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The influence of a new water infrastructure development on the relative abundance of two Australian freshwater turtle species

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Abstract. Development of water infrastructure benefits water security and agriculture but poses risks to habitat and aquatic fauna. Wyaralong Dam was constructed on Teviot Brook in 2010 to provide future urban water supplies for South East Queensland, Australia. Construction of the dam created a large impoundment area and environmental impact assessment predicted significant impacts upon resident freshwater turtle species and their habitats. Differences in habitat requirements, life-history characteristics and sensitivity to change between the Macquarie River turtle (*Emydura macquarii macquarii*) and the common saw-shelled turtle (*Myuchelys latisternum*) were expected to influence the impact of the dam on the spatial and temporal abundance of these species. The relative abundance of each species was monitored at sites located within, upstream and downstream of the impoundment across wet and dry seasons during the dam's first five years of operation. The results of this monitoring program indicate that spatial and temporal variability in the relative abundance of *E. macquarii macquarii* and *M. latisternum* occurred during the study but not all expected impacts were realised. Contrary to expectation, the relative abundance of *E. macquarii macquarii* did not increase over time within, upstream or downstream of the dam. *M. latisternum* showed greater temporal variability at some sites; however, no clear relationship between relative abundance and operational years was observed during the monitoring program. Spatial variability in relative abundance between sites was dependent upon season, with trends generally consistent across both turtle species. Where differences between species were observed, these are suspected to have resulted from the influence of environmental conditions on species-specific movement behaviours. The monitoring program confirmed the use of the upper limits of the impoundment and the plunge pool below the dam wall by both turtle species but relative abundance within the main body of the impoundment remained low throughout monitoring. The results of the study allow for consideration of the suitability of predefined management measures and the development of recommendations for future monitoring programs prescribed for water infrastructure developments.

Additional keywords: conservation, damming, *Emydura macquarii macquarii*, impact, *Myuchelys latisternum*, population monitoring, regulated rivers, species management.

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Introduction

Freshwater turtle species worldwide are under threat from a range of processes including increasing water infrastructure development to address demand for secure global water resources (Dudgeon 2000; Dudgeon *et al*. 2006). Construction and operation of instream water infrastructure, such as dams, weirs and barrages, can result in both direct and indirect impacts on freshwater turtles and their habitat (Tucker 2000; Hamann *et al*. 2007; Hollier 2010; Limpus *et al*. 2011). The initial filling of an impoundment or water storage area, converts shallow, predominantly lotic riverine habitat to deep, lentic environments (Dudgeon 2000; Dudgeon *et al*. 2006). Impacts of this change can include the inundation of aquatic and riparian habitat leading to a reduction in habitat heterogeneity and loss of turtle nesting habitat (Dudgeon 2000; Dudgeon *et al*. 2006; Hollier 2010; McDougall *et al*. 2015). Changes in environmental conditions within the area of impact can include reduced flow, increased water depth, decreased aquatic oxygen levels, temperature stratification and increased nutrient levels (Bodie 2001; McCartney 2009). Changes in water quality and flow regimes also occur downstream of the development in response to the restriction and regulation of flows (Bunn and Arthington 2002). In addition, water infrastructure development can restrict the movement of turtles past the dam/weir wall and reduce connectivity to offstream habitats such as floodplains, wetlands and billabongs (Bunn and Arthington 2002; Limpus *et al*. 2011). Injury and mortality of turtles can result when turtles come in contact with hard surfaces during spilling events, drown in high-turbulence outflows and high-velocity inflows through trash screens, or are crushed or trapped by mechanical gate operation (Limpus *et al*. 2011). Such impacts directly affect the availability and/or suitability of habitat for freshwater turtle species. If the altered habitat no longer provides the necessary features to support a given species, population viability can be reduced, with habitat specialists particularly at risk of impact (Bodie 2001; Alho 2011).

The habitat requirements of freshwater turtles are species-specific and can include shallow fast-flowing riffles, deep instream pools, off-stream wetlands, lakes and impoundments (Wilson and Swan 2003; Cann 2008; Ernst and Lovich 2009). Similarly, life-history characteristics, such as diet, breeding seasons and nesting habitats, can vary substantially between species (Wilson and Swan 2003; Cann 2008; Ernst and Lovich 2009). The potential impact of water infrastructure development on freshwater turtle populations is therefore influenced by species-specific requirements for key activities such as foraging, breeding and migration, and through associated changes to trophic ecology (Bunn and Arthington 2002; Welsh *et al*. 2017). For example, generalist turtle species and/or those located in regions that are prone to dry periods and ephemeral surface waters may benefit from the establishment of permanent water and/or release of environmental flows that occur in association with the construction of a dam or weir (Howard *et al*. 2016). Other species, particularly those with specialist habitat requirements and restricted distributions, are more likely to be at risk of negative impact (Buhlmann *et al*. 2009). As the need for water security and development of agricultural areas for food security increases, so too will risks to availability and suitability of habitat for freshwater turtles. Typically, legislative approvals issued by regulators for infrastructure development projects commit those developments to undertake mitigation measures to alleviate potential impacts; however, studies that report findings are rare and the actual benefits of intervention management strategies are not well understood.

Wyaralong Dam was constructed in 2010 to provide future urban water supplies for South East Queensland, Australia. The dam is situated on Teviot Brook within the Logan River catchment, ~51 km south-west of Brisbane (Fig. 1). The dam has a reservoir area of ~1230 ha, and a total capacity of 102 883 million litres. Prior to construction of the dam, Teviot Brook was an ephemeral system comprising pool/run sequences, riparian zones and offstream wetlands. These areas were known to provide habitat for the Macquarie River turtle (*Emydura macquarii macquarii*) and the common saw-shelled turtle (*Myuchelys latisternum*). *E. macquarii macquarii* is a subspecies of the broader Southern River turtle (*E. macquarii*) which has an extensive distribution throughout the Murray–Darling drainage, central Australia and coastal rivers of New South Wales and Queensland (Georges and Thomson 2010). It is considered to be a habitat generalist common across a variety of still and flowing aquatic habitats including rivers, lagoons, lakes and dams (Wilson and Swan 2003; Cann 2008). In contrast, *M. latisternum* (wide ranging in eastern Australia) is more of a habitat specialist that prefers quieter waterways including tributaries and headwaters of large rivers with a high abundance of instream debris (i.e. submerged logs and rocks) (Wilson and Swan 2003; Cann 2008; Georges and Thomson 2010).

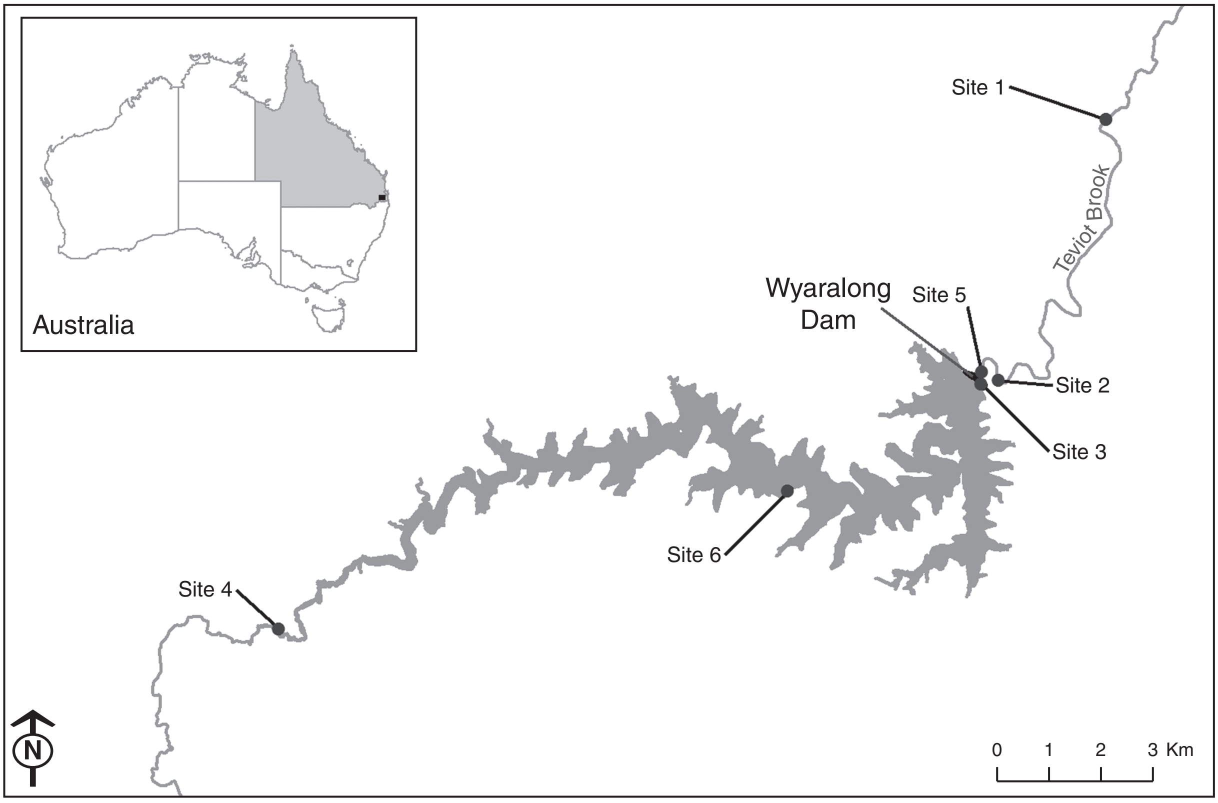

Fig. 1. The locations of the study sites.

Several impacts to these turtle species and their habitats were expected to result from the construction and operation of Wyaralong Dam (Parsons Brinckerhoff 2007; GHD 2009). Differences in habitat requirements, life-history characteristics and sensitivity to change between *E. macquarii macquarii* and *M. latisternum* were expected to influence the impact of the dam on the spatial and/or temporal abundance of these species. As has been observed at other water infrastructure locations throughout Queensland (Tucker 2000), the generalist *E. macquarii macquarii* was predicted to benefit from Wyaralong Dam while the specialist *M. latisternum* was expected to be negatively impacted (Parsons Brinckerhoff 2007; GHD 2009).

In recognition of the expected impacts, the Wyaralong Dam project approval required an adaptive management approach to reconcile the conservation of freshwater turtles with sustainable development (Queensland Government 2008). As part of that commitment, monitoring of turtle abundance during the first five years of operation was conducted. This monitoring provided an opportunity to test the following hypotheses:

- The relative abundance of *E. macquarii macquarii* and *M. latisternum* will vary between sites located within, upstream and downstream of Wyaralong dam.
- The relative abundance of *E. macquarii macquarii* and *M. latisternum* within, upstream and downstream of Wyaralong dam will vary between wet and dry seasons.
- The relative abundance of *E. macquarii macquarii* within, upstream and downstream of Wyaralong dam will increase during the first five years of dam operation.
- The relative abundance of *M. latisternum* within, upstream and downstream of Wyaralong dam will decrease during the first five years of dam operation.

The results allowed for consideration of the relevance of conditions imposed on the dam for turtle population protection and management.

Material and methods

Turtle monitoring was conducted in accordance with the State-regulator-approved Wyaralong Dam Turtle Management Proposal (GHD 2009). The objective of monitoring was to detect change in the abundance of freshwater turtles as a result of potential impacts arising from the construction and operation of the Wyaralong Dam. Findings were to inform the implementation of adaptive management practices, if required.

The construction of Wyaralong Dam commenced in January 2010 and continued for ~18 months, with completion in June 2011. Two turtle-monitoring events were undertaken each year from November 2011 to May 2016 to capture wet and dry seasonality. Monitoring events occurred during the first five years of dam operation, with a total of 10 events described in the study as per Table 1. Fig. 2 details rainfall conditions one and three months before each survey event.

The study area was defined by the water mark from Teviot Brook, 9 km downstream of Wyaralong Dam, to the upper extent of inundation. Monitoring was conducted at six survey sites (Sites 1–6). These included two sites within downstream Teviot Brook (Sites 1 and 2), the plunge pool immediately below the dam wall (Site 5), two sites within the impoundment (Sites 3 and 6), and the upper extent of the impoundment (Site 4) (Table 2; Fig. 1).

Table 1. Summary of monitoring surveys conducted during the Wyaralong Dam turtle monitoring program

Year	Season	Date
Year 1	Wet	December 2011
	Dry	May 2012
Year 2	Wet	November 2012
	Dry	May 2013
Year 3	Wet	November 2013
	Dry	May 2014
Year 4	Wet	November–December 2014
	Dry	June–July 2015
Year 5	Wet	November–December 2015
	Dry	May 2016

Data collection

Turtle surveys were undertaken using the standard methodology of the Queensland Government (Hamann *et al*. 2004; Eyre *et al*. 2014). Cathedral traps were used due to their suitability for the target turtle species and range of habitat conditions in the study area. Ten cathedral traps baited with beef heart were deployed at each monitoring site for ~18 h soak time; each was checked twice during the period of deployment.

Relative abundance measured as number of turtles captured within each trap was recorded for each turtle species. Turtles were tagged between the webbing of the hind foot with a small self-piercing, self-locking monel tag using the methodology specified by the Queensland Department of Environment and Heritage Protection (Limpus *et al*. 2002, 2011; Hamann *et al*. 2007). The tags were positioned within an area containing limited blood vessels and nerves thereby avoiding bleeding and minimising pain of the procedure. Tag placement also minimised overhang with the foot thereby minimising potential impacts of snagging and disruption of nesting in females. Turtles with straight carapace length less than 15 cm were released without being tagged. Turtles were released at the site of capture following data collection.

Survey methodology was developed in accordance with the Queensland *Animal Care and Protection Act 2001*. All field activities were conducted in accordance with methodologies specified by the Queensland Department of Environment and Heritage Protection (Limpus *et al*. 2002, 2011; Hamann *et al*. 2007). Surveys were conducted under a Queensland Government Department of Environment and Heritage Protection Scientific Purposes Permit (WISP11392912) and methodology was approved by the accredited GHD Animal Ethics Committee.

Statistical analysis

Statistical analysis using multifactorial Analysis of Variance (ANOVA) was performed for each turtle species to examine the spatial and temporal trends in relative abundance. Low recapture rates during the monitoring program prevented calculation of population estimates and, as such, relative abundance data were used as a quasi-indicator of species prevalence recognising that it is biased by trapping efficiency.

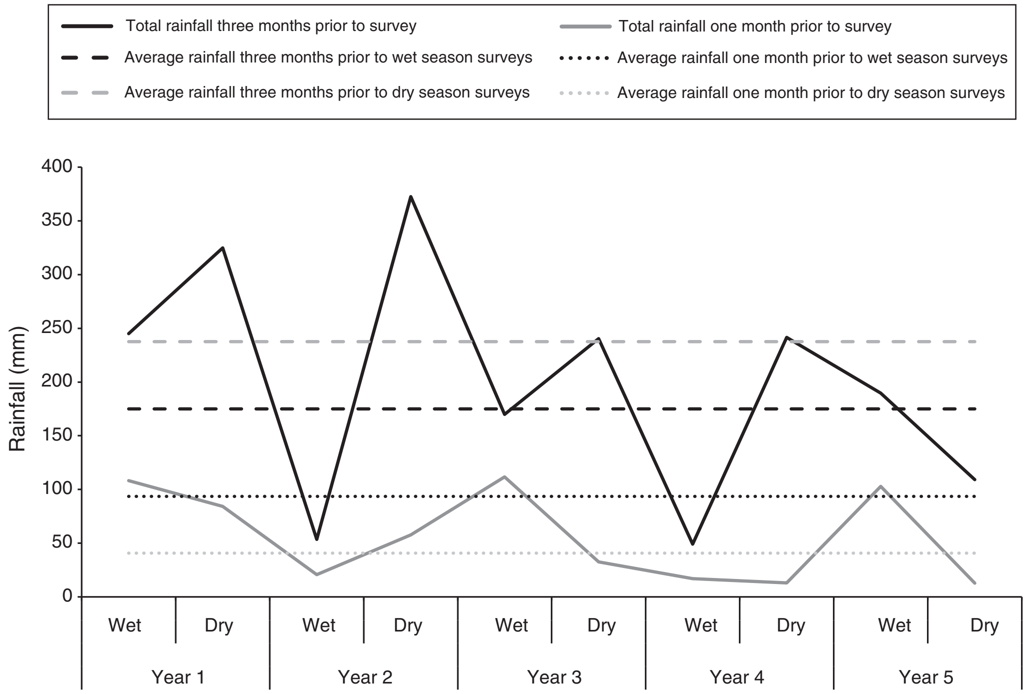

Fig. 2. Total and average rainfall one and three months before monitoring events.

Table 2. Location of the study sites at Wyaralong Dam

Site	Location
1	9 km downstream of dam wall
2	1 km downstream of dam wall
3	Immediately upstream of dam wall
4	Upper limits of impoundment
5	Plunge pool immediately below dam wall
6	Margins of mid-impoundment

The relative abundance of each species was assessed for variation with operation phase year (Years 1–5), season (wet/dry), site (Sites 1–6) and interactions among these factors. For this analysis, operational phase year, season, and site were regarded as fixed, orthogonal factors. The number of turtles recorded in each trap at each site was used as replicates of relative abundance. Prior to analysis, abundance data plus 1.0 was square-root transformed to address normality constraints of ANOVA and the high prevalence of zeros within the data. Significant findings were explored further using Least Squared Means Plots (with associated 95% confidence intervals) and Bonferroni *post hoc* tests. Statistical results are presented as *F*-values followed by the level of statistical significance (e.g. $P \leq 0.05$).

Results

A total of 606 *M. latisternum* and 226 *E. macquarii macquarii* were recorded throughout the five-year monitoring program, of which 42 *M. latisternum* and 18 *E. macquarii macquarii* were recaptures. The total abundance of each species recorded during each monitoring event is detailed in Table 3. Mean relative abundance (measured as number of turtles captured within each trap) at each site during each monitoring event is shown for each species in Fig. 3.

Table 3. Total number of turtles captured during each monitoring event

Year	Monitoring event	Total no. of turtles captured	
		Myuchelys latisternum	*Emydura macquarii macquarii*
Year 1	Wet season	104	39
	Dry season	39	7
Year 2	Wet season	98	35
	Dry season	83	21
Year 3	Wet season	119	32
	Dry season	21	5
Year 4	Wet season	52	43
	Dry season	17	1
Year 5	Wet season	41	37
	Dry season	32	6
Total		606	226

The relative abundance of *M. latisternum* and *E. macquarii macquarii* varied significantly between sites and seasons with a significant interaction (site × season) occurring for both species (*M. latisternum*: $F_{5,550} = 18.71$, $P \leq 0.01$; *E. macquarii macquarii*: $F_{5,550} = 17.05$, $P \leq 0.01$). This interaction remained constant across all five years of monitoring for *E. macquarii macquarii*, with no significant difference in relative abundance of this species occurring between years ($F_{20,550} = 0.50$, $P = 0.97$).

During the dry season, the relative abundance of *E. macquarii macquarii* did not vary significantly between sites located within, upstream or downstream of Wyaralong Dam (d.f. = 540,

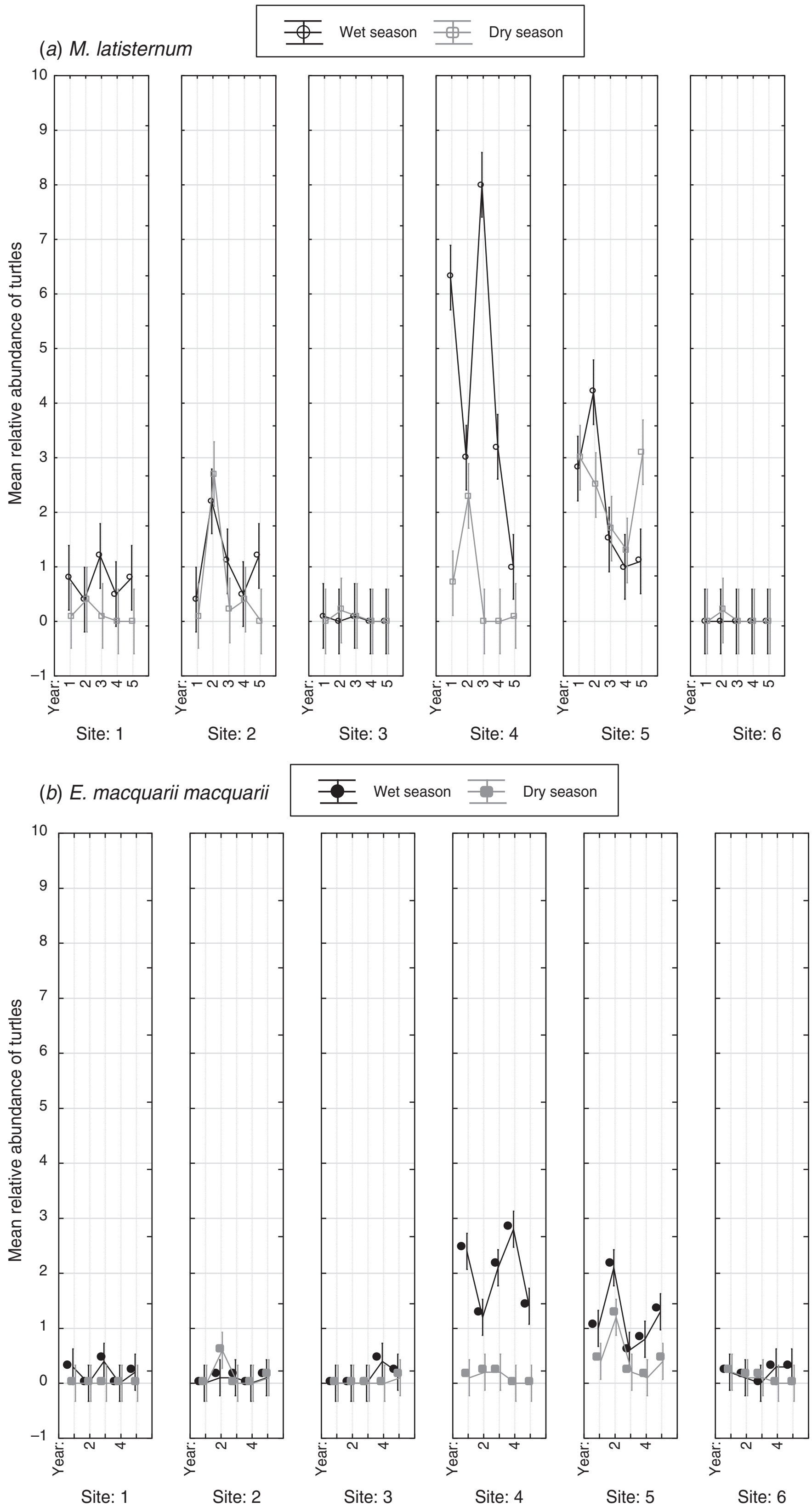

Fig. 3. Influence of sites, season and year on the mean relative abundance (number of turtles per trap) of (*a*) *Myuchelys latisternum* and (*b*) *Emydura macquarii macquarii*.

$P \geq 0.05$). The relative abundance of *E. macquarii macquarii* increased significantly from dry season to wet season within the plunge pool immediately downstream of the dam wall (Site 5) (d.f. = 540, $P \leq 0.02$) and the upper limits of the impoundment (Site 4) (d.f. = 540, $P \leq 0.01$). In some years, a slightly higher abundance of *E. macquarii macquarii* was also recorded during the wet season than the dry season, 9 km downstream of the dam (Site 1) and within the impoundment (Sites 3 and 6) during later years of monitoring (Years 4 and 5); however, these trends were not significant (d.f. = 540, $P \geq 0.05$).

During the wet season, the upper limits of the impoundment (Site 4) supported a significantly higher relative abundance of *E. macquarii macquarii* than all other sites (d.f. = 540, $P \leq 0.01$). The plunge pool (Site 5) also supported a significantly higher relative abundance of *E. macquarii macquarii* during the wet season than sites located within the impoundment (Sites 3 and 6) (d.f. = 540, $P \leq 0.01$) and downstream Teviot Brook (Sites 1 and 2) (d.f. = 540, $P \leq 0.01$).

In contrast to *E. macquarii macquarii*, the relative abundance of *M. latisternum* did vary significantly over time with a significant interaction occurring between years, sites and seasons in this species ($F_{20,550} = 3.06$, $P \leq 0.01$).

During the dry season, the plunge pool immediately below the dam wall (Site 5) generally supported a higher abundance of *M. latisternum* than all other sites; however, this was only significantly higher than all other sites in Year 5 (d.f. = 540, $P \leq 0.007$) and higher than sites within the impoundment (Sites 3 and 6) during Year 1 (d.f. = 540, $P \leq 0.04$). The relative abundance of *M. latisternum* increased significantly between dry and wet seasons within the upper limits of the impoundment (Site 4) during Years 1, 3 and 4 (d.f. = 540, $P \leq 0.02$). In some years, a slightly higher abundance of *M. latisternum* was also recorded during the wet season than the dry season within downstream Teviot Brook (Sites 1 and 2); however, these trends were not significant (d.f. = 540, $P \geq 0.05$).

During the wet season, the upper limits of the impoundment (Site 4) supported a significantly higher relative abundance of *M. latisternum* than: sites within the impoundment (Sites 3 and 6) and downstream Teviot Brook (Sites 1 and 2) during Year 1 (d.f. = 540, $P \leq 0.001$); all other sites during Year 3 (d.f. = 540, $P \leq 0.001$); and sites within the impoundment (Sites 3 and 6) during Year 4 (d.f. = 540, $P \leq 0.002$). No significant difference in relative abundance of *M. latisternum* was recorded between the upper limits of the impoundment (Site 4) and other sites during the wet season of Year 2 (d.f. = 540, $P \geq 0.08$) or Year 5 (d.f. = 540, $P \geq 1$). The plunge pool (Site 5) also supported a significantly higher relative abundance of *M. latisternum* during the wet season than sites located within the impoundment (Sites 3 and 6) and 9 km downstream of the dam wall (Site 1) during Year 2 (d.f. = 540, $P \leq 0.002$).

The greatest influence of dam operational years on the relative abundance of *M. latisternum* occurred within the upper limits of the impoundment (Site 4) during the wet season and within Teviot Brook 1 km downstream of the dam wall (Site 2) during the dry season. During the wet season within the upper limits of the impoundment (Site 4), the relative abundance of *M. latisternum* was significantly higher during Year 1 (d.f. = 540, $P \leq 0.05$) and Year 3 (d.f. = 540, $P \leq 0.001$) than Years 2, 4 and 5. An increase in relative abundance of *M. latisternum* occurred during the dry season of Year 2 within Teviot Brook 1 km downstream of the dam wall (Site 2) and this was significantly higher than the relative abundance of turtles recorded within this site during Year 1 (d.f. = 540, $P \leq 0.05$) and Year 5 (d.f. = 540, $P \leq 0.02$). Similar trends of increased relative abundance during the dry season of Year 2 were also observed within other sites, excluding the plunge pool (Site 5); however, these results were not significantly higher than for other years (d.f. = 540, $P \geq 0.05$). All fluctuations in relative abundance of *M. latisternum* observed over time (i.e. years) during wet and dry seasons within the plunge pool (Site 5) and 9 km downstream of the dam wall (Site 1) were not significant (d.f. = 540, $P \geq 0.05$).

Discussion

The Wyaralong Dam Environmental Impact Statement identified that dam construction and operation had the potential to impact two species of freshwater turtle known to occur within Teviot Brook (Parsons Brinckerhoff 2007; GHD 2009). *E. macquarii macquarii* is described as being a generalist species with the ability to inhabit a range of aquatic habitats, while *M. latisternum* generally requires more structurally complex habitats (Wilson and Swan 2003; Cann 2008). Differences in habitat requirements, life-history characteristics and sensitivity to change between *E. macquarii macquarii* and *M. latisternum* were expected to influence how these two species responded to the first five years of dam operation. The results of this monitoring program indicate that spatial and temporary variability in the relative abundance of *E. macquarii macquarii* and *M. latisternum* occurred during the study but not all expected impacts were realised.

The initial filling of the Wyaralong Dam impoundment occurred within a single flood event during 2011 and resulted in the conversion of Teviot Brook into a large lentic environment characterised by deeper, still waters. The construction of water infrastructure and associated impoundment of riverine habitat has been shown to decrease the abundance of many aquatic species (Abromovitz 1996; Ward 1998; Tucker 2000; Tucker *et al.* 2012). For example, a study by Hunt *et al.* (2013) identified that riparian reptile occupancy and species richness decreased with decreasing distance to dams. Similar trends were observed by Tucker (2000) in the Fitzroy, Kolan, Burnett and Mary River catchments where turtle populations present within impoundments supported a higher abundance of generalist species and lower abundance of specialist species than natural river systems. As such, *E. macquarii macquarii* was expected to be more adaptable than *M. latisternum* to changes in habitat conditions and resource availability within the newly formed Wyaralong Dam impoundment, resulting in an increase in abundance of this species over time. This hypothesis was not, however, supported during this monitoring program. The relative abundance of both *E. macquarii macquarii* and *M. latisternum* remained low at both sites within the impoundment (Sites 3 and 6) throughout the five years of monitoring. This result may suggest that conditions within the dam were not suitable to support larger numbers of these two species or that recruitment into the area via migration or breeding was not occurring. A slight increase in the relative abundance of *E. macquarii macquarii* within the impoundment during the wet seasons of Years 4 and 5 may indicate that the abundance of this species was beginning to increase; however, these changes were not significant and further monitoring would be required to determine whether this trend continues as the age of the impoundment increases.

The low relative abundance of turtles recorded within the impoundment may also be, in part, influenced by the relatively low trapping effort per unit of potential habitat at these sites in comparison to other sites. Effort applied to each survey may have been insufficient to have adequate power to detect any real differences in the turtle population using this area. Future monitoring programs should consider how to best allocate monitoring effort within impoundment habitats to improve data capture within these expansive, and seasonally variable, areas.

Relative abundance was expected to vary spatially between sites located within, upstream and downstream of the dam in response to variation in environmental conditions and dam impacts within these areas. Spatial variability in relative abundance was dependent upon season in both species, and this interaction varied significantly with monitoring years in *M. latisternum*. The plunge pool immediately below the dam wall (Site 5) and the upper limits of the impoundment (Site 4) supported a significantly higher relative abundance of *E. macquarii macquarii* during the wet season than sites within the impoundment (Sites 3 and 6) or within downstream Teviot Brook (Sites 1 and 2). The relative abundance of *M. latisternum* was also generally higher within the plunge pool (Site 5) and upper limits of the impoundment (Site 4) during the wet season; however, significant results only occurred during some years.

Before dam construction, it was predicted that turtles may aggregate in the plunge pool immediately downstream of the dam wall (Parsons Brinckerhoff 2007). This has been previously observed at water infrastructures throughout Queensland, including Theodore Weir, Borumba Dam and Ned Churchward Weir (Hamann *et al*. 2007; Limpus *et al*. 2011). Restriction of turtle movement upstream and the presence of large pool habitat are thought to be responsible for the large numbers of turtles recorded in these areas (Limpus *et al*. 2011).

Aggregation of turtles within the plunge pool (Site 5) occurred during the wet season only in *E. macquarii macquarii* while numbers remained stable between seasons in *M. latisternum*. The variation in relative abundance of *E. macquarii macquarii* between seasons may represent seasonal movement patterns in this species. Seasonal variations in movement behaviour are common in many aquatic species occurring in association with key life cycle phases such as dispersal and breeding/reproduction (Lowe-McConnell 1987; Lucas and Baras 2001). The movement behaviour of freshwater turtles is relatively unknown, with most research indicating that home-range size is relatively small (Tucker 2000; Flakus 2002; Gordos *et al*. 2003; Hamann *et al*. 2007). However, large-scale movements (in the order of tens of kilometres) are thought to occur in some species for the purposes of dispersal, for access to nesting areas and breeding aggregations, and in response to flood events (Tucker 2000; Limpus *et al*. 2011). Aggregation of turtles within the plunge pool at Wyaralong Dam during the wet season may suggest that turtles are trying to move upstream past the dam wall. Conditions imposed for construction of Wyaralong Dam did take account of this potential outcome and included the requirement for a fish lift as part of the infrastructure to facilitate the passage of aquatic fauna. However, as observed elsewhere (Hamann *et al*. 2008; Limpus *et al*. 2011), the relatively large abundance of turtles observed in the plunge pool at Wyaralong Dam suggests that the fish lift is not an effective design supporting movement of turtles upstream into the impoundment. Population growth and stability within the impoundment would be improved by the ability for animals to move readily between upstream and downstream environments for the purposes of dispersal, reproduction/nesting and flow-initiated movements. Future water infrastructure developments should further investigate the impact of turtle movement restriction and consider the requirement for turtle-specific passage options within infrastructure design.

Aquatic habitat within Teviot Brook between the dam wall and the Logan River, ~10 km downstream, has been modified as a result of dam operation, primarily through flow regulation (Parsons Brinckerhoff 2007). Changes to the flow regime have included increased base flows resulting from the operational requirement for environmental flow releases (Queensland Government 2008). For several years, species-specific requirements for key fish species have been incorporated into water management and resource operation plans for the protection of environmental values within regulated river systems (Gehrke and Harris 2001; Gippel 2001; Bunn and Arthington 2002; Arthington *et al*. 2006; Arthington 2012). A study by Howard *et al*. (2016) suggests that it could be of value to determine turtle-specific flow requirements and include these as part of environmental flow release conditions for infrastructure that may affect turtle abundance and habitat. Results of this study suggest that the increase in base flow within the previously ephemeral Teviot Brook may have improved instream connectivity; however, habitat suitability for turtles remained relatively low. The low relative abundance of turtles recorded within downstream Teviot Brook (Sites 1 and 2) throughout the monitoring program (excluding Year 2, which is discussed further below) suggests that habitat conditions were unsuitable to support larger numbers of either *E. macquarii macquarii* or *M. latisternum*. A trend of increased habitat use in the wet season was observed in some years, particularly in *M. latisternum*; however, differences in relative abundance between seasons were not significant. This result may indicate that, like *E. macquarii macquarii*, *M. latisternum* may also undertake upstream movement within Teviot Brook during the wet season but the environmental cues for movement may differ between the two species and are likely to have been altered by the dam. At the time of the field surveys (November), *M. latisternum* may have been moving upstream through the Teviot Brook from the Logan River (as indicated by a higher, but not significant, relative abundance of this species at Sites 1 and 2 during the wet season), while *E. macquarii macquarii* were already aggregated within the plunge pool (Site 5) at this time. Environmental factors known to trigger movement in aquatic fauna include hydrology, water temperature, day length, food availability, fauna biomass and water chemistry (Lucas and Baras 2001; Baran 2006). Alternatively, the difference in seasonal variability of the two species within the plunge pool (Site 5) may result from reduced downstream movement of *M. latisternum* during the dry season in comparison to *E. macquarii macquarii*.

In contrast to the low numbers of turtles recorded within the impoundment and downstream Teviot Brook, Site 4 within the upper limits of the impoundment supported the highest relative abundance of both turtle species recorded during the monitoring program. In general, habitat conditions within the upper reaches of impoundments are thought to be more suitable for freshwater turtles, particularly specialist species, than the deep water (>5 m) areas due to higher oxygen levels, greater light penetration and warmer temperatures (Hamann *et al*. 2008; Limpus *et al*. 2011). Habitat resources for foraging and sheltering (e.g. woody debris, undercut banks, overhanging riparian vegetation, macrophytes, etc.) are also generally greater within the shallow water margins than the main storage area (Hamann *et al*. 2008; Limpus *et al*. 2011). The results of this study support the use of upper impoundments by *E. macquarii macquarii* and *M. latisternum*; however, numbers of turtles recorded at this site displayed large temporal variations, which were not observed within the impoundment itself (Sites 3 and 6) or downstream Teviot Brook (Sites 1 and 2). The relative abundance of turtles within the upper limits of the Wyaralong Dam impoundment display strong seasonal variability in both turtle species, with this interaction influenced significantly by operational year in *M. latisternum*. The large increase in relative abundance of *E. macquarii macquarii* and *M. latisternum* (in some years) at this site during the wet season may suggest a change in habitat suitability for turtles at this site between seasons or may also indicate a bias in trapping efficiency. Wet season conditions in South East Queensland also correlate with increased temperatures. This, in turn, results in a direct increase in activity levels of freshwater turtles (Huey 1982; Haynie 2001; Angilletta *et al*. 2002; Gordos *et al*. 2003; Clark *et al*. 2008). Higher activity levels combined with a potential increase in turtle movement during wet season flow events (as discussed above) is likely to lead to an increase in the potential turtle encounter rate with traps and subsequent increase in relative abundance of turtles recorded during wet season surveys.

The influence of seasons on relative abundance of turtles within the upper limits of the impoundment (Site 4) was consistent throughout the monitoring program in *E macquarii macquarii*; however, significant variation was observed between years in *M. latisternum*. The relative abundance of *M. latisternum* during the wet season was significantly lower during Years 2, 4 and 5, resulting in no significant difference between seasons during those years. The general decrease in relative abundance of *M. latisternum* observed during the wet season over time within the upper limits of the impoundment (Site 4) and also, to some extent (but not significantly), within the plunge pool (Site 5), may indicate that operation of the dam is beginning to impact this species in these areas. This change may be driven by a reduction in habitat suitability for this species at these sites or a disruption of movement behaviours affecting immigration from areas outside the study area. Alternatively, the variation in relative abundance observed between years may indicate a greater sensitivity of this species than *E. macquarii macquarii* to natural longer-term fluctuations in environmental conditions. For example, monitoring in Years 4 and 5 was observed to correspond to a period of below-average rainfall in the three months before wet season survey events (Fig. 2). Lower rainfall may have reduced habitat connectivity and/or disrupted seasonal movement of *M. latisternum* during these years. Similarly, the unusually high abundance of turtles recorded during the dry season of Year 2 (most evident 9 km downstream of the dam wall (Site 2) but non-significant differences observed at most sites) is suspected to have been linked to extensive flooding, and an associated increase in habitat availability and connectivity throughout the catchment in the months preceding the field survey (Fig. 2). Upstream movement of turtles into creeks and tributaries is thought to occur during high flow conditions (Limpus *et al*. 2011) and the results of this study suggest that high levels of turtle movement may be occurring between Teviot Brook and the Logan River downstream.

Conclusion

The results obtained during this study suggest that species-specific differences between *E. macquarii macquarii* and *M. latisternum* have not had an overall influence on the impact of Wyaralong Dam on the spatial and temporal abundance of these species. Contrary to expectations, the relative abundance of *E. macquarii macquarii* did not increase over time within, upstream or downstream of the dam. *M. latisternum* showed greater temporal variability at some sites; however, no clear relationship between relative abundance and operational years was observed during the monitoring program. Spatial variability in relative abundance between sites was dependent upon season, with trends generally consistent across both turtle species. Where differences between species were observed, these are thought to have resulted from the influence of environmental conditions on species-specific movement behaviours. The monitoring program confirmed the use of the upper limits of the impoundment by both turtle species but relative abundance within the main body of the impoundment remained low throughout monitoring. Aggregation of both turtle species within the plunge pool immediately below the dam wall suggests that the fish lift is not currently mitigating the expected barrier to turtle movement.

The relative abundance of these two species within the Wyaralong Dam study area may continue to change over time as new habitat conditions stabilise and impacting processes are reflected in long-term variables such as reproductive success and recruitment, population dynamics and health. On the basis of the results of the study, we propose that monitoring programs that are prescribed as part of the approval process for construction or operation of major water infrastructure should consider allocation of sampling effort over a larger temporal scale (e.g. decades) to capture long-term impacts of dam operations on species composition and relative abundance of turtles. The data collected from Wyaralong Dam during this study provides a baseline against which future studies can compare. Future monitoring programs should also consider inclusion of movement behaviour via remote telemetry to better understand the importance of habitat connectivity and the influence of species-specific requirements and behaviours on relative abundance.

Conflicts of interest

The Wyaralong Dam Turtle Monitoring Program was funded by Queensland Water Infrastructure (construction phase) and Queensland Bulk Water Supply Authority trading as Seqwater (operation phase). Nicolette Osborne was, and remains, an employee of Seqwater during implementation of the monitoring program and publication of this paper. GHD received payment for implementation of the monitoring program in accordance with project approval conditions. Dr N. Clark, Dr C. Mills and Dr K. Neil were, and remain, employees of GHD during implementation of the monitoring program and publication of this paper.

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