Northern Australia Environmental Resources Hub

National Environmental Science Programme

Floodplain productivity of the Gilbert and Flinders Rivers catchments

Final report (component 3)

by Christopher E. Ndehedehe

Griffith UNIVERSITY

This report should be cited as:

Ndehedehe C. 2020. *Floodplain productivity of the Gilbert and Flinders catchments: Component 3 final report*. Griffith University, Brisbane.

Cover photographs

Front cover: Wetland during wet season in Gilbert catchment (photo Michele Burford).
Back cover: Flinders River estuary (photo: Stephen Faggotter).

This report is available for download from the Northern Australia Environmental Resources (NAER) Hub website at nespnorthern.edu.au

The Hub is supported through funding from the Australian Government's National Environmental Science Program (NESP). The NESP NAER Hub is hosted by Charles Darwin University.

ISBN 978-1-925800-48-7

April 2020

Printed by Uniprint

Contents

List of figures

Acronyms

abbrev................abbreviated

AWEI ....Automated Water Extraction Index

MNDWI...............Modified Normalized Difference Water Index

MODIS................Moderate Resolution Imaging Spectroradiometer

NDVI ....Normalized Difference Vegetation Index

NDWI..................Normalized Difference Water Index

OSAVI ....Optimized Soil Moisture Adjusted Index

PCA ....Principal component analysis

Definitions

Aquatic plant biomass Aquatic vegetation composed of diverse species of micro- and macroalgae that accumulates in freshwater habitats.

Cumulative departure A general indicator of trends in hydrological data (e.g. discharge), with the upward and downward gradient indicating a rise and decline, respectively.

Digital elevation data Arrays of regularly spaced elevation values as obtained from satellite data.

Dominant rainfall pattern The leading rainfall pattern accounting for the highest observed total variability; for example, variability between years or variability between seasons.

Discharge pattern Temporal variations of flow based on observed discharge.

Flow connectivity or hydrological connectivity Refers to the movement of water from one part of the landscape or freshwater habitat to another; for example, the movement of water from a main river channel to a nearby water holes and vice versa.

Flow regime The temporal patterns of high and low flows. These patterns can be described in terms of magnitude, frequency, duration, etc.

Hotspot Targeted location where aquatic plant biomass accumulates, including isolated freshwater bodies, intermittent channels, and waterholes covered with vegetation.

Indicator A metric to detect the presence of either surface vegetation or inundation. It can also mean a standardised metric or index obtained from hydrological data (e.g. rainfall and discharge) to determine hydrological condition based on long term observations. Example, standardised precipitation index.

Inundation The presence of flood water or open water features such as rivers, isolated water holes and narrow channels.

Inundation metric A normalized difference water index derived from satellite remote sensing observation and is used in the mapping of open water features and freshwater habitats.

Lacustrine Large waterbodies situated in a topographic depression or river channels that are largely open-water features.

Maximum monthly water level anomaly Observed maximum monthly water level after removing the mean.

Mean monthly water level Monthly water level averaged from daily observations.

Mutual information criteria A measure used to understand the dependence between two hydrological time series that appear to be related or independent (e.g. rainfall and discharge).

Normalised difference vegetation index A satellite-derived measure of the state of plant health based on the how a plant reflects near infrared and red light frequencies.

Normalised difference water index A satellite-derived measure of changes in water level or flooding that uses green and near infrared light frequencies.

Palustrine Floodplains and vegetated wetlands such as swamps, including small, shallow, permanent or intermittent floodplain waterbodies.

Primary productivity The rate at which plants and other photosynthetic organisms convert energy into organic substances, which are accrued in plants in the form of biomass.

Rainfall mode Spatial and temporal rainfall patterns obtained through a multivariate analysis of long term continuous rainfall data, be it monthly or yearly.

Vegetation metric A normalised difference vegetation index derived from satellite remote sensing observation that is used to map surface vegetation in terrestrial and aquatic ecosystems.

Wetland connectivity Refers to the connections between and within wetland ecosystems as a result of flood and overbank flow.

Acknowledgements

This work was supported by Griffth University and the Australian Government's National Environmental Science Program. The Landsat and MODIS data used in this study were retrieved from USGS data portal. The authors are grateful to the Queensland Government for the river discharge observations and precipitation data, which was accessed from the SILO climate database.

Executive summary

Freshwater habitats and wetlands have numerous cultural, recreational and economic values, such as supporting commercial fisheries and as places of ecotourism. Floodplain inundation is an important process in the persistence of these habitats. The alteration of river flows, the loss of flow connectivity, and the degradation or disruption of the physical processes that sustain aquatic food chains threaten both the productivity of these habitats and aquatic biodiversity. It is therefore essential that large-scale assessments of freshwater habitats inform the development of water resource management plans, climate change mitigation and resource monitoring strategies. Yet these assessments are complicated by the inaccessibility of many large wetland systems during times of inundation, making *in situ* sampling nearly impossible at the time when high levels of aquatic primary productivity are generating food for higher-order aquatic consumers. We used a framework that integrates biophysical indicators (vegetation and inundation) derived from remote sensing with hydrological data (rainfall and river discharge) to undertake a large-scale assessment of the productivity of remote floodplains in the catchments of the Gilbert and Flinders rivers in the southern Gulf of Carpentaria, Queensland.

The Gilbert River catchment, with its generally higher rainfall, was more productive than the Flinders catchment in terms of floodplain inundation and resulting aquatic plant biomass. Because of this higher rainfall, water resource development in the Gilbert catchment is less likely to negatively impact freshwater habitats and aquatic plant biomass ‘hotspots’ than the development of water resources in the Flinders catchment.

Yet for both rivers, discharge from the upstream catchment contributed significantly to river flows and consequent flooding in the downstream catchment. In the drier Flinders catchment, flows from the upstream catchment were proportionally more important to downstream discharge than in the Gilbert catchment. This means that water extraction and infrastructure (e.g. dams) in the upstream catchment that reduce the flows of water downstream have potential consequences for the productivity of the floodplains in the downstream catchment.

Conservation planning and wetland management require spatial estimates of the aquatic habitats needed to maintain of aquatic biodiversity. The outputs of this study can be used to prioritise areas for conservation protection. This new knowledge of wetland hydrology and floodplain productivity of the Gilbert and Flinders rivers can be used to guide wetland conservation, water resources planning and future investment in water infrastructure.

1. Introduction

In freshwater systems, extreme wet periods (characterised by above-normal precipitation) and high water flows result in an abundance of aquatic plants (e.g. macrophytes, algae) and higher order organisms (e.g. fish, invertebrates and waterfowl), which form a food web and highly productive habitats (Kingsford et al., 2014; Gidley, 2009). However, several factors, including extreme droughts and human activities (e.g. construction of dams and development of water infrastructure; pollution), threaten freshwater habitats and aquatic biodiversity in streams and riverine systems (Kingsford et al., 2014; Bunn and Arthington, 2002). These threats are evidenced by the degradation and destruction of floodplain wetland ecosystems, alteration of flow connectivity, and disruption of physical processes that sustain different levels of organisms (e.g. primary and quaternary producers) who depend upon these freshwater habitats (Ward et al., 2013; Davranche et al., 2010; Bunn et al., 2006). Monitoring floodplain productivity and changes in the spatial extent of freshwater habitats is required to predict the impacts of climate variability and the consequences of changes in flow regimes on floodplain wetland ecosystems, be they riverine (e.g. rivers, streams), lacustrine (large water holes in low elevation areas) or palustrine (swamps, intermittent floodplain water channels) systems (Ward et al., 2013; Tockner et al., 2010; Midwood and Chow-Fraser, 2010). This assessment is essential for water resources planning and the development of climate change mitigation and resource management strategies.

Isolated and discrete water holes within the wet-dry tropical systems of Australia have been identified as highly productive ‘hotspots’ of phytoplankton production, where macrophytes, periphyton and other primary producers generate large amounts of biomass that is then eaten by aquatic herbivores (Ward et al., 2016; Waltham et al., 2013; Faggotter et al., 2013). Inundation extent in saline supratidal mudflats in wet-dry tropical regions of Australia was found to be an important indicator of the rates of primary productivity (Burford et al., 2016). The vulnerability of freshwater systems and aquatic habitats to climate influence and potential land use change reinforce the need for large-scale assessments. Such assessments, however, are complicated by the inaccessibility of many large wetland systems during times of inundation, particularly in remote parts of Cape York. This can make *in situ* sampling nearly impossible at the time when high levels of aquatic primary productivity are generating food for higher order aquatic consumers. The use of satellite remote sensing techniques for large-scale environmental monitoring and assessment of floodplain wetlands is therefore crucial.

In this study, indicators derived from remote sensing (i.e. vegetation and inundation metrics) were combined with hydrological data (rainfall and discharge) to (i) assess large-scale floodplain inundation patterns; (ii) predict the distribution of hotspots of aquatic plant biomass; and (iii) examine the key hydrological drivers of floodplain productivity and connectivity in the freshwater habitats of the Gilbert and Flinders rivers in the Gulf of Carpentaria. The threats to water resources in the Gulf are increasing owing to a broad range of climate and environmental stressors such as land use change and agricultural expansion (Tulbure and Broich, 2019). The use of remote-sensing methods to determine floodplain productivity during times of inundation over the Gulf rivers is key to understanding the large-scale inter-connected impacts of these stressors on floodplain wetlands.

1.1 The Gulf rivers

The study region is the catchments of the Gilbert and Flinders rivers, which flow into the southern section of the Gulf of Carpentaria in northern Australia. The region has a semi-arid tropical climate. Our analyses were based around the downstream section of the Gilbert catchment ('Gilbert downstream') and the Canobie-Saxby Roundup constriction in the downstream section of the Flinders catchment ('Flinders downstream'; Figure 1).

Previous studies in the Australian wet-dry tropics have highlighted the dynamics of inundation patterns and the aquatic plant biomass associated with inundation (Ward et al., 2016, 2013). The catchments have a rich cultural heritage and are environmentally diverse. Their numerous water bodies, complex mosaic of mangroves, extensive freshwater floodplains, and a network of persistent and intermittent water holes (e.g, Bunn et al., 2015; Ward et al., 2014; Faggotter et al., 2013) provide important habitat for a range of aquatic species (e.g. fish, crustaceans, etc.). In a study conducted on the Cloncurry River in the Flinders catchment, land surface conditions, such as evaporation, affected water storage volumes in water holes, which in turn influenced the production of phytoplankton biomass (Faggotter et al., 2013). While the importance of inundation extent in driving the rates of aquatic primary productivity in shallow coastal habitats of the wet-dry tropics of Australia has been identified (Burford et al., 2016), others have noted the key implications of dynamics in surface water resources and wetland connectivity for aquatic biota (Ward et al., 2013; Karim et al., 2012). Some location-specific studies on the drivers of phytoplankton biomass production and aquatic food webs within these freshwater systems have suggested that large-scale assessments of floodplain inundation and the distribution of aquatic plant biomass are needed (Faggotter et al., 2013; Burford et al., 2012; Bunn et al., 2003). Moreover, understanding the link between climatic variables (local rainfall and discharge) and floodplain inundation is a critical first step to strengthen knowledge of the broad-scale spatial variation in hydro-climatology within these regions, and how it contributes to variations in the distribution of aquatic plant biomass in freshwater habitats.

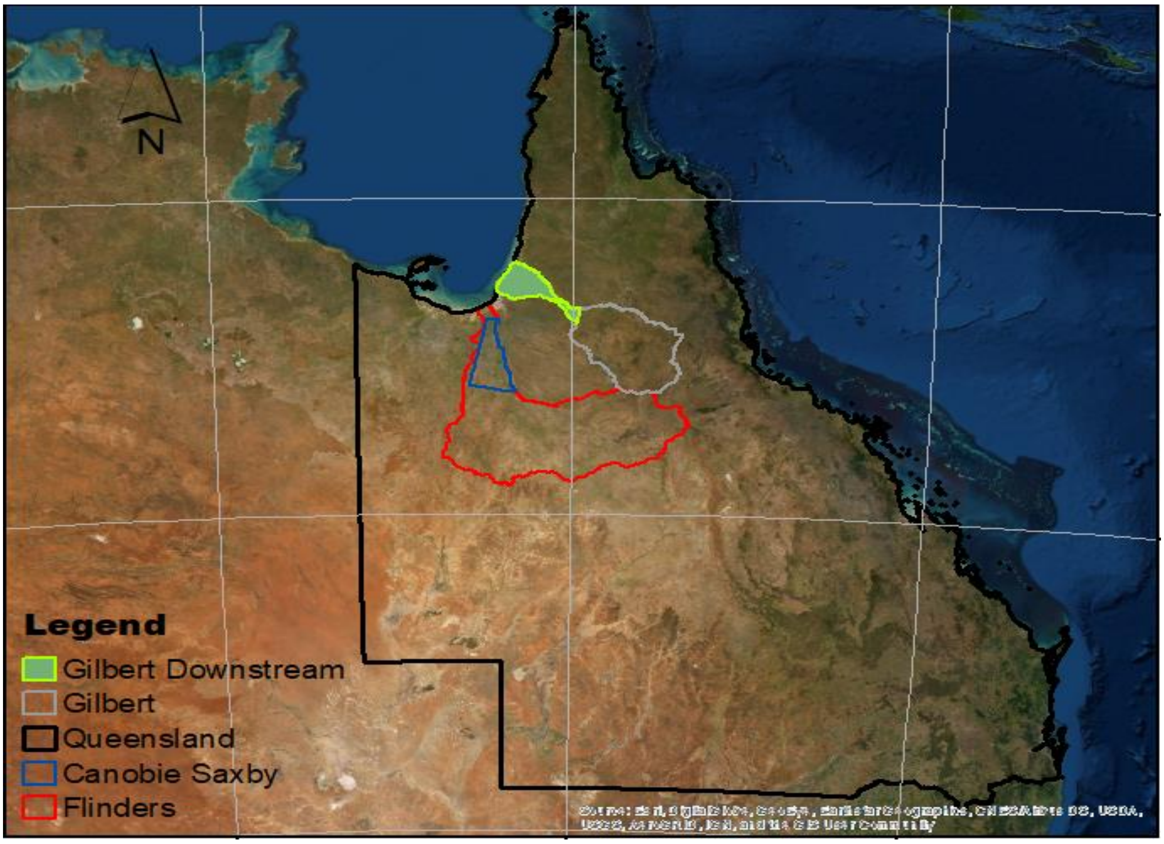

Figure 1. Study region showing the Gilbert and Flinders catchments in Queensland. The Gilbert downstream and Canobie-Saxby Roundup constriction (downstream area of the Flinders catchment) are areas where the analysis was based.

2. Methods

The focus of the study in the Gilbert catchment was to quantify historical changes (1991–2019) in the floodplain using Modified Normalised Difference Water Index (MNDWI; Xu, 2006) and vegetation (NDVI) metrics. But in the Flinders catchment, additional inundation metrics (Normalized Difference Water Index; NDWI) and other indicators (Optimised Soil Moisture Adjusted Index; OSAVI) were combined with flood-water depth to characterise the spatial distribution of inundation and predict the spatial distribution of hotspots of aquatic plant biomass. Automated water extraction indices (Feyisa et al., 2014) were also used to quantify the big summer floods of 2009 and 2019.

2.1 Data and image processing

Key data sets used in this study were the Landsat series, MODIS satellite observations, gauge observations (rainfall and river discharge) and digital elevation data. Historical level 1 terrain corrected (L1T) Landsat 5 thematic mapper (TM) and Landsat 8 OLI imageries (1991–2019) were retrieved from the archives of the United States Geological Survey through an online data portal (earthexplorer.usgs.gov). As with several optical systems, the Landsat scenes covering the Gulf rivers were affected by clouds. So, the images with cloud cover greater than 28%, especially those that affected the floodplain corridors (i.e. along the Gilbert River) were excluded, while others were preprocessed using a cloud-removal algorithm. For the cloud-impacted images, the Fmask algorithm of Zhu et al. (2015) was applied to flag and remove the presence of all clouds and shadows from all multi-band images. The Fmask is one of the most widely used algorithms in the successful detection and separation of clouds and shadows from multi-band imagery. Thereafter the images were calibrated to standard surface reflectance through atmospheric correction. The atmospheric correction was achieved using the Quick Atmospheric Correction Code (QUAC, Bernstein et al., 2005) module implemented in ENVI 5.5 (Exelis Visual Information Solutions). In the Flinders catchment, Landsat images retrieved were wet season images (i.e. available cloud-free imageries of January–March) of 2009, 2010, 2015, 2016 and 2019. The MODIS surface reflectance data was used to map the February 2019 flood in the Flinders. Hydrological data and floodplain inundation were analysed using multivariate methods (principal component analysis and singular spectral analysis), cross-correlograms, regression, and estimation of mutual information.

2.2 Floodplain inundation and hotspots of aquatic plant biomass

In this study, the spatio-temporal patterns of floodplain inundation and water bodies were quantified by applying the widely used MNDWI. The need to improve on the accuracy of flood mapping of the Flinders River floodplain resulted in the assessment of multiband-derived water-extraction metrics, the automated water extraction indices. The distribution of hotspots of aquatic plant biomass (inundated areas with plant biomass or freshwater covered with aquatic species, e.g. macrophytes) in the catchment were mapped by combining the MDNWI and NDVI (normalised difference vegetation index) in a decision tree framework. This approach was slightly modified for the Flinders catchment and included OSAVI, NDWI and a digital elevation model. This was because of the need to improve aquatic biomass distribution in the slightly different but more complex terrain of the Flinders catchment compared with the Gilbert catchment. It resulted in a slightly different classification tree model in the detection of hotspots on the floodplain.

2.3 Statistical analysis

To assess the roles of key hydrological indicators (rainfall and river flow) as drivers of freshwater onto the floodplains, both rainfall and discharge in the Flinders catchment were analysed using multivariate methods. In the Gilbert catchment, temporal series of seasonal rainfall and discharge were compared with floodplain productivity (inundation and distribution of aquatic biomass). Since the focus in the Flinders catchment was to assess large-scale inundation patterns and predict the spatial distribution of hotspots of aquatic plant productivity, local rainfall was also compared with the dominant discharge pattern using cross correlograms. In addition to using linear regression to assess relationships, mutual information criteria (Moon et al., 1995) was employed as a more reliable measure of statistical dependence between two variables (rainfall or flow with aquatic plant biomass) because of its merits over other statistical measures that rely on residual sum of squares.

3. Results

3.1 Gilbert River

The most productive period (floodplain inundation and the spatial distribution of hotspots) in the catchment since 1991 to date was the period between 1998 and 2010 (Figure 2). The dearth of hotspots of aquatic plant biomass in relatively dry years or during dry spells (periods during 1993–1997 and 2014–2019, excluding 2018 and other years affected by clouds) is in sharp contrast to the abundant distribution of hotspots during productive years in the catchment (Figure 2). Except for overwhelming flood periods (e.g. February 1991, January 1998, January 2009, and March 2018; Figure 2), the temporal patterns of the predicted hotspots show that there is a reasonable correlation between the area of floodplain inundated and the development of hotspots of primary production (r = 0.73).

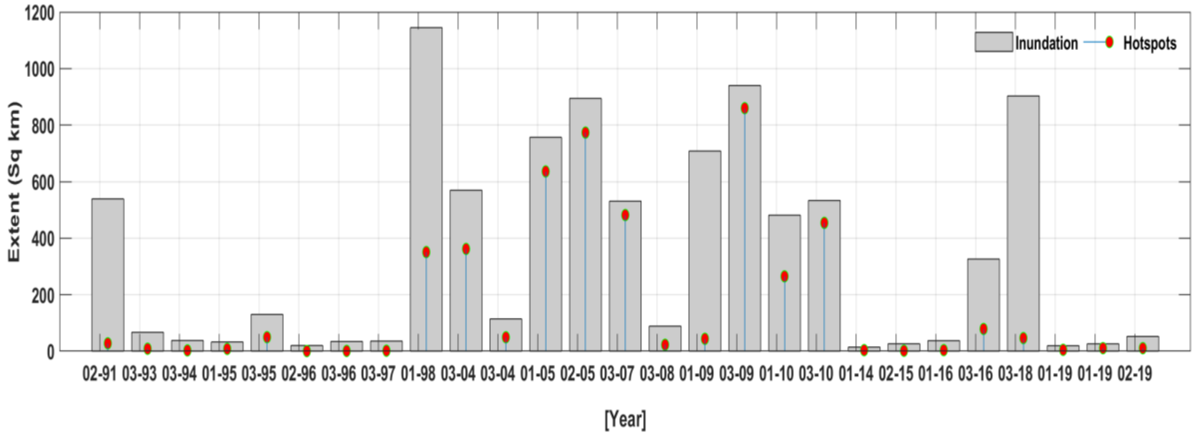

Figure 2. Historical patterns of the extent of floodplain inundation during the wet season and the predicted extent of hotspots of aquatic plant biomass derived from a combination of vegetation (NDVI) and inundation (MNDWI) metrics. These vegetation and inundation metrics were employed in a decision tree framework to estimate hotspots of aquatic plant biomass and aquatic ecosystems.

Floodplain inundation influenced the spatial patterns of aquatic habitats, especially water holes and the hotspots of aquatic plant biomass (Figure 3a–j). The accumulation of biomass in aquatic plants in water holes (Figure 3a) and the persistence of similar freshwater habitats depend upon floodplain rivers spilling over their banks and into these freshwater domains during extreme or severe wet periods (Figure 3d, f–g, and i).

The connectivity of slightly isolated water holes and other intermittent water bodies to adjacent rivers during such productive and extreme wet periods could last up to four months and more (Figure 3f–g). Note that Figure 3j does not imply the disappearance of the floodplain river but rather a contraction of the river to less than the 30 m pixel size that Landsat can capture. This contraction could be caused by change in precipitation patterns, which in turn influence flow variability and subsequently floodplain inundation patterns. We also found that, as the dry season approaches, some tributaries of the Gilbert River remain disconnected in relatively dry years with no significant floods, while in wet years the riverine systems remain connected. Some wet years have excessive flood waters along the floodplain rivers, as was the case in 2009 and 2018.

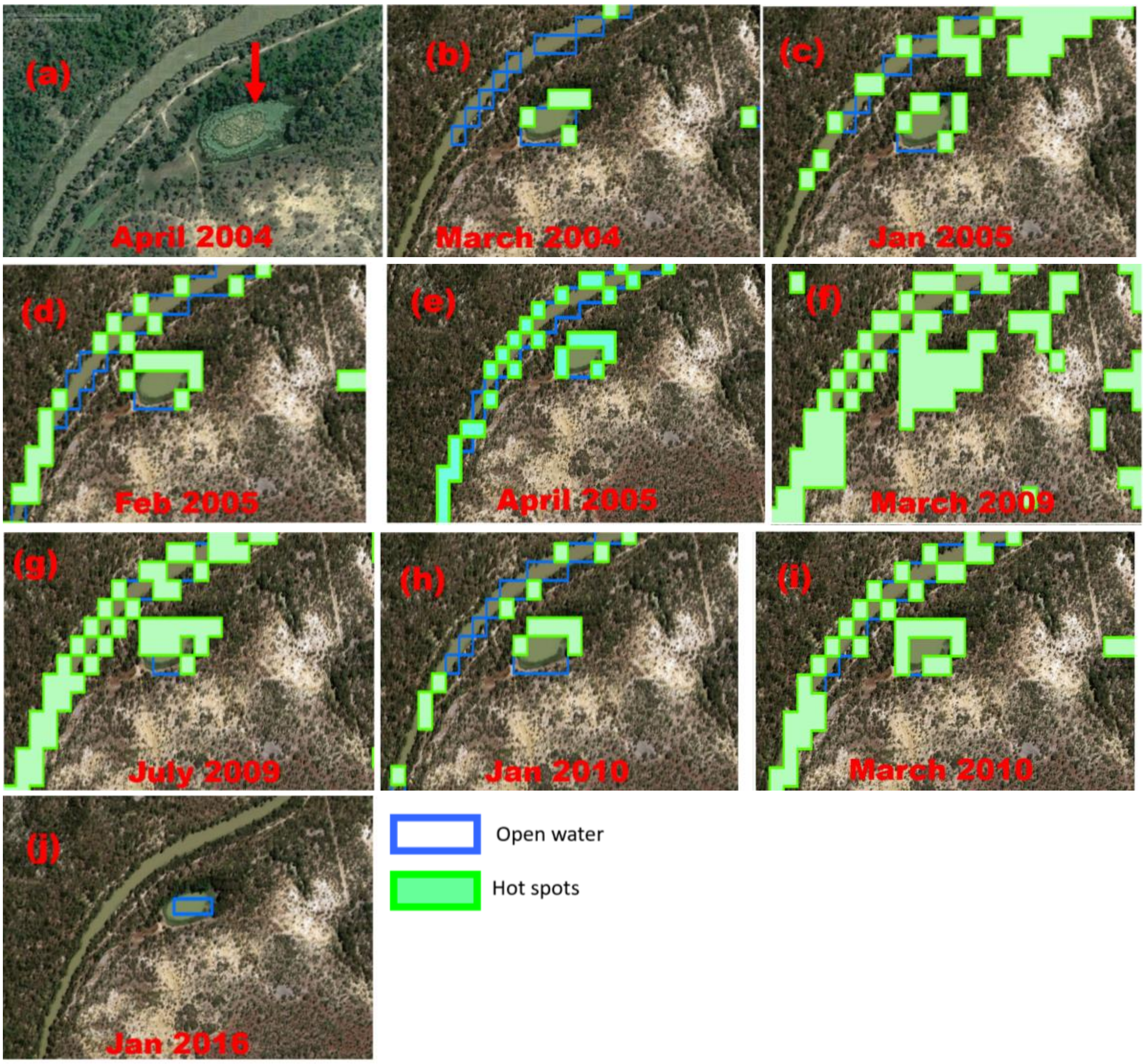

Figure 3. Seasonal floodplain inundation and impacts on the physical dynamics of aquatic habitats and centres of aquatic plant biomass ('hotspots'). (a) Freshwater habitats showing intermittent floodplain water bodies in the downstream Gilbert catchment (red arrow is a typical water hole covered with macrophytes-hotspot of primary production); (b-j) indicate the changing patterns of inundation and hotspots of aquatic plant biomass in these freshwater habitats. The high-resolution satellite image in (a) is taken from Google Earth archives and was captured in April 2004 while other background images in (b-j) were taken from World Imagery archives (May 2015).

The association of summer rainfall over the Gilbert catchment with mean monthly water level (r = 0.83) or maximum monthly water level anomalies (r = 0.87) and discharge at the downstream catchment is high and significant. The monthly cumulative departures of averaged wet season rainfall in the Gilbert catchment are also strongly associated with downstream water levels in the wet season (r = 0.96). Together, these results confirm the explicit contribution of the upstream catchment to downstream floodplain productivity. Yet they also imply that variability in annual rainfall plays a critical role in the characteristics of downstream floodplain inundation on the Gilbert River, which in turn impacts the connectivity of freshwater habitats and the distribution of aquatic vegetation.

Moreover, the floodplain had a high biomass of aquatic plants during the summer wet season, based on the correlation between aquatic biomass accumulation (hotspots) and inundation (r = 0.83 @ phase lag < 1 month) during this period (Figure 4). River discharge (r = 0.68 @ lag=1 month) at the Gilbert downstream catchment appears to be a relatively stronger indicator of hotspots of floodplain biomass accumulation than local rainfall (r = 0.57 @ lag = 3 months). However, local rainfall tends to be a better predictor of downstream inundation (r = 0.71 @ lag = 0 month) than is discharge (r = 0.65 @ lag = 1 month). While other biophysical factors could promote the growth of aquatic primary producers, it is clear that the spread of hotspots is strongly tied to the presence of water on the floodplain (Figure 4a–l). The considerable association (r = 0.96) between monthly departures of averaged wet season rainfall in the Gilbert catchment and those of stream water levels confirms the contributions of the high-elevation upstream catchment (cf. Figure 1a) to downstream floodplain productivity.

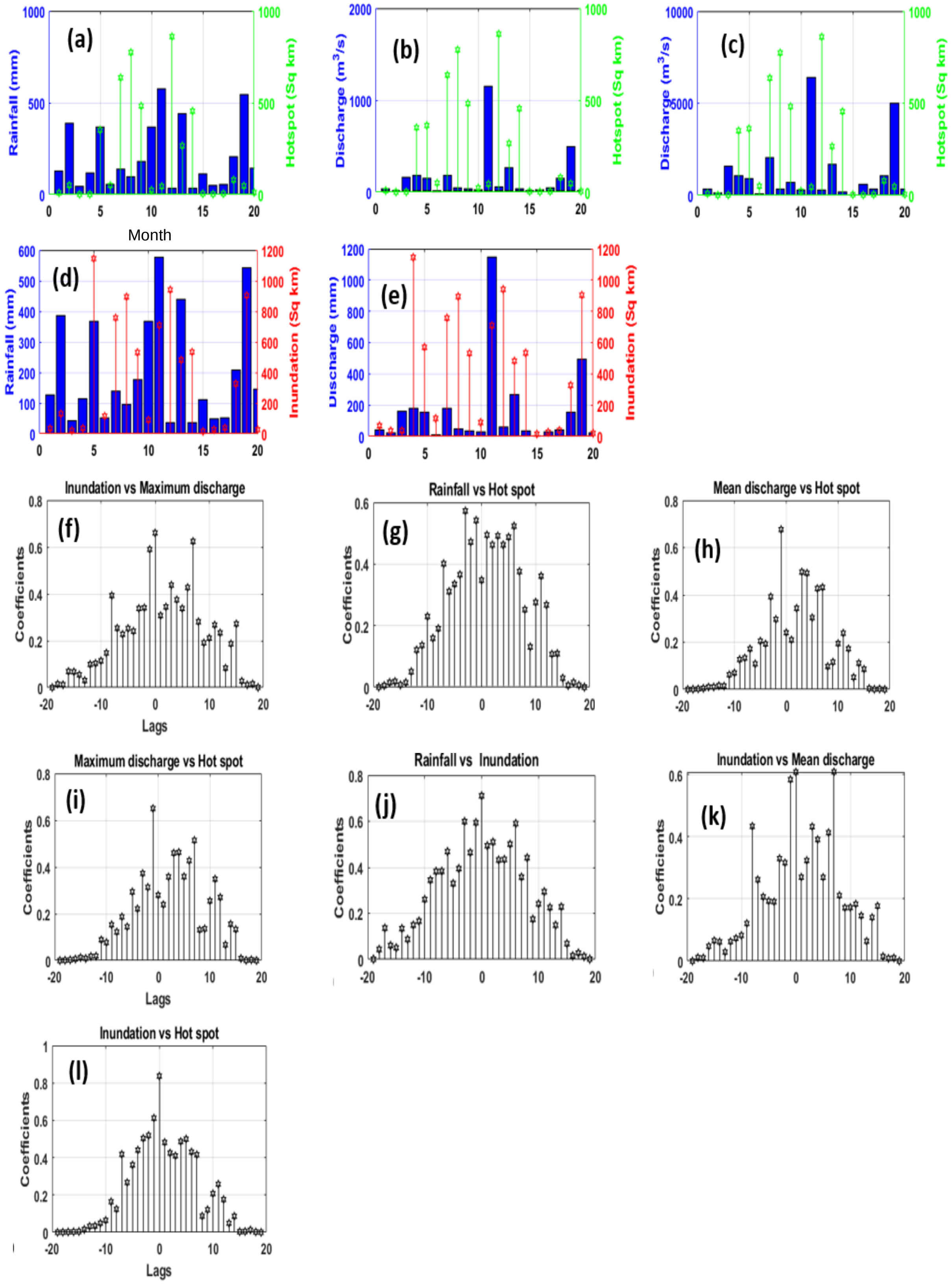

Figure 4. The relationship between total monthly rainfall amount, the predicted extent of hotspots of aquatic plant biomass and total inundation extent are indicated in (a)-(e). Panels (f–k) are their corresponding cross-correlograms during the same period with lags indicated in months. Panels (f and i) are the cross-correlograms of observed maximum discharge at downstream catchment with floodplain inundation and hotspot while (l) is the cross-correlogram between floodplain inundation and hotspot.

3.2 Flinders River

In the Flinders catchment, the area inundated after the floods in the summers of 2009 and 2019 declined by approximately 89% and 87% within 14 and 10 days, respectively (Figure 5a-d). Further, despite the magnitude and intensity of the 2009 flood, within 15 days of the observed flood maximum on 27 February 2009 (2522 km^2), the area inundated receded rapidly to 265.7 km^2 and 102.7 km^2 by 15 and 31 March of the same year, respectively (Figure 5a-b). From the MODIS-derived inundation mapping, the flood during the summer of 2019 on the Flinders floodplain was stronger in magnitude than the flood in the summer of 2009. This is consistent with observed hydrological records (e.g. river flow) and water levels, which were more than 10 m in depth in the downstream catchment.

The extent of floodplain inundation as at 10 February 2019 was approximately 7095 km^2 and greatly exceeded the 2009 flood (Figure 5c). However, by 18 February 2019 the flood had receded to about 808.6 km^2, a decline of approximately 87% (Figure 5d). Despite the differences in magnitude between the 2009 and 2019 floods, the decline in post-flood inundation after 10 days was similar in both years. By 23 February 2019, the estimated extent of inundation (140.3 km^2) confirmed the similarity in flood recession patterns (i.e. within 15 days) in the Flinders catchment after the extreme 'big wet' period of 2019 and the flood of 2009. Ward et al. (2013) reported a 15-day flood recession, based on MODIS data, in their mapping of the inundation from the 2009 summer flood in the Mitchell catchment. While the extreme 2009 flood was an event that affected the entire coastal and wet-dry tropical regions of Queensland, the recent 1-in-50-year flood in the Flinders catchment, which occurred in the first week of February 2019, appears to be a location-specific event for the Flinders.

Moreover, the spatial extent of floodplain inundation in the Flinders showed substantial temporal variation. Plotting the peak extent of floodplain inundation during the wet season in the Flinders catchment (Figure 5e) shows that 2009 and 2019 were the wettest periods on record during the last decade. The spatio-temporal variability of rainfall and discharge reflected in strong amplitude in flood extent. As with changes in inter-annual rainfall, changes in rainfall patterns were observed in the spatial patterns of inundation (Figure 6). The flooding of existing isolated water holes and freshwater habitats will impact positively on the production of aquatic plants. As illustrated in Figure 6a-f, isolated water holes and intermittent floodplain water bodies in the Flinders have more water and appear to be connected during periods of large inundation.

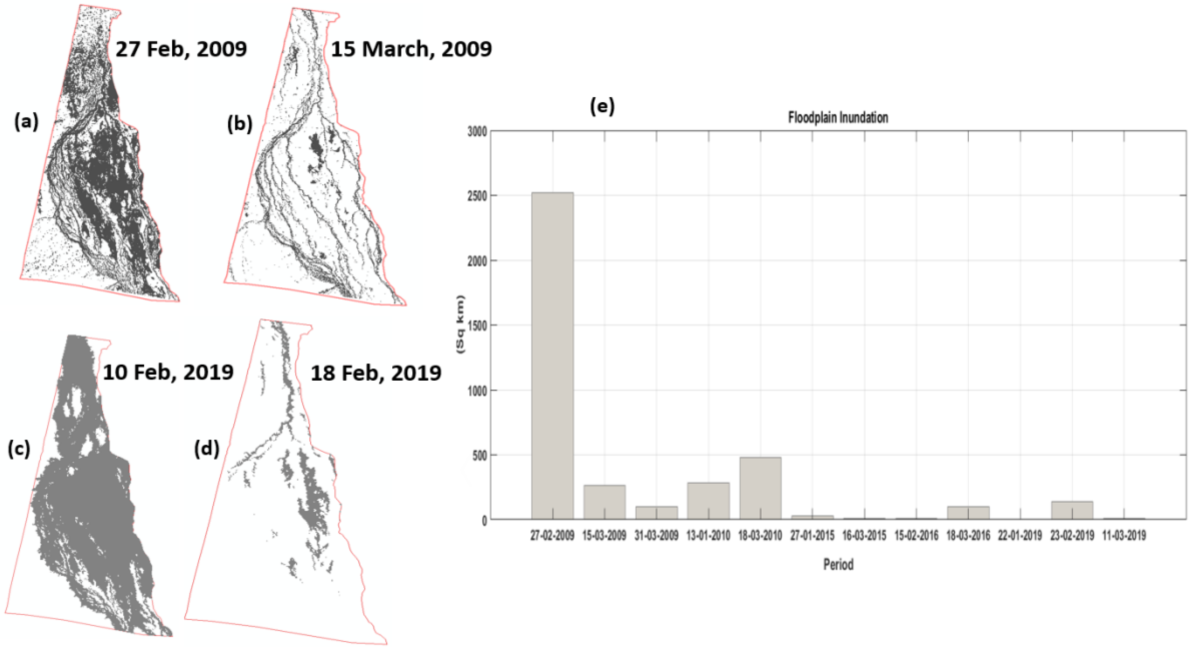

Figure 5. Spatial and temporal distribution of floodplain inundation: (a-d) the summer 2009 and 2019 floods in the Flinders catchment estimated from Landsat (30 m) and MODIS surface reflectance product (500 m), respectively, using the Modified Normalized Difference Water index; and (e) Landsat-derived summer total floodplain inundation extents based on the Modified Normalized Difference Water index for 2009/2010, 2015/2016 and 2019 (i.e. after the big flood).

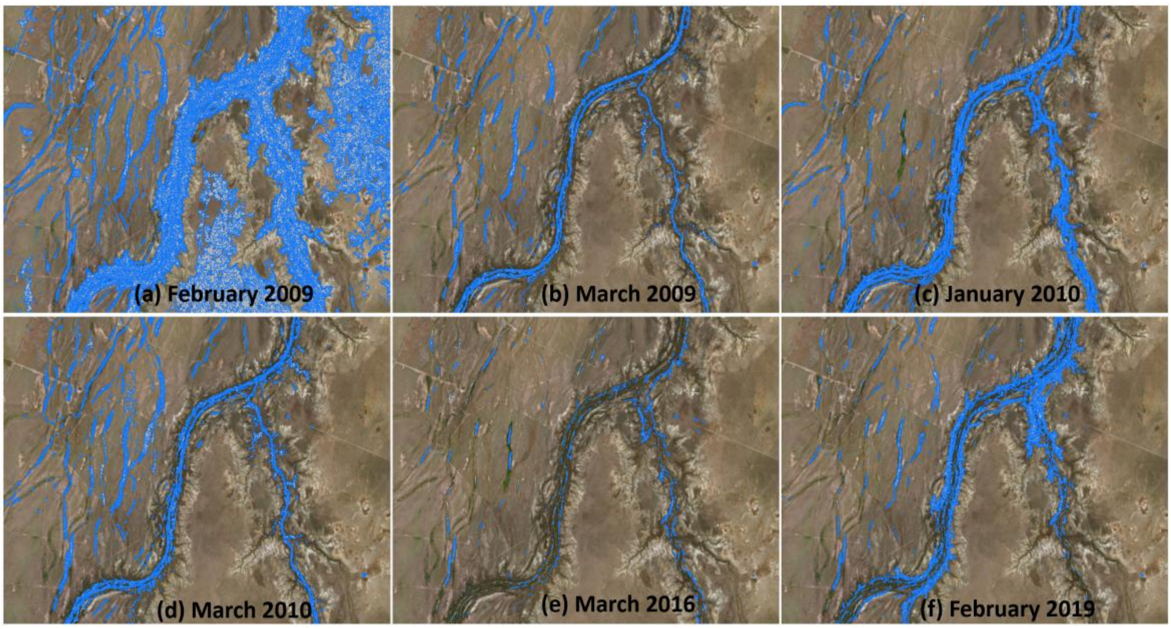

Figure 6. Spatial patterns of floodplain inundation (blue) and impact on the connectivity of freshwater habitats in downstream Flinders. Panels (a–f) show the characteristics of inundation in riverine systems and intermittent water bodies for some wet season periods as indicated, in 2009, 2010, 2016 and 2019.

The maps of winter inundation and flood water depth (estimated using elevation and the flood inundation map) isolate permanent open-water features and flooded vegetation/wetlands/channels from freshwater bodies and intermittent water bodies where aquatic plant biomass is present. As would be expected, the Flinders floodplain is more productive in years with heavy inundation than in relatively dry years (Figure 7). In the Flinders catchment, an estimated 95% of surface runoff occurs during the wet season (Waltham et al., 2013). Floodplain productivity is determined to a large extent by how long water stays on the floodplain. In this regard, the Gilbert catchment is far more productive than the Flinders, especially given the contributions of local rainfall to floodplain inundation and the distribution of aquatic plant biomass in the downstream area of the Gilbert catchment. Although flood recession patterns in the summers of 2009 and 2019 were similar, the spatial extent of inundation (in February) and hotspots (in March) were significantly different (Figure 5e, Figure 7), with more water and hotspots in 2009 than 2019. Furthermore, because of the extent of the 2009 flood, most downstream parts of the Flinders catchment were characterised by open water, as opposed to 2010 when the majority of vegetation and seasonally inundated aquatic habitats became flooded (Figure 7). This flood resulted in a relatively higher distribution of hotspots (26.5 km^2). Generally, higher floodplain productivity was very much typical of extreme wet years characterised by higher amounts of rainfall. While such inundation also revived intermittent channels in the downstream catchment (Figure 6), there was a strong decline in the surface extent of aquatic habitats/hotspots in relatively dry summers or years with below average summer rainfall, e.g. 2015 and towards the latter end of the 2019 summer after the flash flood, which occurred in the first week of February (Figure 7, Figure 8).

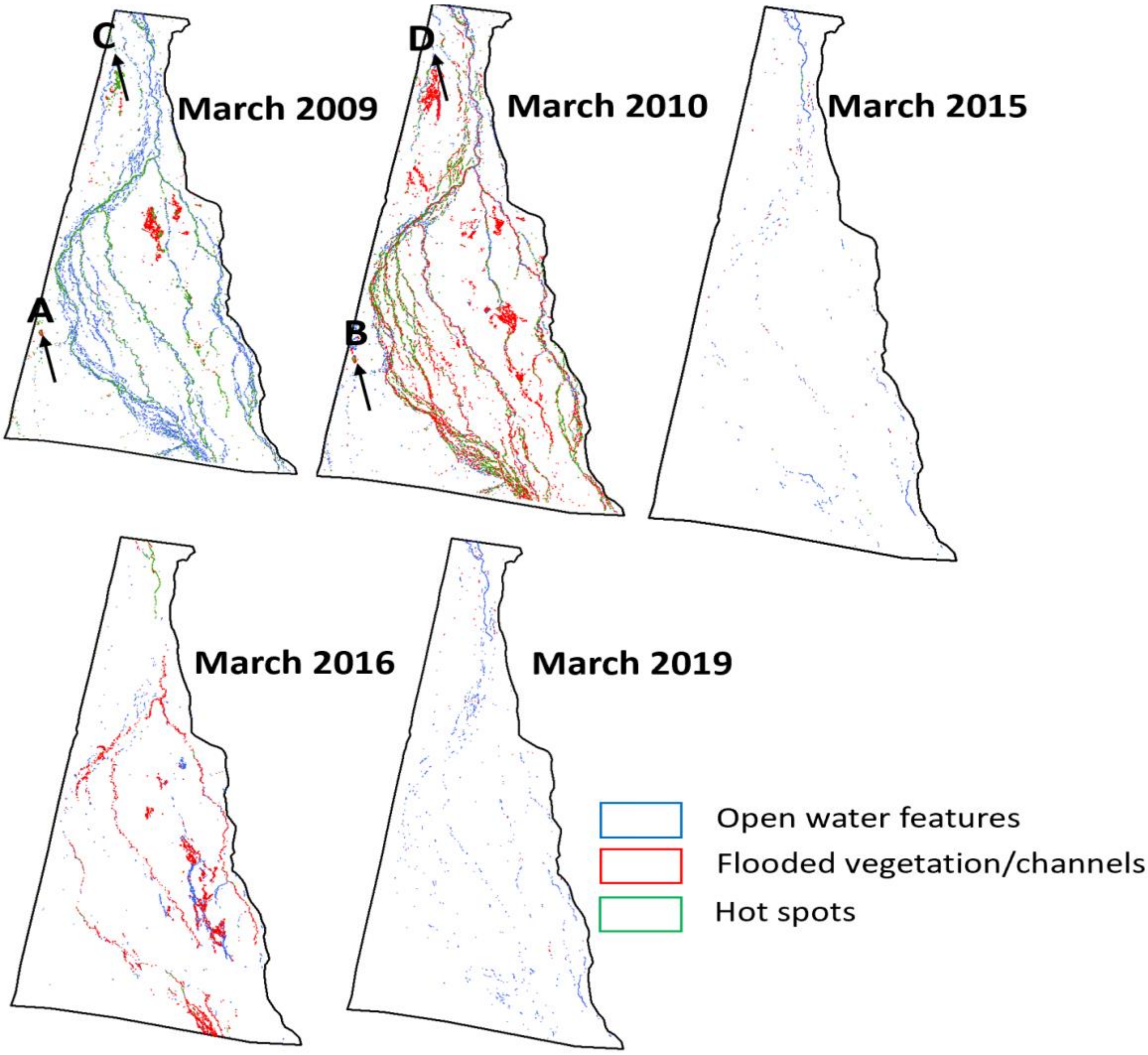

Figure 7. Predicted spatial distribution of open water features, hotspots and flooded vegetation/channels and wetlands for years with major flood events (2009 and 2010) and relatively dry periods (2015, 2016 and 2019; i.e. period after the mega-flood)) based on a classification tree model. The arrows A-D show the locations presented in Figure 8 to highlight the physical dynamics of aquatic habitats and hotspots of aquatic plant biomass in downstream (C and D) and mid-stream (A and B) sections of the Flinders catchment. The acquisition dates of all satellite imageries in each year are nearly similar, ranging from 11–18 March of each year.

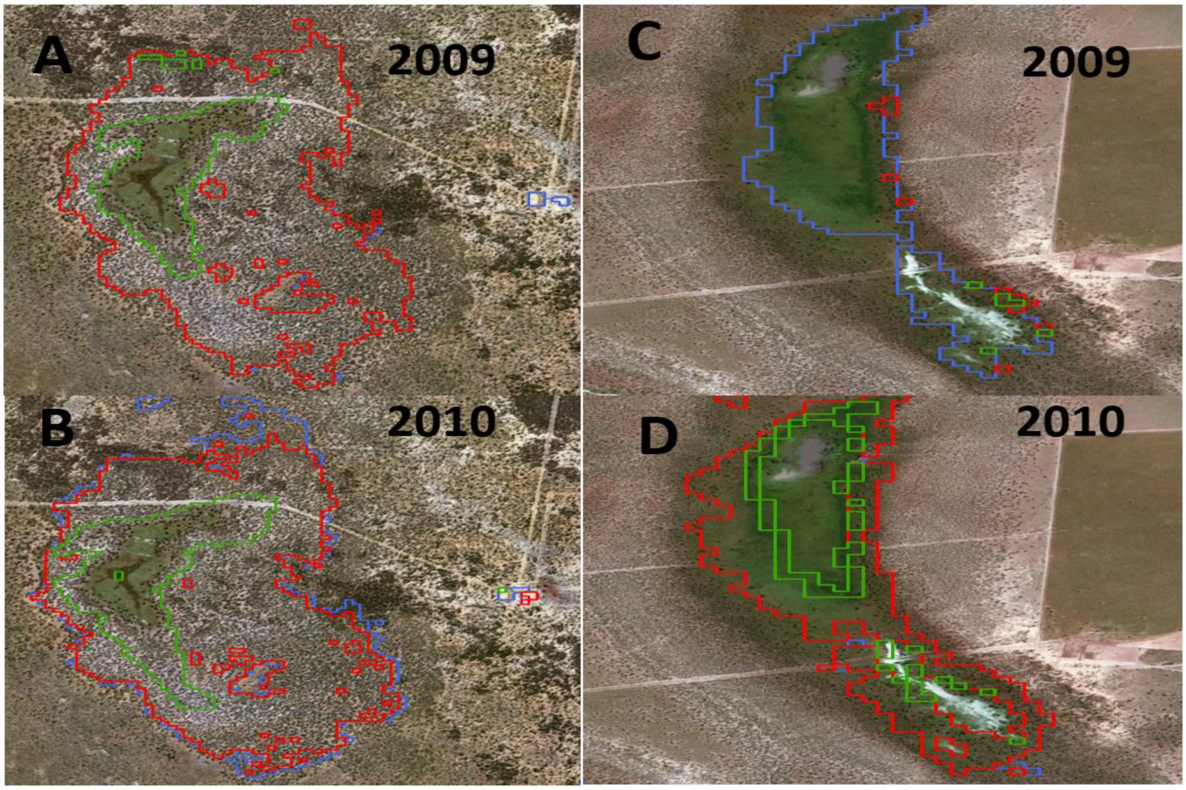

Figure 8. The spatial distribution of predicted hotspots, flooded vegetation and surface water features in isolated water holes and intermittent floodplain water bodies for locations in the mid-stream and downstream sections Flinders catchment in 2009 and 2010, corresponding to A, B, C and D in Figure 7. The blue, red, and green polygons represent open water features, flooded vegetation/channel, and hotspots of aquatic plant biomass, respectively.

The spatial extent of hotspots in downstream locations (Figure 8, A and B) in 2009 and 2010 were approximately 0.38 km_2 and 0.52 km_2, respectively. By 16 June 2016, the spatial distribution of aquatic plant biomass in the same downstream location (i.e. Figure 8, A and B with a center point coordinate of 140◦ 28’ 33”E;19◦ 18’ 18.6”S) as observed on a 0.5 m high-spatial resolution image (World Imagery archives) was approximately 0.15 km_2. We note that the loss in surface extent of aquatic plant biomass (hotspots) is usually associated with the loss of freshwater habitats in the Flinders catchments, caused primarily by limited rainfall and surface flow. Although identifying the key driver of floodplain inundation was not the aim of this study, statistical analyses of rainfall over the Flinders catchment and downstream river discharge suggest both local rainfall and river discharge play a significant role in regulating floodplain productivity of the Flinders catchment. This is similar to the Gilbert catchment.

4. Discussion

Results from this study show that river flows and floodplain inundation in the Gulf river catchments of northern Queensland could serve as key indicators of floodplain productivity. The significant association of flow with floodplain inundation, for example, emphasises the importance of floodplain rivers. Specifically, statistical relationships developed between discharge, rainfall and the distribution of aquatic plant biomass, including the use of mutual information criteria, confirm that both river flows and local rainfall are key predictors of floodplain inundation and sites of high aquatic plant biomass. River flows are a better indicator of aquatic plant biomass than local rainfall. In the Gilbert catchment, both downstream rainfall and river flows influenced the dynamics of floodplain aquatic plant biomass. This underscores the importance of flows from the upstream catchment in driving floodplain inundation and aquatic plant biomass in the downstream catchment. It also suggests that fluctuations in river flows and rainfall are the key constraints on freshwater habitats and the growth of primary producers. Nonetheless, human disturbance of river flows will amplify flow variability, resulting in significant impacts on freshwater habitats and the development and distribution of hotspots of aquatic plant biomass. This study has illustrated that such constraints will affect the spatio-temporal pattern, connectivity and spatial heterogeneity of hotspots of aquatic plant biomass and freshwater habitats.

Rainfall seasonality influenced the interannual variability of predicted hotspots of aquatic plant biomass and floodplain inundation in the downstream sections of the Gilbert catchment. Increased variability in annual rainfall over the Gilbert catchment will likely translate into strong variations in flow in the downstream area. The evidence for how the upstream catchment impacts the downstream catchment is two-fold. First, stream water levels (maximum and monthly) show strong correlations (0.87 and 0.83 respectively) with rainfall in the downstream catchment. Even their cumulative departures show considerable agreement (r = 0.96) with averaged rainfall over the entire Gilbert catchment. This implies that changes in rainfall (i.e. decline or increase) in the Gilbert catchment will impact stream water levels, river flows and floodplain inundation in general. Second, the leading rainfall mode localised over the downstream/mid-stream catchment was associated with observed river discharge (r = 0.83 or $R2$ = 68%) and stream water levels (r = 0.68 or $R2$ = 47%) at Gilbert downstream. Variation in rainfall between years, rather than variation in rainfall within or between seasons, accounted for approximately 90% of the total variability of observed rainfall over the Gilbert catchment. Considering that annual rainfall translates into strong and variable flows, as evidenced in the rainfall–discharge relationship, we conclude that the distribution of aquatic plant biomass in the Gilbert downstream catchment is strongly tied to the presence of water on the floodplain.

In the Flinders downstream catchment (i.e. Canobie-Saxby Roundup constriction, Figure 1), we characterised floodplain inundation and predicted hotspots of aquatic plant biomass based upon multiple remote sensing indicators. The downstream catchment appears to be relatively dry compared with the Gilbert but extreme events lead to considerable changes. Apart from the 2009 and 2019 extreme flood events, which showed similar recession patterns, estimated floodplain inundation extents (between 2010 and 2019) are generally much lower in the Flinders downstream catchment than those of the Gilbert. In other words, hotspots of aquatic plant biomass are somewhat restricted due to interannual variability in rainfall. While major floods, such as occurred in summer 2009, revive intermittent channels in the downstream catchment and result in extensive hotspots immediately after the wet season, this was not the case in 2019 summer flood. The flood in early February 2019 appears to have been a flash flood that quickly receded and had little positive impact on freshwater habitats in the downstream floodplain. Rivers and freshwater bodies, including water holes, can benefit from moderately high flood events, when stored nutrients are mobilised during storms and then processed by primary producers when water levels decline (Talbot et al., 2018). These nutrients later constitute a major source of support to aquatic ecosystems, stimulating primary production. Nontheless, large high-intensity floods can transport these nutrients from floodplain rivers to the nearby ocean, thereby negatively impacting on productivity of aquatic food webs. Hotspots of aquatic plant biomass in the Flinders downstream catchment are more likely to develop in the presence of steady flood waters caused by moderately higher annual rainfall on the floodplain or from flows from the upstream section of the catchment.

The predicted extent of hotspots in relatively dry summers or in years with below average rainfall (e.g. 2015 and 2019) were limited and consistent with total floodplain inundation. Although there is a general pattern in flood recession in the catchments in the wet-dry tropics, in the Flinders catchment freshwater is not retained in wetlands and few flood events reach isolated water bodies immediately after the summer wet season, the period when most primary production happens. This is because annual rainfall is low and much (95%) of the surface runoff occurs during the wet season (Waltham et al., 2013). The strong linear relationship between the dominant rainfall pattern over the Flinders downstream catchment and river discharge suggests that river systems in the Flinders are not only indicators of floodplain inundation but also vehicles for the transport of nutrients. Imagine that connectivity between rivers and intermittent water holes in the catchment is required to sustain aquatic biodiversity, fish populations and other higher consumers, and that high levels of aquatic primary producers are generating food and energy sources for higher order consumers during peak heavy inundation (see for example, Pettit et al., 2017). And if food nutrients are being transported during such times, then, these floodplain rivers are expected to be essential indicators of aquatic production in Flinders. The strong flows in 2009 and 2010, which were consistent with the extensive distribution of hotspots and flooded vegetation in the catchment, underscores the possible use of river flows and consequent floodplain inundation as indicators of the growth of these hotspots. Generally, the spatial distribution of hotspots of aquatic plant biomass coincided with peak amplitudes of the dominant modes of rainfall and river discharge. Similarly, in 2015–2016 and 2019 (i.e. after the extreme summer flood) periods when annual river flow was restricted, the spatial distribution of hotspots of aquatic plant biomass diminished significantly. Because more open-surface water features (including those existing as discrete and intermittent water bodies) are found on the floodplain in years with stronger annual amplitudes in river discharge, river flows may act as a critical indicator of aquatic plant biomass in the Flinders catchment, in addition to rainfall.

While the importance of inundation extent in driving the rates of aquatic plant biomass in shallow coastal habitats of wet-dry tropics of Australia have been identified (Burford et al., 2016), past studies have noted the key implications of the dynamics in surface water resources and wetland connectivity for aquatic biota in wet-dry tropics of Australia (Karim et al., 2012; Bunn et al., 2006). Our findings in the Gilbert and Flinders catchments have established the link between hydrological variables (rainfall and flow) and floodplain inundation as a critical first step to strengthen knowledge of how the broad-scale spatial variation in hydro-climatology in these regions contributes to variation in the distribution of aquatic plant biomass in freshwater habitats. For example, with about 93% of the total annual rainfall occurring during the wet season and 84% of rainfall being lost to evaporation in the Gilbert catchment (CSIRO, 2013), the sustainability of freshwater ecosystems in this region will be underpinned by frequent monitoring of large-scale freshwater habitats. Our approach and framework will lead to better understanding of how human activities and climate change will influence wetland hydrology and aquatic plant biomass. The continued, large-scale assessment of these remote floodplains using improved optical remote sensing methods will support management and water resources planning.

5. Recommendations and conclusions

This study has provided contemporary understanding of the key drivers of inundation and the distribution of aquatic plant biomass over time in downstream areas of the Gilbert and Flinders floodplain. River discharge (flow) and local rainfall are key predictors of floodplain inundation and the distribution of aquatic plant biomass. While local rainfall in the Gilbert downstream catchment is the primary driver of floodplain inundation, river discharge is a better indicator of aquatic plant biomass. The combined influence of local rainfall and flow on floodplain productivity suggest that, generally, the productivity of the Gulf river catchments is strongly tied to the presence of water on their extensive freshwater floodplains. The Gilbert catchment is comparatively more productive than the Flinders catchment, based upon the distribution over time of total inundation and aquatic plant biomass. This is because of the lower annual rainfall and lower discharge volumes in the Flinders catchment than in the Gilbert. Also, a greater proportion of total discharge occurs in the wet season in the Flinders catchment. In both catchments, flows from the upstream region contributed significantly to total floodplain inundation of the downstream catchment, which replenished freshwater habitats and stimulated aquatic primary production. This emphasises the role of upstream catchments in the productivity of downstream areas.

The wetland hydrology and floodplain inundation patterns in these ecosystems are currently only driven by climate. In the Flinders catchment, development of major water resources along the upstream floodplains could amplify flow variability and negatively impact freshwater habitats and hotspots of aquatic plant biomass. Water resource developments are less likely to significantly disrupt the productivity of the Gilbert catchment because of its hydro-climatology. In the Gilbert catchment, local rainfall makes a greater contribution to floodplain inundation and the distribution of aquatic plant biomass than in the drier Flinders catchment. The spatial estimates of aquatic habitats from this study can be used to prioritise areas for wetland conservation and management. The methods presented here also provide a framework to better understand the ecological implications of human activities and the influence of climate change on wetland hydrology and floodplain productivity in the Australian wet-dry tropics. This understanding can be directly incorporated into policy frameworks and used in wetland conservation planning to enable strategic water resource management.

References

Bernstein, L. S., Adler-Golden, S. M., Jin, X., Gregor, B., and Sundberg, R. L. (2012). Quick atmospheric correction (quac) code for vnir-swir spectral imagery: Algorithm details. In 2012 4th Workshop on Hyperspectral Image and Signal Processing: Evolution in Remote Sensing (WHISPERS), pages 1–4. doi:10.1109/WHISPERS.2012.6874311.

Bunn, S. E., Davies, P. M., and Winning, M. (2003). Sources of organic carbon supporting the food web of an arid zone floodplain river. Freshwater Biology, 48(4):619–635. doi:10.1046/j.1365-2427.2003.01031.x.

Bunn, S. E. and Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management, 30(4):492–507. doi:10.1007/s00267-002-2737-0.

Burford, M. A., Valdez, D., Curwen, G., Faggotter, S. J., Ward, D. P., and O'Brien, K. R. (2016). Inundation of saline supratidal mudflats provides an important source of carbon and nutrients in an aquatic system. Marine Ecology Progress Series, 545:21–33. doi:10.3354/meps11621.

Burford, M., Webster, I., Revill, A., Kenyon, R., Whittle, M., and Curwen, G. (2012). Controls on phytoplankton productivity in a wet–dry tropical estuary. Estuarine, Coastal and Shelf Science, 113:141 – 151. doi:10.1016/j.ecss.2012.07.017.

CSIRO (2013). Agricultural resource assessment for the Gilbert catchment: An overview report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the north Queensland irrigated agriculture strategy. CSIRO. CSIRO Water for a Healthy Country and Sustainable Agriculture flagships, Australia. Accessed online on 14th August 2019.

Davranche, A., Lefebvre, G., and Poulin, B. (2010). Wetland monitoring using classification trees and SPOT-5seasonal time series. Remote Sensing of Environment, 114(3):552 – 562. doi: 10.1016/j.rse.2009.10.009.

Faggotter, S. J., Webster, I. T., and Burford, M. A. (2013). Factors controlling primary productivity in a wet–dry tropical river. Marine and Freshwater Research, 64:585–598. doi:10.1071/MF12299.

Feyisa, G. L., Meilby, H., Fensholt, R., and Proud, S. R. (2014). Automated water extraction index: A new technique for surface water mapping using landsat imagery. Remote Sensing of Environment, 140:23 – 35. doi: 10.1016/j.rse.2013.08.029.

Gidley, S. L. (2009). Using high resolution satellite imagery to map aquatic macrophytes on multiple lakes in northern indiana. Unpublished Msc thesis, Indiana University. Retrieved from core.ac.uk/download/pdf/46956355.pdf on 15th April 2019.

Karim, F., Kinsey-Henderson, A., Wallace, J., Arthington, A. H., and Pearson, R. G. (2012). Modelling wetland connectivity during overbank flooding in a tropical floodplain in north Queensland, Australia. Hydrological Processes, 26(18):2710–2723. doi:10.1002/hyp.8364.

Moon, Y.-I., Rajagopalan, B., and Lall, U. (1995). Estimation of mutual information using kernel density estimators. Phys. Rev. E, 52:2318–2321. doi:10.1103/PhysRevE.52.2318.

Midwood, J. D. and Chow-Fraser, P. (2010). Mapping floating and emergent aquatic vegetation in coastal wetlands of eastern Georgian Bay, Lake Huron, Canada. Wetlands, 30(6):1141–1152. doi:10.1007/s13157-010-0105-z.

Pettit, N.E., Naiman, R.J., Warfe, D.M. *et al* (2017). Productivity and Connectivity in Tropical Riverscapes of Northern Australia: Ecological Insights for Management. *Ecosystems* **20,** 492–514. https://doi.org/10.1007/s10021-016-0037-4

Talbot, C.J., Bennett, E.M., Cassell, K. *et al* (2018). The impact of flooding on aquatic ecosystem services. *Biogeochemistry* **141,** 439–461. https://doi.org/10.1007/s10533-018-0449-7.

Tockner, K., Lorang, M. S., and Stanford, J. A. (2010). River flood plains are model ecosystems to test general hydrogeomorphic and ecological concepts. River Research and Applications, 26(1):76–86. doi:10.1002/rra.1328.

Tulbure, M. G. and Broich, M. (2019). Spatiotemporal patterns and effects of climate and land use on surface water extent dynamics in a dryland region with three decades of Landsat satellite data. Science of The Total Environment, 658:1574 – 1585.doi:10.1016/j.scitotenv.2018.11.390.

Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. International Journal of Remote Sensing, 27(14):3025–3033. doi:10.1080/01431160600589179.

Waltham, N., Burrows, D., Butler, B., Wallace, J., Thomas, C., James, C., and Brodie, J. (2013). Waterhole ecology in the Flinders and Gilbert catchments. A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy. CSIRO Water for a Healthy Country and Sustainable Agriculture flagships, Australia.

Ward, D. P., Hamilton, S. K., Jardine, T. D., Pettit, N. E., Tews, E. K., Olley, J. M., and Bunn, S. E. (2013). Assessing the seasonal dynamics of inundation, turbidity, and aquatic vegetation in the australian wet–dry tropics using optical remote sensing. Ecohydrology, 6(2):312–323. doi:10.1002/eco.1270.

Ward, D. P., Pettit, N. E., Adame, M., Douglas, M. M., Setterfield, S. A., and Bunn, S. E. (2016). Seasonal spatial dynamics of floodplain macrophyte and periphyton abundance in the Alligator Rivers region (Kakadu) of northern Australia. Ecohydrology, 9(8):1675–1686. doi:10.1002/eco.1757.

Zhu, Z., Wang, S., and Woodcock, C. E. (2015). Improvement and expansion of the fmask algorithm: cloud, cloud shadow, and snow detection for landsats 4–7, 8, and sentinel images. Remote Sensing of Environment, 159:269 – 277. doi:10.1016/j.rse.2014.12.014

Northern Australia Environmental Resources Hub

National Environmental Science Programme

www.nespnorthern.edu.au

This project is supported through funding from the Australian Government's National Environmental Science Program.

Griffith UNIVERSITY