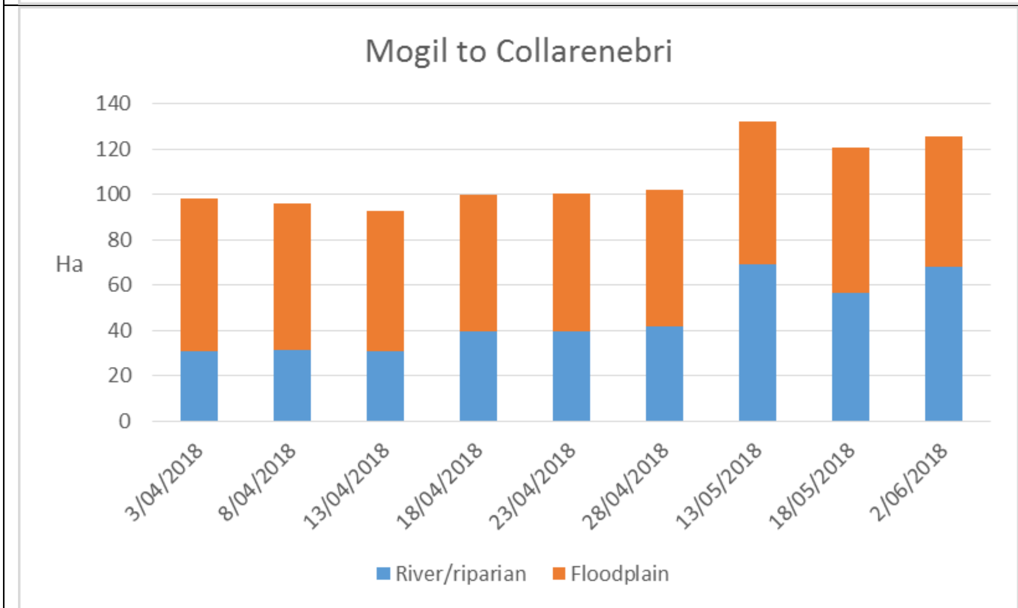
## Farm Storage Area Measurements

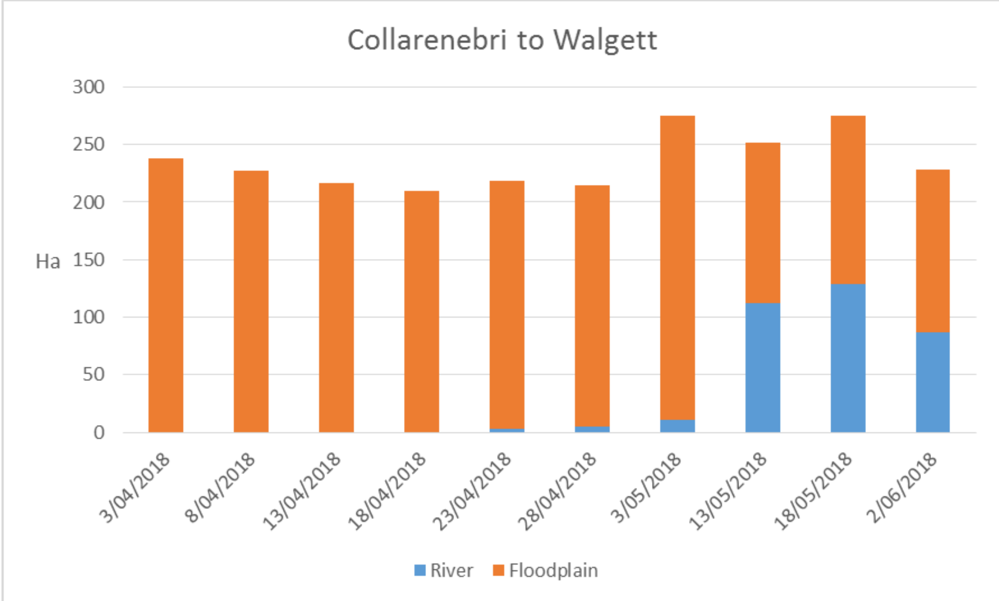
The following plots show how the total area of water as measured both in the river channel and on the wider floodplain (see description above) changed for each of the zones analysed in the Barwon-Darling catchment, for the image dates as provided. If any date was excessively cloudy or not appropriate for analysis that result was not included.




Boomi to Mogil
Ha
0
5
10
15
20
25
30
35
40
8/04/2018
13/04/2018
18/04/2018
23/04/2018
28/04/2018
13/05/2018
18/05/2018
2/06/2018
River
Floodplain


Mogil Mogil
Ha
0
1
2
3
4
5
6
3/04/2018
8/04/2018
13/04/2018
18/04/2018
23/04/2018
28/04/2018
3/05/2018
13/05/2018
18/05/2018
2/06/2018
River
Floodplain


Mogil to Collarenebri
Ha
0
20
40
60
80
100
120
140
3/04/2018
8/04/2018
13/04/2018
18/04/2018
23/04/2018
28/04/2018
13/05/2018
18/05/2018
2/06/2018
River/riparian
Floodplain


Collarenebri to Walgett
300
250
200
Ha 150
100
50
0
3/04/2018
8/04/2018
13/04/2018
18/04/2018
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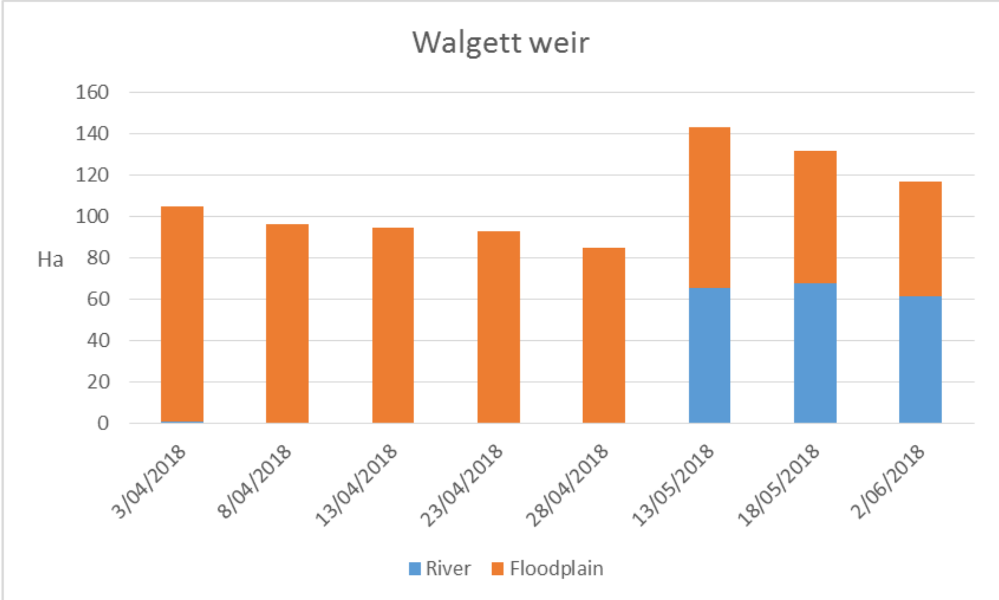
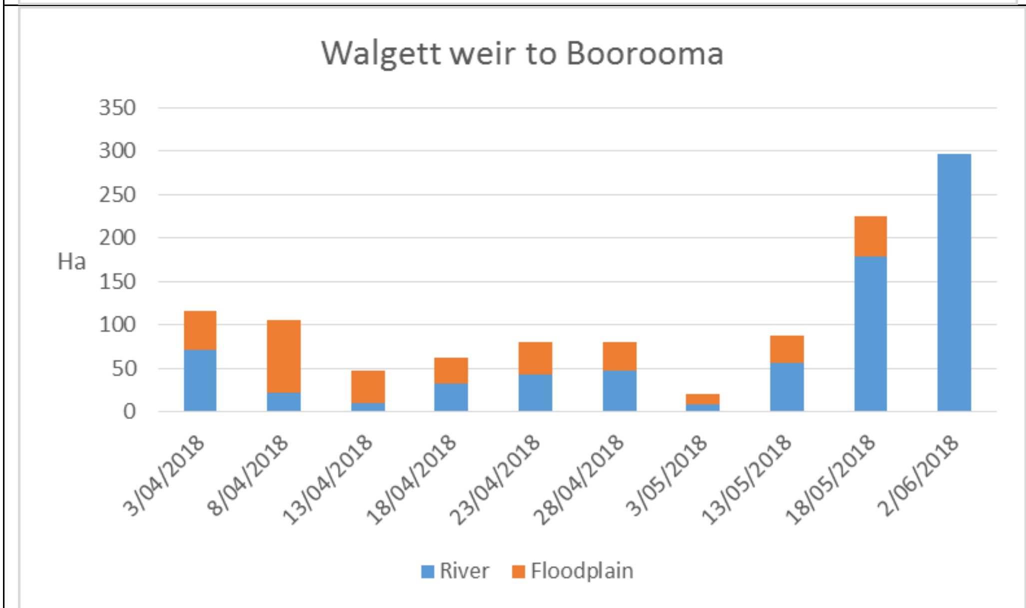
28/04/2018
3/05/2018
13/05/2018
18/05/2018
2/06/2018
River
Floodplain


Walgett weir
160
140
120
100
Ha 80
60
40
20
0
3/04/2018
8/04/2018
13/04/2018
23/04/2018
28/04/2018
13/05/2018
18/05/2018
2/06/2018
River
Floodplain


Walgett weir to Boorooma
350
300
250
200
Ha
150
100
50
0
3/04/2018
8/04/2018
13/04/2018
18/04/2018
23/04/2018
28/04/2018
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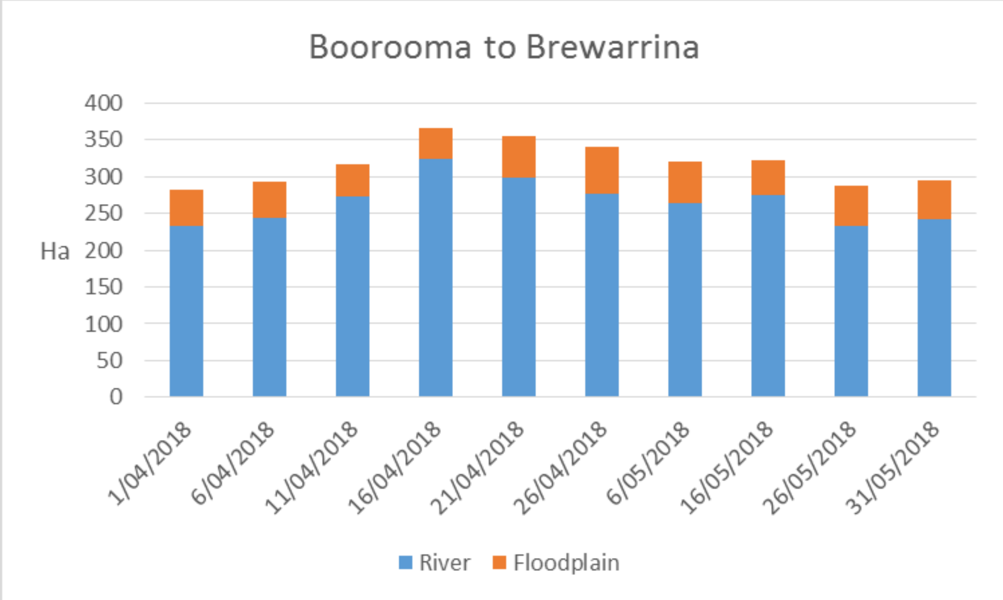
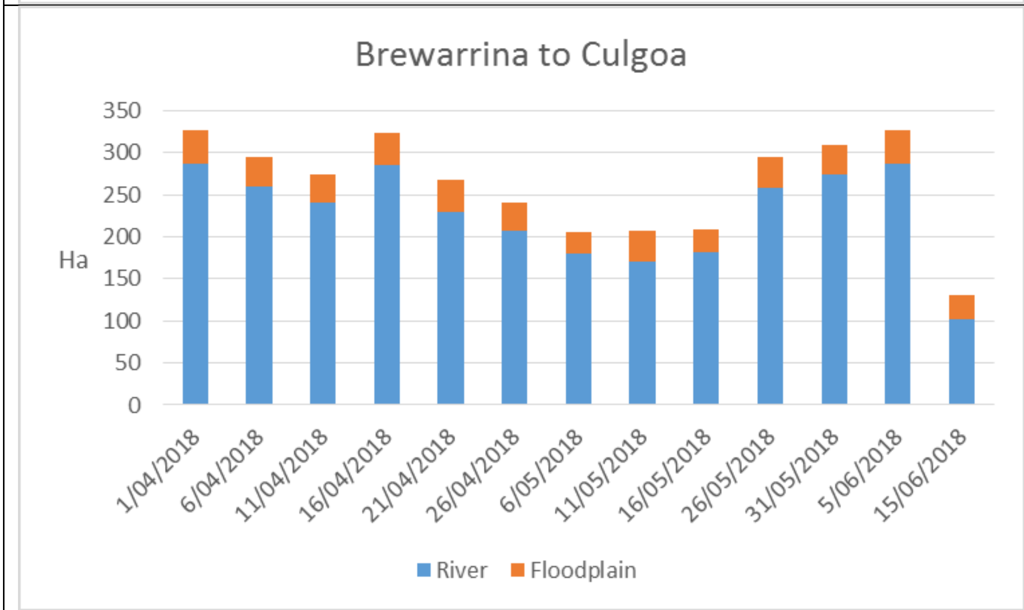
13/05/2018
18/05/2018
2/06/2018
River
Floodplain


Boorooma to Brewarrina
400
350
300
250
Ha 200
150
100
50
0
1/04/2018
6/04/2018
11/04/2018
16/04/2018
21/04/2018
26/04/2018
6/05/2018
16/05/2018
26/05/2018
31/05/2018
River
Floodplain


Brewarrina to Culgoa
350
300
250
200
Ha
150
100
50
0
1/04/2018
6/04/2018
11/04/2018
16/04/2018
21/04/2018
26/04/2018
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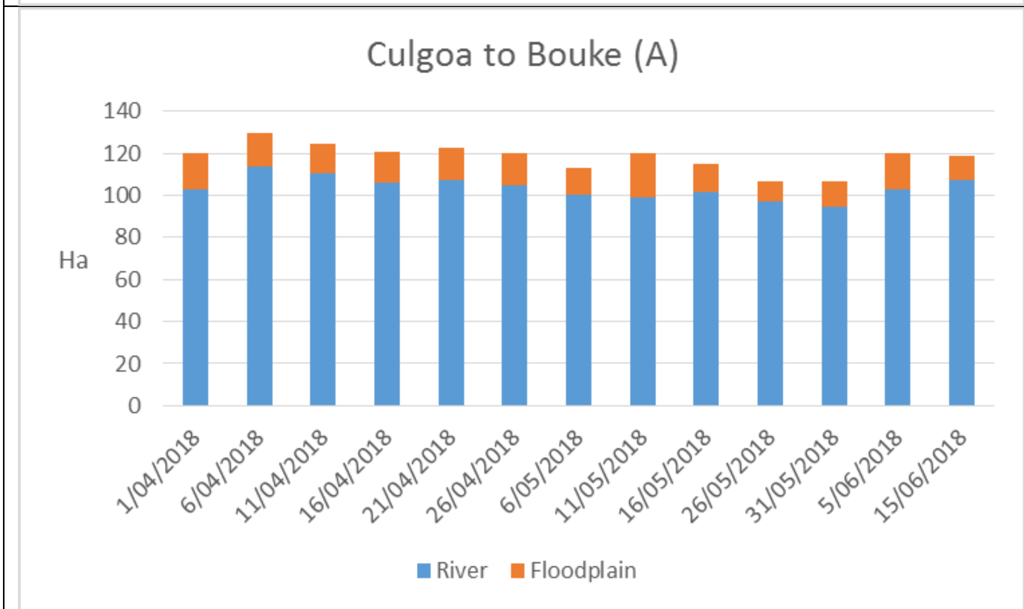
16/05/2018
26/05/2018
31/05/2018
5/06/2018
15/06/2018
River
Floodplain


Culgoa to Bouke (A)
140
120
100
80
Ha
60
40
20
0
1/04/2018
6/04/2018
11/04/2018
16/04/2018
21/04/2018
26/04/2018
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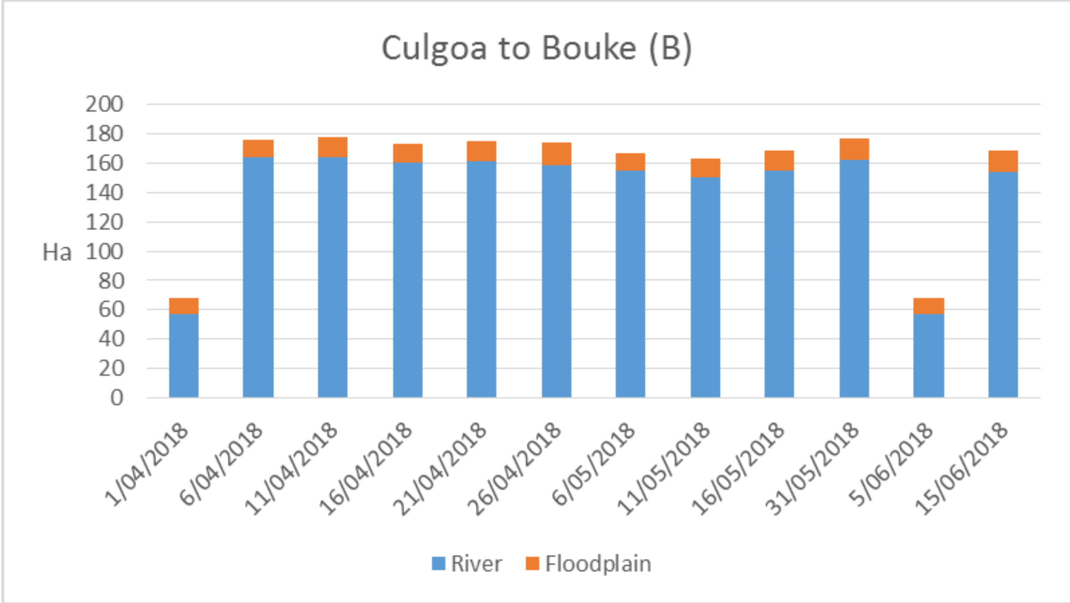
5/06/2018
15/06/2018
River
Floodplain


Culgoa to Bouke (B)
Ha
200
180
160
140
120
100
80
60
40
20
0
1/04/2018
6/04/2018
11/04/2018
16/04/2018
21/04/2018
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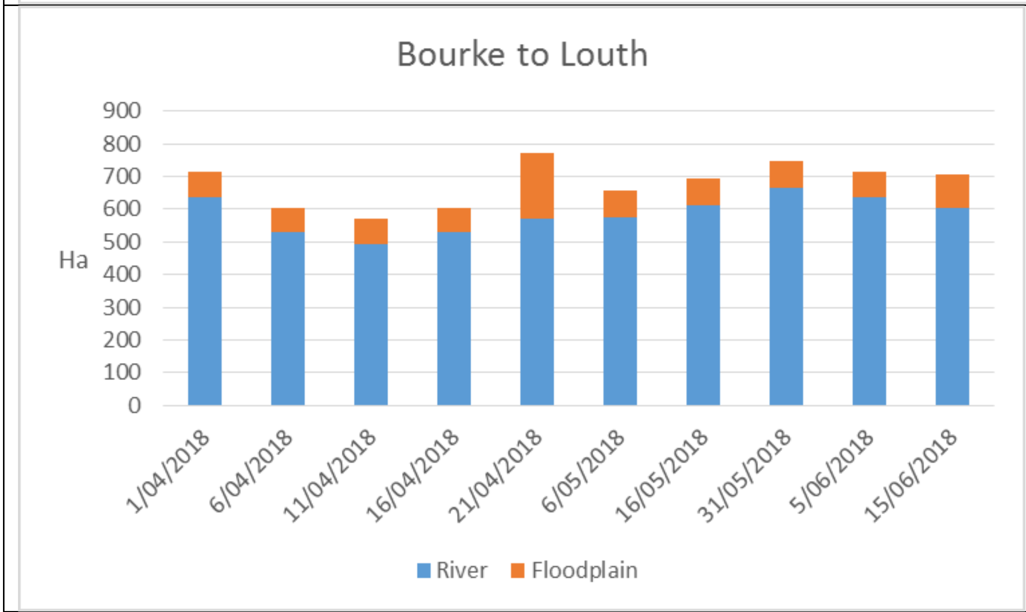
5/06/2018
15/06/2018
River
Floodplain


Bourke to Louth
Ha
900
800
700
600
500
400
300
200
100
0
1/04/2018
6/04/2018
11/04/2018
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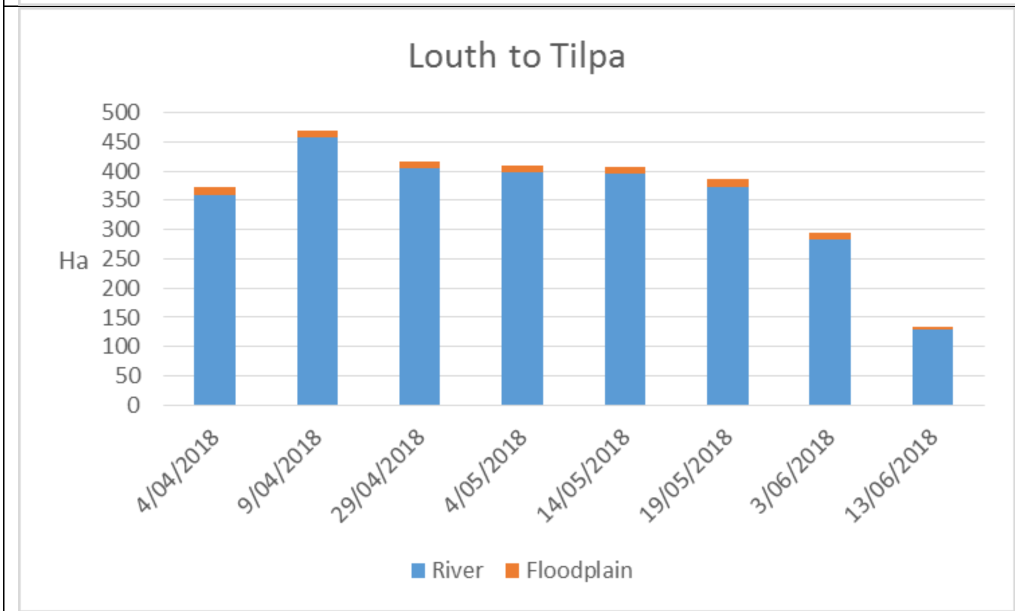
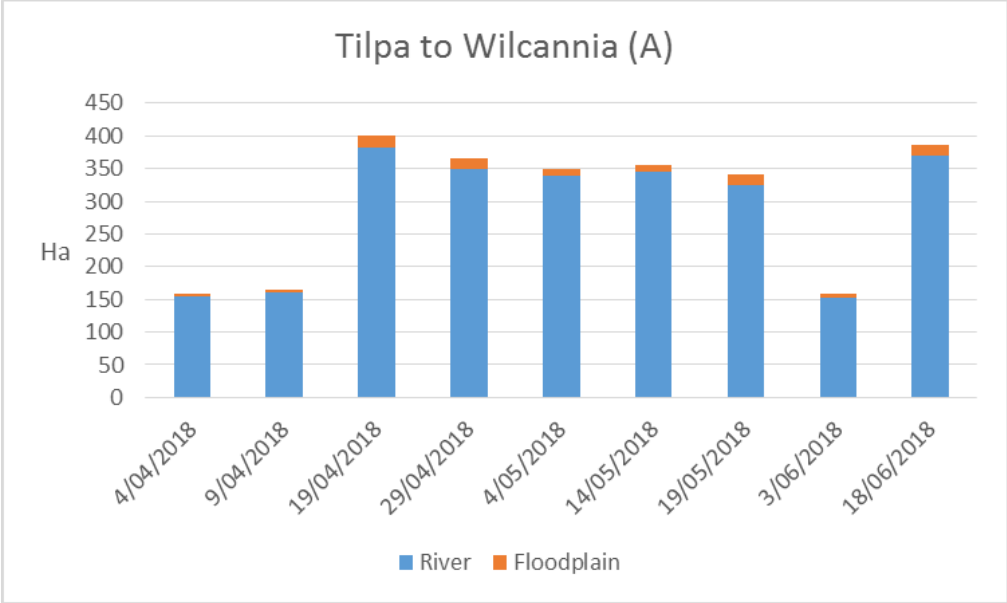
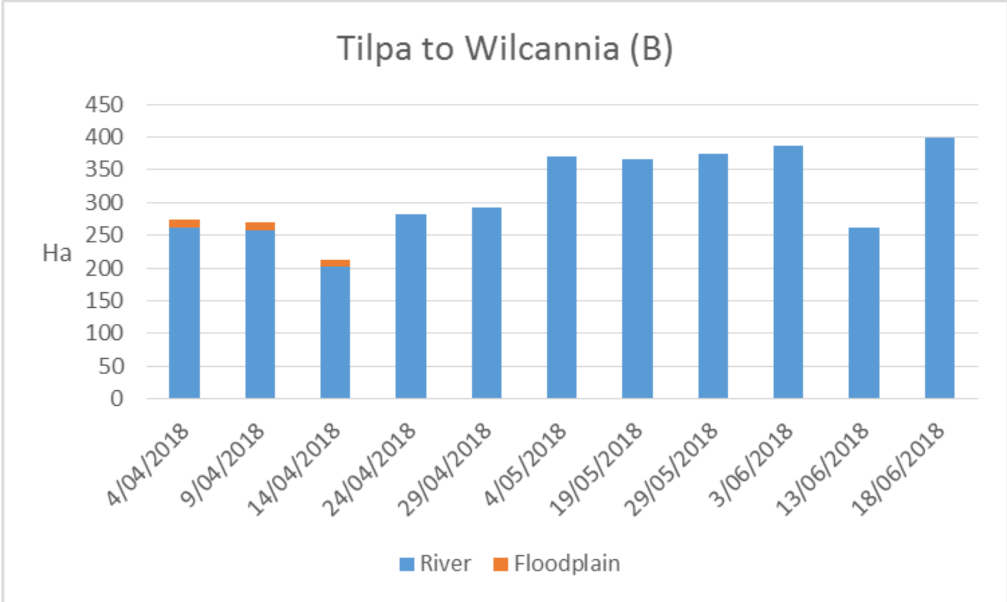
16/05/2018
31/05/2018
5/06/2018
15/06/2018
River
Floodplain

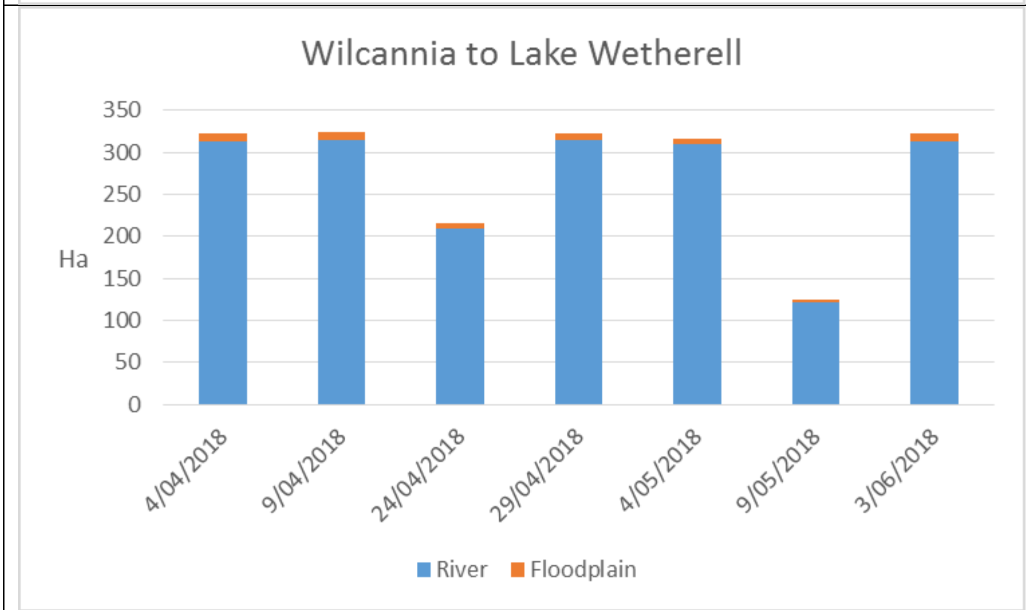

Louth to Tilpa
Ha
500
450
400
350
300
250
200
150
100
50
0
4/04/2018
9/04/2018
29/04/2018
4/05/2018
14/05/2018
19/05/2018
3/06/2018
13/06/2018
River
Floodplain



Tilpa to Wilcannia (A)
Ha
450
400
350
300
250
200
150
100
50
0
4/04/2018
9/04/2018
19/04/2018
29/04/2018
4/05/2018
14/05/2018
19/05/2018
3/06/2018
18/06/2018
River
Floodplain

Tilpa to Wilcannia (B)
Ha
450
400
350
300
250
200
150
100
50
0
4/04/2018
9/04/2018
14/04/2018
24/04/2018
29/04/2018
4/05/2018
19/05/2018
29/05/2018
3/06/2018
13/06/2018
18/06/2018
River
Floodplain

Wilcannia to Lake Wetherell
Ha
350
300
250
200
150
100
50
0
4/04/2018
9/04/2018
24/04/2018
29/04/2018
4/05/2018
9/05/2018
3/06/2018
River
Floodplain

Office locations
Adelaide
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Canberra
Goondiwindi
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