

Nesting behaviour of the endangered Mary River turtle: monitoring and modelling to inform e-flow strategies

T. Espinoza^{A,E}, M. Connell^{B,C}, S. Marshall^A, R. Beukeboom^D and A. McDougall^A

^ADepartment of Natural Resources, Mines and Energy, 16–32 Enterprise Street, Bundaberg, Qld 4670, Australia.

^BTiaro and District Landcare Group, PO Box 6, Tiaro, Qld 4650, Australia.

^CResearch Institute for the Environment and Livelihoods, School of Environment, Charles Darwin University, Darwin, NT 0909, Australia.

^DInstitute of Environmental Biology, Behavioural Ecology Group, Utrecht University, PO Box 80125, 3508 TC Utrecht, The Netherlands.

^ECorresponding author. Email: thomas.espinoza@dnrme.qld.gov.au

Abstract. The Mary River turtle (*Elusor macrurus*) is an endemic, monotypic species with multiple impacts across its life-history, including overharvesting of eggs, nest predation and habitat degradation. Long-term recruitment failure has led to protection measures established under state, federal and international authority. Previous research has demonstrated that *E. macrurus* lives instream but nests on river banks, requiring specific habitat for breeding, nesting and recruitment. Ecohydrological rules represent the critical water requirements contributing to a species' life history and can be used to develop and assess environmental flow strategies for species affected by water resource development. This study investigated the nesting behaviour of *E. macrurus*, including the environmental drivers that affect nest inundation. Monitoring showed that nesting by *E. macrurus* peaked in October and November, driven by rainfall events (>10 mm), with potential impacts from flow events (20% of nests established <2.5 m above water level at time of nesting). These ecohydrological rules were modelled against 109 years of simulated natural flow and rainfall data. The 'potential nesting and nest inundation' (PNNI) indicator revealed that nesting for *E. macrurus* was assured in a majority of years under the natural flow scenario. The results of this study will inform the development and assessment of e-flow strategies for nesting by *E. macrurus* in terms of current, and future water resource development, along with climate change impacts.

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Introduction

The Mary River has been described as the most significant biodiversity and conservation habitat in south-east Queensland (Arthington and Bunn 2008). A multitude of threatened species inhabit this catchment, including six species of freshwater turtle across five genera, making it one of the richest in Australia in terms of freshwater turtle diversity (Limpus 2008). The Mary River turtle (*Elusor macrurus*) is an endemic, monotypic species with a history of impacts across multiple life-history stages (DEWHA 2008), including overharvesting of eggs for the pet trade, habitat degradation, and nest predation (Cann and Legler 1994; Flakus 2002; Van Kampen *et al.* 2003; Limpus 2008). Low rates of recruitment have been observed since the 1960s, leading to protection measures established under the *Nature Conservation Act 1992*, the *Environment Protection and Biodiversity Conservation Act 1999* and the IUCN Red List of Threatened Species (Limpus 2008). Changes in hydrology and streamflow have been listed as a key threat to recovery of *E. macrurus* (TSSC 2008).

Water resource development (WRD) can alter riverine habitat and flow regimes and, in turn, impact on important life-history stages of aquatic species (Bunn and Arthington 2002; Olden and Kennard 2010; Calapez *et al.* 2017). WRD has affected freshwater turtle populations around the world (Bodie 2001; Clark *et al.* 2009) with impacts most evident around water storages (Tucker 2000). Direct impacts include fragmentation of populations, habitats and mortality of adults from dam overflow events (Limpus 2008). Indirect effects include habitat modification (lotic to lentic), trophic changes and impacts to the downstream environment (Tucker 2000; Ellis and Jones 2013). Along the east coast of Australia, urbanisation and associated WRD is increasing rapidly, particularly in the south-east Queensland region (DIP 2009).

Several water storages exist within the natural distribution of *E. macrurus*, including small dams, low-level weirs and salt-water barrages. Proposals for larger dams on the Mary River have also been considered (Sinclair Knight Merz 2007; Arthington and Bunn 2008) because of drought impacts and

population expansion in the south-east Queensland region (QWC 2010). Although the socioeconomic and environmental drivers were considered, the proposal was eventually rejected by the Australian federal government because of 'unacceptable impacts' to the habitat of threatened species including the Mary River cod (*Maccullochella mariensis*), the Australian lungfish (*Neoceratodus forsteri*) and the Mary River turtle (DSEWPAC 2009).

E. macrurus needs specific habitat for breeding, nesting and recruitment (Micheli-Campbell *et al.* 2013, 2017) though information on specific nesting behaviour is scarce. As with many Australian freshwater turtle species, rainfall is an environmental trigger of nesting activity, provides substrate moisture for construction of nest chambers (Bowen *et al.* 2005; Booth 2010) and connects habitats. Connectivity is important throughout the reproductive season for partnering/breeding and female access to nesting habitat (Flakus 2002), supporting population connectivity and gene flow (Hermoso *et al.* 2012; Hughes *et al.* 2013). Freshwater turtles present further challenges to water managers as they live instream but emerge to nest on river banks (Bodie 2001; Hamann *et al.* 2008; McDougall *et al.* 2015), habitat that is also subject to many human impacts that can affect the nesting ecology of freshwater turtles (Bodie 2001).

E. macrurus nests in aggregations on steep, sandy river banks in spring and early summer (October–December) (Flakus 2002; Micheli-Campbell *et al.* 2013). Developing embryos, in particular, are subject to various terrestrial factors during the incubation period (~52 days), including temperature, predation, desiccation and inundation (Micheli-Campbell *et al.* 2011; Beukeboom 2015). Inundation of some freshwater turtle eggs is lethal (Plummer 1976; Kennett *et al.* 1993; Hollier 2012). WRD can affect the vegetation, erosion and sedimentation of nesting habitat, with unseasonal or irregular flows having the added potential impact of flooding or drying nest sites (Tucker 2000). The protection of terrestrial areas around wetlands has been identified as a key recovery action for freshwater turtles (Steen *et al.* 2012) to improve nesting success for habitat specialists such as *E. macrurus* (Micheli-Campbell *et al.* 2013). Overall, Limpus (2008) highlighted that the biggest impediment to successful recovery of *E. macrurus* is the lack of knowledge of its biology in the wild, including dietary, habitat and environmental flow requirements.

Provisions within Queensland's water legislation enable assessment of ecosystem water requirements to guide water management towards sustainability (Mcgregor *et al.* 2017). Ecohydrological rules are quantitative thresholds of flow dependency demonstrated by aquatic species, and are integral to the ecological assessment of Queensland's water plans (DSITIA 2014). Consequently, the establishment of ecohydrological rules is an important platform towards effective environmental flow (e-flow) strategies and ecologically sustainable development.

E-flows incorporate flow timing, frequency, duration and volume as part of strategies for sustainable ecological outcomes, whilst ensuring that human water needs are secured (Acreman *et al.* 2014; Bunn *et al.* 2014; Stewardson *et al.* 2017). E-flows are not limited to flow delivery from water storages, but can also involve management of water levels within storages, unsupplemented water, and the conditions under which that water may be taken (The Brisbane Declaration 2007). This has been

demonstrated through implementation of Queensland's *Water Act* and water plans (DSITIA 2014).

Amendments to water legislation in Queensland require consideration of climate change in the development of water plans (Queensland Government 2017). Climate change can affect the development, implementation and assessment of e-flow strategies (Lester *et al.* 2011). Even in unregulated catchments, climate change can impact riverine flow through alteration in distribution and intensity of rainfall (Chiew and McMahon 2002). Adverse effects to Australian freshwater turtle populations from climate change have been projected for the Murray River turtle (*Emydura macquarii*), the broad-shelled snake-necked turtle (*Chelodina expansa*) and the eastern long-necked turtle (*Chelodina longicollis*) (Bowen *et al.* 2005; Chessman 2011). Impacts were primarily attributed to changes in rainfall delivery, reduced water availability, and reduced floodplain inundation, affecting nesting strategies and predation rates.

Data collected from this four-year study of a nesting population of *E. macrurus* in the lower Mary River catchment aimed to quantify the hydrological conditions required for nesting, and prevention of nest inundation. We hypothesise that nesting of *E. macrurus* is triggered by seasonal rainfall, and potential nest inundation from flow regimes is within the scope of water resource management. Nesting and nest inundation thresholds are summarised into a set of ecohydrological rules to assess potential nesting ecology of *E. macrurus* from 1890 to 1999, using simulated natural flow data and historical rainfall records used in the development of the *Water Plan* (Mary Basin) 2006 (the Mary water plan) (Queensland Government 2016). The results of this assessment will contribute to the review and development of e-flow management strategies for the new Mary water plan to support the long-term viability of *E. macrurus* in terms of current, and future water resource development, together with potential climate change impacts.

Methods

The Mary River, in south-east Queensland, Australia, has a catchment area of 9 595 km² and flows for 300 km from the Conondale Ranges near Maleny, down to its mouth at River Heads, west of Fraser Island. The Mary River is not heavily regulated along its main trunk, with only a barrage at the saltwater interface, though dams and weirs exist on four of its tributaries (Fig. 1). Four traditional nesting banks that have supported the largest nesting aggregations of *E. macrurus* were selected in the lower Mary River to record nesting and nest inundation parameters (Flakus 2002; Limpus 2008).

Camera trapping

Camera trapping was used to consolidate knowledge of turtle nesting requirements and behaviour including response to environmental triggers (rainfall) and periods of activity (nesting season). Four wildlife cameras (Reconyx Inc. PC800 Hyperfire Professional IR) were placed at nesting bank A (Fig. 1) in September 2014 (two weeks before the start of the nesting season) and remained in place until all clutches had hatched. The time-lapse feature on the cameras was set to take pictures every 2 min between 1900 and 0600 hours, including both

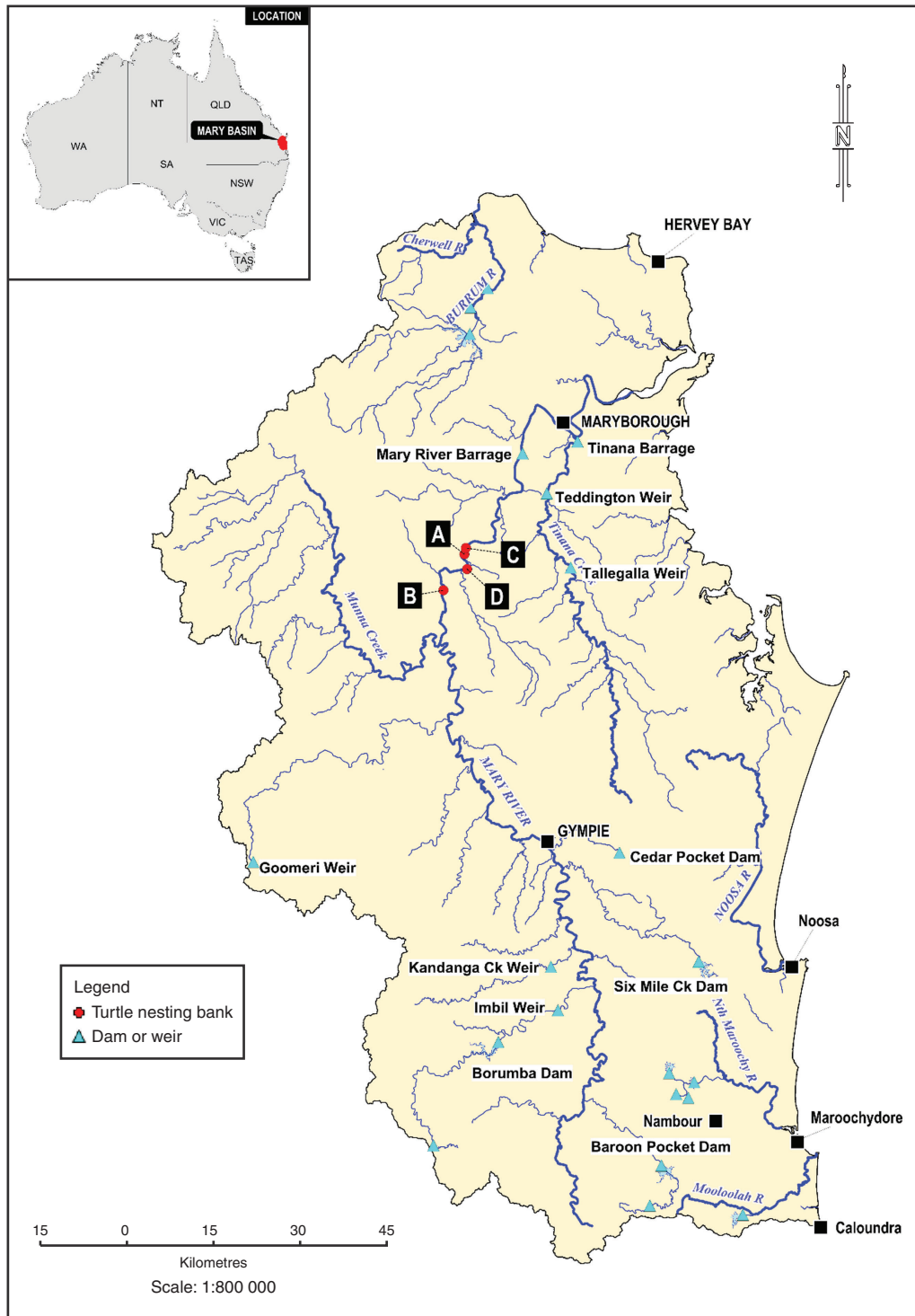


Fig. 1. Map of the Mary River catchment, including study sites, dams and weirs. Note: only infrastructure within the known distribution of *E. macrurus* is labelled.

crepuscular periods (Micheli-Campbell *et al.* 2013; Beukeboom 2015). Three cameras were evenly distributed across the bank on 2.3 m-high posts facing the river, while the fourth camera faced parallel to the bank and 0.5 m above the ground. Two other cameras were also installed on smaller nesting banks

immediately adjacent to the main nesting bank A, but still part of the overall nesting location. The cameras were strategically placed to focus on potential nesting activity on known nesting banks. All pictures were analysed manually, recording the date and time of turtle appearance, and activity (e.g. walking

or nesting). Previous work has identified the nocturnal emergence of *E. macrurus* onto nesting banks that occurred in association with nesting behaviour (Micheli-Campbell et al. 2013).

Nest monitoring

Four *E. macrurus* nesting banks were monitored (Fig. 1) in collaboration with the Tiaro and District Landcare Group (TDLG), through the nesting season (October–December), over a four-year period (2011–15). Nesting bank D was identified as an important nesting aggregation site in 2013, and was incorporated into the study in 2014. Nesting aggregation sites were identified by means of local expert knowledge and satellite imagery. TDLG members identified and recorded nests daily, confirmed the presence of eggs, and marked the nest location using 300 mm plastic sand pegs and labels. Marking of the nests allowed surveying later in the season, and provided precise GPS locations and heights (Australian Height Datum) of nests using global navigation satellite systems technology (Real Time Kinematics). Depth/temperature data-loggers (Diver, Schlumberger Ltd) were also installed in the river adjacent to nesting banks. Locations and heights of data-loggers were also surveyed to cross-reference water levels to the heights of nests, providing water levels at time of nesting.

The date and height of nests of *E. macrurus* were plotted against continuous water level and rainfall data to determine any relationships. Rainfall data were aggregated for three days (the day of nest detection plus two days prior) to account for turtle movement to nesting habitat in response to rainfall, regional variations in timing of rainfall, and institutional rainfall-recording procedures (rainfall recorded at 24-h intervals from 0900 hours).

Cumulative percentage curves were used to summarise relationships between the heights of *E. macrurus* nests, water levels and rainfall (McDougall et al. 2015).

Ecohydrological rules

Key threshold values specifying the required rainfall to initiate significant rates of nesting, together with water levels that would inundate an important proportion of nests, form the basis of the ecohydrological rules in this study (Table 1). Because of the conservation status of *E. macrurus*, a conservative approach was used to set the ecohydrological rules in order to provide a greater likelihood of increased nesting survivorship. An aggregate rainfall volume was identified that triggered at least 50% of female turtles in the breeding population to breed synchronously. The median was selected as this species uses the *Arribada* nesting strategy (large-scale synchronised nesting to saturate predation) (Spencer et al. 2016) to ensure recruitment into the population. For nest inundation, a rate of 20% of nest inundation

was chosen as this follows a similar approach for managing the inundation of nests of the critically endangered *Eseya albagula* in the adjacent Burnett River (McDougall et al. 2015). In addition, these threshold levels were established in consultation with regional turtle experts (C. Limpus and D. Limpus, Department of Environment and Heritage Protection).

Ecohydrological rules for nesting (aggregate rainfall) and nest inundation (water level) were applied to simulated (Integrated Quantity Quality Model (IQQM): Simons et al. 1996) daily (predevelopment scenario) flow data (ML day⁻¹) and rainfall data (1890–1999) used in the development of the Mary water plan (DNRM 2016), using reporting node 049 (Home Park GS 138014A). This node is a maximum of 9 km downstream from the study site. Rainfall data were extracted from the SILO Patched Point dataset (DSITI 2017) for Tiaro (40203), which is a maximum distance of 12 km from the study site. The water level threshold was converted to discharge (ML day⁻¹) based on the rating curve for GS138014A – Mary River at Home Park (DNRM 2017). The recurrence of threshold exceedance over the assessment period (1890–1999) was assessed using the River Analysis Package (RAP 3.0.7) (Marsh et al. 2003).

A matrix of the frequency and timing of exceedance of the two ecohydrological thresholds was used to calculate the ‘potential nesting and nest inundation indicator’ (PNNI) (Table 2). The PNNI is defined as an indicator that reflects both the likelihood of nesting based on rainfall for each nesting season, as well as the likelihood of nest inundation in the same nesting season. Scores for the ecohydrological rule for rainfall related to the number of months during the nesting season (October–December) where the aggregate rainfall events exceeded the ecohydrological rule and would therefore trigger at least 50% of the female nesting population (range 0–3). Scores for the ecohydrological rule for water level were based on the number of months during the incubation period (October–January) where the river levels exceeded the threshold to inundate more than 20% of nests (range 0–4). The matrix identified seasons where optimal rainfall across all months coincided with no flooding events and would potentially maximise nesting for *E. macrurus* (PNNI = 2). This is compared with seasons where there was limited rain and some level of nest inundation (PNNI = 1, 0 or -1), and seasons with less suitable rainfall events and frequent flooding (PNNI = -2). This analysis

Table 2. Matrix of ‘potential nesting and nest inundation’ (PNNI) indicators for *E. macrurus*

Number of months with rainfall events exceeding ecohydrological threshold (October–December) versus number of months with flood events exceeding threshold (October–January)

		No. of months with rainfall events exceeding ecohydrological threshold			
		0	1	2	3
No. of months with flood events exceeding ecohydrological threshold	4	-2	-2	-1	0
	3	-2	-1	0	0
	2	-1	0	0	1
	1	0	0	1	2
	0	0	1	2	2

Table 1. Ecohydrological rules for nesting success by *E. macrurus*

	Time of year	
	October–December	October–January
Ecological response	Nesting	Incubation
Environmental variable	Rainfall	River height/discharge
Threshold	>10 mm	<2.5 m/16 000 ML day ⁻¹
Rationale	Trigger nesting	Prevent nest inundation

was conducted for each year during the simulation period (1890–1999) and the annual PNNI values for *E. macrurus* were presented as a time series of PNNI values to allow interpretation and discussion.

Results

Camera trapping

A total of 227 529 photographs were analysed, of which 590 included *E. macrurus* captured either nesting or walking over sandy riverbanks in preparation for nesting. Camera trapping confirmed that nesting activity commenced in October after the first significant rainfall event of the nesting season (>10 mm) (Fig. 2). Of a total of 590 photographs taken of turtles on the nesting bank, 37% were taken in October, 44% in November, 13% in December and 6% in January (Fig. 2). Nesting activity centred on two events in October and November, both preceded by 10–20 mm of rain. While turtles appeared on nesting banks after minimal rainfall (<10 mm), nest construction occurred only after at least 10 mm of rainfall. All nesting activity occurred between dusk and dawn.

Nest monitoring

In total, 123 *E. macrurus* nests were monitored over four consecutive breeding seasons, at the four nesting banks in the lower Mary River catchment (Fig. 3). Of these nests, 60% were established in October, 38% in November and December, and the remaining 2% in January (Fig. 4). In addition, nesting abundance varied from year to year, both within and between nesting banks.

Nesting bank A was the most productive with 56 nests identified over the four nesting seasons. Nesting bank B produced

a relatively high number of nests in 2011 ($n=21$), though productivity declined in subsequent years. Nesting bank C underwent significant geomorphic changes after a large flood in early 2012, which precluded further nesting after an initially productive year in 2011 ($n=14$). Finally, productivity at nesting bank D was good in the 2014 nesting season ($n=16$).

Nest heights for *E. macrurus* ranged from 0.9 to 12.2 m above water level at the time of nesting (Fig. 5). Of the 123 *E. macrurus* nests recorded, 20% were established within a height of 2.5 m of the water level at time of nesting, 50% within 3.8 m, and 80% within 5.7 m (Fig. 5). Approximately 10% of all nests monitored were inundated by natural flow events owing to nests being laid late in the nesting season (December–January) and experiencing early wet-season floods (Fig. 3).

Aggregate rainfall totals associated with nesting ranged from 0 to 46 mm, with the three largest nesting events preceded by 11, 21 and 31 mm (~37% of total nests) (Fig. 3). Of the 123 nests recorded, 50% were preceded by 10 mm rainfall, and 80% were preceded by up to 20 mm rainfall (Fig. 6).

Establishment of ecohydrological rules

Data collected for nesting by *E. macrurus* was summarised into a set of quantitative ecohydrological rules (Table 1). Through camera trapping and nest monitoring, the nesting season for *E. macrurus* was confirmed as October–December (Fig. 4), with peak nesting activity in October and November. A rainfall threshold of at least 10 mm of aggregated rainfall was chosen because this triggered at least 50% of the female nesting population. In addition, a water level threshold of 2.5 m was chosen because this inundated no more than 20% of

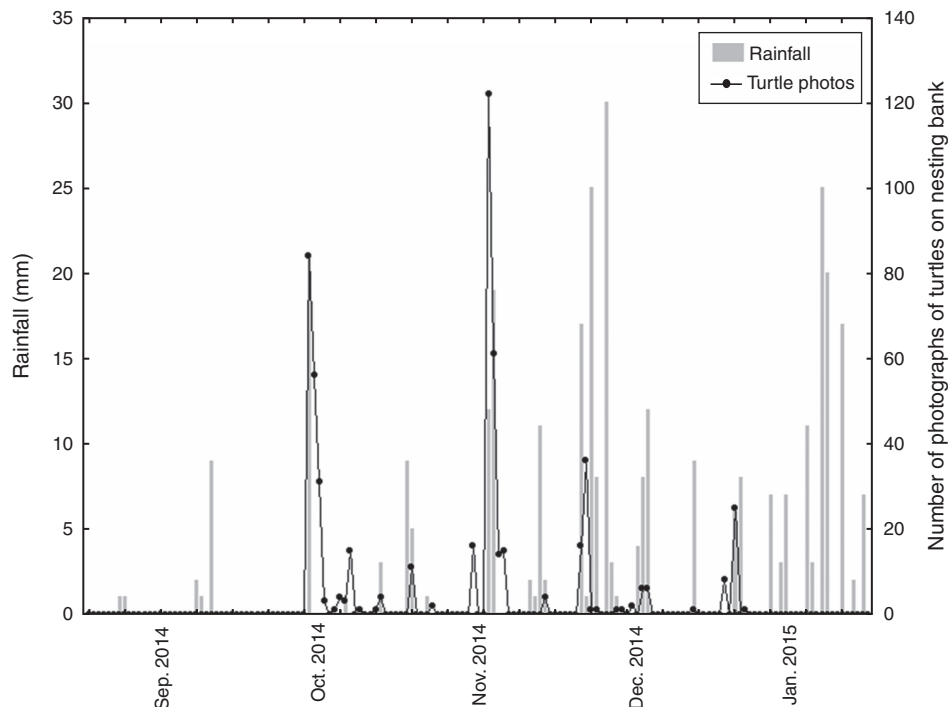


Fig. 2. *E. macrurus* nesting plotted against daily rainfall for nesting bank A over the 2014 nesting period.

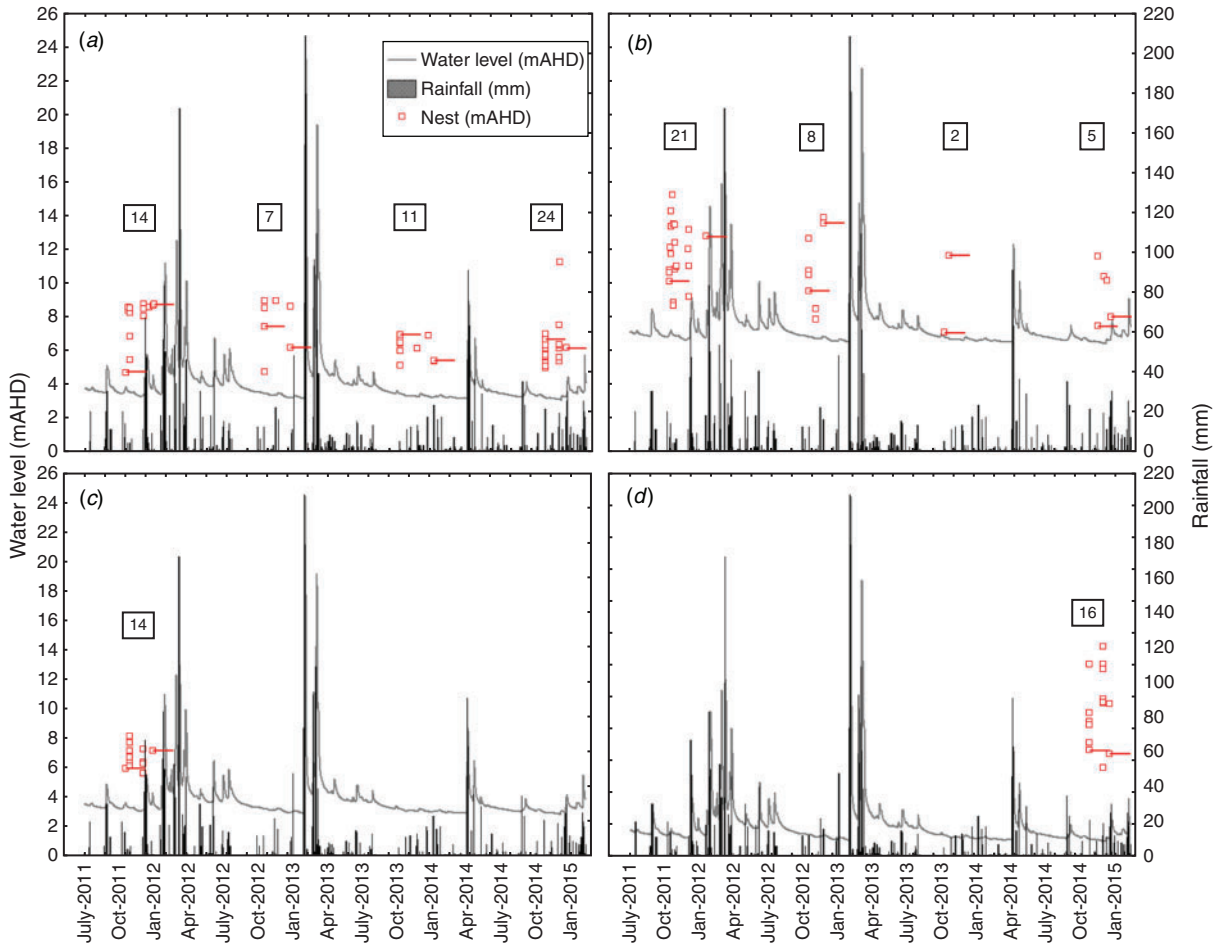


Fig. 3. Nest heights, incubation periods and environmental data for four important nesting banks in the lower Mary catchment (2011–15). (a) Nesting bank A, (b) nesting bank B, (c) nesting bank C and (d) nesting bank D. Squares denote *E. macrurus* nests, horizontal lines denote the 52-day incubation period for first and last nest of the season, boxed numbers indicate the number of nests per season, the solid black line indicates the water level, and black bars indicate rainfall.

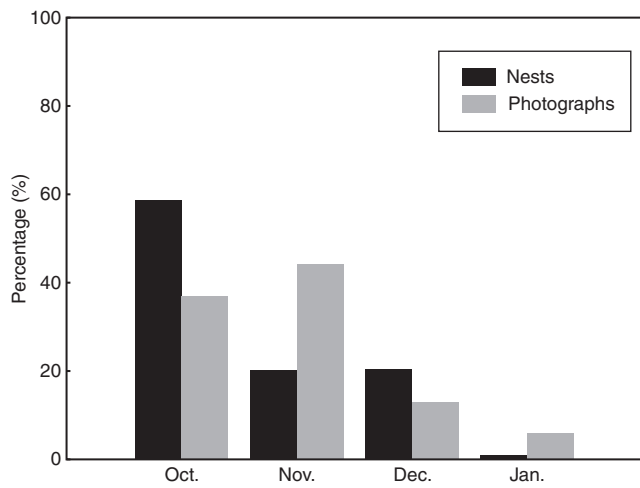


Fig. 4. Monthly variation in the percentage of photographs of female *E. macrurus* on nesting banks (camera trapping) and actual nests observed per month (nest monitoring).

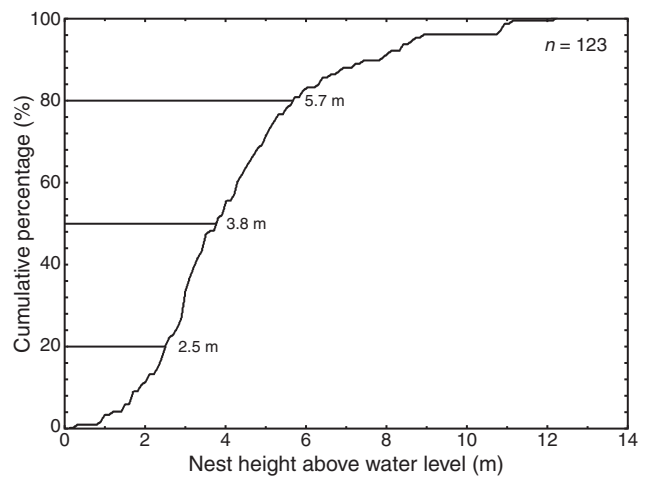


Fig. 5. Cumulative proportion of heights of *E. macrurus* nests above water level, at time of nesting.

E. macrurus nests through the incubation period (October–January). This 2.5 m water level rise equates to a flow threshold of 16 000 ML day⁻¹.

Ecohydrological rule assessment

The threshold for rainfall (Table 1) was first applied to the extrapolated rainfall data (SILO: DSITI 2017) for the study reach from 1890 to 1999. All years had aggregate rainfall totals exceeding 10 mm in at least one month of the nesting season (October–December) (Fig. 7). The average of the largest

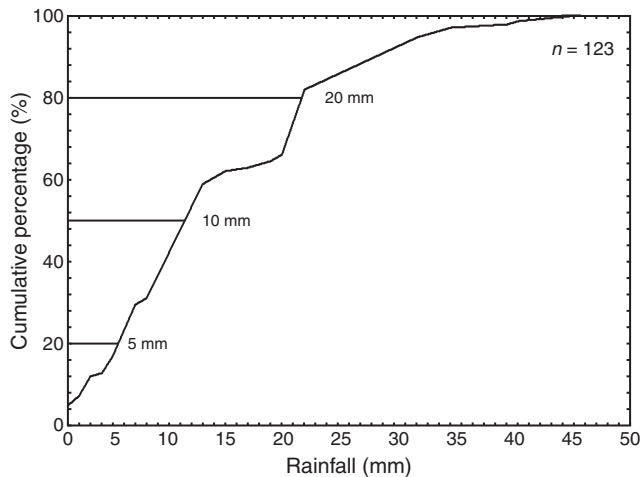


Fig. 6. Cumulative proportion of *E. macrurus* nests established in relation to aggregate (three days) rainfall.

individual rainfall events for October, November and December over the assessment period ($n=109$) was 28 (s.d.=25), 32 (s.d.=21) and 49 mm (s.d.=36) respectively. Of the 953 aggregated rainfall events (>10 mm) over the 109 years, 24% occurred in October, 32% in November and 44% in December. Sequential years with low rainfall (events <10 mm) include 1918–1923 and 1977–1981, where rainfall was absent primarily in October (Fig. 7).

The ecohydrological rule for water level was applied to simulated natural flow data for node 49 (Mary River–Home Park) of the Mary IQQM from 1890 to 1999 (Fig. 8). The average of the largest individual peak flow events in October, November, December and January, through the assessment period ($n=109$) were 4280 (s.d.=12 280), 4750 (s.d.=11 145), 18 860 (s.d.=40 215) and 49 440 (s.d.=104 670) ML day⁻¹ respectively. Of the 106 inundation events ($\geq 16 000$ ML day⁻¹) within the nesting season (October–January), 6% occurred in October, 7% in November, 30% in December and 57% in January (Fig. 8). This highlights the higher potential risk for nest inundation later in the season.

Applying the PNNI indicator over the assessment period (1890–1999) revealed, first, that most years (~92%) contained positive PNNI values for *E. macrurus* (Fig. 9). Second, years with neutral PNNI values were scarce (~8%), and did not occur in consecutive years. No years in the assessment period were found to have negative PNNI values.

Discussion

The Mary River turtle (*Elusor macrurus*) is endemic to a single catchment that is not heavily regulated yet is adjacent to one of

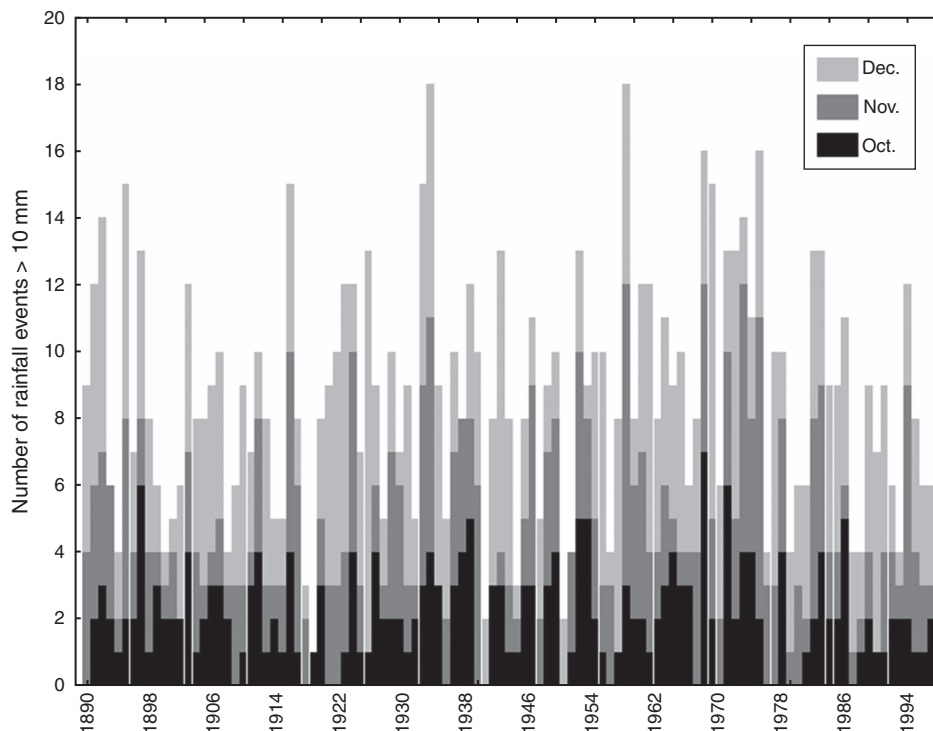


Fig. 7. Number of rainfall events greater than 10 mm (October–December) (1890–1999).

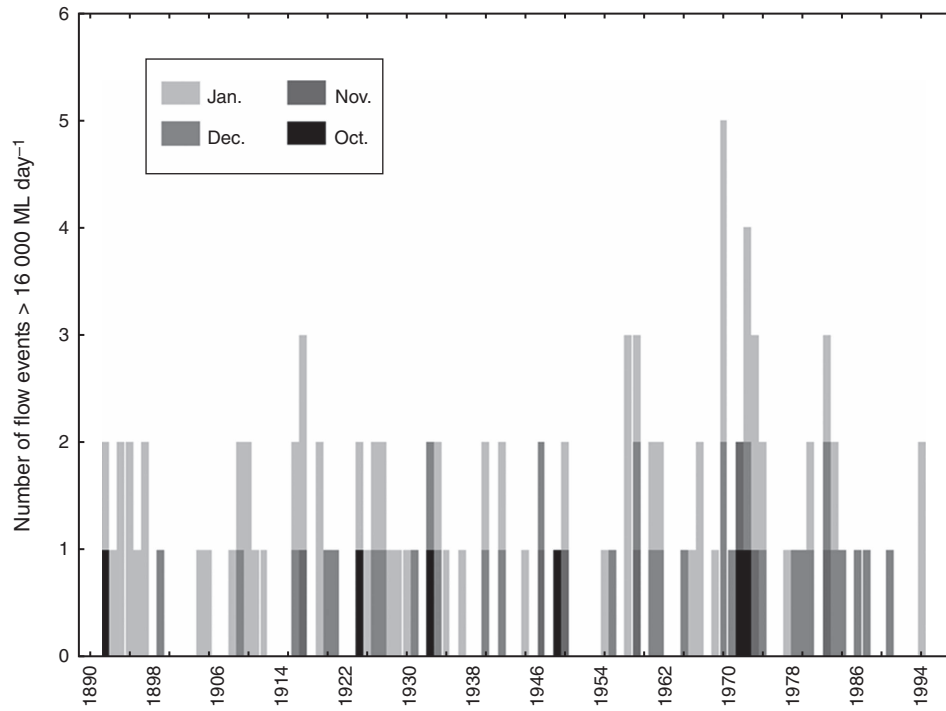


Fig. 8. Number of flow events greater than 16 000 ML day⁻¹ (October–January) (1890–1999).

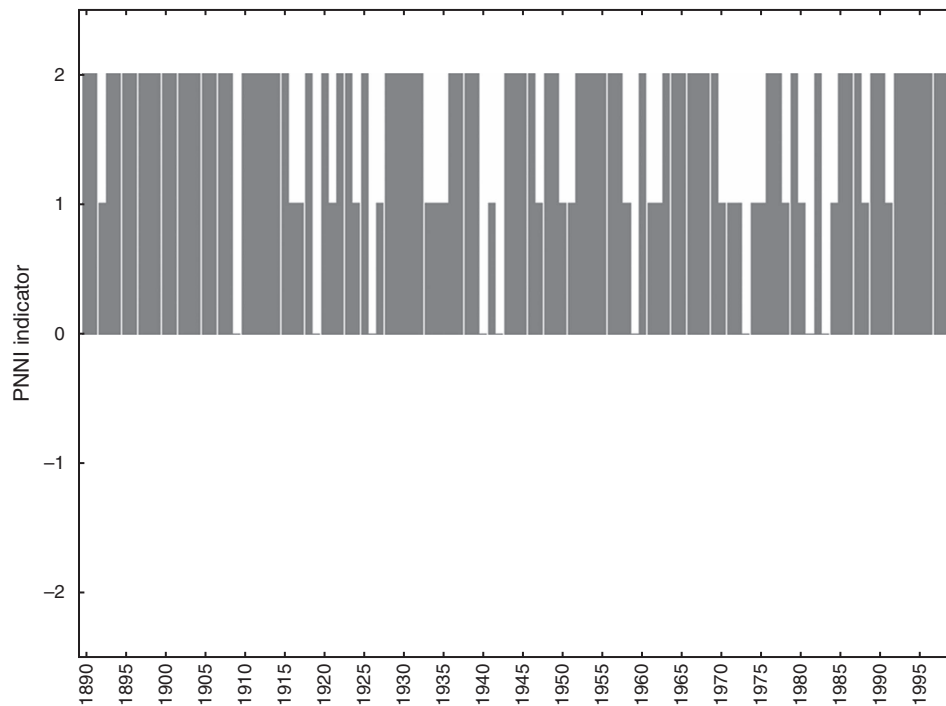


Fig. 9. Annual ‘potential nesting and nest inundation’ (PNNI) indicator values for *E. macrurus* (1890–1999). See Table 2 for scoring definitions.

the fastest growing urban centres in Australia, with the highest water storage *per capita* in the world (DIP 2009; Sahin *et al.* 2016). Recent droughts (i.e. the Millennium Drought) have

underlined proposals for large dams and greater consolidation of the region’s water resources (QWC 2010). In turn, there is potential for increased risk to the environment, exacerbated by

high uncertainty around the specific water requirements of aquatic ecosystems, and climate change impacts. Understanding the critical water requirements of native aquatic species and their habitats has therefore become increasingly important (Davies *et al.* 2014; Ocock *et al.* 2017; also see Clark *et al.* 2009).

Ecohydrological rules are thresholds that describe the critical water requirements of an aquatic ecosystem component (Mcgregor *et al.* 2017). These rules detail critical hydraulic habitat, include discrete aspects of the flow regime (e.g. magnitude, timing and duration), and may also incorporate environmental data such as water quality, rainfall and biological data related to the species. Incorporation of critical water requirements and environmental variability into e-flow strategies is particularly important for threatened species such as *E. macrurus*, which has multiple threats to its current and future conservation. One of the key priority actions for threat abatement for *E. macrurus* is 'to identify and protect areas critical to the survival of the species, such as nesting sites' (Threatened Species Scientific Committee 2008). Investigation of nesting behaviour and nest inundation rates under near-natural conditions is an important first step in understanding the environmental drivers for population viability of *E. macrurus*.

This study has established important ecohydrological rules for nesting and nest inundation of *E. macrurus*. Through camera trapping and nest monitoring, nesting activity was determined to peak in October and November. Although a greater number of turtles nested in October after the first significant spring rainfall, more turtles were photographed on nesting banks during November. Higher rates of nesting in October may be related to the timing and magnitude of local rainfall events providing clear triggers for nesting rather than time spent digging 'test holes' without laying eggs (Micheli-Campbell *et al.* 2013). Reduced rainfall in November may have caused more frequent, yet speculative, emergence of nesting females seeking suitable substrate moisture for nesting.

Quantification of minimum rainfall required to trigger nesting (10 mm), together with nest inundation thresholds (2.5 m), allowed assessment of the effects of the natural flow regime on nesting and nest inundation over a simulated natural flow period (1890–1999). This study found 'potential nesting and nest inundation' (PNNI) values for *E. macrurus* to be positive over most of the 109-year assessment period, based on a natural flow regime and rainfall.

Low rainfall and rising temperatures in the Queensland spring (Bunn *et al.* 2006) enable sufficient moisture for nest establishment, followed by optimal temperatures for rapid incubation and minimal exposure to terrestrial predators (Micheli-Campbell *et al.* 2013). Rising temperatures, however, also signal the onset of the Queensland wet season, increasing the likelihood of large flows that can inundate nests and cause eggs to perish (Plummer 1976; Kennett *et al.* 1993; Hollier 2012). Nesting success of *E. macrurus* therefore requires a balance of nest timing (to take advantage of warmer temperatures) and seasonal rainfall, without incurring summer wet season flows that result in nest inundation. In this study, most nests were established in October and November, therefore the 7–8-week (~52 days) incubation period was predominantly met before large flow events arrived in late December and January. The 10% of nests in the lower Mary

catchment that were inundated from natural flow events in this study would still be considered a positive result in terms of the PNNI indicator used in this assessment.

Climate change in south-east Queensland has been forecast to increase temperatures, reduce the frequency of rainfall events, yet increase the intensity of rainfall and associated flood events (CSIRO and Bureau of Meteorology 2015). Reduced floodplain inundation, reduced water availability and the close coupling of nesting and rainfall have all been cited as potential drivers of adverse impacts from climate change on other Australian freshwater turtle species (Bowen *et al.* 2005; Chessman 2011). This is likely to have multiple impacts on the nesting behaviour of *E. macrurus*. Increases in ambient temperature without spring rainfall may potentially contract the nesting season of *E. macrurus* and push it later into spring and summer (Beukeboom 2015). Incubation failure may then occur as incubation temperatures above 29°C have been shown to reduce hatching success and hatchling fitness in *E. macrurus* (Micheli-Campbell *et al.* 2011). Extreme rainfall and flood events can not only inundate increased proportions of nests but also affect the geomorphology of traditional nesting banks (Bodie 2001). In this study, nesting banks were abandoned following large floods, likely due to scouring or deposition, resulting in coarser substrates unsuitable for nesting (authors' unpubl. data).

Climate change can have further impacts around water storage infrastructure. Temperature increases can accelerate rates of evapotranspiration from large water bodies, and reduced rainfall can result in lower storage levels in spring and early summer (the Queensland dry season) (Wallace *et al.* 2017). *E. macrurus* nests through this period (Micheli-Campbell *et al.* 2013), so reduced rainfall can depress nesting triggers, make females nest at lower elevations or desiccate nesting habitat. In contrast, rates of nest inundation can also potentially increase from extreme rainfall and subsequent flood events. These climate-driven effects can lead to redistribution of species, as has been demonstrated in marine and terrestrial environments (Pecl *et al.* 2017). However, redistribution is difficult for a riverine specialist, endemic to a single river system and averse to crossing dry land or hypersaline environments.

Management implications

Ecohydrological rules for nesting behaviour and nest inundation of *E. macrurus* using the PNNI indicator can be used to conduct more comprehensive assessments of potential impacts to *E. macrurus* populations from future water management options in the Mary River basin. It is recommended that e-flow management strategies for *E. macrurus* assess the implications of this study across the entire Mary River catchment, including climate change. Although the largest nesting aggregations have been identified in the lower catchment, nesting also occurs in the upper Mary River and major tributaries (including the Tinana–Coondoo Creek complex) (authors' unpubl. data).

If *E. macrurus* is nesting within water storages, the relationship between nesting behaviour and water levels at the time of nesting may be used to minimise nest inundation (see McDougall *et al.* 2015). Connectivity between habitats and individuals should also be provided early in the breeding

season to maximise genetic mixing of the population, and access to nesting banks. Genetic subpopulations have been detected for this species (Schmidt *et al.* 2017), so spatially explicit risk assessment of flow-related impacts is required to manage *E. macrurus* populations within the catchment. In turn, this information can inform review and development of e-flow strategies for other riverine turtles with similar nesting behaviour, such as the Fitzroy River turtle (*Rheodytes leukops*) and Irwin's turtle (*Elseya irwini*) (Cann 1998; Limpus *et al.* 2011).

Modelling of ecohydrological rules for nesting of a sympatric species (*Elseya albagula*), in an adjacent catchment, led to changes in management of water storages to reduce the risk of nest inundation (McDougall *et al.* 2015). Water level fluctuations within water storage infrastructure were shown to potentially augment rates of nest inundation of *E. albagula*, constituting a risk to its long-term population viability (McDougall *et al.* 2015). Modified operating rules were enacted, which focused on raising barrage storage levels during peak nesting times (May–July), with subsequent water extraction dropping water levels and reducing the likelihood of nest inundation through the hatching period (December–January).

E-flow strategies that minimise changes to natural flow regimes will benefit not only *E. macrurus*, but provide suitable conditions for the broader aquatic ecosystem, including sympatric threatened species such as the Mary River cod and Australian lungfish. In the case of *E. macrurus*, and many other turtles in the Mary River, the current primary threat to recovery is the extensive and persistent depredation of clutches by the introduced red fox (*Vulpes vulpes*) (Limpus 2008). Although the longevity of this species suggests that recruitment opportunities will occur over time, any further loss of nests from WRD can be detrimental to the resilience of *E. macrurus*. Importantly, managing water resources is only one part of a complete range of activities required to ensure persistence, recovery and long-term viability of *E. macrurus* populations in the Mary River basin.

The management of water resources for sustainable ecological outcomes requires knowledge of the critical water requirements of key aquatic ecosystem components such as freshwater turtles. Ecohydrological rules can be incorporated into adaptive management frameworks and used to evaluate future risk in relation to water management and climate change scenarios modelled for the *Water Plan (Mary Basin) 2006* (DNRM 2016). For *E. macrurus*, nesting behaviour and nest inundation are important considerations to be included in the review of e-flow strategies to ensure the long-term viability of this threatened species.

Conflicts of interest

The authors declare no conflicts of interest.

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