



Wetlands and floodplains: connectivity and hydro-ecological function

Part II - Quantification of overbank and channelised wetland connectivity in the Tully-Murray floodplain



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Australian Government
Department of the Environment,
Water, Heritage and the Arts



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Acronyms and Abbreviations

1-D	One-dimensional
2-D	Two-dimensional
ADI	Alternating Direction Implicit
ARI	Average Recurrence Interval
BOM	Australian Bureau of Meteorology
CRC-FORGE	Cooperative Research Centre for Catchment Hydrology (now eWater CRC)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital Elevation Model
DERM	Queensland Department of Environment and Resource Management
DEWHA	Commonwealth Department of the Environment, Water, Heritage and the Arts (now Sustainability, Environment, Water, Population and Communities)
DHI	Danish Hydrological Institute
GBR	Great Barrier Reef
IEA	Institution of Engineers Australia
LiDAR	Light Detection and Ranging
MHWS	Mean High Water Spring
MTSRF	Marine and Tropical Sciences Research Facility

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Executive Summary

Hydrological connectivity between floodplain wetlands and rivers is the principal driving mechanism for the diversity, productivity and interactions of the major biota in river-floodplain systems. This wetland connectivity is initiated by overbank floods, but it can continue after flooding via the stream and rain network on the floodplain. This report describes the application of hydrodynamic modelling to quantify the timing, duration and spatial extent of both flood-induced overbank connectivity and post-flood drainage network connectivity between a number of wetlands and the main rivers in the Tully-Murray catchment, northern Queensland, Australia.

The wetlands on the floodplain were identified using high resolution laser altimetry (LiDAR) data incorporated with aerial photogrammetry data to form a digital elevation model (DEM) of the floodplain. Propagation of flood waves and associated floodplain inundation were simulated using a 2-D hydrodynamic model (MIKE 21) that computed water depth and flow velocity on a 30 m grid. Connectivity between ten wetlands of different types (natural and artificial) and the two main rivers (Tully and Murray) was estimated for flood events of one, twenty and fifty year recurrence intervals. The duration of connection of individual wetlands varied from 0 to 12 days depending on flood magnitude and location in the floodplain, with some wetlands only connected during large floods. All of the wetlands studied were connected to the Tully River for shorter periods than they were to the Murray River, due to their proximity to the Murray River and the higher bank heights and levees on the Tully River. These variations in wetland connectivity could affect the movement of aquatic biota during floods and the variability of habitat and biodiversity of individual wetlands.

Post-flood wetland connectivity via the drainage network was quantified using a 1-D hydrodynamic model (MIKE 11) to calculate the timing and duration of connectivity of seven wetlands of different types (natural and artificial) and the two main rivers during 2007 and 2008. The location and size of the wetlands and the extent and size of the stream and drain network were identified using high resolution laser altimetry (LiDAR) and these data formed key inputs to the hydrodynamic model. The MIKE 11 model was calibrated using measured discharges and water depths at several locations in the rivers, streams and drains. We found that wetlands which are located near the rivers and/or have good network connection maintain longer connection times with the rivers. Drainage network connectivity to both rivers varied from 30 to 365 days, and was much greater than flood inundation connectivity for the same wetlands (0-12 days) described above. The connectivity of artificial wetlands varied greatly, from ten to one hundred percent of the year, according to the type of network connection they have; a result that has important implications for the location of these types of wetlands. We also show how this kind of connectivity modelling can be used to identify when water levels in a drainage network fall below critical thresholds for fish movement using readily available river gauge data. These types of relationships are central to the concept of setting environmentally acceptable flows in floodplain rivers. Quantitative connectivity modelling will also be useful for helping to explain spatial variation in habitat structure, water quality and the composition of biotic communities in individual wetlands over time.

1. Introduction

Habitat quality and the ecological integrity of floodplain wetlands depends on many factors, but a key determinant is how the wetland is hydrologically connected to the main river channel over time (Junk *et al.* 1989; Paterson and Whitfield, 2000; Tockner *et al.* 2000; Bunn and Arthington, 2002; Frazier and Page, 2006). In a wet tropical region, permanent flows often provide continuous in-stream connectivity; however, off-stream wetlands may be isolated for significant periods when low flows are constrained to the main stream channels. Flood flows provide opportunities for these off-stream wetlands to be connected with the main streams. During floods there is an exchange of water, sediments, chemicals and biota between the main channels and floodplain wetlands (Thoms, 2003). The importance of overbank flow connection for the productivity and exchanges of major aquatic biota in river-floodplain systems has been emphasised in many studies (e.g. Junk *et al.* 1989; Bayley, 1991; Heiler *et al.* 1995; Middleton, 2002; Welcomme *et al.* 2006). The single most important factor for the persistence of the fish assemblage in an isolated wetland is the flow connection between the wetland and a main stream (Arthington *et al.* 2005; Lasne *et al.* 2007; Sheldon *et al.* in press). A high connectivity level is needed to conserve native fish diversity because the number of protected and native species increases with connectivity and the number of alien species and individuals can increase when natural patterns of connectivity are disrupted (Bunn and Arthington, 2002; Balcombe *et al.* 2007; Lasne *et al.* 2007). In a wet tropical region, permanent river flows may provide continuous connectivity to many floodplain wetlands, especially those that have good stream network connection with the main river channel. However, wetlands that are located at a distance from the main river and/or have poor network connection may be isolated from the main river for a significant period of time when main channels have low flows during dry periods. At these times distant wetlands may either become completely disconnected from the rivers or only retain connection via very shallow and slow moving water. This information is currently unknown for the majority of floodplain wetlands but it can be critical in determining fish assemblage structure, recruitment and abundance (Pearson *et al.* 2010).

The wetlands of the Tully-Murray catchment in the Wet Tropics bioregion of northern Queensland are considered very significant as they provide habitat for aquatic and riparian biota in addition to potentially improving water quality delivered to rivers and the Great Barrier Reef (GBR) Lagoon. They constitute a substantial proportion of the remnants of a large number of similar habitats that existed in the Wet Tropics prior to agricultural development, which has led to as much as 75% of these wetlands being drained and filled (Johnson *et al.* 1997; EPA, 1999). Many of the remaining wetlands have become degraded ecologically, mainly due to alterations in their hydrological connection with the main streams. The Tully-Murray wetlands are also reported as among the highest value in the GBR catchment from a fishery perspective (Veitch and Sawynok, 2005). An important issue for the management of the remaining wetlands is, therefore, to know the extent, timing and duration of their connectivity in order to derive ways to maintain or even enhance an optimal level of connection and biophysical exchanges between off-stream wetlands and a main channel or several channels. However, accurate information on wetland connectivity is scarce since field based monitoring of connectivity for numerous individual wetlands is both difficult and time consuming (Rosenfield and Hatfield, 2006). Several studies have used a combination of remotely sensed inundated area and concurrent river flow to predict how flooded area changes with river flow (Townsend and Walsh, 1998; Overton, 2005). The same approach has also been used to quantify how the number of inundated wetlands changes with river flow (Shaikh *et al.* 2001; Frazier *et al.* 2003). However, this approach is not dynamic and only gives information on potential wetland inundation when flow is not changing rapidly (due to the time difference between when the remote sensing images can be obtained and the peak of inundation) and it is not possible to define the duration of wetland connectivity, which can have an important influence on wetland ecology.

This report describes a novel application of 2-D and 1-D hydrodynamic modelling which can quantify the time course of flood inundation and the flow and depth of water in the drainage network after the floods have receded. By combining these data with high resolution topography, the duration, frequency and timing of connectivity between wetlands and the main streams in the Tully-Murray floodplain can be quantified both during and after flooding. Connectivity during floods is quantified using a 2-D hydrodynamic model. Although there have been some recent hydrodynamic studies of wetland connectivity during floods (e.g. Chormanski *et al.* 2009; Tuteja and Shaikh, 2009), none of these studies considered low flow connectivity after flooding when flows are fully confined within the channel network. We also describe a novel application of a 1-D hydrodynamic model to quantify the duration and timing of connectivity via streams and drains for a number of floodplain wetlands in the Tully-Murray floodplain.

2. Methodology

2.1 Study area

2.1.1 Catchment properties

This study was carried out in the Tully and Murray catchments located in the southern part of the Wet Tropics bioregion on the northeastern coast of Australia (Figure 1). These two catchments share a common floodplain in their lower reaches and during flood events runoff from both catchments merges together on the floodplain. We therefore considered the floodplains of these two catchments as a single unit, referred to as the 'Tully-Murray floodplain'. The combined area of the catchments is 2,072 km², of which 832 km² is floodplain (Karim *et al.* 2008). Topography varies from steep rainforest covered mountains at the upper ends to the low relief floodplain containing agriculture (mainly sugarcane, grazing and bananas) at the lower ends.

The Tully and Murray Rivers are the two main waterways on the floodplain that receive catchment runoff through numerous tributaries, and both carry water to the GBR lagoon (Karim *et al.* 2008). Floodplain wetlands are linked to these rivers through an extensive network of natural streams and artificial drains. The wetlands are connected to and disconnected from these rivers depending on the depth and flow of water in the combined stream and drain network. The catchment receives a mean annual rainfall of between 2,000 and 4,000 mm depending on the location in the catchment. Most rainfall (60-80%) occurs during the wet season between December and April (Wallace *et al.* 2008; 2009). During this period the floodplain wetlands are inundated by flood pulses that occur three to four times a year on average (Wallace *et al.* 2009). In between flood pulses in the wet season there is generally continuous flow through streams and drains that connect to the main Tully and Murray Rivers. Towards the end of the dry season flows in the drainage network decline and some of the wetlands can become disconnected from the main rivers. Further details of catchment hydrological properties are presented by Karim and others (2009).

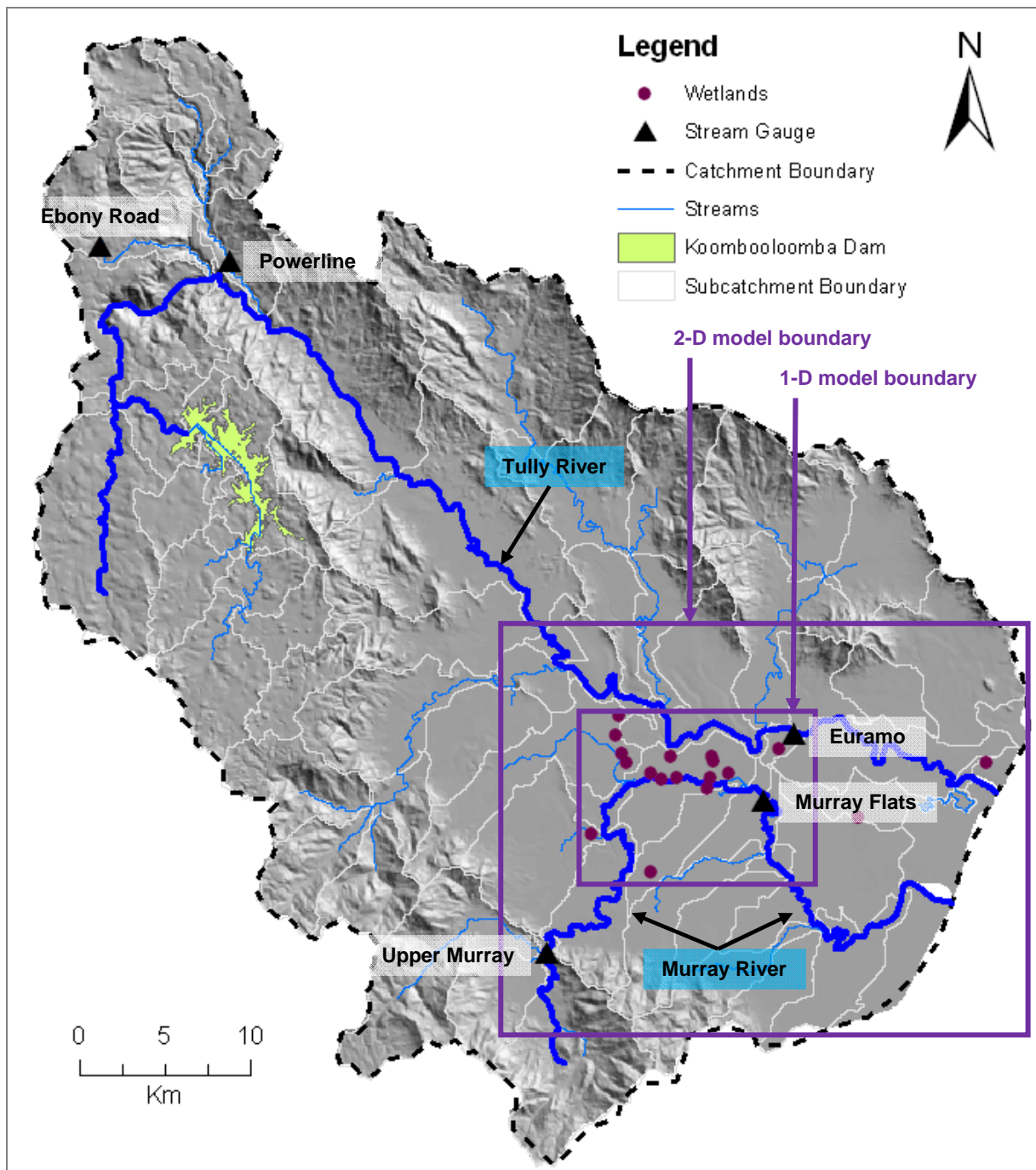


Figure 1: A schematic map of the Tully and Murray River catchments, showing the locations of wetlands, gauging stations and the main rivers. The boundaries of the 1-D and 2-D hydrodynamic models are also shown.

2.1.2 Wetlands

The Tully-Murray floodplain consists of an extensive network of permanent and ephemeral wetlands, many of which are located off-stream. The main wetlands are complemented by a network of smaller natural and artificial wetlands, some of which have been developed primarily to reduce the impacts of adjacent farming by acting as sediment and nutrient sinks, flood detention basins or both (Veitch and Sawynok, 2005). A few of these wetlands connect directly to the rivers, but the majority connects to the rivers indirectly through a stream or drain, or a combination of both. Ephemeral wetlands are located relatively distant from the main streams and have less stream connection with the rivers. These wetlands become connected to the rivers during floods. The Tully-Murray floodplain receives flood waters three to four times a year during the wet season (Wallace *et al.* 2008) and these connect a number of wetlands depending on the flood magnitude.

The wetlands of the Tully-Murray catchment constitute a substantial proportion of the remnants of a large number of similar habitats that existed in the Wet Tropics prior to agricultural development, which has led to as much as 75% of these wetlands being drained and filled (Johnson *et al.* 1997; EPA, 1999). The Tully-Murray wetlands have the highest diversity of fish species in this region (Herbert and Peeters, 1995). A recent study by Pearson and others (2010) identified a total of 22 fish species, including six migratory species that require access to estuarine or marine areas for spawning and/or larval development. The extent of hydrological connectivity between floodplain wetlands and the stream network appeared to influence fish assemblage structure and the size structure of fish species among lagoons by determining the timing and duration of accessibility for migratory fishes to individual wetlands. The physical properties of the selected wetlands are summarised in Table 1.

Table 1: Physical properties of major wetlands in the Tully-Murray floodplain.

Wetland	Type*	Area (ha)	Distance from		Lateral distance from	
			Tully River mouth (km)	Murray River mouth (km)	Tully River (km)	Murray River (km)
Barrett's	N	18.70	13.7	10.1	4.4	5.1
Boongaray	N	1.10	27.2	28.4	8.2	0.2
Bunta	N	4.64	29.9	35.4	3.8	4.9
Carroll's	N	9.22	17.8	17.0	6.7	0.3
Digman's I	A	0.58	24.4	29.5	6.3	2.5
Digman's II	A	0.81	24.7	29.2	6.6	2.3
Hassall I	N	0.97	30.6	33.8	3.5	1.6
Hassall II	N	2.63	30.7	33.4	3.6	1.2
Kyambul	N	5.94	36.5	37.9	9.2	1.2
Lagoon Creek	N	0.78	30.6	35.1	3.4	5.6
Landcare	A	0.49	23.2	27.2	3.8	0.4
Raccanello's	N	6.60	34.1	37.9	0.9	5.6
Selby's	N	2.12	27.0	28.1	7.9	0.1
Zamora's	A	1.29	30.8	31.7	4.6	1.1

* A = Artificial; N = Natural.

2.2 Hydrological data and topographic analysis

2.2.1 Rainfall and stream flow

Rainfall and evaporation data were obtained from the Australian Bureau of Meteorology (BOM) for seventeen rain gauges located across the catchments, with an average distance of 9.2 km between gauges. Considering proximity among the stations and data quality, records from eleven rain gauges were used to estimate mean areal rainfall using the Thiessen-polygon method to delineate areas of equal rainfall (Subramanya, 1994). As rainfall varies across the catchment we estimated the mean rainfall (P_{mean}) over any area (A_i) as,

$$P_{mean} = \sum_{i=1}^M P_i \frac{A_i}{A} \quad (1)$$

where M is the number of rainfall zones, A is the total area and P_i is the rainfall recorded in area A_i .

River stage height and discharge data were obtained from the Queensland Department of Environment and Resource Management (DERM). Mean daily discharge and water height data were obtained for five stream gauges; three located in the upper part of the catchment and two located in the floodplain (see Figure 1). Stream gauges at Ebony Road and Powerline record sub-catchment runoff in the Tully catchment, while the Upper Murray gauge records sub-catchment runoff in the Murray catchment. Data from these three gauges were used to calibrate a rainfall-runoff model. The gauges at Euramo on the Tully River and at Murray Flats on the Murray River are located in the floodplain. Stage height and discharge data from these two gauges were used to calibrate the hydrodynamic models.

2.2.2 Land topography

The topography of the entire Tully-Murray floodplain was obtained from a 30 m grid DEM originally developed by Connell Wagner (2006). This DEM is primarily based on aerial photogrammetry data derived by Connell Wagner (2006) giving one coarse resolution (± 0.7 m vertical accuracy) data set for the entire floodplain area and one fine resolution (± 0.15 m vertical accuracy) data set along the main highway and railway. The bathymetry of the Tully and Murray Rivers and major streams was added to the DEM using surveyed cross-sections. As stream widths are relatively small (10 to 70 m) and at many locations less than the grid size, the DEM was updated by a manual adjustment of selected grid elevations to reproduce major streams into the DEM. The topography of the central floodplain that contains the majority of the wetlands was obtained by a LiDAR survey (Karim *et al.*, 2009). Finer scale details for the main wetlands in the floodplain were embedded into the 30 m DEM using resampled 3 m LiDAR data. Bathymetry of the wetlands was estimated using a combination of LiDAR data (i.e. above their end of dry season water level) and field surveys of the submerged bathymetry. Wetlands were reproduced in the model using a set of rectangular grids ensuring the surface area was kept as close as possible to the actual wetland area.

2.2.3 Stream network and cross-sections

A 1-D combined river-stream-drain network, hereafter referred to as the 'drainage network', was developed using a high resolution LiDAR DEM. We used colour contoured and shaded relief images of a 3 m DEM derived from the higher resolution LiDAR data to manually digitise network links representing rivers, streams, drains and wetlands of significance in the floodplain. This identified the network of possible flow connections between each wetland

and the main rivers. Streams and drains that have direct or indirect links to a wetland were reproduced in the 1-D hydrodynamic model.

An accurate representation of stream and drain cross-sections is essential in order to obtain an acceptable description of the discharges and water depths using 1-D hydrodynamic modelling. Obtaining the large number of cross-sections required using ground based survey would be laborious. On the other hand, LiDAR survey is a useful and efficient way to obtain fine resolution cross-section data for a large number of streams and drains (Marks and Bates, 2000). In this study, channel cross-section data were primarily extracted from the raw, highest resolution (~25 cm horizontal and 5 cm vertical) ground returns from an airborne LiDAR survey. This LiDAR survey was conducted in October 2007, when most streams and drains were completely dry or had very shallow water depths. Where some streams and drains were found to contain water during LiDAR capture, manual adjustments were made to the LiDAR derived cross-section profiles based on field surveys. Channel cross-section locations and widths within the drainage network were then defined manually for rivers and wetlands and automatically at a regular interval for drains (30 m interval) and for streams (100 m interval). In some small streams, cross-section locations were also defined manually. For each cross-section an average height profile was derived by averaging all of the bare ground LiDAR returns one metre either side of the cross-section location.

2.2.4 Surface roughness

We used Manning's roughness coefficient n to represent land surface resistance to the propagating flood wave. For 2-D floodplain modelling, a surface roughness map was developed for the hydrodynamic domain with the same size grid as the 2-D hydrodynamic model. Initial roughness coefficients were estimated based on land use following Connell Wagner (2006), and then refined as a part of the model calibration process. Land use in the Tully-Murray floodplain is dominated by sugarcane plantations, interspersed with some grazing land. The next largest land use is banana farming, which is concentrated in the upstream reaches of the Tully floodplain (Armour *et al.* 2007). To produce a hydraulic roughness map, land cover was classified into five land uses: sugarcane, banana, grazing, cereal and urban. Water bodies were categorised as wetlands, streams or rivers. Sugarcane roughness is very dependent on the cane growth stage at the time of flooding (i.e. a fallow field can create a flow path while a fully mature cane field can act as a strong impediment to flow). River flow records show that most of the overbank events occur between January and March (Wallace *et al.* 2008), when cane fields are generally fully covered by plants, so a high roughness value was adopted for cane areas.

For the 1-D river flow model initial surface roughness coefficients for rivers, streams and drains were estimated using the method described by Chow (1959). These were then refined using the land use based hydraulic roughness information for the Tully-Murray catchments reported by Connell Wagner (2006) and BMT WBM (2008). The roughness coefficients were finally updated during the calibration process to allow for channel specific characteristics of the rivers and drains. For example, the rivers and many of the streams in the Tully-Murray floodplain have riparian vegetation along their banks. This means that woody debris and vegetation are common on the stream beds in this area and this produces a relatively high resistance to stream flow (large n). Furthermore, the Murray River (40-80 m width) is narrower than the Tully River (~100-200 m width) and stream flow is influenced more by riparian vegetation on its banks. We therefore used a higher n value for the Murray River. We also used higher n values for the upper river reaches than in the lower river reaches as the upper reaches are relatively narrow and have more riparian vegetation. As the drains are narrow and shallow, surface resistance to flow is high. In contrast, wetlands are relatively wide and deep, therefore, flow resistance is small in wetlands unless there is significant submerged vegetation.

2.3 Overbank connectivity modelling

Spatial and temporal water depth information for the thirteen floods which occurred between 2006 and 2008 were computed using a 2-D hydrodynamic model. This gave the temporal history of water depths at each wetland and along the intervening pathways, from which the timing and duration of connection with surrounding water bodies and/or with main streams were estimated. A total of ten wetlands were investigated (Figure 2) based on their size, distance from the main rivers and perceived importance for aquatic biota. The hydrodynamic model setup and the techniques of connectivity analyses are briefly outlined in the following sections.

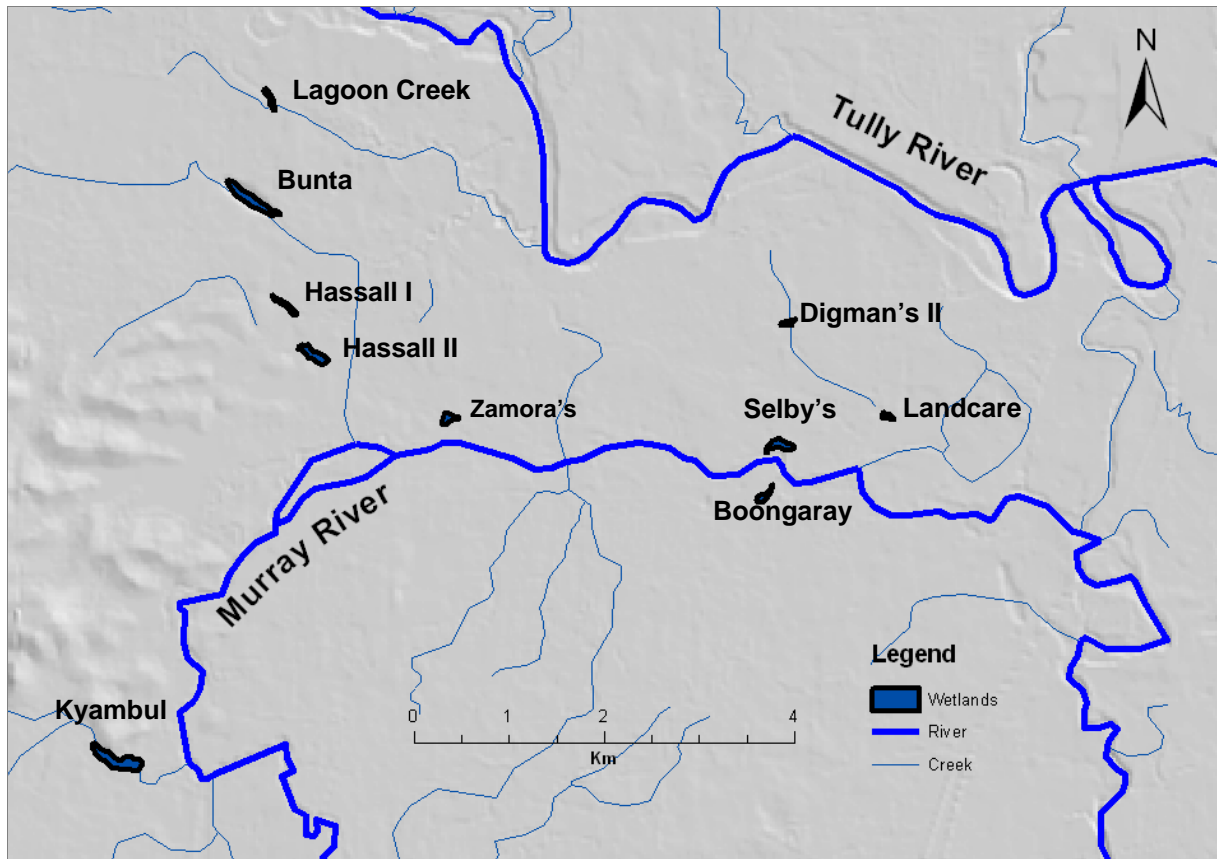


Figure 2: The Tully-Murray floodplain showing the location and size of ten wetlands analysed for their connectivity to the Tully and Murray Rivers.

2.3.1 Floodplain model setup

Runoff model

There are two sources of water that cause the flood pulse on the Tully-Murray floodplain. The main source is the stream flow through the Tully and Murray Rivers which originates in the upper parts of the catchments. The other source of water is the rainfall-generated runoff within the floodplain. Runoff for storm events was simulated using the NAM rainfall-runoff model (DHI, 2008a), which is a physically based lumped hydrological model. The model is based on a set of linked mathematical equations that represent various components of the rainfall-runoff process by continuously accounting for water content in different but mutually linked stores. The model computes runoff using nine parameters that govern surface runoff,

sub-surface runoff and base flow. Initial model parameters were estimated based on soil properties (Cannon *et al.* 1992) and land uses (Armour *et al.* 2007). Final parameters were obtained by a calibration process. Runoff peaks and low flows, timing of peaks and low flows, and total volume of runoff were the key variables considered during calibration.

The Tully and Murray catchments were divided into a number of sub-catchments based on land topography. Sub-catchment boundaries and stream networks were generated using *Arc-GIS Hydro Tools* (Smith and Brough, 2006). The area above the hydrodynamic model domain was divided into fifteen sub-catchments with an average area of 96 km², based on stream networks that carry upper catchment runoff to the floodplain. The Tully and Murray Rivers and four smaller streams carry runoff from these catchments into the floodplain. Flows from these sub-catchments were specified as inflow sources at a point of intersection between a stream and the hydrodynamic model boundary. Runoff for individual sub-catchments was estimated separately and then propagated through sub-catchments further downstream. Routing of runoff water between individual sub-catchments to the hydrodynamic model boundary was done using the MIKE 11 model (DHI, 2008b).

Runoff within the hydrodynamic domain was simulated using much smaller sub-catchments with an average area of 9.7 km². Sub-catchment boundaries and the locations of their outlets were obtained from previous hydrodynamic modelling studies by Connell Wagner (2006). A total of 66 sub-catchments, 19 linked with the Tully River and 47 linked with the Murray River, were used in the floodplain. Runoff was estimated using the NAM model described above and modelled runoff (time varying flow rates) were added to the hydrodynamic model as a point source at the outlet of each sub-catchment.

2-D hydrodynamic model

Propagation of the flood wave across the floodplain and associated inundation levels were simulated using the MIKE 21 hydrodynamic model, a fully dynamic two-dimensional flow model (DHI, 2008c). The model is based on the depth-averaged Saint Venant equations describing the evolution of water levels, and two Cartesian velocity components (Garcia and Kahawita, 1986). Governing flow equations were solved by an implicit finite difference scheme with the variables defined on a space-staggered rectangular grid. An alternating direction implicit (ADI) algorithm was used to calculate variables at each time step. The governing equations and details of the solution techniques are available in Rungo and Olesen (2003). The solution results in grid-based water levels and velocities in the *x* and *y* directions over the entire computational period.

The computational domain was 720 km² (30 km × 24 km) covering the entire floodplain (Figure 1), which is 32% of the total catchment area. Inputs to the model were land elevation, surface roughness and water sources. Model boundaries include inflows through the Tully and Murray Rivers, and through four streams. At the downstream, seaward boundary water levels equal to the Mean High Water Spring (MHWS) tide were used. The downstream boundaries were set sufficiently distant from the floodplain so that boundary effects (if any) were insignificant on floodplain flows.

2.3.2 Flood flow simulation

Flood scenarios were investigated for three storm events of different size with average recurrence intervals (ARIs) of one, twenty and fifty years. Design rainfalls for these storm events were estimated using rainfall frequency analyses for the Tully area by BMT WBM (2008). These estimates were based on the CRC-FORGE method (Durrant and Bowman, 2004), which is a regional analytical method for developing point rainfall at different risk levels from data records of a relatively short period. Predicted rainfall magnitudes for one, twenty and fifty ARI storm events were 408, 672 and 813 mm respectively. These results

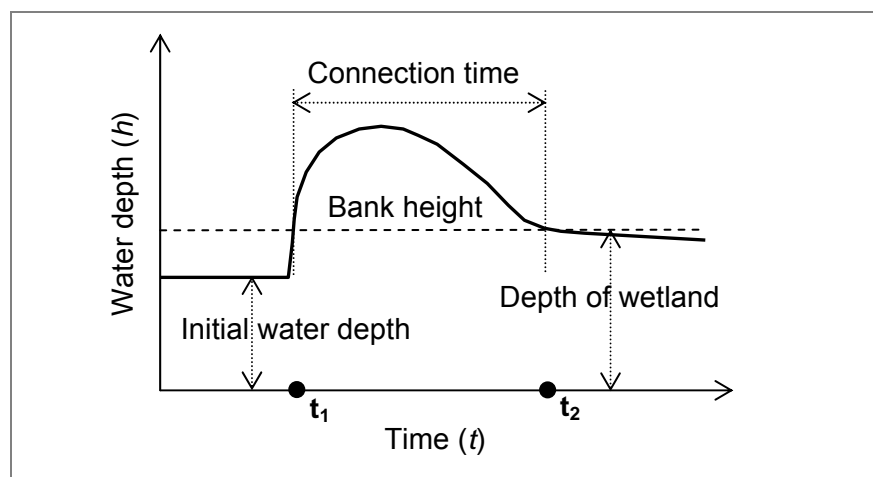
represent averaged rainfall over the catchment without consideration of spatial variation. Temporal distributions of rainfall for these events were obtained using four-hourly temporal pattern hyetographs were derived from the Institution of Engineers Australia (IEA) (Pilgrim *et al.* 2001). The critical storm duration for floods in the Tully-Murray floodplain is 72 hours (BMT WBM, 2008). Combining this with temporal pattern hyetographs gave rainfall distributions for 72-hour storms that were divided into 18 periods each of four hours duration. Runoff values were then simulated using the previously calibrated NAM runoff model.

The hydrodynamic model domain was divided into 800,000 computational grids, each 30 m by 30 m. The computational time increment was derived after satisfying numerical stability criteria. A time step of four seconds was used as this produced a stable solution for floods with an ARI of up to fifty years. Simulation of each flood event was carried out for twelve days to include the full flooding period of the largest flood. Computed time-varying water depths were recorded hourly at some selected points and two-hourly for all computational points. These data were then used to calculate the extent of flooding and inundation depth across the floodplain.

2.3.3 Connectivity assessment

Connectivity during floods was defined as overbank flow connection between a wetland and the main rivers. Connection and disconnection during overbank flooding were identified using a threshold water depth of 30 cm. We first simulated spatial and temporal water depths using the 2-D hydrodynamic model. This gave a time series of water depths at each wetland and along the intervening overbank pathways, from which the timing and duration of connection with surrounding water bodies and/or with main streams was estimated. A wetland was considered connected with other water bodies when it started receiving water from other sources by overbank flow, and was considered disconnected when water receded below its bank level. This definition of connectivity is graphically illustrated in Figure 3 using a hypothetical water depth at a wetland. In this figure, ' t_1 ' represents the start and ' t_2 ' the end of hydrologic connection, while the difference between t_2 and t_1 is the duration of connection. Connection time and duration of connection are different for floods of different magnitudes. In general, large floods produce early and longer duration of connection. The estimation of connection time of a particular wetland to the river system was based on time series water depths derived from the hydrodynamic model at two-hourly time steps. To do this, an algorithm was developed to uniquely identify areas of contiguous water during each time step, by tagging all water bodies and river sections which were contiguous in that time step. The same procedures were repeated for all time steps and the results were accumulated to obtain the temporal sequence of connection and disconnection.

Figure 3: A schematic representation of wetland connectivity based on water depth and wetland bank height. Connection to the flood waters and surrounding water bodies starts at time t_1 and ends at t_2 when the depth of inundation falls below the wetland bank height.



2.4 Channelised connectivity modelling

This part of the study computed water depth information at a large number of points within the stream network using a 1-D hydrodynamic model. Time varying water depths through the drainage network were estimated by interpolating model outputs. This gave the temporal history of connection and detachment between a wetland and a main stream for a specified threshold water depth. By accumulating this information, the timing and duration of connection for wetlands of interest were obtained. The method of hydrodynamic flow simulation and the techniques of connectivity analyses are briefly described in the following sections.

2.4.1 *Stream flow hydrodynamic model*

The MIKE 11 1-D (or strictly quasi-2D) hydrodynamic model (DHI, 2008b) was used to simulate flow and water depth within the floodplain drainage network. MIKE 11 is an implicit, finite difference mathematical model for the computation of unsteady flow in river-floodplain networks. The model solves depth integrated 1-D equations of conservation of continuity and momentum (the Saint Venant equations) under the assumptions of large wave length, which ensures that the flow everywhere can be regarded as being parallel to the land surface. The equations are simultaneous, quasi-linear, first order, partial differential equations of the hyperbolic type (Garcia and Kahawita, 1986) and are solved numerically using an implicit finite difference scheme known as the six-point Abbott scheme (Abbott and Ionescu, 1967). The transformations of these equations into a set of finite difference equations are performed in a computational grid consisting of alternating flow (Q) and height (h) points. Q points are always placed midway between the two adjacent h points, while the distances between the h points may differ. The governing equations and details of the solution techniques are available in Rungo and Olesen (2003). The main inputs to the model are described in the following sections.

The Tully and Murray Rivers receive catchment runoff through numerous streams and drains, and these two rivers are the major sources of water in the floodplain. In addition, several streams (e.g. Brick and Boundary Creeks) flow continuously across the floodplain. When it rains the wetlands can also receive locally generated runoff within the floodplain. Water sources from the upper part of the catchment were added to the hydrodynamic model at inflow boundaries and rainfall-generated runoff was added to the model as lateral flows. We used the NAM hydrological model (DHI, 2008a) to simulate rainfall-generated runoff. The parameters were calibrated for the Tully-Murray catchments during the 2-D hydrodynamic modelling (Section 2.3.1) and the same parameters were used in this 1-D hydrodynamic study.

The stream network model that has been used for 1-D hydrodynamic flow simulation is shown in Figure 4. It consists of 69 branches, eight inflow sources that carry catchment runoff to the floodplain and two downstream water height boundaries. The stream network was used to compute water heights and discharges across the network. Water heights were computed at points for which channel (stream or drain) cross-section data were derived (see section below). Discharges were computed midway between each pair of water height points. In total there were 457 water height computing points, 404 discharge points and 64 nodes (meeting point of two or more branches). The total schematised length of the drainage network was 104,684 m with an average distance of 260 m between two consecutive cross-sections. The minimum distance between two computing points was 30 m for drains, 74 m for streams, 150 m for the Murray River and 400 m for the Tully River. We used relatively close computational points in drains to capture small changes in elevation and/or width of these drains. The wetlands were reproduced in the model by using three to six cross-sections and the distance between two consecutive sections varied in the range of 40-108 m.

2.4.2 Flow simulation

Flow simulations in the drainage network were performed by satisfying the Courant stability criterion which is a function of flow velocity, distance between two consecutive computation points and computational time step. A time step of four seconds or less was found to produce a stable solution for all model runs. Our model setup was limited to a maximum number of computational time steps, which restricted us from running the model for a year at a time. Instead the model was run as twelve interlinked runs, each of one month duration. For the first month's simulation, initial conditions were estimated from available field data and literature data. Initial conditions for the subsequent simulations were obtained from the previous run. It took about eight hours of computer time to simulate one month of real time. Model outputs were stage, water depth, velocity and discharge at all the computational points in the drainage network and data were saved at daily intervals to reduce the output data volume.

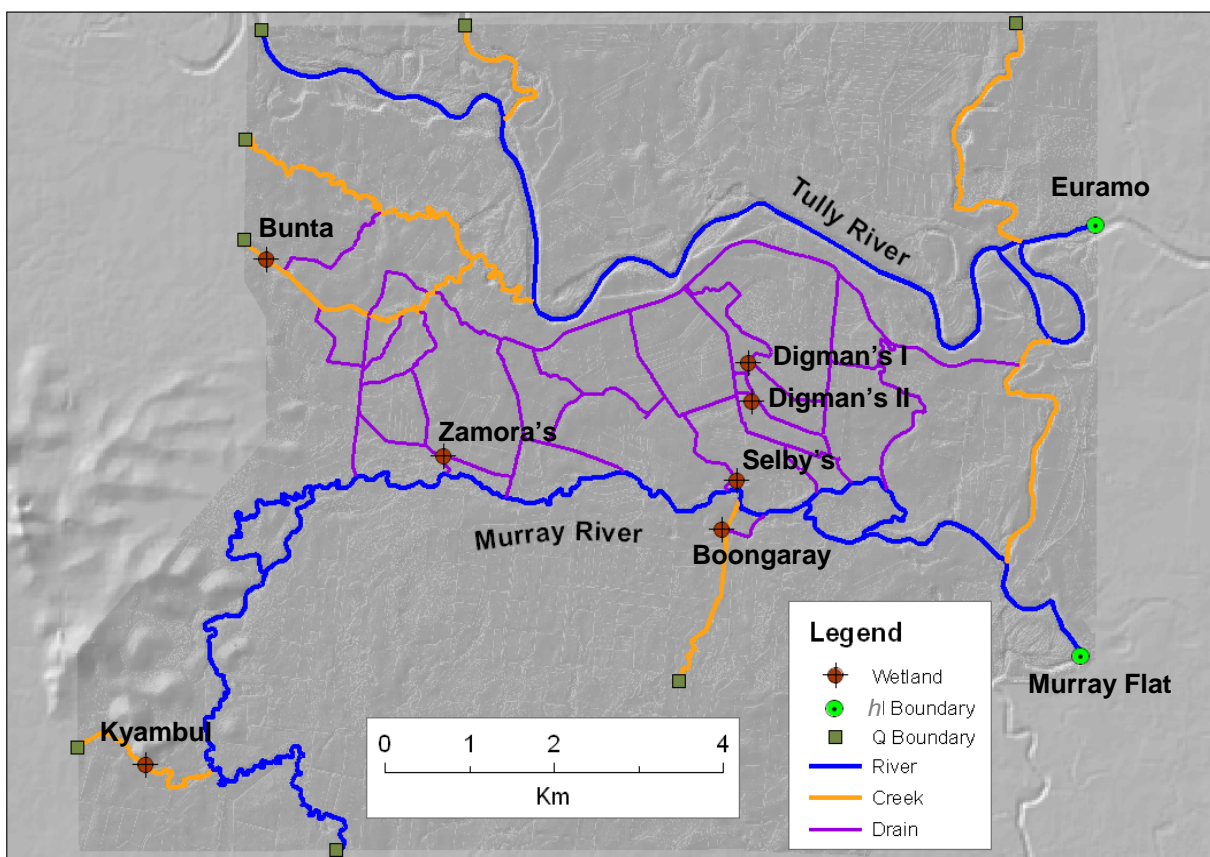


Figure 4: The drainage network used in the 1-D (MIKE11) hydrodynamic model showing water ways (river, stream and drain) and location of wetlands on the network branches. Model boundaries are also depicted at appropriate locations (h denotes water level and Q denotes discharge).

2.4.3 Connectivity assessment

The time sequence of water depths throughout the stream networks generated by the above 1-D hydrodynamic model was used to determine the connectivity between any given wetland and the two main rivers. A wetland was considered connected with a river when the water depth along any pathway from a wetland to the river was equal to or greater than a specified threshold depth. By accumulating this information over an entire year, the timing and duration

of connection for each wetland were obtained. For practical reasons we produced 10 m grid water depth maps for all time steps. Then using the chosen threshold water depth value, grids were defined as either a wet cell (water depth greater or equal to threshold depth) or a dry cell (depth less than threshold value). Unique identification codes were introduced for the grids representing rivers and wetlands. Connection of each wetland to the river system was then established by identifying all contiguous wet cells for each daily time step. By then comparing identification codes with those coinciding with wetlands and rivers for that time step it was possible to establish a time series of connection and disconnection for individual wetlands with the Tully and Murray Rivers. Connectivity was assessed for three different threshold water depths 5 cm, 10 cm and 15 cm.

3. Results and Discussion

3.1 Model calibration

3.1.1 Floodplain 2-D hydrodynamic model

Inflows to the 2-D hydrodynamic model were obtained from the NAM rainfall-runoff model. The NAM model was calibrated by adjusting its parameters iteratively to obtain reasonable agreement between measured and simulated runoff volumes, peaks and low flows. Sensitivity of each parameter was investigated and parameters influencing the runoff volume and timing of peaks and lows were identified. The parameters were calibrated for two sub-catchments, the Cochable Creek sub-catchment in the upper Tully and the upper Murray sub-catchment in the Murray catchment. As shown in Table 2, calibrated parameters for these two sub-catchments differ considerably as they are sensitive to both catchment physical properties and the hydrological behavior of the catchment. Calibrated parameters were kept unchanged in the subsequent simulations. Figure 5 shows a comparison between simulated and observed runoff at the Powerline gauge in the Cochable Creek sub-catchment which is located in the upper Tully catchment (Figure 1). The results show good agreement between simulated and observed flow rates throughout the hydrograph (Figure 5a). Simulated accumulated flow is also very close to the observed accumulated flow (Figure 5b). The differences between simulated and observed mean and peak discharges were only 0.5% and 1.6%, respectively. The results were evaluated in terms of commonly used statistical parameters, namely root mean square error (RMSE), correlation coefficient (r^2) and relative error (RE). The RMSEs were $0.70 \text{ m}^3\text{s}^{-1}$ or 3.5% of the mean flow for the Powerline gauge and $3.46 \text{ m}^3\text{s}^{-1}$ or 17.5 % of the mean flow for the Upper Murray gauge. The r^2 values were 0.96 and 0.81 for the Powerline and Upper Murray gauges respectively.

The hydrodynamic model was calibrated for the mean annual flood using an actual flood in 2007 (19 February to 1 March), which had an ARI of one year. During the calibration process, floodplain topography was slightly modified at some locations to rectify model instability due to very high velocities that occurred at sharp gradients. Surface roughness coefficients (Manning's n) were varied iteratively for the major land uses (sugarcane, banana, grazing and urban) within the recommended range to attain close agreement between measured and simulated water heights in the river and on the floodplain. Roughness coefficients for water bodies were estimated using the guidelines given by Chow (1959) and were held constant during calibration. A brief summary of the calibrated roughness coefficients is given in Table 3. The calibrated n value for sugarcane is 0.20 which is the maximum among the land uses followed by urban areas ($n = 0.12$) and banana fields ($n = 0.10$). We used relatively large n for wetlands as the wetlands in the Tully-Murray floodplain are surrounded by tall grasses and small to large trees.

Table 2: Calibrated NAM model parameters for the Cochable Creek and Murray River sub-catchments. The parameters are U_{max} (maximum water content in surface storage), L_{max} (maximum water content in root zone storage), CQ_{OF} (overland flow runoff coefficient), CK_{IF} (time constant for routing inter flow), CK_{OF} (time constant for routing overland flow), T_{OF} (root zone threshold value for overland flow), T_{IF} (root zone threshold value for interflow), T_G (root zone threshold value for groundwater recharge) and CK_{BF} (time constant for routing base flow).

Catchment	U_{max} (mm)	L_{max} (mm)	CQ_{OF}	CK_{IF} (hours)	CK_{OF} (hours)	T_{OF}	T_{IF}	T_G	CK_{BF} (hours)
Cochable Creek	6	14	0.85	500	48	0.05	0.10	0.38	2,000
Murray River	16	24	0.12	351	10	0.15	0.21	0.80	2,982

Table 3: Calibrated Manning's roughness coefficient (n) for different land types used in the 2-D hydrodynamic (MIKE21) model.

Land use	Investigated	Calibrated	Connell Wagner (2006)
Sugarcane	0.10-0.60	0.20	0.09
Banana	0.08-0.20	0.10	0.10
Grazing	0.08-0.20	0.09	0.12
Cereal	0.10	0.10	0.10
Urban	0.10-0.30	0.12	-
River	0.025	0.025	0.025
Stream	0.05	0.05	0.06
Wetland	0.04	0.04	-

Figure 5(a): Comparison between observed and computed discharge for the Cochable Creek sub-catchment (gauge location shown in Figure 1).

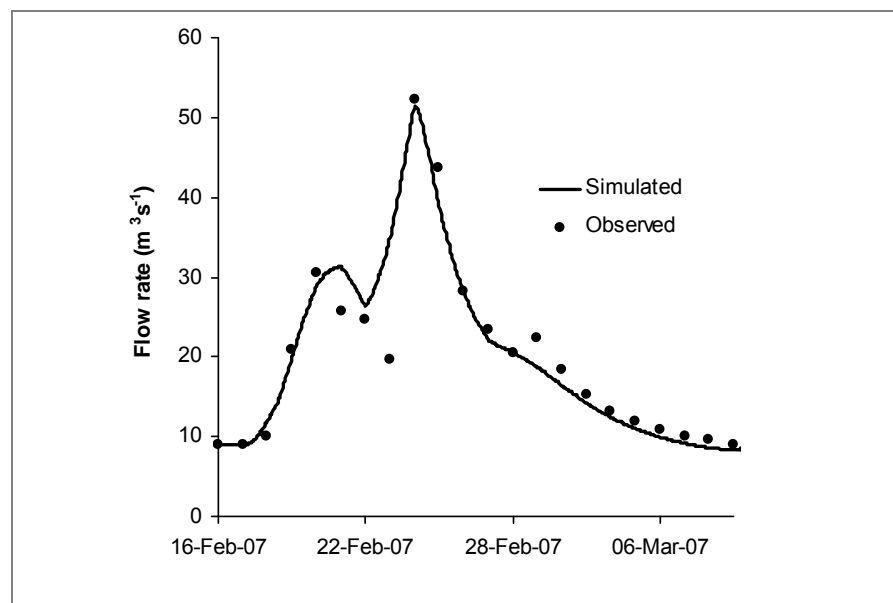
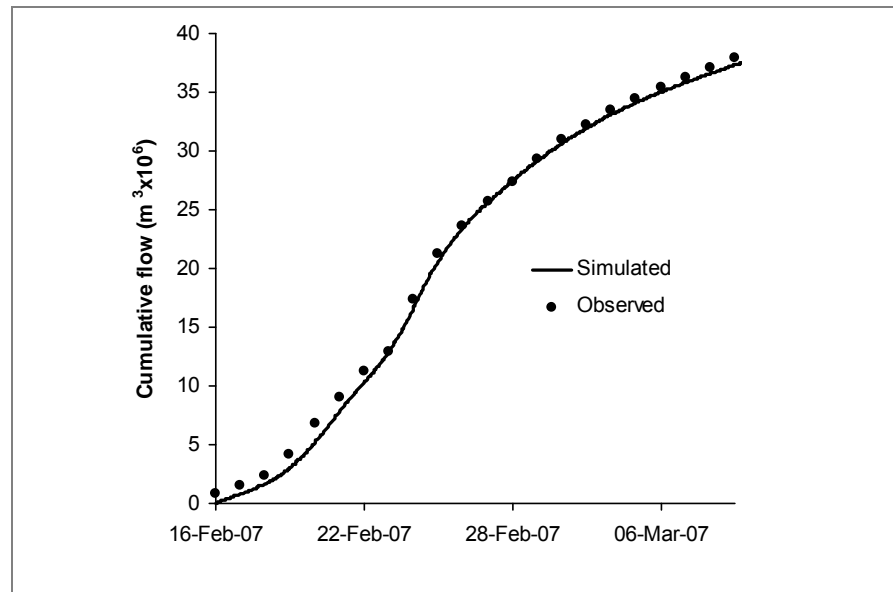


Figure 5(b): Comparison between observed and computed cumulative discharge for the Cochable Creek sub-catchment (gauge location shown in Figure 1).



3.1.2 Stream flow 1-D hydrodynamic model

The hydrodynamic model was calibrated by using measured discharges and water depths in rivers and across the stream network at a large number of points. The main calibration parameter was the surface roughness coefficient, Manning's n . However, stream bed elevations at junctions were slightly modified to rectify model warnings due to different bed levels of streams meeting at a junction. The value of roughness coefficient was adjusted until the best match was obtained between simulated and measured data, determined when the summation of the root mean square deviations between measured and simulated values was minimum. Figure 6 shows a comparison of flow hydrographs at Euramo for May 2009. The overall agreement between simulated and measured discharges is very good and the differences at any time are less than $\pm 8\%$. It can be seen that the simulated peaks are very close to the measured peaks and that simulated low flows are close to measured low flows. The resultant values of the calibrated roughness coefficients are given in Table 4 along with a comparison with equivalent values used in previous hydrodynamic studies of the Tully-Murray floodplain. Our calibrated n values are similar to previously used values (where they exist).

A second test of the hydrodynamic model was made by comparing measured and simulated water depths at a number of locations within the drainage network mostly in drains (Figure 7). Although the correlation between simulated and measured depth is positive the scatter in the data is quite high ($r^2 = 0.42$). This is quite common in the calibration of hydrodynamic models which can reproduce discharge more accurately than individual point heights (e.g. see Connell Wagner, 2006). Height discrepancies arise from differences in the exact location of the field measurements in relation to the model location (which can be several meters apart) and difficulties in manually measuring shallow water depths in field drains which contain undulations and grasses on the stream bed. Also the trend for simulated water depths to be lower than the measured water depths (Figure 7) may be because the one metre resolution network cross-section model tends to smooth out the lowest point of the cross-section.

Table 4: Calibrated Manning’s roughness coefficients (*n*) for stream flow 1-D hydrodynamic (MIKE 11) model.

Stream	Extracted from Chow (1959)	BMT WBM (2008)	Connell Wagner (2006)	Calibrated
Tully River	0.025-0.060	0.05-0.06	0.025	0.03
Murray River (upper)	0.025-0.060	0.045-0.06	0.025	0.04
Murray River (floodplain)	0.025-0.060	0.045-0.06	0.025	0.035
Large Streams (e.g. Jara and Banyan)	0.030-0.080	0.045-0.07	0.06	0.05
Other Streams	0.030-0.080	0.06	0.06	0.06
Drains	0.025-0.120	-	-	0.08
Wetlands	-	-	-	0.04

Figure 6: Comparison between simulated and measured flow hydrographs at Euramo for the 1-D (MIKE 11) hydrodynamic model calibration run.

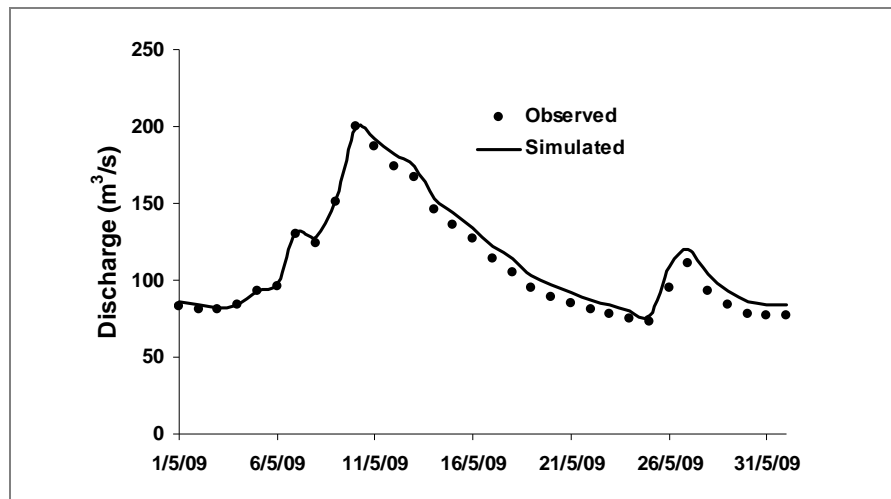
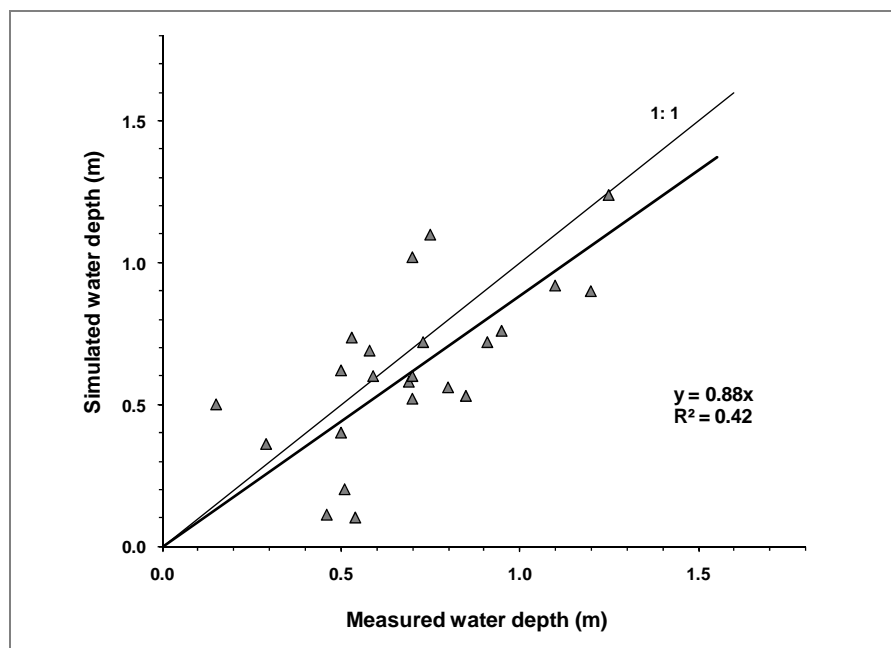


Figure 7: Scatter plot of 1-D (MIKE 11) model simulated and measured water depths across the stream network in the calibration period (19-21 May 2009).



3.2 Overbank connectivity

3.2.1 Floodplain inundation

The extent of floodplain inundation was estimated by superposing simulated maximum water heights over the DEM and Figure 8 shows the extent of inundation for floods with ARIs of one and twenty years. It also shows inundated wetlands under each flood. The floodplain inundation areas include the area of water bodies (e.g. rivers, streams and wetlands) on the floodplain and Table 5 gives a summary of total inundation under different flood magnitudes. Relatively frequent floods (ARI = 1 year) inundate over a third of the floodplain and this increases to just over half of the floodplain with larger floods (ARI = 20 years). There is little further increase in flooded area with a larger flood (ARI = 50 years) because these rarer events add relatively small amounts of additional water into parts of the floodplain with a steeper slope, since most of the low-lying lands are already inundated by a twenty year ARI flood.

Another important effect of floods on wetland habitats is the duration of inundation, which increases with flood size. We used two-hourly flood depth information derived from the MIKE 21 2-D hydrodynamic model to estimate the duration of inundation at each model grid for the entire period of simulation. A typical example of inundation duration at different parts of the floodplain is shown in Figure 9. It can be seen that areas adjacent to the Murray River flooded for longer durations than areas adjacent to the Tully. This is primarily due to the low bank height of the Murray River and lower land elevation near the Murray River (up to four metres lower than the equivalent areas adjacent to the Tully River).

The timing of floods is also important to wetland biota and we therefore examined seasonal variations of flood timing in these catchments using 38 years of recorded flood data. The results of this analysis show flooding is generally confined to the wet season with the largest flood flows occurring in January (Figure 10a), when several cubic kilometres of water can inundate the floodplain (Wallace *et al.* 2009). However, floods have been recorded as early as 11 December and as late as 20 June. In contrast to flood volume, the number of floods reaches a maximum later in the year between February and March (Figure 10b), coincident with the maximum monthly rainfall. During these months, flooding occurs almost every year (on average), whereas the flood frequency is about half of this in January and April (i.e. one in two years) and much rarer in December (one in eight years), May (one in thirteen years) and June (one in 38 years). For the entire wet season flooding can occur up to ten times, but on average there are three to four overbank floods per year.

The first flood of any wet season may be particularly important to aquatic biota, so these floods were analysed separately. On average, first floods were not any different in size from other floods, but they tended to occur earlier in the year, around January. Individual flood durations ranged from one to thirteen days, with the longer duration associated with the larger floods. For the entire wet season the floodplain can be inundated for up to 34 days; however, there is an average of twelve days each year when freshwater biota can exploit the wetland connections associated with floodplain inundation.

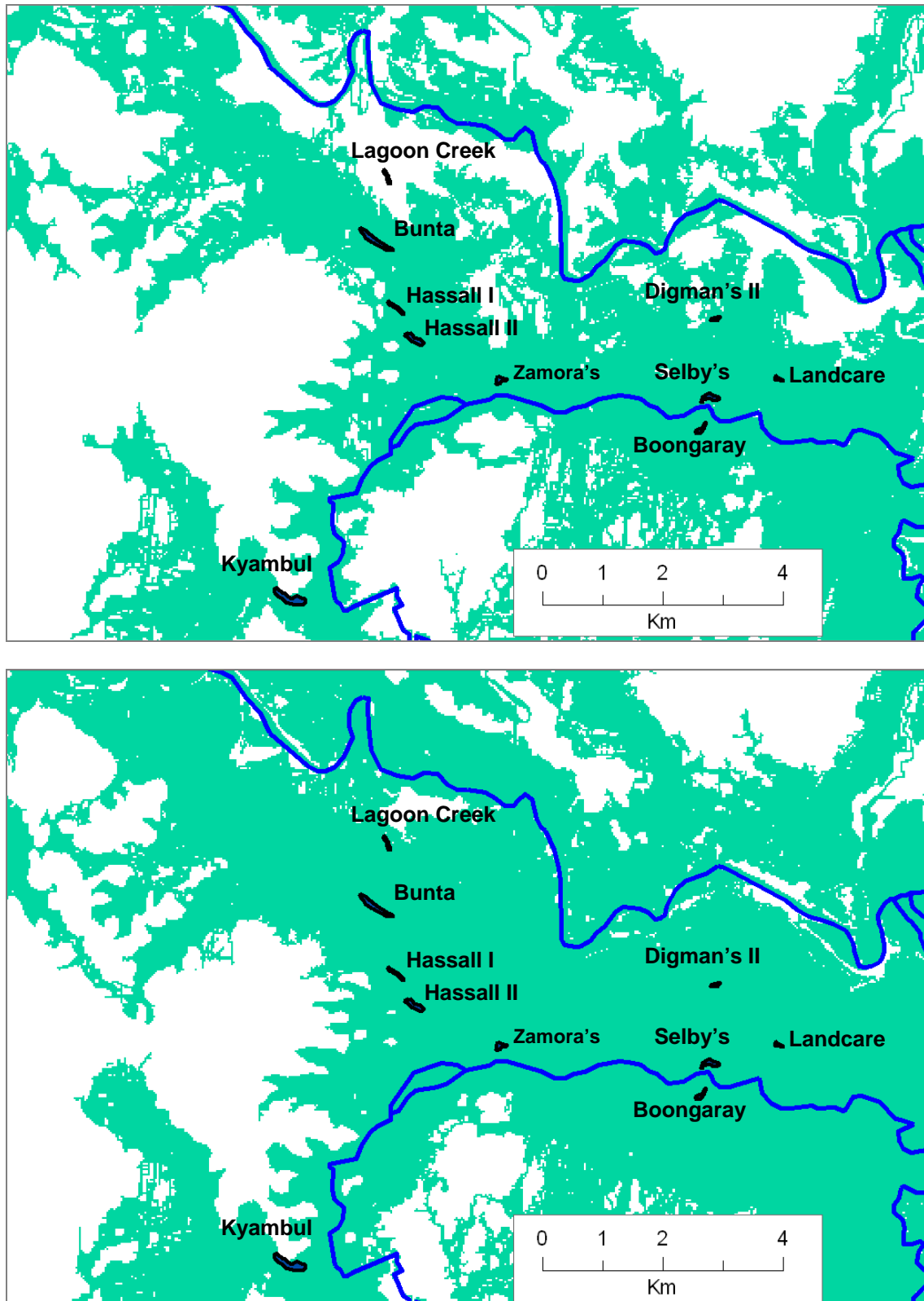


Figure 8: Areal extent of floodplain and wetland inundation for floods with magnitude of ARIs of one year (*top*) and twenty years (*bottom*).

Table 5: Simulated floodplain inundation area for floods with ARIs of one, twenty and fifty years.

Event magnitude	Rainfall volume (km ³)	Inundated area	
		(km ²)	(%)
No floods	-	60	7.2
1 year ARI	0.85	308	37.0
20 year ARI	1.39	429	51.6
50 year ARI	1.68	456	54.8

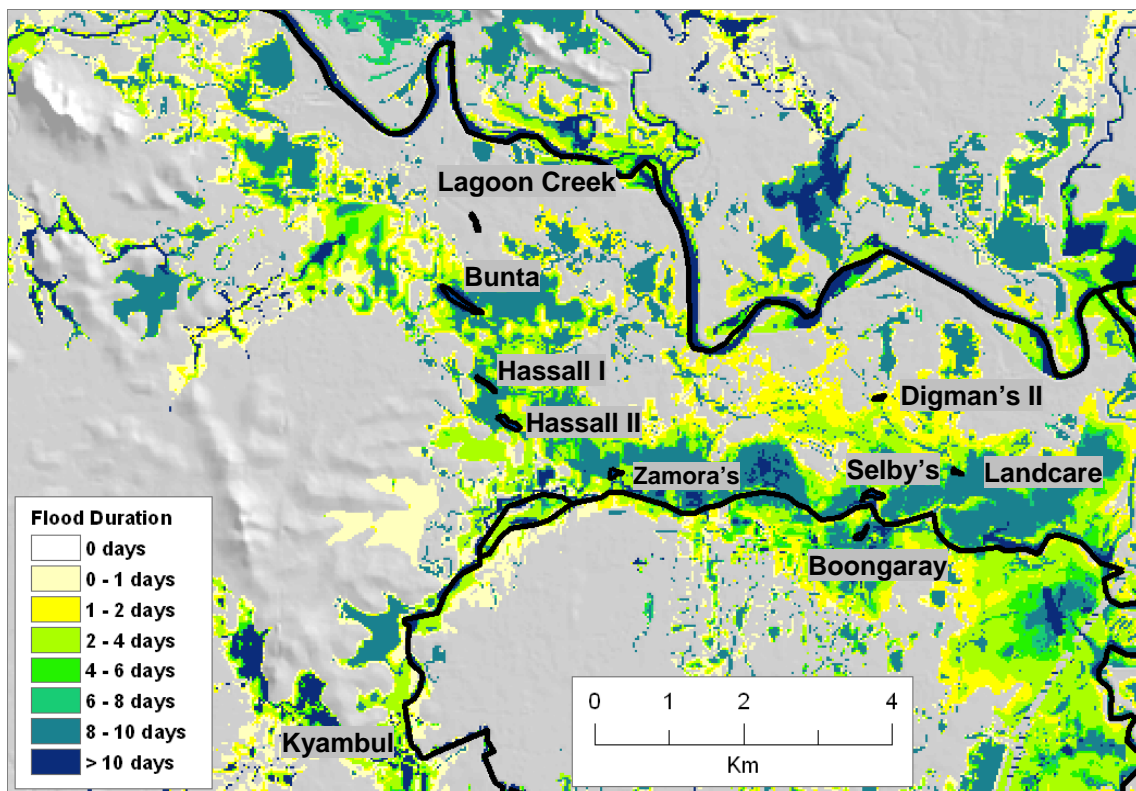
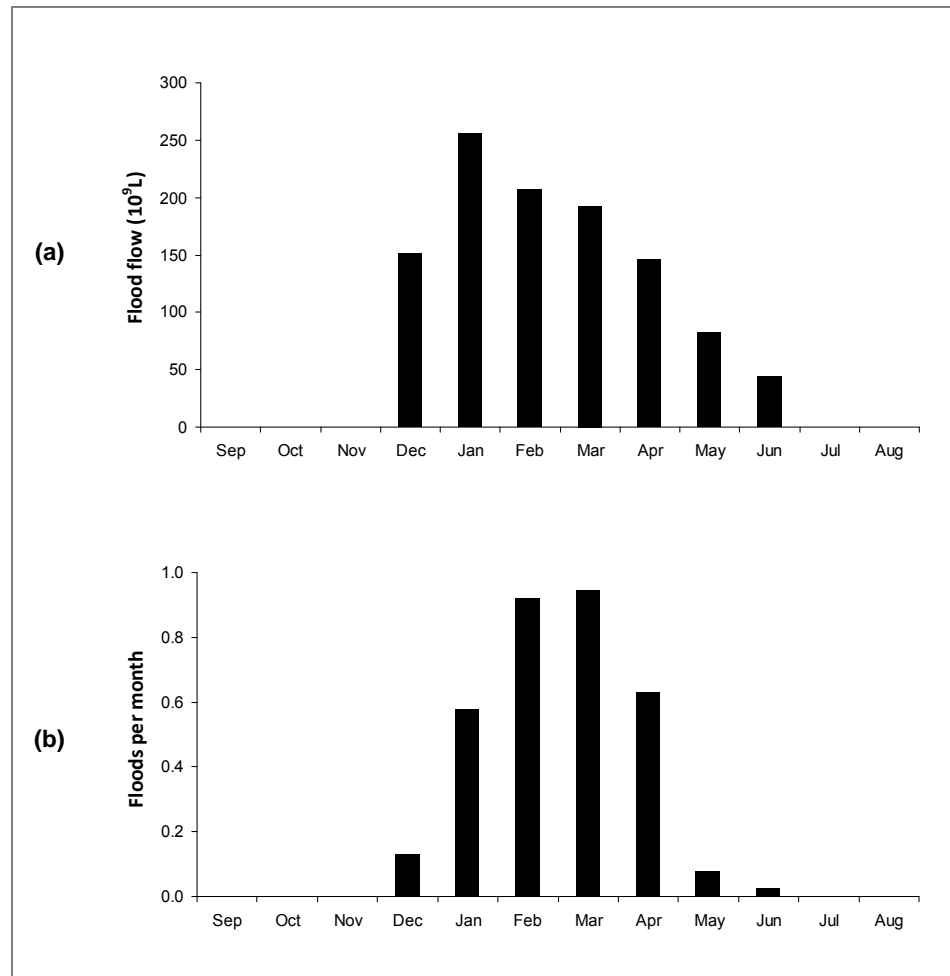


Figure 9: A typical example of the spatial variation in inundation duration across the Tully-Murray floodplain for a flood having a return period of one year.

Figure 10: Seasonal variations in monthly average (a) flood flow and (b) number of floods.



3.2.2 Connectivity with rivers

An example of overbank flood connection between a wetland (e.g. Bunta Wetland) and surrounding water bodies is shown in Figure 11 for one- and twenty-year floods. A sharp rise in water depth signals the start of the overbank flow connection and it can be seen that initial connection for a twenty-year ARI flood occurred earlier than with a one-year ARI flood. This is because the larger flood produced a higher velocity and hence faster moving flood wave. The duration of connection with surrounding water bodies is longer for the larger flood as the greater amount of flood water takes longer to drain from the floodplain.

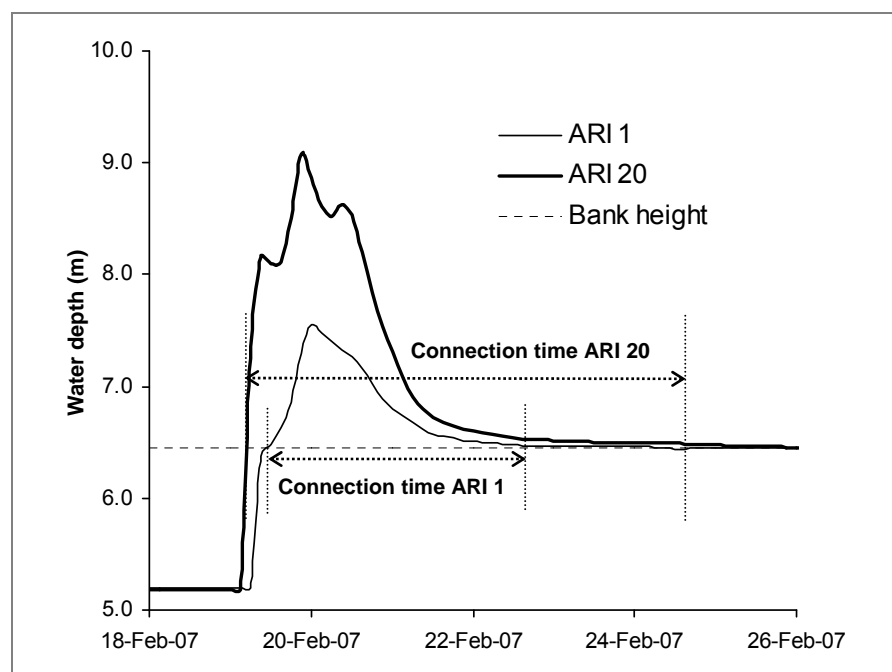
Connectivity of wetlands to the Tully and Murray Rivers was computed by identifying contiguous flow paths at every two-hour time step. To do this a threshold water depth needs to be chosen to ensure continuous water connection across minor topographic variations in the landscape and because we are interested in wetland connectivity that may allow movement of fish (McGuckin, 2000; Bunn and Arthington, 2002), which can be impeded at low water depths (Sanger, 2000). For overbank flooding we chose a threshold depth of 30 cm to distinguish between connected and disconnected water bodies. Figure 12 shows an example of this type of connectivity analysis for a single time step around 4½ days (106 hours) into a flood with an ARI of one year. Different interconnected regions for this particular time are shown on this figure. For example, during the fifth day after the start of the one-year ARI flood, the wetlands within region 2 were connected with each other and with the Murray River, but not connected with the Tully River. At the same time wetlands in region 1 were connected with neither river. By checking contiguous water at every time step and accumulating this information for the entire flood period, connectivity of each wetland with the

two rivers was obtained. As indicated previously, larger floods produce longer durations of flooding and they also create longer durations of connectivity. Summaries of connection time and duration of connection of the wetlands to the Murray River are shown in Figure 13 and to the Tully River Figure 14. It can be seen that Lagoon Creek was not connected to either river for the flood with an ARI of one year, but was connected to both for the larger floods with twenty to fifty year ARIs. This is because Lagoon Creek is relatively elevated and flood water only reaches it during large floods. The duration of connection of wetlands to the Murray River is consistently longer than to the Tully River, due mainly to the lower elevation of the Murray River.

Figure 14 also shows that nearly all of the wetlands connect and disconnect with the Tully River at the same time. This is because the connection and disconnection of the largest body of flood water to the Tully River is via a single drainage line situated well upstream in this catchment. Sedimentation and constructed levees along the Tully River contribute to this constrained connectivity behavior. Figure 13 show that Boongaray and Landcare wetlands retain their connection to the Murray River even after the main flood has receded. These wetlands provide examples of where overbank flow conditions (due to the low bank heights of the Murray) have maintained a much longer period of connectivity to nearby wetlands. It can also be seen that flood events with a second, but smaller peak may reconnect some of wetlands that become disconnected after the first peak recedes (e.g. see Selby's wetland during the one-year ARI flood, Figure 13a). The distances of connecting pathways between the wetlands and the Tully and Murray Rivers are shown in Figure 15. Connection distances to the Murray River (often <1.5 km) are much shorter than to the Tully River (several kilometres) and this difference may have an impact on the opportunities for the migration of some aquatic biota.

The durations of connectivity for all ten wetlands for each of the three different ARI floods are summarised in Table 6. For the majority of the wetlands the duration of connectivity during flooding ranges from one to four days with the Tully River as flood size increases. Connectivity is much longer to the Murray River; 2-12 days as flood size increases. As flood size increases from an ARI of twenty to fifty years, connectivity with the Tully River does not greatly increase, whereas connectivity with the Murray River increases quite markedly. Again this may be due to the presence of levees on the Tully River leading to the single connection point which is inundated in either a 20-50 year ARI flood.

Figure 11: An illustration of overbank connectivity at Bunta wetland based on water depths derived from the 2-D (MIKE 21) hydrodynamic model. Two flood sizes are shown with average return intervals (ARIs) of one and twenty years.



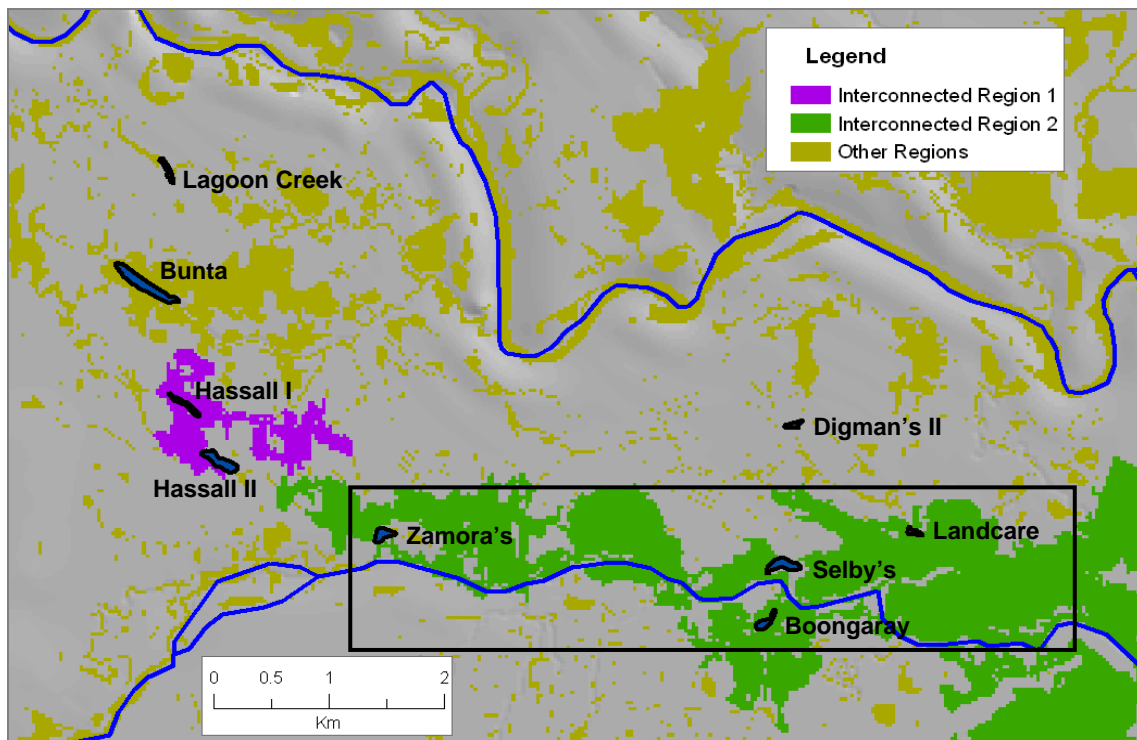
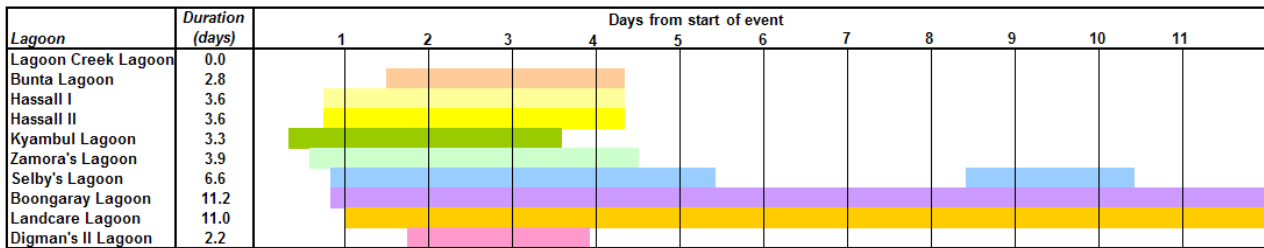
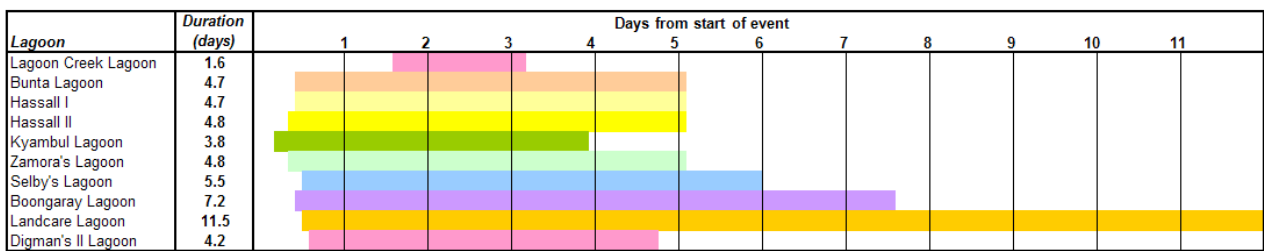


Figure 12: An example of the flood inundation connectivity analysis based on water depths derived from the 2-D (MIKE 21) hydrodynamic model. The different colours shows contiguous water bodies 106 hours after the start of a flood with an annual return period of one year.

(a) ARI – One Year



(b) ARI – Twenty Years



(c) ARI – Fifty Years

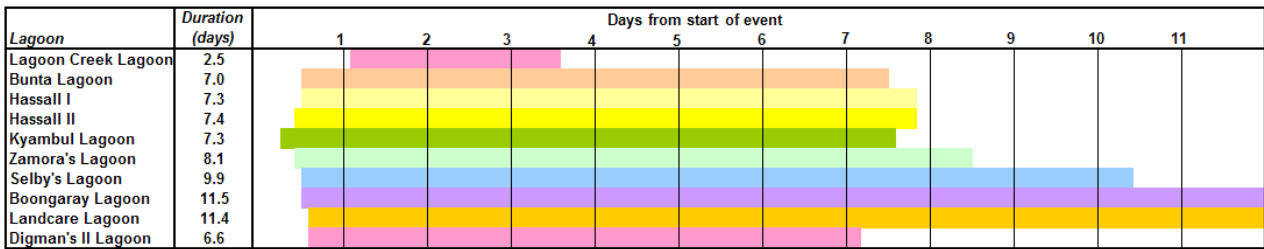
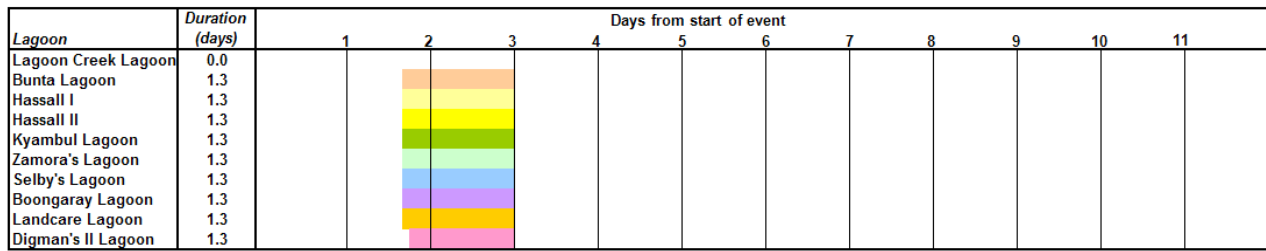
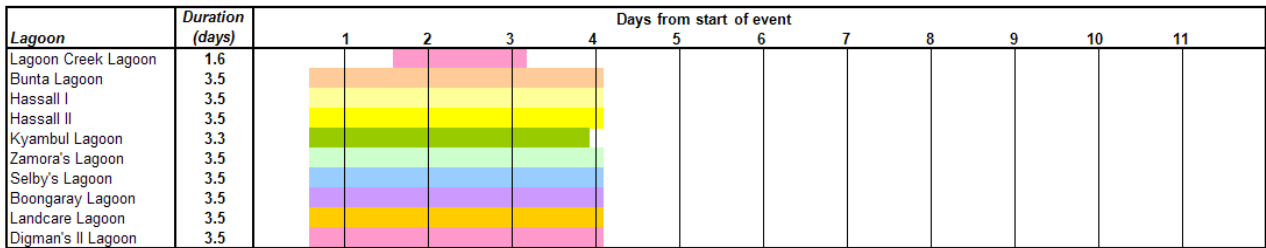


Figure 13: Summary of the timing and duration of connectivity of ten floodplain wetlands to the Murray River for floods with annual return intervals (ARIs) of (a) one, (b) twenty, and (c) fifty years.

(a) ARI – One Year



(b) ARI – Twenty Years



(c) ARI – Fifty Years

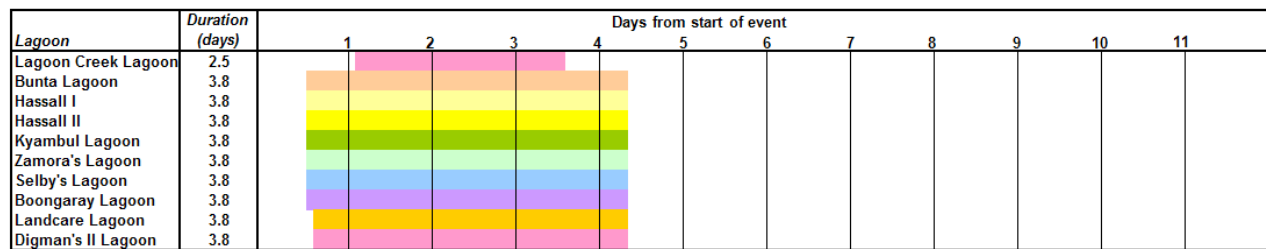
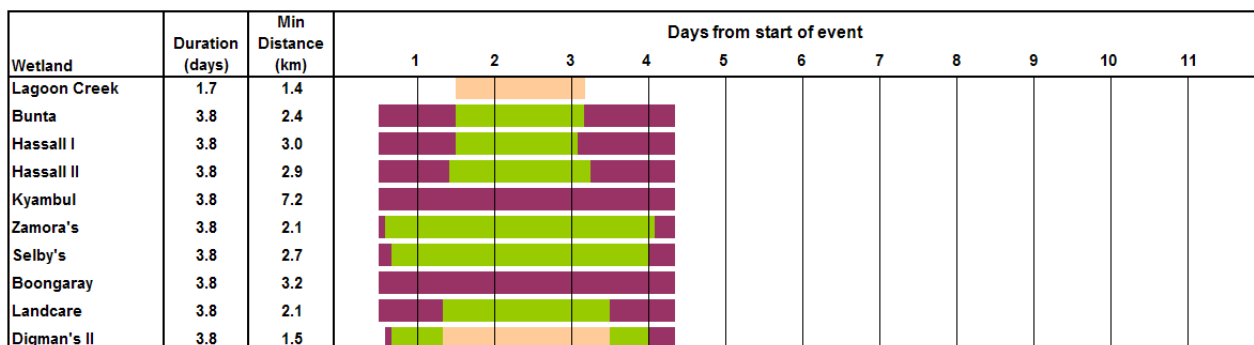


Figure 14: Summary of the timing and duration of connectivity of ten floodplain wetlands to the Tully River for floods with annual return intervals (ARIs) of (a) one, (b) twenty, and (c) fifty years.

(a) Connection to Tully River



(b) Connection to Murray River

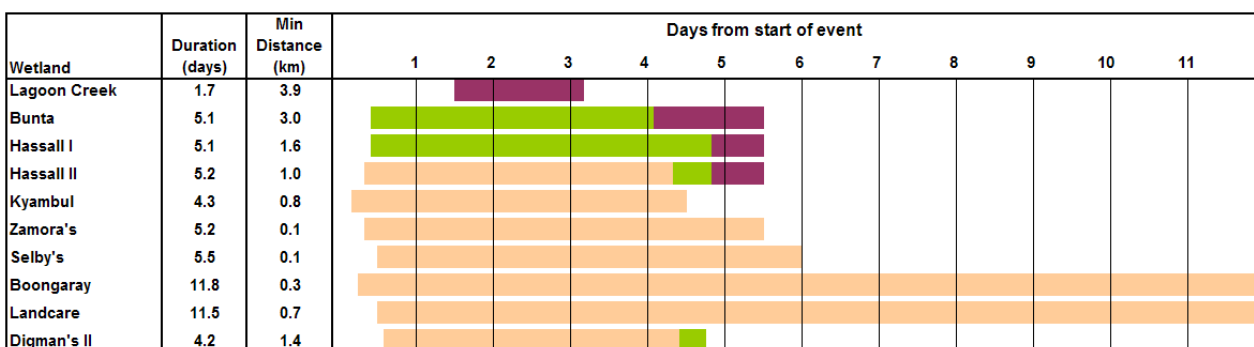


Figure 15: Connectivity duration and minimum connecting path distance between individual wetlands and (a) the Tully River and (b) the Murray River for a flood of ARI 20 years.

Table 6: Summary of overbank wetland connection durations for floods with annual return intervals of 1, 20 and 50 years.

Name	Duration of connection (days)					
	ARI 1		ARI 20		ARI 50	
	Tully	Murray	Tully	Murray	Tully	Murray
Boongaray	1-2	11-12	3-4	6-7	3-4	11-12
Bunta	1-2	2-3	3-4	4-5	3-4	7-8
Digman's II	1-2	2-3	3-4	4-5	3-4	6-7
Hassall I	1-2	3-4	3-4	4-5	3-4	7-8
Hassall II	1-2	3-4	3-4	4-5	3-4	7-8
Kyambul	1-2	3-4	3-4	3-4	3-4	7-8
Lagoon Creek	0	0	1-2	1-2	2-3	2-3
Landcare	1-2	11-12	3-4	11-12	3-4	11-12
Selby's	1-2	4-5	3-4	5-6	3-4	11-12
Zamora's	1-2	3-4	3-4	4-5	3-4	8-9

3.3 Channelised connectivity

3.3.1 *Connectivity with rivers*

An example of the connectivity of wetlands to the Tully and Murray Rivers is shown in Figure 16. This depicts the status of the stream links on 2 May 2007 for a threshold water depth of five centimetres. Each different colour on this figure represents the interconnected stream links at this particular time step. It can be seen that Bunta, Zamora's, Selby's and Boongaray are connected to the Tully and Murray Rivers, however Digman's I and Digman's II are not connected to either river. This is because the latter two are small artificial wetlands located relatively distant from the two main rivers.

Figures 17-20 show the summary of the timing and duration of connections between seven wetlands to the Tully and Murray Rivers in 2007 and 2008 for three threshold water depths. Some wetlands (e.g. Boongaray, Bunta, Kyambul, Selby's and Zamora's) maintain connection with the Murray River for most or all of the year. Kyambul lagoon is an example of a remnant riverine wetland through which water flows continuously, albeit with very low flow at the end of the dry season. Other wetlands with long connection times tend to be those which are very close to the Murray River (see Figure 4 for location). The two artificial wetlands Digman's I and II have the least connectivity with the two main rivers (~30-40 days) from which they are disconnected for long periods during the dry season. Summaries of the duration of connection of the wetlands to the Tully and Murray Rivers are given in Table 7 for three threshold depths: 5, 10 and 15 cm. For threshold depths greater than ten centimetres, most of the wetlands retain their connection to the Murray River for longer periods than they do to the Tully River because they have direct or very short links to the Murray River. For the five centimetre threshold depth the connection times for all wetlands to both the Tully and Murray Rivers are the same. This implies that there is a continuous connection between the Tully and Murray Rivers for this low water depth (i.e. 5 cm), so connection to one river would result in connection to both.

Connectivity to the Tully River is more dependent on the threshold water depth than it is for the Murray River. For example, leaving aside the two short duration connectivity wetlands (Digman's I and II), a five centimeter change in the threshold depth leads to a 36% change (on average) in the connectivity duration to the Tully River, but only a six percent change (on average) in the connectivity duration to the Murray River. Wetland connectivity to the Murray River is therefore less sensitive to water depth than is connectivity to the Tully River.

3.3.2 *Lateral connectivity gradient*

Connectivity is clearly affected by proximity to a river and this is summarised in Figure 21 which shows the average connection time (in days per year) between the wetlands analysed and the Murray River for the fifteen centimetre threshold water depth. It can be seen that wetlands close to the river maintain flow connection for the entire year. The Bunta, Digman's I and Digman's II wetlands are located relatively distant from the river and have shorter annual average connection times. The connection times of Digman's I and II are much shorter than Bunta lagoon presumably because they are artificial wetlands and only have connection to the river via drains, whereas Bunta is a natural wetland which has good stream connection to the river. These different levels of connectivity may have important ecological implications.

Table 7: Summary of channelised connectivity between wetlands and the Tully and Murray Rivers in 2007 for threshold water depths of 5, 10 and 15 cm.

Wetland	Connection to Tully River (days)			Connection to Murray River (days)		
	For the water depth of:			For the water depth of:		
	5 cm	10 cm	15 cm	5 cm	10 cm	15 cm
Boongaray	185	159	129	185	159	133
Bunta	365	249	157	365	365	365
Digman's I	43	41	37	43	41	37
Digman's II	47	41	41	47	41	41
Kyambul	337	249	157	337	333	261
Selby's	365	249	157	365	365	365
Zamora's	365	249	157	365	365	365

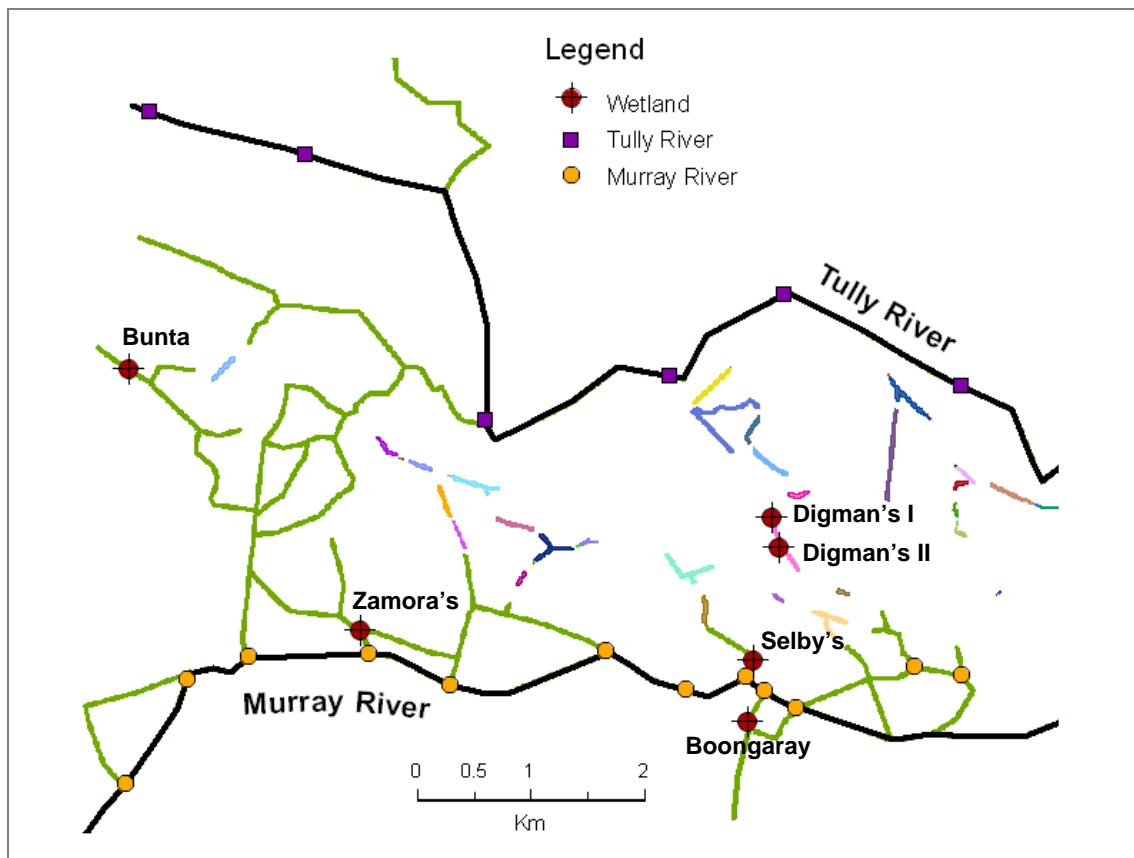


Figure 16: An example of the connectivity analysis output for 2 May 2007 for a threshold water depth of five centimetres. Each colour shows inter-connected stream links (— connected to river) for this particular time. In this example the Bunta, Zamora's, Selby's and Boongaray wetlands are connected to the Tully and Murray Rivers whereas Digman's I and Digman's II wetlands are not connected to either river.

(a) Connectivity for 5 cm or more water depth

Lagoon	Duration (days)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bunta	323	[Pink bars indicating connectivity]											
Kyambul	365	[Brown bars indicating connectivity]											
Zamora's	365	[Yellow bars indicating connectivity]											
Selby's	365	[Light green bars indicating connectivity]											
Boongaray	365	[Dark green bars indicating connectivity]											
Digman's I	31	[Blue bars indicating connectivity]											
Digman's II	37	[Purple bars indicating connectivity]											

(b) Connectivity of 10 cm or more water depth

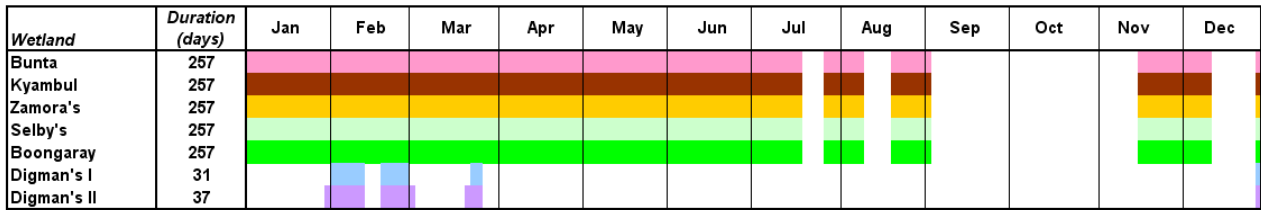
Lagoon	Duration (days)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bunta	301	[Pink bars indicating connectivity]											
Kyambul	365	[Brown bars indicating connectivity]											
Zamora's	365	[Yellow bars indicating connectivity]											
Selby's	365	[Light green bars indicating connectivity]											
Boongaray	365	[Dark green bars indicating connectivity]											
Digman's I	29	[Blue bars indicating connectivity]											
Digman's II	35	[Purple bars indicating connectivity]											

(c) Connectivity for 15 cm or more water depth

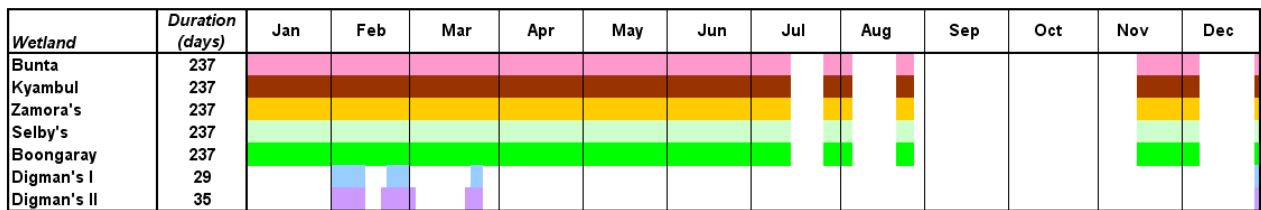
Lagoon	Duration (days)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bunta	223	[Pink bars indicating connectivity]											
Kyambul	319	[Brown bars indicating connectivity]											
Zamora's	365	[Yellow bars indicating connectivity]											
Selby's	365	[Light green bars indicating connectivity]											
Boongaray	365	[Dark green bars indicating connectivity]											
Digman's I	29	[Blue bars indicating connectivity]											
Digman's II	31	[Purple bars indicating connectivity]											

Figure 17: Connectivity timing and duration of connection and disconnection of individual wetlands via the drainage network to the Murray River during 2007 for threshold water depths of (a) 5 cm, (b) 10 cm and (c) 15 cm.

(a) Connectivity for 5 cm or more water depth



(b) Connectivity of 10 cm or more water depth



(c) Connectivity for 15 cm or more water depth

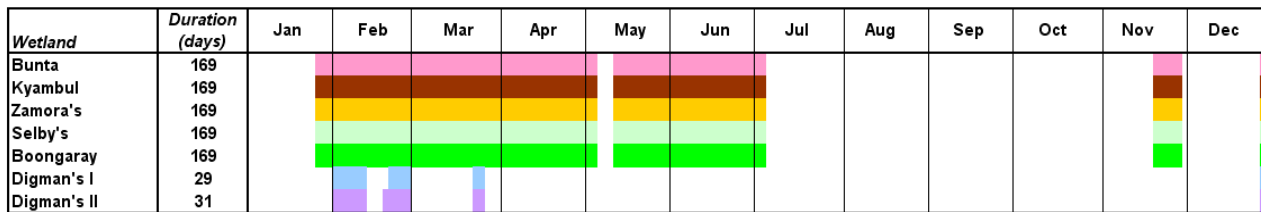


Figure 18: Connectivity timing and duration of connection and disconnection of individual wetlands via the drainage network to the Tully River during 2007 for threshold water depths of (a) 5 cm, (b) 10 cm and (c) 15 cm.

(a) Connectivity for 5 cm or more water depth

Lagoon	Duration (days)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bunta	345	[Pink bar]											
Kyambul	365	[Brown bar]											
Zamora's	365	[Yellow bar]											
Selby's	365	[Light Green bar]											
Boongaray	365	[Dark Green bar]											
Digman's I	31	[Purple bars]											
Digman's II	41	[Purple bars]											

(b) Connectivity of 10 cm or more water depth

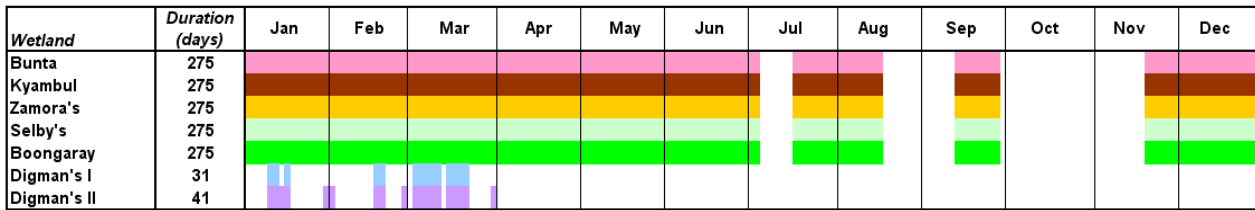
Lagoon	Duration (days)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bunta	295	[Pink bar]											
Kyambul	365	[Brown bar]											
Zamora's	365	[Yellow bar]											
Selby's	365	[Light Green bar]											
Boongaray	365	[Dark Green bar]											
Digman's I	31	[Purple bars]											
Digman's II	39	[Purple bars]											

(c) Connectivity for 15 cm or more water depth

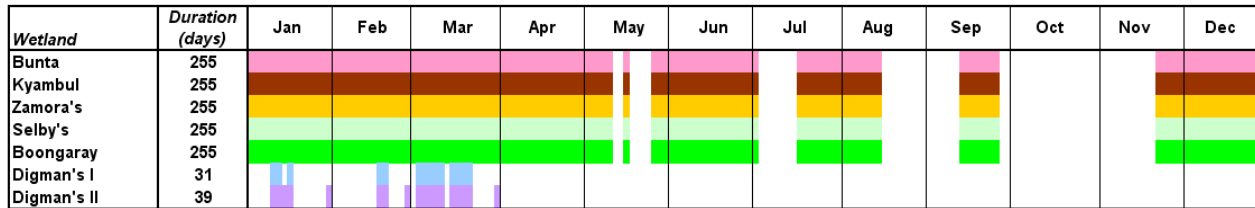
Lagoon	Duration (days)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bunta	233	[Pink bar]											
Kyambul	341	[Brown bar]											
Zamora's	365	[Yellow bar]											
Selby's	365	[Light Green bar]											
Boongaray	365	[Dark Green bar]											
Digman's I	29	[Purple bars]											
Digman's II	35	[Purple bars]											

Figure 19: Connectivity timing and duration of connection and disconnection of individual wetlands via the drainage network to the Murray River during 2008 for threshold water depths of (a) 5 cm, (b) 10 cm and (c) 15 cm.

(a) Connectivity for 5 cm or more water depth



(b) Connectivity of 10 cm or more water depth



(c) Connectivity for 15 cm or more water depth

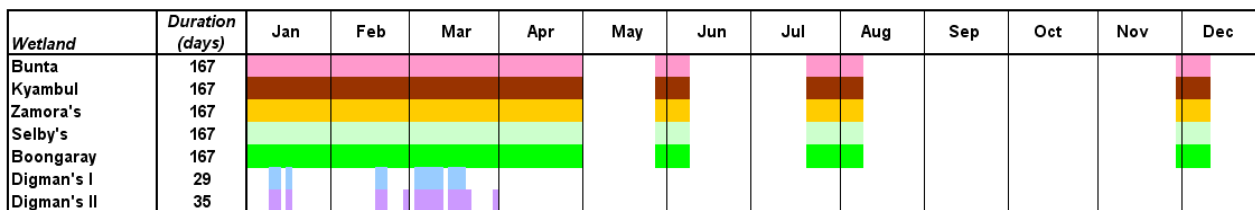
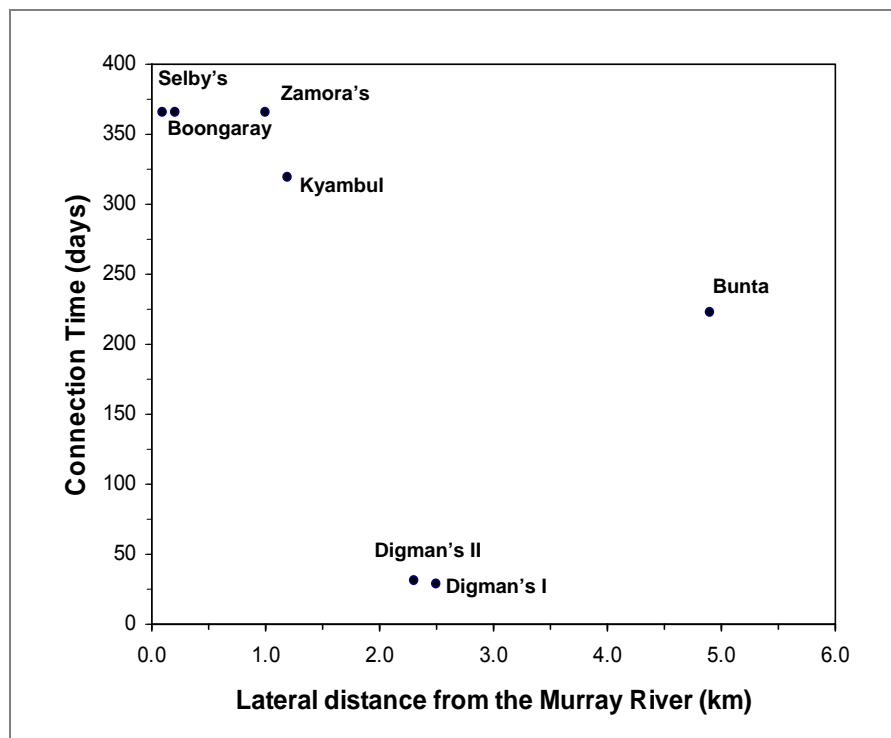


Figure 20: Connectivity timing and duration of connection and disconnection of individual wetlands via the drainage network to the Tully River during 2008 for threshold water depths of (a) 5 cm, (b) 10 cm and (c) 15 cm.

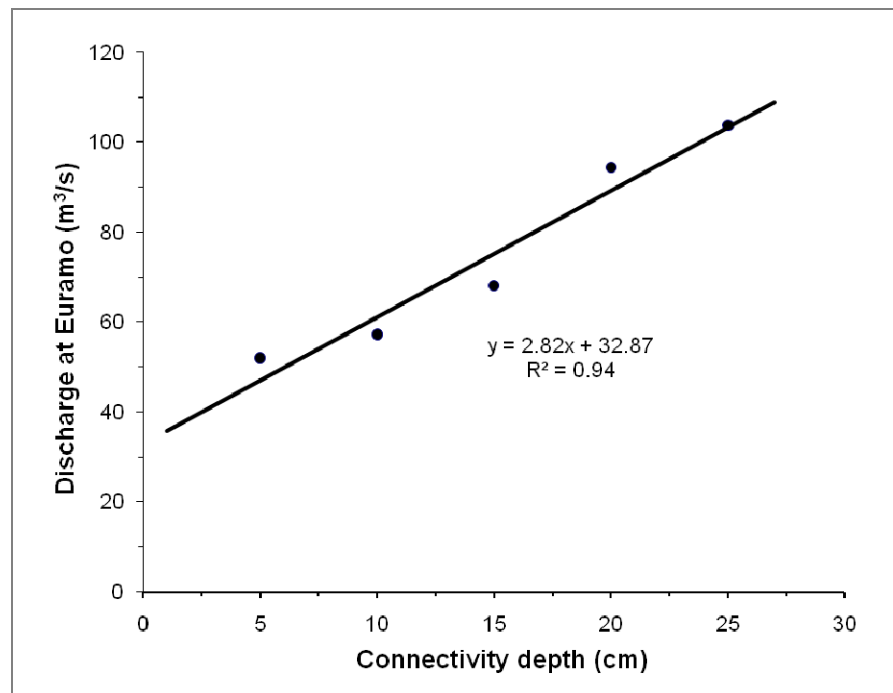
Figure 21: Variations of wetland connectivity with lateral distance from the Murray River for 15 cm (more more) water depth.



3.3.3 Connectivity and river flow

In order to provide information that could be useful for estimating the environment flow requirement for the ecological integrity of common fish species, we explored the relationship between connectivity threshold depth and the readily available Tully River flow at Euramo. For the five wetlands that connect to and disconnect from the Tully River concurrently, we identified the periods in which this occurred during 2007 and 2008, and noted the corresponding mean discharge at Euramo from the gauged data record. This was repeated for five different threshold water depths (5, 10, 15, 20 and 25 cm) and the results are shown in Figure 22. Connectivity depth increases with flow in the Tully River and the fitted line can be used to determine the discharge at which connectivity depth falls below any chosen threshold depth.

Figure 22: Relationship between wetland connectivity threshold depth and the Tully River flow at Euramo. Note: Discharge was estimated based on connectivity of five wetlands that connect to and disconnect from the Tully River concurrently.



4. Conclusions and Recommendations

4.1 Overbank connectivity

This study has demonstrated how hydrological connectivity of floodplain wetlands can be quantified using hydrological and hydrodynamic modelling. This novel method can predict the timing and duration of connectivity of a large number of wetlands of different types under a range of flood sizes. In the Tully-Murray floodplain we found that the majority of the wetlands are regularly inundated as they connect to the rivers during floods with a one-year ARI. Larger floods connect these wetlands for longer periods and also connect a few more wetlands that are located on higher ground further from the rivers. However, connection time and the duration of connectivity of each wetland differ according to its location and/or proximity to these rivers. Flood size also affects the duration of wetland connectivity, which can range from 0 days (no connection) to 12 days as flood ARI increases from 1 to 50 years. Some wetlands appear to be connected only during large floods (e.g. Lagoon Creek wetland). We also found that wetlands on the Tully-Murray floodplain are connected to the Murray River for longer periods than they are to the Tully River and this has been attributed to both their proximity to the Murray River and the higher bank heights in the Tully River. This is a good demonstration of how measures to reduce flooding (in the Tully River) using levees have changed the timing and duration of wetland connectivity to this river. These variations in wetland connectivity may have important implications for (i) the movement and recruitment patterns of aquatic biota during and after flood events, (ii) wetland habitat characteristics and water quality, (iii) the biodiversity of individual wetlands over time, and (iv) the potential for wetland processes to influence the quality of water flowing to the GBR lagoon.

4.2 Channelised connectivity

We have also demonstrated how the connectivity of different wetlands through the floodplain stream and cane drain network can be quantified using hydrodynamic modelling. Results indicate that connection time and the duration of connectivity of each wetland to the major rivers differ according to wetland proximity to rivers and/or wetland connection to stream network. Some wetlands retain their connection with the main rivers throughout the year, although water depths in the drainage network are very low during the dry season. Other wetlands, which are located more distant from the main rivers, maintain connection with the main rivers during the wet season but disconnect during the dry season.

Wetland connectivity via the drainage network was greater to the Murray River than the Tully River. This is due to the better drainage network links and the closer proximity of many of the wetlands to this river. Wetland connectivity during floods was also found to be better to the Murray River due to the lower bank heights along this river. However, drainage network connectivity to both rivers (30-365 days) was much greater than flood inundation connectivity for the same wetlands (0-12 days) described above.

The connectivity of artificial wetlands can vary greatly according to the type of network connection they have. For example, Zamora's wetland has a good stream and drain network and as a result connects to two main rivers for 40-100% of the year (depending on threshold depth), whereas Digman's two artificial wetlands are only connected to drains that are relatively distant from the rivers and this results in a much shorter connection time of ~10% of the year. This illustrates that the current network connectivity modelling approach could be useful for identifying better locations for placement of an artificial wetland where its connectivity is considered important.

This kind of connectivity modelling can also be used to identify when water levels in a drainage network fall below critical thresholds for fish movement using readily available river

gauge data. These types of relationship are central to the concept of setting environmentally acceptable flows, particularly where these are affected by significant water abstractions for human use. Quantitative connectivity modelling will also be useful to help explain the variation in habitat structure, water quality and faunal composition of individual wetlands over time. As the hydrodynamic model is driven by daily rainfall it should also be possible to quantify the potential impacts of climate change on wetland connectivity, if the future changes in rainfall can be specified.

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