Hydrological changes and ecological impacts associated with water resource development in large floodplain rivers in the Australian tropics.

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Abstract

The majority of rivers in the Australian tropics possess near-natural flow regimes and are an ecological asset of global significance. We examined flow variability in large floodplain rivers in the Gulf of Carpentaria, northern Australia, and the potential ecological impacts of future water resource development (WRD). Flow metrics based on long-term records were used to classify flow regimes and predict hydrological drivers of ecological function. Flow regimes of selected rivers were then compared with those simulated for pre- and post-WRD flows in the Darling River, a highly modified river in Australia's south-east. Generally, rivers were classified as typically 'tropical' (more permanent, regular flows) or 'dryland' (more ephemeral, with greater flow variability). In addition, all rivers displayed wet-dry seasonality associated with changes in flow magnitude or number of zero-flow days. We propose that these features (flow permanence and regularity; flow variability and absence; wet-dry seasonality) are the key hydrological drivers of biodiversity and ecological function in the floodplain rivers of Australia's north. In terms of WRD, inter-annual flow variability was predicted to increase or decrease depending on rivers' natural flow regimes, specifically their tendency toward lower or higher flow magnitudes. Either outcome is expected to have adverse effects on the biodiversity and ecological function of these relatively pristine rivers and floodplain habitats. In particular, reduced and homogenised habitat, loss of life-history cues, inhibited dispersal and shifts in community composition, as a result of WRD, threaten the ecological integrity of rivers adapted to the three hydrological drivers above. These findings serve as a caution for careful consideration of water resource development options for rivers in the Australian tropics and for those with similar flow regimes the world over.

Introduction

Currently, rivers and floodplains in the Australian tropics are among the continent's most undeveloped, supporting high levels of biological diversity and ecological health (ATRG, 2004). Hence, their current hydrology represents a natural, or near natural, condition of flow. These factors identify Australia's northern rivers as an ecological asset of global significance, particularly in comparison with rivers throughout the world's tropics (ATRG, 2004; Douglas *et al.*, 2005; Latrubesse *et al.*, 2005). Unfortunately, little research, hydrological or otherwise, has been documented for these rivers (Hamilton and Gehrke, 2005), and hydro-ecology in northern Australia has received close attention only recently (Erskine *et al.*, 2005; Finlayson, 2005; Townsend and Padovan, 2005). This knowledge gap is especially noticeable in comparison with Australia's southern rivers, such as those in the Murray-Darling Basin (e.g. Boulton and Lloyd, 1991; Sheldon and Walker, 1998; Kingsford, 2000; Reid and Brooks, 2000; Balcombe *et al.*, 2006).

In a global context we have a general understanding of the basic principles linking flow and ecology (Bunn and Arthington, 2002); namely, that:

> Principle 1: flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition;
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> Principle 2: aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes;
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> Principle 3: maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species;
>
> Principle 4: invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes.

Despite the lack of specific knowledge about the relationships between ecological processes and flow in Australia's northern rivers, the basic principles linking flow to ecological response are still expected to apply. However, the specifics of this response will reflect the dominant flow regime evident in any one river.

Australia is one of the driest continents on the planet with flow regimes of its unregulated rivers characterised by low discharges and high variability (Finlayson and

McMahon, 1988; Puckridge *et al.*, 1998). This is due to a number of factors including an expanse of low-relief topography, which leads to increased evapotranspiration and variability in both rainfall and runoff (Finlayson and McMahon, 1988; Lake, 1995), and the influence of the El Niño/Southern Oscillation (ENSO) phenomenon (Walker *et al.*, 1995; Chiew *et al.*, 1998; Thoms and Sheldon, 2000a). In Australia's more arid regions, these factors combine with the complex riverine landscape to produce highly variable levels of connectivity, typical of 'dryland' rivers (Bunn *et al.*, 2006; Marshall *et al.*, 2006; Sheldon and Thoms, 2006). In contrast, 'tropical' river hydrology is characterised by predictable flows often associated with seasonal patterns of flooding and drying (Latrubesse *et al*., 2005). This is true of Australian drainages north of the Tropic of Capricorn, 23° 27' S, where rivers undergo an 'extreme late summer' flow regime due to seasonal variation in rainfall (Finlayson and McMahon, 1988). Anti-cyclones deliver monsoonal rains during the wet season, generally between November and April (Erskine *et al.*, 2005), and are associated with massive inundation of low-relief floodplains. In the dry season, drawdown and evapotranspiration of floodwaters create isolated river and floodplain waterbodies, although some main channels flow throughout the year. These are the typically 'tropical' rivers of Australia's north.

Given the broad geographical coverage of the Australian tropics (roughly one third of the mainland) and the diversity of catchment types, it is likely that both 'dryland' and 'tropical' flow regimes exist in the region. Therefore, the range of ecological responses to natural flow conditions in these systems may be substantial. Indeed, the alternation between seasonal flows in typically 'tropical' Australian rivers is likely to be associated with different effects on riverine communities and function: high-flow periods on downstream floodplain environments, base-flow periods on in-stream ecosystem function (Brodie and Mitchell, 2005; Douglas *et al.*, 2005; Townsend and Padovan, 2005). For Australian dryland rivers, highly variable states of hydrological fragmentation, in both space and time, relate to diverse and concomitantly variable community compositions (Bunn *et al.*, 2006; Marshall *et al.*, 2006; Sheldon and Thoms, 2006). These relationships are likely to be found in the typically 'dryland' rivers of the Australian tropics.

The variability of potential flow regimes, and therefore ecological responses, across the Australian tropics suggests that the impacts of water resource development

(WRD) on river-floodplain ecology may be diverse and not easily encapsulated in a single conceptual model. Ecological impacts of WRD on riverine biota and function have been observed in many systems throughout the world (Ward and Stanford, 1995; Poff *et al.*, 1997; Bunn and Arthington, 2002; Aarts *et al.*, 2004), however, current knowledge specific to the Australian tropics is limited to the few systems that have undergone WRD. The Ord River in Western Australia was subjected to major WRD in the 1960s and 1970s, and two large dams now provide water for irrigated agriculture in the lower catchment. This flow regulation (overall reduction in magnitude and variability combined with reduced wet season flows and increased dry season flows) has been associated with dramatic changes in the community compositions of aquatic macrophytes and riparian vegetation (Doupe and Pettit, 2002; DW, 2006). However, for the majority of rivers in the Australian tropics, the full direction and extent of potential impacts, in terms of flow variability and ecological function, is unknown. Fortunately, insights can be gained through comparison of flow characteristics with those of existing modified and ecologically impacted systems, for which relevant data is available, using a 'bench-marking' approach (e.g. Richter *et al.*, 1996; Sheldon *et al.*, 2000; Poff *et al.*, 2006).

The Murray-Darling Basin, in Australia's south-east, has a history of water extraction and flow regulation of over one hundred years (Reid and Brooks, 2000) and much of the WRD is of the kind likely to be implemented in the Australian tropics (cf. DNRM, 2003; DW, 2006). River and floodplain communities of the Murray-Darling Basin have undergone numerous changes since WRD and impacts on overall ecosystem function have also been observed (e.g. Kingsford, 2000). Thus, the hydrological changes associated with this WRD can be used as a tool to predict ecological responses to flow modification in pristine systems (e.g. Sheldon *et al.*, 2000), such as Australia's northern rivers. To this end, hydrological analysis of large Gulf of Carpentaria rivers will first be conducted in order to classify flow regimes, particularly in terms of 'dryland' and 'tropical' features, and to predict important hydrological drivers of ecological function. Secondly, potential ecological impacts of WRD will be proposed by comparing flow regimes of selected rivers in the southern Gulf of Carpentaria with hydrological changes that have occurred in the Darling River, Murray-Darling Basin, since WRD. We predict that WRD will be associated with substantial changes in the natural flow variability of Australia's northern rivers that will, in turn, affect their overall productivity along with the composition, diversity and life history cues of their biota.

The approach we outline for highlighting potential hydrological changes associated with predicted water resource development builds on the work of others (e.g. Thoms and Parsons, 2003; Poff *et al.*, 2006). Our approach adds to this 'tool box' of hydrological change prediction and is appropriate not only for Australia but also many other regions where water resource development is still increasing. In Central and South America and northern Asia, the damming of tropical rivers for hydroelectric power, navigation and water diversion is an ongoing concern for the ecological integrity of these rivers (Dudgeon, 2000; Anderson *et al.*, 2006a; Anderson *et al.*, 2006b; Zengi *et al.*, 2007). Our findings will have important implications for future decisions concerning the natural resource management of rivers in the Australian tropics and rivers displaying similar characteristics elsewhere in the world.

Methods

Study region

The Australian tropics occur north of the Tropic of Capricorn (23° 27' S) and include all or part of six of the twelve drainage divisions in the country (AWRC, 1976), including the Gulf of Carpentaria in north-east Australia (Figure 1). The Gulf of Carpentaria division covers 638 500 km^2 (8 % of the continent) including the borders of inland arid-zone country. It has the largest average annual exorheic runoff in northern Australia (30 % of the continent's total), with average annual runoff equivalent to 131×10^9 m^3 (205 mm) (AWRC, 1976; Lake, 1995). Average annual temperatures and rainfall range, respectively, from 18 °C and 400 mm in southern sections to 36 °C and 1600 mm in the north (Bureau of Meteorology, 2007). Land use is dominated by grazing and agriculture, with mining, fishing and tourism also strong industries in the region (DNRM, 2003).

The southern Gulf of Carpentaria includes five mainland sub-catchments (Settlement, Nicholson, Leichhardt, and Flinders Rivers and Morning Inlet). It is chiefly savannah woodland and grassland country (Cole, 1986; DEWR, 2000), particularly in lower floodplain areas. The predominant land use is pastoralism, dominated by cattle grazing, and is associated with over 90 % of land area (Southern Gulf Catchments, 2005). Mean annual rainfall ranges from 380 to 1100 mm, although the majority falls in the austral summer (December to February) (Southern Gulf Catchments, 2005; Bureau of Meteorology, 2007). This study examined the Nicholson and Flinders Rivers sub-catchments in more detail (Figure 1). The Nicholson catchment area (52 300 km^2) is primarily associated with permanent, aquifer-fed rivers (e.g. the Gregory River) and their tributaries. Uplands include conservation areas, such as Boodjamulla National Park. Pastoral activities are common in the lowland floodplains, which often become inundated during the wet season. In contrast, the Flinders catchment area (109 400 km^2) contains turbid, anastomosing channels that flood widely during the wet season and become reduced to disconnected waterholes in the dry. The Flinders catchment has among the highest land use intensity of the Gulf region, due mainly to pastoral activities, and has one of the largest demands for increased water supply as a response to proposed irrigated agriculture (DNRME, 2004).

A number of rivers in sub-catchments from other Australian drainage basins were included for analysis purposes (Figure 1). Large rivers in the Timor Sea drainage division (Australian tropics), Lake Eyre Basin (inland arid-zone Australia) and Murray-Darling Basin (dryland Australia) were used to place Gulf of Carpentaria rivers in a more biogeographical context. The more temperate Darling River (Murray-Darling Basin; Figure 1), which has undergone extreme WRD, was used to explore the potential impacts of WRD on northern Australia’s large floodplain rivers. This river drains a large proportion of the Basin’s landmass, with major inflows from tributaries in the smaller catchments to its north (near the Tropic of Capricorn). Although high flows can be generated by winter rainfall in its southern tributaries, the dominant flood signal is driven by degenerating tropical lows providing rainfall to these northern tributaries during the summer months (Thoms *et al.*, 1996). Additionally, WRD across the entire Darling River catchment (comprising nine major headwater dams, many small weirs and large-scale water abstraction for irrigation), has resulted in significant hydrological changes (Thoms and Sheldon, 2000b) and includes many options likely to be implemented in the southern Gulf of Carpentaria (cf. DNRME, 2004).

Classification of Gulf of Carpentaria flow regimes

Mean daily flow data (measured in megalitres per day, ML d^{-1}) from sub-catchments in the Gulf of Carpentaria, with streamflow gauging stations monitored by the Queensland Department of Natural Resources and Mines (DNRM, 2005), were analysed in order to classify flow regimes of large unregulated rivers and to predict important hydrological drivers of ecological function. For purposes of standardisation, analysis was restricted to rivers with catchments greater than 1000 km^2 and 20 years of continuous flow records (Table I). The earliest flow records available were used to reduce interference from human-induced flow modification (cf. Walker *et al.*, 1995; Puckridge *et al.*, 1998). Effects of flow regulation were also minimised by excluding rivers with major upstream flow controls such as concrete weirs or reservoirs. Flow records from 15 gauging stations (out of a total of 148) satisfied data requirements and were used in subsequent analyses.

Hydrological metrics that describe ecologically relevant features of the flow regime (facets), based on medians and other summary statistics, including means, were used to describe flow characteristics in the chosen Gulf of Carpentaria rivers (Table II). Although non-parametric measures of central tendency (e.g. medians) are the most appropriate measures to describe the majority of flow regimes (as most rivers have non-normal flow distributions due to less frequent large flows and more frequent low flows) (Walker *et al*., 1995), parametric measures (e.g. means) were also used as many rivers had median discharges of zero, which would otherwise limit meaningful comparisons. Flow metrics described either a facet’s set aspect (i.e. magnitude and duration) or the variability of its set aspect (i.e. coefficient of variation of magnitude). Coefficients of variation (standard deviation/mean) were used rather than spread (range/median) to avoid division by zero medians. For annual and seasonal time periods, magnitude was described by median and total flows, as well as by skewness in terms of median to mean flow ratio (low values represent high skew, and therefore less regularity of flows, and vice versa). Duration was described by the number of zero flow days experienced in the same time periods as above, to indicate longitudinal connectivity. Ordinations and clustering techniques were then applied to these metrics to show how rivers group, or otherwise, based on their flow regimes.

Flow metrics (Table II) were calculated in the Time Series Analysis module of the River Analysis Package (RAP) software (Marsh, 2004) and multivariate analyses on resulting data were performed in PRIMER 5 (PRIMER-E, 2002). Mean daily flow data were standardised by upstream catchment area before hydrological metrics were calculated to prevent differences among rivers being masked by catchment size-related effects. For multivariate analysis, metrics were range-standardised to allocate measures to the same scale and were separated into categories (‘indicators’ in PRIMER 5) based on their description of the rivers’ flow regimes (set aspects of flow magnitude; variability of flow magnitude; set aspects of zero flow duration) and type of record characterised [whole record; inter-annual; seasonal defined by austral summer (December-February), autumn (March-May), winter (June-August), and spring (September-November); seasonal defined by dry (May-October), and wet (November-April)] (Table II).

Two clusters using the Euclidean distance measure (based on group averages) were generated: one using all flow metrics for the 15 rivers, the other defined by the dry and wet season categories of flow metrics. Non-metric multidimensional scaling (MDS) ordinations (based on Euclidean distance matrices using 100 random starts) were generated using the following categories of flow metrics: set aspects of flow magnitude, variability of flow magnitude and set aspects of zero flow duration. The main river ‘types’ identified by the first cluster analysis were then superimposed onto the ordinations to visually represent the differences between ‘types’. Further, the main flow metrics associated with the difference between these *aposteriori* ‘types’ were identified using ‘bubble-plots’ of variables’ values superimposed on the ordinations. These depict values of variables as circles, with larger circles reflecting greater values, and an example is provided with each ordination presented.

One additional metric, describing variability of magnitude, was calculated in order to provide comparison with four of Australia’s previously studied large dryland rivers: the unregulated Cooper Creek and Diamantina River in the Lake Eyre Basin; and the regulated Darling River and Lower River Murray in the Murray-Darling Basin (Figure 1). This metric is the Index of Flow Variability (F_V) (see Sheldon and Thoms, 2006) and is calculated as $F_V = (Q_{90} – Q_{10})/Q_{50}$, where Q_{50} is the median flow, and Q_{90} and Q_{10} equal the flow exceeded 90 and 10 percent of the time, respectively, across the whole record. Coefficients of variation (C_V) of annual flows were also used to compare with known values for other large Australian rivers in different seasonal flow regime zones (McMahon and Finlayson, 2003). These are Broken River in the Murray-Darling Basin and Ord River in the Timor Sea drainage division (Figure 1). (Note that both C_V and F_V are independent of catchment size-standardisation).

Assessment of post-water resource development impacts

Mean daily flow data (ML d^{-1}) from five gauging stations in the southern Gulf of Carpentaria were used for comparison with pre- and post-water resource hydrology in the Murray-Darling Basin (Table III). Simulated mean annual discharges (ML d^{-1}) from two gauging stations on the Darling River (Table III) were used to represent pre-development ('natural') and post-WRD flow conditions (the 'capped' 1993 level of water diversion developments) using data from the New South Wales Department of Land and Water Conservation's Integrated Quantity and Quality Model (IQQM) (DLWC, 1995). This model simulates flow data representative of pre- and post-WRD conditions (e.g. water abstractions), based on physical features of a river system and the water management system that has been applied to it (Black *et al.*, 1995; Thoms *et al.*, 1996). IQQM flow data for the Darling River gauging stations were chosen as they represented large, impacted Murray-Darling Basin rivers with upstream catchment areas greater than 1000 km^2. All data were standardised by upstream catchment area (km^2) to exclude catchment size-related effects. Mean annual discharges were then calculated for 20 consecutive years for both southern Gulf of Carpentaria and Murray-Darling Basin rivers to represent their long-term patterns of flow condition (i.e. their flow regimes).

A simple linear regression of post-development (1993 conditions) on pre-development ('natural') flows for the Darling River (combining 20 years of IQQM simulated mean annual discharges, in ML d^{-1} km^{-2}, at both gauging stations) was calculated. The resulting equation was used to predict potential post-development mean annual discharges (ML d^{-1} km^{-2}) for the chosen southern Gulf of Carpentaria rivers based on their current ('natural') discharges. Flow metrics representing ecologically relevant features of the flow regime (Table IV) were then calculated for southern Gulf of Carpentaria and Murray-Darling Basin rivers using both pre- and post-development flow data.

Principal Components Analysis (PCA; conducted in PRIMER 5) was used to explore variation among rivers that could be explained by gradients of change in facets of their flow regimes. This analysis was also used to explore potential changes in southern Gulf of Carpentaria rivers, in principal components space, due to flow modification modelled on that which has occurred in the Murray-Darling Basin. Input data included all flow metrics calculated from 20 years of pre- and post-development mean annual flows (Table IV). These were standardised prior to the PCA, which was based on a correlation cross-products matrix. Eigenvector loadings of the input flow metrics on the first two orthogonal components of the PCA were used to indicate dominant gradients of change.

Results

Classification of Gulf of Carpentaria flow regimes

Set aspects and variability of magnitude

Compared with all other rivers, Lukin River in the Coleman catchment had the highest 20 year total flow (12408 ML d^{-1} km^{-2}), and Julia Creek in the Flinders catchment the lowest (499 ML d^{-1} km^{-2}). Wenlock, Lukin and Mitchell Rivers had lower total flow variability (coefficients of variation) across their whole records, inter-annually and in the dry season, compared with other rivers (Table V). Gregory River also showed low total flow variability in the dry season (C_V = 0.65) relative to other rivers.

Set aspects of duration

Gregory, Wenlock, and Mitchell Rivers had lower numbers of zero flow days (0, 0, 111, respectively) across their 20-year records, making them more permanent compared with other large rivers, particularly Julia Creek in the Flinders catchment (6551 d). In terms of seasonality, the Gregory, Wenlock, and Mitchell Rivers had lower numbers of zero flow days in summer and autumn, and in dry seasons, than other large rivers (Table V). Leichhardt River (57 d) and Walsh River (in the Mitchell Catchment) (43 d) showed the largest difference between number of zero flow days experienced during wet and dry seasons.

Comparison with other Australian Rivers

A number of rivers had median flows of zero, which prevented determination of their F_V. Among those rivers for which F_V could be calculated, Lower River Murray and Darling and Gregory Rivers all scored comparatively low (less than 10) (Table VI), suggesting these three rivers experienced regular flows across their 20 years of record. However, both Lower River Murray and Darling River are regulated, whereas Gregory River is unregulated. Tate River had a high F_V score (5870), similar to Cooper Creek and Diamantina River (4922 and 2108, respectively). However, it can be expected that rivers in the Flinders and Leichhardt catchments along with Robertson and Lynd Rivers would also have had high F_V scores given their extremely low whole record median flows (i.e. zero). Coefficients of variation of total annual flows for Ord, Mitchell, Lukin and Wenlock Rivers were all below 1, indicating lower inter-annual flow variability compared with other rivers (Table VI).

Multivariate analysis

Multivariate analysis of Gulf of Carpentaria river hydrology separated large rivers with higher flow magnitudes and more stable (less skewed) flow regimes (Type 1 rivers) from those with greater variation in flow characteristics and greater numbers of zero flow days (Type 2 rivers) (Figures 2, 3 and 4). In effect, the first cluster analysis separated rivers into those that were more permanent with more regular flows, and those that were more ephemeral with greater variability of flow. Type 1 rivers had more stable, higher magnitude flows (over the whole record as well as annually and seasonally) and included Lukin (in the Coleman catchment), Gregory, Mitchell and Wenlock Rivers. However, there were differences among rivers within this group (Table V). Compared with other Type 1 rivers, Gregory River had a higher whole record and lower inter-annual median to mean flow ratio (0.24 and 0.51, respectively), indicating lower overall skewness of the hydrograph yet higher skew inter-annually. Lukin River had lower median spring and winter totals (0 and 0.82 ML d^{-1} km^{-2}, respectively), and the greatest inter-annual median to mean flow ratio (0.90; indicating low inter-annual skew) and number of zero flow days over 20 years (3265 d) among Type 1 rivers. Both Gregory and Wenlock Rivers had no zero flow days over their entire 20-year records. Regardless of these differences, the overall hydrology of Type 1 rivers was typically ‘tropical’, showing strong and predictable patterns of seasonal wetting and drying associated with summer monsoons, without evidence of extreme flow variability.

In contrast, Type 2 rivers were more typically dryland in nature, with high levels of flow variability similar to the levels found in large dryland rivers of central Australia (like Cooper Creek in the Lake Eyre Basin; see above). Type 2 rivers were also prone to flash floods, zero flows and low overall discharges, and included large rivers in the Flinders, Leichhardt, Gilbert and Mitchell catchments. Across 20 years of record for these rivers, total flows ranged from 499 (Julia Creek) to 5691 (Tate River) ML d^{-1} km^{-2}, and coefficients of variation ranged from 4.2 (Tate River) to 11.4 (Leichhardt River). Lynd, Tate and Walsh Rivers in the Mitchell catchment together with Gilbert River had a tendency for greater flow magnitudes and less zero flow days than other Type 2 rivers (rivers in the Flinders and Leichhardt catchments plus Robertson River in the Gilbert catchment), forming a sub-group within this Type (Figure 2). Total number of zero flow days over 20 years for rivers in this sub-group ranged from 1212 to 3881, where as the remaining Type 2 rivers ranged from 4613 to 6551. Rivers in the sub-group were also distinguished from other Type 2 rivers by their lower medians for number of zero flow days occurring in summer, autumn and winter (Table V).

In terms of seasonality, the second cluster analysis based on dry and wet season flow metrics separated rivers into three main groups (Figure 5). This grouping tended to separate rivers with dry-wet seasonality featuring changes in flow magnitude from those featuring changes in zero flow days. Group 1 included the Lukin, Wenlock and Mitchell Rivers (all Type 1 rivers), which tended to have higher median flow magnitudes in both the dry and wet seasons, and greater differences between these dry and wet season medians than other rivers (Table V). Group 3 comprised large rivers in the Flinders and Leichhardt catchments and Robertson River in the Gilbert catchment. These were all Type 2 rivers with a tendency for higher dry and wet season flow variability (i.e. coefficients of variation), higher median numbers of zero flow days in dry and wet seasons, and greater differences between these dry and wet season medians (Table V). Group 2 included Gregory (Type 1 river) and Gilbert River and most Mitchell catchment rivers (Type 2 rivers), and represented rivers either with flow metrics in between the extremes of Group 1 and 3 or a combination of both.

Assessment of post-water resource development impacts

Pre-development flow metrics

Flinders River at Glendowner and Gregory and Cloncurry Rivers tended to have higher Mean, Median and Min scores (like Darling River at Bourke) than Flinders River at Richmond and Julia Creek (like Darling River at Wilcannia) (Figure 6). Darling River at Wilcannia had the lowest pre-development Max (0.04 ML d^{-1} km^{-2}), much lower than other rivers, for which Max scores ranged from 0.50 (Flinders River at Richmond) to 0.79 (Gregory River) ML d^{-1} km^{-2} (Figure 6). Julia Creek (C_V = 2.04; F_V = 4.87) and Flinders River at Richmond (C_V = 1.32; F_V = 6.87) showed the greatest flow variability among sites (Figure 6). Flow variability of the Darling River (F_V = 2.84 at Bourke, 3.40 at Wilcannia) was similar to the majority of southern Gulf of Carpentaria rivers (F_V = 2.90 at Gregory River, 3.06 at Cloncurry River, 3.51 Flinders River at Glendowner).

Pre- to post-development changes

Regression of post- on pre-development Darling River discharges was highly significant (R^2 = 0.99, p < 0.0001). The resulting equation, post-development flows = 0.01 + 0.80*pre-development flows, was used to predict post-development flow data for southern Gulf of Carpentaria rivers. Mean, Median, Max and Min all decreased post-development, while C_V and F_V both increased for all rivers (Figure 6).

Post-development mean values ranged from 70 % (Darling River at Wilcannia and Julia Creek) to 75 % (Flinders River at Glendowner) of pre-development values. Changes in Median and F_V showed opposite trends, with post-development Medians ranging from 34 % (Julia Creek) to 73 % (Flinders River at Glendowner) and F_V from 110% (Flinders River at Glendowner) to 211 % (Julia Creek) of pre-development values. Post-development Max values were all around 80 % of pre-development scores. Flinders River at Glendowner showed the greatest reduction in Min post-development (16 % of the pre-development score), however, Flinders River at Richmond and Cloncurry River both reduced to zero. The greatest percent increase in C_V post-development was seen in Darling River at Wilcannia (121 % of the pre-development score) and the least was observed for Flinders River at Glendowner (108 % of the pre-development score).

Principal components analysis

The first two Principal Components axes explained 87 % of the variation among the flow regimes of rivers described by six flow metrics (Table VII; Figure 7). PC1, explaining 64 % of the variance, described a gradient of change in mean and median, minimum flows, with rivers with lower magnitudes aligned positively along the axis. PC2, explaining 23 % of variation among rivers, described a gradient of change in the coefficient of variation and maximum mean annual flow. Rivers with lower C_V and maxima loaded positively with PC2. Two main directions of change between pre- and post-development conditions of rivers' flow regimes were apparent on the PCA plot (Figure 7). The first was in a positive direction along PC1 and PC2 for Darling River at Wilcannia, Flinders River at Glendowner, and Cloncurry and Gregory Rivers; indicating long-term declines in central tendencies, along with decreasing variability and extremes of mean annual flows. The second direction of change occurred positively along PC1 and negatively along PC2 for Darling River at Bourke, Flinders River at Richmond and Julia Creek. This described a similar pattern along PC1 as the first direction of change (i.e. long-term declines in central tendencies), but was instead associated with increasing variability and range of mean annual flows.

Discussion

Hydrological drivers of ecological function

A mix of 'dryland' and 'tropical' flow features was expected for large unregulated rivers in the Gulf of Carpentaria, as the drainage area extends from arid-zones in central Australia to humid regions in the north that are dominated by summer rainfall (Bureau of Meteorology, 2007). This was confirmed by hydrological analysis, and apart from the Gregory River in the southern Gulf of Carpentaria, the gradient of change from dominant 'dryland' hydrology to 'tropical' hydrology generally equates to a geographical distinction between southern catchments bordering inland arid-zones and the more northern catchments (see Figure 1). This finding was also confirmed by comparison of measures of flow variability in Gulf of Carpentaria rivers with those of other large rivers in Australia. Additionally, all rivers in the Gulf of Carpentaria drainage division showed patterns of flow associated with wet-dry seasonality, a chief trait of tropical rivers (Latrubesse *et al*., 2005). However, depending on the river, these patterns were associated with different features of the flow regime. The typically 'tropical' rivers (Type 1) had wet and dry seasons distinguished by changes in flow magnitude, while 'dryland' rivers (Type 2) were distinguished by differences in no flow days. This suggests that while discharge in some rivers usually becomes reduced in the dry season, other rivers are more likely to cease flowing for extended periods of time. If these periods are sustained long enough, rivers of the latter type are likely to become reduced to a series of disconnected waterbodies when standing water levels drop as a result of evaporation. At these times, the rivers would likely reflect the vast waterhole networks typical of many Australian dryland rivers (Bunn *et al.*, 2006; Sheldon and Thoms, 2006).

As the Australian tropics covers a large expanse, with similar geographical constraints as in the Gulf of Carpentaria drainage division, it is reasonable to expect that large unregulated rivers in the rest of northern Australia present a similar combination of ‘dryland’ and ‘tropical’ flow characteristics along with a strong seasonal signal. Given this, what are the hydrological requirements for maintenance of ecological diversity in the Australian tropics? The indigenous riverine biota of Australia has been argued to be adapted to the low flow conditions typically occurring in many unregulated Australian rivers, including periods of no flow (McMahon and Finlayson, 2003). However, it is proposed here that for floodplain rivers in the Australian tropics, biota must not only be adapted to these ‘dryland’ conditions, but must also be able to survive, or take advantage of, the more regular and higher flow magnitudes (i.e. ‘tropical’ conditions) experienced in many rivers during the wet season. It is also proposed that the ecology and biodiversity of many of these rivers are intimately linked to the spatial heterogeneity of habitats that no doubt exists due to the natural levels of flow variability and extended periods of no flow (resulting in waterbody disconnection) that distinguish their hydrology. Indeed, this has been documented for dryland rivers in the southern regions of Australia (e.g. Walker *et al.*, 1997; Puckridge *et al.*, 2000; Sheldon *et al.*, 2002; Arthington *et al.*, 2005; Balcombe *et al.*, 2006; Marshall *et al.*, 2006) and as such, Australia’s northern rivers should only be different in that regularity of flow in some of these rivers may be a more dominant feature of the hydrograph than flow variability. In this sense, the distinct hydrological features of Australia’s northern rivers indicate that high levels of spatial and temporal biodiversity exist across the region. We suggest that these features (flow permanence and regularity; flow variability and absence; wet-dry seasonality) are the key hydrological drivers in maintaining and explaining the ecological function and biodiversity of large rivers in Australia's north, including their associated wetlands and floodplains.

Impacts of post-water resource development

The majority of rivers in the Australian tropics flow unimpeded and those in the southern Gulf of Carpentaria are no exception. Indeed, flow regimes of large rivers in this region, specifically those in the Nicholson and Flinders sub-catchments, have been shown to be representative of those across the whole Gulf of Carpentaria drainage division (displaying both Type 1 and Type 2 features), and are likely to be representative of large rivers in Australia's north (see above). With increasing demands on access and use of freshwater within Australia's States and Territories, including potential abstraction and impoundment of rivers for irrigation of tropical farmlands and use by the mining industry and urban sector (e.g. DNRME, 2004), we have an imperative to predict impacts of flow modification on the ecological function of these rivers. This has been made even more urgent given recent influx of funding and proposals to investigate the potential for additional water-resource development in northern Australia (e.g. Australian Government, 2007). To this end, predictions based on the above analyses (Table VIII) are discussed below, however it must be remembered that these are based on *potential* flow modification scenarios (e.g. water impoundment and abstraction) only. As such, the true range of impacts on Australia's large northern rivers is likely to be underestimated.

Impacts of WRD were predicted to involve substantial changes to natural flow variability, based on hydrological changes that have occurred in the Darling River, Murray-Darling Basin (Thoms and Sheldon, 2000b). Use of the Darling River as a referencing tool for assessing post-development hydrological change in southern Gulf of Carpentaria rivers is appropriate (*sensu* Poff and Ward, 1989; Sheldon *et al.*, 2000) as natural flow variability and annual flow magnitudes in the Darling River (pre-development) were shown to compare with these rivers. Based on changes in flow simulated for the Darling River between pre- and post-WRD (IQQM data), rivers in the southern Gulf of Carpentaria tended to show reduced magnitudes of flow (in terms of central tendencies and extremes) and increased inter-annual variability given similar development circumstances. However, multivariate analysis on their pre- and post-development flows predicts that the nature of hydrological change in these northern rivers due to human-induced flow modification may depend on whether they naturally experience lower or higher annual flow magnitudes. For rivers like the Flinders, Cloncurry and Gregory that have comparatively high flow magnitudes, post-development flows may in fact be expected to have lower inter-annual variability along with lower flow extremes than those currently experienced. This suggests large flow pulses and low flows will become reduced in magnitude, and flow regimes will become more regular. For rivers that tend to experience lower flow magnitudes, like Julia Creek and some sections of the Flinders River, inter-annual flow variability may increase post-development and extremes of the flow regime intensify in magnitude. Many of northern Australia's large rivers may therefore experience similar changes in flow variability (increased or decreased) post-WRD.

Flow and its variability affect the spatial and temporal configuration of habitats and are seen as providing the underscore to ecosystem function (Vannote *et al.*, 1980; Junk *et al.*, 1989; Walker *et al.*, 1995; Poff *et al.*, 1997; Puckridge *et al.*, 1998). Additionally, movement of water elicits biotic responses that are associated with a three-scale flow hierarchy: the flow pulse (a flow event), the flow history (a sequence of events before a particular point in time), and the flow regime (long-term statistical representation of flow) (Walker *et al.*, 1995; Puckridge *et al.*, 1998). Dramatic changes at any of these scales may have adverse consequences for species specifically adapted to previous conditions. In terms of the flow regime, long-term changes such as increased variability or regularity, as predicted to occur in the Australian tropics as a result of WRD, may lead to significant habitat modification, species extinctions, and reduced diversity (Sheldon *et al*., 2000; Bunn and Arthington, 2002).

Our analyses have suggested that three features of the flow regime are likely to be the key hydrological drivers of ecological function in Australia's northern rivers. These are: 1) flow permanence and regularity; 2) flow variability and absence; and 3) wet-dry seasonality. Thus, WRD resulting in increased flow variability is likely to have more adverse ecological impacts on ecosystems adapted to the first and third of these features. Conversely, development resulting in decreased variability (increased regularity) is likely to impact more negatively upon those adapted to the second driver. These impacts, in reference to flow regimes of Australia's northern rivers, will be discussed below (as summarised in Table VIII).

Using the basic principles linking flow with aquatic biodiversity, we recognise that flow is a strong driver of physical habitat in rivers, which then influences biotic composition (Principle1, Bunn and Arthington, 2002). With increased regularity of flows, habitats and therefore biotic communities are likely to become homogenised as a result of sustained connection (Ward and Tockner, 2001), particularly in systems previously adapted to high levels of flow variation and no flow events. Indeed, divergence in macroinvertebrate assemblages (*high* spatial biodiversity) in Australian dryland river systems has been postulated to result from natural flow variability and hydrological disconnection (Sheldon *et al*., 2002; Marshall *et al*., 2006; Sheldon and Thoms, 2006). Decreased flow variability has also been linked to reduced ecosystem function as a result of loss of the large flow pulses that stimulate boom phases of production in dryland rivers (Bunn *et al*., 2006). It is likely that similar effects would occur in ‘dryland’ rivers in the tropics. For large northern rivers in general, it is also likely that loss of large flow pulses will lead to loss of many floodplain refugia. Overbank flows replenish floodplain waterholes that persist during dry phases and provide a scarce resource (refugial habitat) for many aquatic and terrestrial biota (Paltridge *et al*., 1997; Robinson *et al*., 2002). This implies that disappearance of floodplain refugia will reduce the number and diversity of biota able to re-colonise new habitat when flow resumes. Loss of large flows and increased regularity may also effect reproduction of organisms reliant on these phenomena for dispersal and migration, as has been suggested for dominant riparian plant species in the regulated Ord River catchment (Doupe and Pettit, 2002). Thus, it is predicted that for many of northern Australia’s large floodplain rivers, if WRD results in flows that are more regular along with loss of ‘boom’-style floods, reduced biodiversity and ecosystem function will be inevitable.

Increased flow variability and extremes of flow may be just as detrimental to riverine ecosystems as reduced flow variability. Spawning in many fish species is triggered by seasonal base flows or floods (Bunn and Arthington, 2002; Arthington and Pusey, 2003; Winemiller, 2004) and for species like these that are adapted to regular cycles of high and low seasonal flows typical of many rivers in the tropics, increased inter-annual variability may dampen or eliminate these triggers and lead to declines in abundance and diversity, possibly resulting in major variation of community structure

(Puckridge *et al*., 1998). If, along with increased variability, extremes of magnitude are intensified, biota with life-history stages reliant on flow-based cues may become severely impacted. These predictions encapsulate the second principle linking flow to ecological response, which states that life history strategies of aquatic species have evolved in direct response to natural flow regimes (Bunn and Arthington, 2002).

Additionally, overall productivity of floodplain rivers in the tropics is linked to regular cycles of wet and dry season flows such that natural patterns of flooding and connection within river channels are essential to population viability of riverine species (Principle 3, Bunn and Arthington, 2002). Movement of organic matter and nutrients, produced during stable dry seasons, across the river-floodplain network by wet season floods is an important driver of function in tropical ecosystems (Junk *et al*., 1989). This concept has recently been summarised in a general principle for riverine food-webs in the Australian tropics that emphasises the importance of seasonal hydrology (Douglas *et al.*, 2005). Disruption of seasonal cycles and floodplain inundation from increased flow variability as a result of WRD in Australia's more regular 'tropical' rivers would therefore be likely to reduce ecosystem function dramatically and across a vast area. For the 'dryland' rivers of the Australian tropics that naturally possess a high level of flow variability, WRD that intensifies this may impact upon even those species adapted to high levels of variation and will no doubt lead to shifts in biotic community composition (cf. Puckridge *et al.*, 1998).

Considerations and conclusions

The above predictions have been made based on changes in flow regime calculated from annual averages. It has been suggested that for rivers with high levels of natural flow variability or with dry-seasons associated with low flows (as has been demonstrated to occur for many large rivers in the Australian tropics), predictions of ecological impact and subsequent recommendations for ecosystem flow requirements based on annual statistics may not be appropriate (Georges *et al*., 2002; Hamilton and Gehrke, 2005). One reason for this is that dry season flows generally represent only a small fraction of the annual flow (Georges *et al*., 2002): thus, low flows and intra-annual seasonality may not be adequately represented by annual flow statistics (Thoms and Parsons, 2003). For example, if flow modification leads to the complete loss of dry season flows, an annual flow statistic may not be able to reflect this change even if it becomes reduced in magnitude itself. However, it has been proposed here that adverse effects on biodiversity and ecosystem function can be expected to occur in many rivers of the Australian tropics if the predicted changes in mean annual flows due to certain types of flow modification take place, namely flow regulation due to water abstraction and impoundment. More extreme effects on the hydrology of these rivers would be expected if predictions were instead based on daily, monthly or seasonal flow statistics. If so, the ecological outlook post-water resource development worsens. As such, it is strongly advised that future decisions concerning the natural resource management of rivers in the Australian tropics take into account the variety of hydrological regimes present in these systems and the associated ecologies that rely upon these different aspects of flow. If more intense but less frequent tropical cyclones are likely to occur in parts of northern Australia as a result of future climate change (Walsh *et al.*, 2002), then it is probable that increased or decreased flow variability associated with water resource development, as predicted by this study, will be exacerbated. Consequently, the importance of ecologically sound water resource development in the Australian tropics cannot be understated.

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Table I: Characteristics of gauging stations of large rivers in the Gulf of Carpentaria and daily flow records used to classify flow regimes.

Station name	Code	Sub-catchment	Latitude	Longitude	Upstream catchment area (km^2)	Start of continuous 20-year record
Gregory River at Gregory Downs	Gr	Nicholson	18:38:32S	139:15:09E	12690	1970
Gunpowder Creek at Gunpowder	Gu	Leichhardt	19:41:16S	139:21:39E	2427	1972
Leichhardt River at Doughboy Creek	Le	Leichhardt	20:18:48S	139:44:28E	3524	1979
Flinders River at Richmond	FR	Flinders	20:41:56S	143:07:57E	17382	1972
Flinders River at Glendower	FG	Flinders	20:42:48S	144:31:29E	1958	1973
Cloncurry River at Cloncurry	C	Flinders	20:40:24S	140:29:32E	5975	1969
Julia Creek at Julia Creek	J	Flinders	20:39:31S	141:45:30E	1353	1971
Gilbert River at Rockfields	Gi	Gilbert	18:12:09S	142:52:34E	10987	1968
Robertson River at Robin Hood	R	Gilbert	18:47:05S	143:36:15E	1019	1967
Lynd River at Lyndbrook	Ly	Mitchell	17:49:28S	144:26:37E	1278	1969
Mitchell River at O.K. Bridge	M	Mitchell	16:28:15S	144:17:22E	7724	1968
Tate River at Ootann	T	Mitchell	17:28:31S	144:35:54E	1620	1968
Walsh River at Rookwood	Wa	Mitchell	16:58:53S	144:17:12E	4927	1968
Lukin River at Old Bamboo	Lu	Coleman	14:37:14S	143:04:42E	1077	1968
Wenlock River at Moreton	We	Wenlock	12:27:14S	142:38:20E	3265	1959

Table II: Flow metrics used to classify flow regimes of rivers in the Gulf of Carpentaria and categories used in multivariate analysis, including: their ecologically relevant description of a river's flow regime (facet); aspect of these facets described by the metric; and the relevant period of record described by the metric.

Flow metric	Facet	Aspect	Record
Total flow (ML d^{-1}) over a 20 y period	Magnitude	Set	Whole record
Median flow (ML d^{-1}) for the 20 y period	Magnitude	Set	Whole record
Ratio of median to mean flow for the 20 y period	Magnitude	Set	Whole record
C_V[a] of mean daily flows over the 20 y period	Magnitude	Variability	Whole record
Number of zero flow days for the 20 y period (d)	Duration	Set	Whole record
Median of total annual flows (ML d^{-1})	Magnitude	Set	Inter-annual
Ratio of median to mean annual flows	Magnitude	Set	Inter-annual
Median number of annual zero flow days (d)	Duration	Set	Inter-annual
C_V of total annual flows	Magnitude	Variability	Inter-annual
Median of total seasonal flows (ML d^{-1})	Magnitude	Set	Seasonal (S/A/W/Sp)[b]
Median number of seasonal zero flow days (d)	Duration	Set	Seasonal (S/A/W/Sp)[b]
C_V of total seasonal flows	Magnitude	Variability	Seasonal (S/A/W/Sp/D/We)[b]
Median of total dry season flows (ML d^{-1})	Magnitude	Set	Seasonal (Dry)
Median of total wet season flows (ML d^{-1})	Magnitude	Set	Seasonal (Wet)
Absolute difference between above 2 metrics (ML d^{-1})	Magnitude	Set	Seasonal (Dry-Wet)
Median number of dry season zero flow days (d)	Duration	Set	Seasonal (Dry)
Median number of wet season zero flow days (d)	Duration	Set	Seasonal (Wet)
Absolute difference between above 2 metrics (d)	Duration	Set	Seasonal (Dry-Wet)

[a] C_V = coefficient of variation; [b] S = summer, A = autumn, W = winter, Sp = spring, D = dry, We = wet.

Table III: Characteristics of Murray-Darling Basin (MDB) gauging stations and flow data used to assess potential post-water resource development impacts on southern Gulf of Carpentaria (SGC) rivers.

Station name	Source	Code	Drainage Division	Sub-catchment	Latitude	Longitude	Upstream catchment area (km^2)	Start year of data
Darling River at Wilcannia	DLWC[a]	DW	MDB	Darling	143:22:41S	31:33:36E	569800	1966[c]
Darling River at Bourke	DLWC	DB	MDB	Darling	145:56:24S	30:05:17E	38600	1966[c]
Gregory River at Gregory Downs	DNRM[b]	G	SGC	Nicholson	18:38:32S	139:15:09E	12690	1970
Flinders River at Richmond	DNRM	FR	SGC	Flinders	20:41:56S	143:7:57E	17382	1972
Flinders River at Glendowner	DNRM	FG	SGC	Flinders	20:42:48S	144:31:29E	1958	1973
Cloncurry River at Cloncurry	DNRM	C	SGC	Flinders	20:40:24S	140:29:32E	5975	1969
Julia Creek at Julia Creek	DNRM	J	SGC	Flinders	20:39:31S	141:45:30E	1353	1971

[a] New South Wales Department of Land and Water Conservation (DLWC, 1995); [b] Queensland Department of Natural Resources and Mines (DNRM, 2005); [c] Simulated data based on IQQM models of pre- and post-water resource development conditions in the MDB.

Table IV: Ecologically relevant hydrological measures used in the assessment of post-water resource development impacts on southern Gulf of Carpentaria rivers, calculated from mean annual flow data standardised by upstream catchment area.

Flow metric describing a 20-year period	Code	Ecological relevance
Mean annual flow (ML d^{-1} km^{-2})	Mean	Clausen and Biggs (1997) and as summarised in Rea *et al*. (2002)
Median mean annual flow (ML d^{-1} km^{-2})	Median	Clausen and Biggs (1997)
Maximum mean annual flow (ML d^{-1} km^{-2})	Max	As summarised in Puckridge *et al*. (1998) and Rea *et al*. (2002)
Minimum mean annual flow (ML d^{-1} km^{-2})	Min	As summarised in Puckridge *et al*. (1998) and Rea *et al*. (2002)
Coefficient of variation of mean annual flows	C_V	Jowett and Duncan (1990), Poff and Allan (1995), McMahon and Finlayson (2003) and as summarised in Bunn and Arthington (2002)
Index of flow variability [a]	F_V	As summarised in Bunn and Arthington (2002)

[a] Note that this metric, based on mean annual flows here, will yield different results to the F_V values used in the classification of Gulf of Carpentaria flow regimes, which are based on daily flow data.

Table V: Flow metrics, standardised per km^2 upstream catchment area, used to classify flow regimes of rivers in the Gulf of Carpentaria.

	Gr	Gu	Le	FR	FG	C	J	Gi	R	Ly	Mi	T	Wa	Lu	We
Total flow (ML d^{-1}) over a 20 y period	1088	1213	1368	740	1300	1102	499	2757	3798	2805	5472	5691	4679	12408	8235
Median flow (ML d^{-1}) for the 20 y period	0.04	0	0	0	0	0	0	0	0	0	0.06	0	0.01	0.01	0.10
Ratio of median to mean flow for the 20 y period	0.24	0	0	0	0	0	0	0	0	0	0.08	0	0.02	0	0.09
C_V[a] of mean daily flows over the 20 y period	5.36	7.83	11.44	7.70	5.24	7.87	9.75	6.79	6.55	4.87	3.84	4.22	4.28	3.38	2.25
Number of zero flow days for the 20 y period (d)	0	5217	4613	4763	4778	5144	6551	2196	4820	3881	111	3441	1214	3265	0
Median of total annual flows (ML d^{-1})	28.0	29.3	29.9	13.8	52.2	34.8	8.1	69.4	79.0	103.0	193.2	238.8	179.4	561.6	320.5
Ratio of median to mean annual flows	0.51	0.48	0.44	0.37	0.80	0.63	0.33	0.50	0.42	0.74	0.71	0.84	0.77	0.91	0.78
Median number of annual zero flow days (d)	0	260	242.5	271.5	247	272.5	327.5	144.5	260	199	0	174.5	62	154	0
C_V of total annual flows	1.22	1.53	1.90	1.32	1.03	1.08	2.03	1.72	1.69	1.12	0.88	1.03	1.10	0.71	0.57
Median of total summer flows (ML d^{-1})	3.42	0	0.02	0	0.17	0	0	0.06	0	0	1.85	0	0.25	0	2.46
Median of total autumn flows (ML d^{-1})	13.0	22.0	18.8	6.1	17.9	20.6	3.5	38.4	60.2	74.5	102.4	133.2	86.8	171.9	120.4
Median of total winter flows (ML d^{-1})	6.81	4.54	3.47	1.41	4.70	2.31	0.02	8.06	9.26	15.5	51.3	60.4	33.0	299.5	201.2
Median of total spring flows (ML d^{-1})	2.89	0	0	0	0.11	0	0	0.04	0	0.07	4.97	0.01	0.63	0.82	8.53
Median number of summer zero flow days (d)	0	90	87	91	86	91	91	74	91	91	0	91	43	91	0
Median number of autumn zero flow days (d)	0	32	29	44	37	35	64	3	31	25	0	13	0	20	0
Median number of winter zero flow days (d)	0	56	45	58	37	53	86	0	53	0	0	0	0	0	0
Median number of spring zero flow days (d)	0	92	92	90	86	92	92	48	92	61	0	77	0	44	0
C_V of total summer flows	0.65	2.05	3.33	2.82	1.50	1.59	4.36	1.78	2.21	2.52	0.99	3.25	1.77	3.35	0.78
C_V of total autumn flows	1.65	1.70	1.62	1.57	1.26	1.38	2.37	1.91	1.87	1.16	1.08	1.13	1.26	1.08	0.81
C_V of total winter flows	1.46	1.18	3.25	1.57	1.14	2.27	2.73	1.59	1.63	1.42	1.07	1.29	1.35	0.83	0.66
C_V of total spring flows	0.65	3.94	2.61	4.13	2.77	2.24	4.36	2.11	3.43	2.66	0.33	1.64	1.08	1.08	0.71
Median of total dry season flows (ML d^{-1})	4.65	0	0	0.01	0.73	0	0	0.36	0	0.47	10.41	0.58	2.11	10.66	19.00
Median of total wet season flows (ML d^{-1})	24.6	26.1	32.2	10.4	42.0	35.0	4.1	66.6	74.3	104.1	190.6	234.6	156.5	446.8	293.1
Absolute difference between above 2 metrics (ML d^{-1})	19.9	26.1	32.2	10.4	41.2	35.0	4.1	66.3	74.3	103.6	180.2	234.0	154.4	436.1	274.1
Median number of dry season zero flow days (d)	0	153	151	146	141	153	153	78	153	91	0	107	0	74	0
Median number of wet season zero flow days (d)	0	113	94	113	117	115	181	50	112	92	0	80	43	75	0
Absolute difference between above 2 metrics (d)	0	40	57	33	24	38	28	28	41	1	0	27	43	1	0
C_V of total dry season flows	0.65	3.91	3.17	3.35	1.84	2.49	3.88	1.47	2.68	1.94	0.40	2.62	1.02	0.70	0.77
C_V of total wet season flows	1.29	1.59	1.87	1.41	1.01	1.07	2.19	1.81	1.76	1.15	0.96	1.06	1.15	0.79	0.59

[a] C_V = coefficient of variation.

Table VI: Comparison of flow variability metrics among large rivers in the Gulf of Carpentaria drainage division and other previously studied Australian rivers.

Drainage Division [a]	Seasonal Regime [b]	River	F_V [c]	C_V [d]
Lake Eyre Basin	Unclassified/Extreme Late Summer	Cooper Creek at Cullyamurra	4922	-
		Diamantina River at Birdsville	2108	-
Murray-Darling Basin	Unclassified	Darling River at Wilcannia	5.19	-
	Unclassified/Extreme Winter	Lower River Murray at Lock 6	9.18	-
	Extreme Winter	Broken River at Goorambat	-	1.00
Timor Sea	Extreme Late Summer	Ord River at Coolibah Pocket	-	0.71
Gulf of Carpentaria	Extreme Late Summer	Gregory River	3.75	1.22
		Gunpowder Creek	dzm	1.53
		Leichhardt River	dzm	1.90
		Flinders River at Richmond	dzm	1.32
		Flinders River at Glendowner	dzm	1.03
		Cloncurry River	dzm	1.08
		Julia Creek	dzm	2.03
		Gilbert River	318.12	1.72
		Robertson River	dzm	1.69
		Lynd River	dzm	1.12
		Mitchell River	23.93	0.88
		Tate River	5870	1.02
		Walsh River	89.66	1.10
		Lukin River	862.33	0.71
		Wenlock River	38.10	0.57

[a] Flow metrics for Gulf of Carpentaria rivers calculated using DNRM (2005) discharge data. [b] Seasonal flow regimes as allocated by Finlayson and McMahon (1988): note that some rivers rise in a different seasonal regime zone to the main zone through which they flow. [c] F_V = Index of Flow Variability: note that this metric, based on daily flow data here, will yield different results to the F_V values used to assess the impacts of post-water resource hydrology on Gulf of Carpentaria rivers, which are based on mean annual flows; dzm = division by zero median; Murray-Darling and Lake Eyre Basins' values are from Sheldon and Thoms (2006) ; - not available. [d] C_V = coefficient of variation of annual discharge; Murray-Darling Basin and Timor Sea values are from McMahon and Finlayson (2003); - not available; note that C_V for Ord River at Coolibah pocket is based on data exclusive of Ord River Dam (Lake Argyle) effects.

Table VII: Eigenvector loadings of flow metrics on the first two principal components, PC1 and PC2, for the PCA analysis described in Figure 7. Variance explained by each principal component is given in parentheses and the two highest loading values on each axis are shown in bold.

Flow metric [a]	PC1 (64 %)	PC2 (23 %)
Mean	**-0.48**	-0.19
Median	**-0.48**	-0.04
Max	-0.33	**-0.60**
Min	**-0.46**	-0.07
C_V	0.30	**-0.65**
Fv	0.36	-0.42

[a] Flow metric codes are given in Table IV.

Table VIII: Potential ecological impacts of predicted hydrological changes associated with water resource development in large floodplain rivers of Australia's north, adapted to different flow regimes as represented by three key hydrological drivers of ecosystem function.

Hydrological Driver	PWRD[a] Hydrology	Ecological Impact on Indigenous Fauna and Ecosystem Function [b]
Flow regularity and permanence	Increased flow variability	Loss of spawning and other life-history stage triggers resulting in decreased species abundance and diversity
		Reduced ecosystem function
	Decreased flow variability	Reduced refugial habitat resulting in decreased species abundance and diversity
		Inhibited dispersal and migration of biota
Flow variability and absence	Increased flow variability	Shifts in community composition
	Decreased flow variability	Reduced species beta (among habitat)-diversity
		Reduced refugial habitat resulting in decreased species abundance and diversity
		Inhibited dispersal and migration of biota
		Reduced ecosystem function
Wet-dry seasonality	Increased flow variability	Loss of spawning and other life-history stage triggers resulting in decreased species abundance and diversity
		Reduced ecosystem function
	Decreased flow variability	Reduced refugial habitat resulting in decreased species abundance and diversity
		Inhibited dispersal and migration of biota

[a] PWRD = post-water resource development; [b] See Discussion for reasoning and references. Note that the ecological impacts in this table refer only to increased or decreased flow variability in relation to the proposed hydrological drivers and are not intended to cover all potential impacts of altered hydrology.

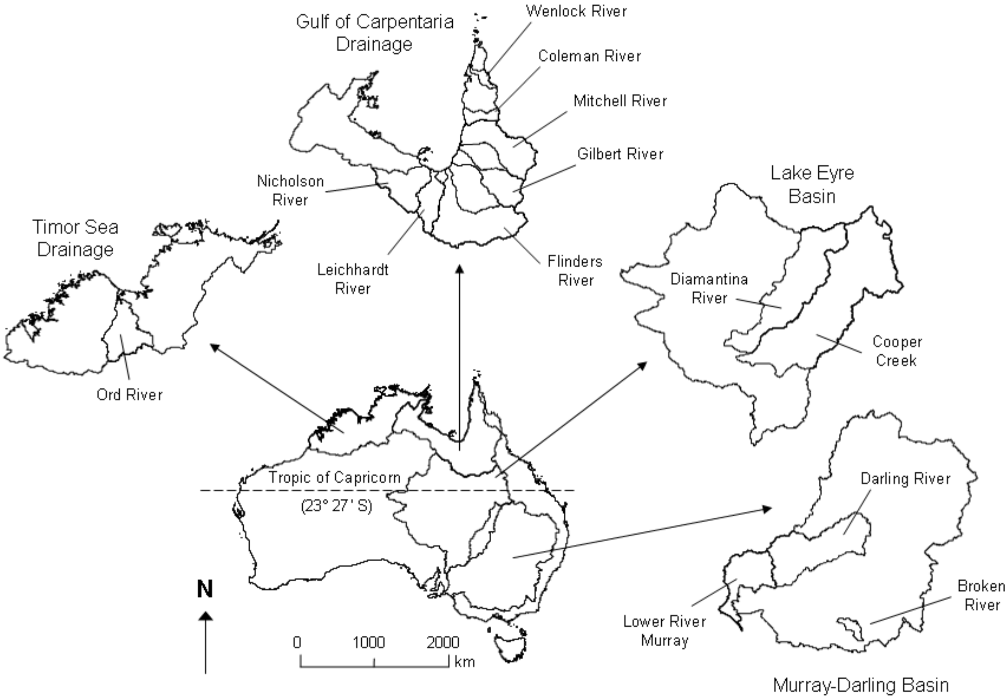

Figure 1: Map of Australia showing major drainage divisions (Gulf of Carpentaria, Timor Sea, Lake Eyre Basin and Murray-Darling Basin) and sub-catchments of interest to this study, as described in Geoscience Australia (2004).

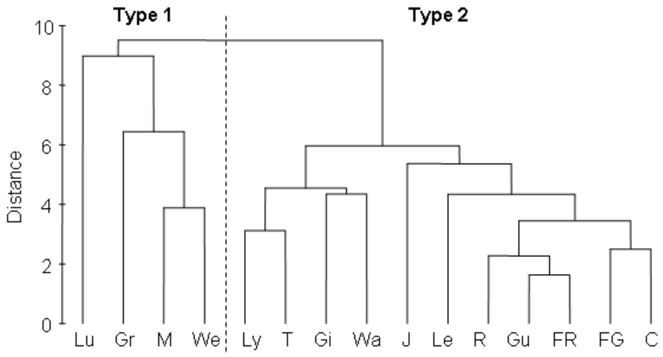

Figure 2: Group average dendrogram, using a normalised Euclidean distance similarity matrix, of flow metrics calculated for 15 large rivers in the Gulf of Carpentaria drainage division, indicating differentiation (dashed line) between Type 1 and Type 2 rivers. River codes are given in Table I and flow metrics are given in Table II.

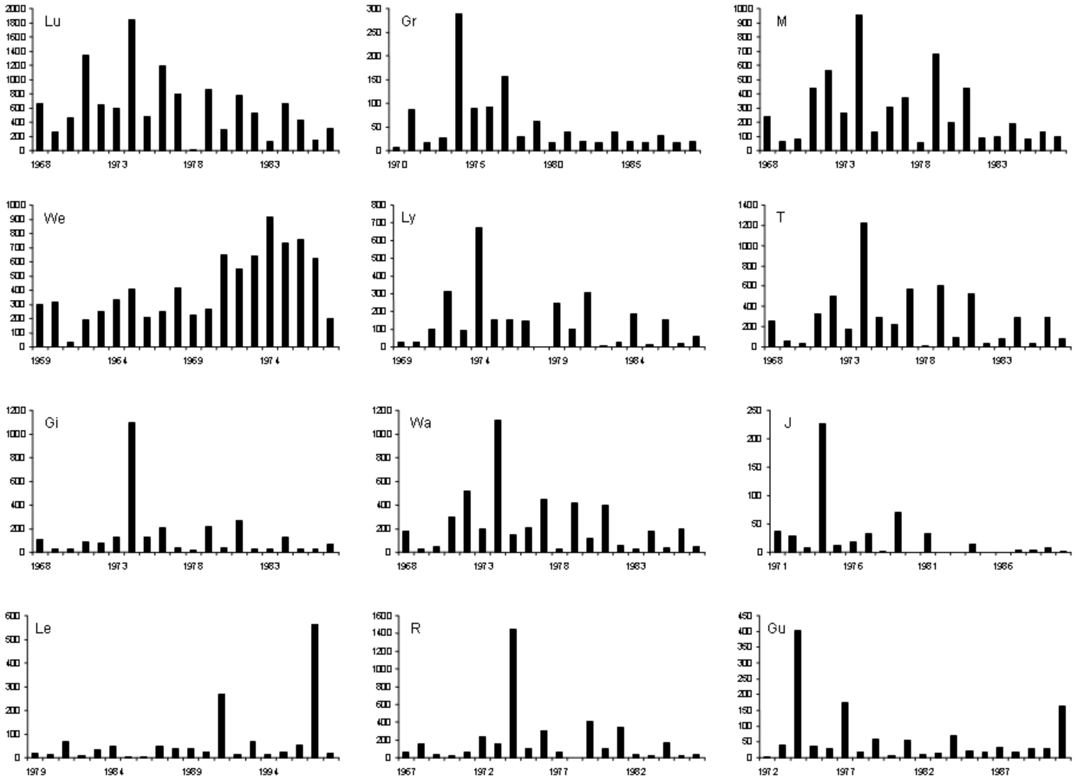

Figure 3: Twenty-year hydrographs of annual discharges (ML) standardised per km^2 catchment area for 15 large rivers in the Gulf of Carpentaria drainage division. From top to bottom, and left to right: Type 1 rivers include Lu, Gr, M and WE; Type 2 rivers include Ly, T, Gi, Wa, J, Le, R, Gu, FR, FG and C. River codes are given in Table I.

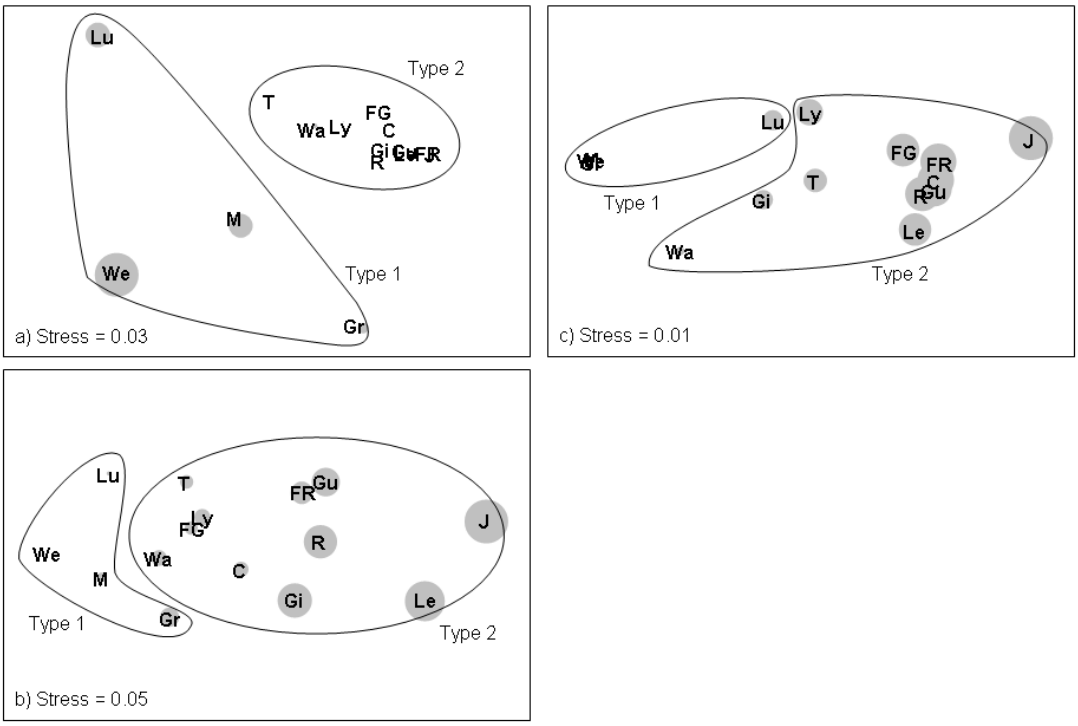

Figure 4: MDS plots of two-dimensional solutions for 15 large rivers in the Gulf of Carpentaria drainage division, based on normalised Euclidean distance similarity matrices of: a) set aspects of flow magnitude, with ‘bubble-plot’ of the median dry season flow; b) variability of flow magnitude, with ‘bubble-plot’ of the coefficient of variation of annual flows; and c) set aspects of zero flow duration, with ‘bubble-plot’ of the median number of annual zero flow days. Type 1 and Type 2 rivers are encircled. River codes are given in Table I and flow metrics are given in Table II.

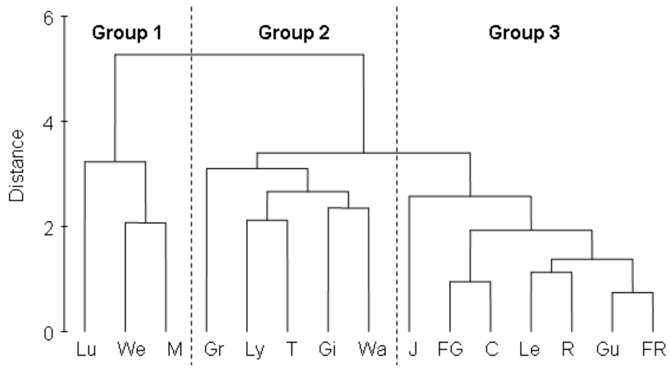

Figure 5: Group average dendrogram, using a normalised Euclidean distance similarity matrix, of dry and wet season flow metrics calculated for 15 large rivers in the Gulf of Carpentaria drainage division. Groups are indicated by dashed lines. River codes are given in Table I and flow metrics are given in Table II.

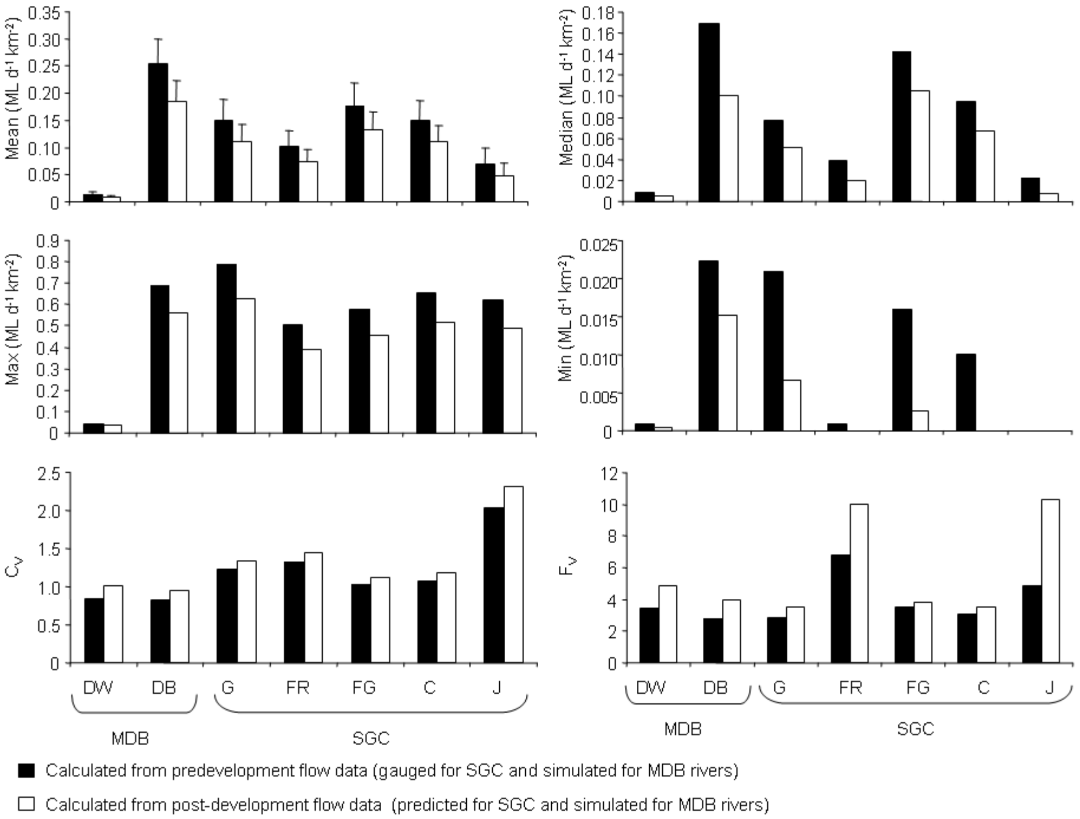

Figure 6: Flow metrics for two Murray-Darling Basin (MDB) and five southern Gulf of Carpentaria (SGC) rivers, based on 20 years of mean annual discharges (ML d^{-1}) standardised by upstream catchment area (km^2). Means are presented with + 1 standard error bars. River codes are given in Table III and flow metric codes are given in Table IV.

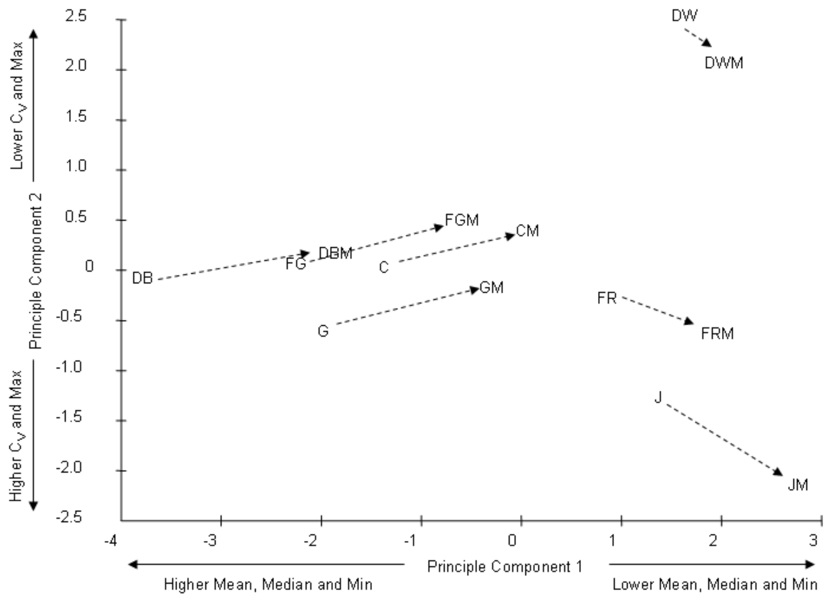

Figure 7: PCA plot of the first two principal component axes (PC1 versus PC2) for flow metrics of pre- and post-development conditions for five southern Gulf of Carpentaria and two Murray-Darling Basin rivers. Solid arrows indicate gradients of change in flow metrics that have dominant eigenvector loadings on PC1 and PC2. Broken arrows indicate direction of change defined in two-dimensional PCA space between pre- and post-development conditions. River codes are given in Table III; M after the river code denotes post-development (modified) flow conditions. Flow metric codes are given in Table IV. Flow metric loadings on each component are given in Table VII.