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IMPLEMENTING ENVIRONMENTAL FLOWS IN SEMI-REGULATED AND UNREGULATED RIVERS USING A FLEXIBLE FRAMEWORK: CASE STUDIES FROM TASMANIA, AUSTRALIA

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ABSTRACT

Despite the many methodologies available for undertaking environmental flow assessments, there are few published examples of environmental flow recommendations that arise from those assessments, and even fewer that evaluate their implementation. This is somewhat surprising considering environmental flow recommendations are effectively testable hypotheses of flow-ecology responses. We describe a framework to guide the assessment and recommendation of environmental flow regimes in Tasmania, Australia, where environmental values are highly catchment specific and rivers are largely semi-regulated or unregulated. This means that environmental flows must be focussed on setting water use thresholds to prevent degradation in condition, rather than delivering water to restore condition. The framework retains the philosophy and elements of many other methodologies but differs by having the flexibility to support application across different catchments while catering for catchment-specific issues. We present two case studies that demonstrate the application of our Framework, its use in the development of scientifically defensible environmental flow recommendations, and their implementation in catchment water management plans. The strengths of the Framework are: (i) using specific ecosystem values to define and communicate the objectives of environmental flows; (ii) using a non-prescriptive and flexible approach to incorporate catchment-specific issues; and (iii) framing recommendations in a manner that clearly illustrates flow linkages with ecosystem values so that stakeholders and managers understand the risks associated with water abstraction. Our experience demonstrates the imperative that scientists are not only involved in water planning but also in the implementation, monitoring, and evaluation of plans so that the benefits of adaptive management can be realized. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS: flow regime; flow–ecology relationships; ecosystem values; environmental water requirements; water planning

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INTRODUCTION

Abstraction of water from rivers by consumptive users poses a significant threat to lotic ecosystems (Arthington *et al.*, 2010; Strayer and Dudgeon, 2010; Vörösmarty *et al.*, 2010), and alteration to streamflows associated with global climate change is likely to compound this impact in many regions of the world (Palmer *et al.*, 2008). The need to retain natural flow regime components in rivers for environmental purposes (‘environmental flows’) is widely recognized as being essential for maintaining freshwater biodiversity and ecosystem processes, and achieving environmentally sustainable water resource management (Poff *et al.*, 1997; Bunn and Arthington, 2002; Acreman and Ferguson, 2010).

Ideally, environmental flow assessments should account for the flow-related requirements of aquatic flora and fauna, and the array of processes that support healthy riverine ecosystems, by identifying and conserving influential components of the natural flow regime (Poff *et al.*, 1997). Holistic methods of assessing environmental flows are designed to meet this goal and are seen as superior to earlier approaches targeting individual species or only low-flow conditions (Arthington *et al.*, 1992; Tharme, 2003). Holistic methods, however, still have some limitations in either their design or their application. For example, they are (i) generally tailored for rivers with regulated flow regimes rather than managing water use in free-flowing rivers, (ii) often focussed on large basins rather than small catchments that can have unique values yet intense localized water use, (iii) often resource intensive and may rely on expert panels that can lack transparency or be influenced by expert biases, and like many environmental flow methods, and (iv) reliant on detailed knowledge of ecosystem responses to flow alteration.

The Ecological Limits of Hydrologic Alteration (ELOHA) framework was developed to address some of these issues and encourages extrapolation of flow–ecology knowledge between rivers with similar flow regimes (Poff *et al.*, 2010). The ELOHA approach has promise but relies on similar

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flow–ecology targets (or values), and develops robust flow–ecology relationships, across a gradient of flow alteration or within flow classes (Nui and Dudgeon, 2011). Such knowledge is not yet broadly available for many rivers in Australia (Schofield and Burt, 2003), nor globally (Sanderson *et al*., 2012), but is gradually being collected and developed to support flow–ecology characterizations at catchment and regional scales (e.g. DPIPWE, 2010; Poff and Zimmerman, 2010).

Although there are a plethora of environmental flow methods available, relatively few applications of methods, complete with evaluations of the implemented environmental flows, have been published in the peer-reviewed literature (Schofield and Burt, 2003; Lind *et al*., 2007). This suggests there is little evidence that environmental flows actually meet the broad objectives of maintaining, or enhancing, freshwater biodiversity and achieving the sustainable management of water resources (Hart and Calhoun, 2010; Harris and Heathwaite, 2012). Furthermore, the lack of such evidence makes justifying the value of environmental flows in a water management context, which is effectively a socio-economic context (Loch *et al*., 2011), a challenging prospect (Schofield and Burt, 2003).

In the few examples found, it appears that although determining environmental flows may be underpinned by a detailed method, the method itself is often adapted during its application. Such adaptation may be required for various reasons, such as the often limited time and financial resources with which to conduct assessments (e.g. Gippel *et al*., 2009), balancing the competing uses for water and a restricted capacity to restore ‘natural’ flow regime components (e.g. Jowett and Biggs, 2006; Bradford *et al*., 2011), or having to focus on single high-value attributes (e.g. Jowett and Biggs, 2006). Assessment methods may also be altered because of a lack of scientific knowledge of flow-dependent ecosystem values, or of the flow requirements of those values (e.g. Esselman and Opperman, 2010; Sanderson *et al*., 2012). Thus, it appears that a flexible approach to assessment is paramount in deriving environmental flow recommendations that have a higher likelihood of implementation (King *et al*., 2010).

Another issue arising from the sparse literature on environmental flow implementation is that the recommendations themselves are rarely published. Part of the reason may be that tools and methods are often developed in isolation of on-ground water management and that assessments may not necessarily be conducted in a hypothesis-testing framework or published in the primary literature. Environmental flow recommendations are effectively testable hypotheses, and their implementation can be viewed as a manipulative flow experiment (Souchon *et al*., 2008), complementary to water management planning. Such a view can potentially provide fruitful avenues for bridging the apparent disconnect between environmental flow assessment and implementation, and thereby support genuine adaptive management (Lind *et al*., 2007; King *et al*., 2010; Brooks *et al*., 2011).

In the few cases where environmental flows have been positively received and successfully implemented (e.g. Lind *et al*., 2007; King *et al*., 2009; King *et al*., 2010), transparent communication of the science (and its uncertainty), clear goals or targets of environmental flows, and flexibility in the logistics of their implementation appear to be key factors in their success. Ultimately, stakeholders and society at large make the final decision on how water is used, so clear and comprehensive communication of the science will improve its saliency, credibility, and legitimacy (Cash *et al*., 2003), and ensure management decisions are well informed (Sanderson *et al*., 2012).

Building on previous limitations and successes in delivering environmental flows in Tasmania, Australia, and on those observed in the literature, we have developed a flexible approach to environmental flow assessment by focussing on an appropriate scale for water management and freshwater biodiversity conservation. This approach identifies ecosystem attributes within a catchment on the basis of their conservation value in a state-wide context, communicates the importance of the natural (or current) flow regime in maintaining these ecosystem attributes to community stakeholders, and forms a key component of the Tasmanian water planning process. Such an approach provides consistency across different catchments but ensures each assessment is catchment-specific. The Tasmanian Environmental Flows Framework (TEFF) was developed in 2007 and has been applied in four Tasmanian catchments; case studies of its application in two of these catchments are presented in this paper. The case studies illustrate the highly catchment-specific nature of both freshwater ecosystem values and water use, and the advantages of using a flexible framework for both the assessment and implementation of environmental flows.

STUDY REGION

Tasmania is a small island state, *approx*. 68 500 km^2, off the south-east coast of Australia (Figure 1a). It lies in a temperate climatic zone (40–43°S, 144–148°E), with warm summers and cold, generally wet winters. It has a rugged topography such that catchments are generally small (<2000 km^2) with little water exchange between most of them (except where hydro-electric infrastructure exists), and often with high species endemicity and unique ecosystem values (McQuillan *et al*., 2009). The majority of Tasmanian rivers draining agricultural regions are unregulated with water allocations directly abstracted from river channels, or semi-regulated with run-of-river instream storages. As a result,

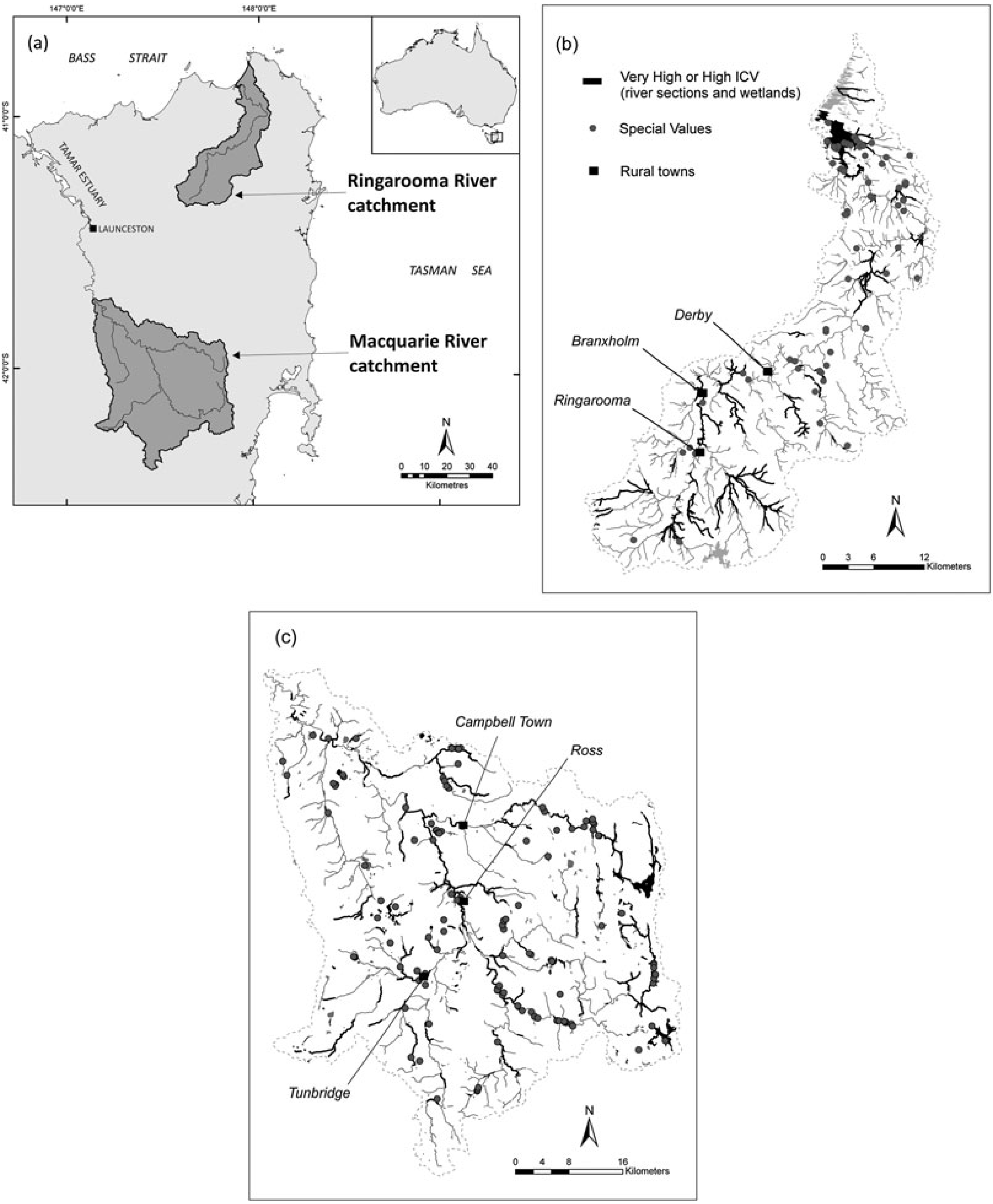

Figure 1. (a) The location of the Ringarooma River and Macquarie River catchments in Tasmania, Australia. (b) The Ringarooma River and (c) Macquarie River catchments showing river sections and wetlands of high or very high integrated conservation value (ICV, in black), and locations of freshwater-dependent special values (dark grey circles) derived from the Conservation of Freshwater Ecosystem Values database (see text for explanation and Appendix A for specific details of values). Townships in each catchment are also identified (black squares)

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most rivers retain natural high-flow and flood patterns. Across the northern and eastern parts of the state, where agricultural production is most developed, water use is spatially localized and seasonally concentrated, and water use and environmental values across catchments are consequently highly variable.

ENVIRONMENTAL FLOW ASSESSMENT FRAMEWORK

Historically, environmental flow assessments in Tasmania have focussed on providing minimum flows for instream fauna, namely macroinvertebrates and fish, including introduced brown trout (*Salmo trutta*) as a recreational value. With increasing recognition that a wide range of flow conditions are required to sustain freshwater-dependent ecosystems (Naiman *et al*., 2008; Poff *et al*., 2010), the Tasmanian State Government developed an holistic framework in 2007 (DPIW, 2007), known locally as the TEFF.

The TEFF is based on the premise that freshwater ecosystems have evolved in response to the natural flow regime and that natural patterns of flow variability provide the basis for healthy, functioning, and biodiverse freshwater-dependent ecosystems (Poff *et al*., 1997; Naiman *et al*., 2008). Ideally, like most environmental flow methodologies, the TEFF aims to minimize the impacts of water abstraction on the natural flow regime using the best available science. Given that detailed knowledge of both flow-dependent attributes and flow–ecology response relationships is often lacking, a reliance on the natural flow regime provides the best chance of ensuring that our incomplete knowledge does not result in overlooking ecosystem attributes and processes (Poff *et al*., 1997; Harris and Heathwaite, 2012). The intention of the TEFF is to explicitly link facets of the flow regime to ecosystem attributes and the derived environmental objectives via six steps, as follows: (i) identifying freshwater ecosystem values; (ii) characterizing the natural, current, and likely future flow regimes; (iii) developing conceptual models and translating flow–ecology linkages to stakeholders; (iv) setting objectives of environmental flows; (v) assessing flow-related requirements of ecosystem attributes; and (vi) deriving environmental flow recommendations (Figure 2) (DPIW, 2007).

From our own experience, and as amply demonstrated around Australia and globally (Cash *et al*., 2003; Hart and Calhoun, 2010; Harris and Heathwaite, 2012; Sanderson *et al*., 2012), recommendations for the sustainable management of natural resources, even if based on the most robust science available, will not succeed without adequate communication and translation of the science to stakeholders. Consequently, the TEFF explicitly incorporates steps where an emphasis is placed on explaining the science, and any associated uncertainty, to stakeholders (Figure 2). Although consultation, monitoring, and plan reviews are part of the water management planning process in Tasmania (Figure 2), the core of the TEFF focusses on the scientific development of environmental flow recommendations and is thus a complementary but intrinsic process to water planning.

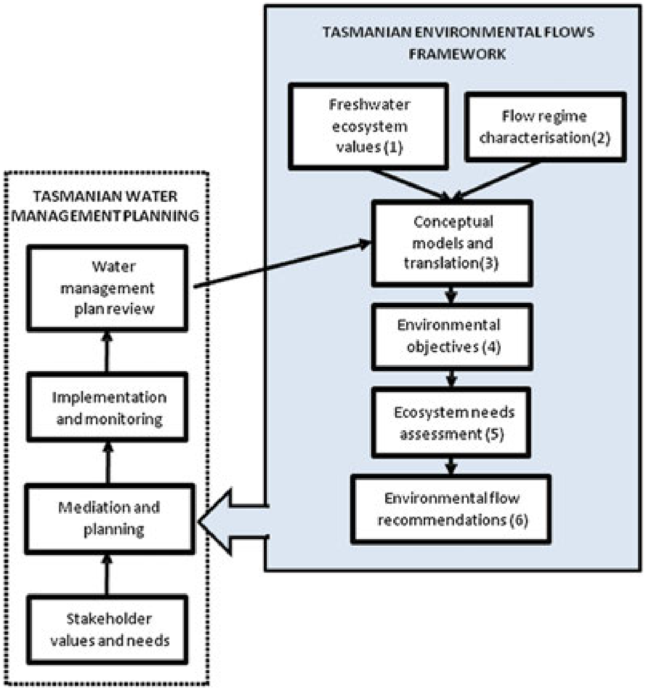

Figure 2. The Tasmanian Environmental Flows Framework and how it relates to water management planning in Tasmania. The solid box on the right encapsulates each step (numbered) of the Framework (see text for detail), whereas the dotted box on the left describes the broader water management planning process

The TEFF has similar elements to other methodologies, for example the FLOWS (DNRE, 2002) and Flow Events (Stewardson and Cottingham, 2002) methods; however, our approach differs in two ways. First, it has been designed to be flexible and therefore adaptable to specific catchments and their environmental values, water demands, and infrastructure for water management. Second, the TEFF identifies freshwater-dependent ecosystem attributes on the basis of their conservation value, an approach that provides more scientifically defensible targets for environmental flows and enhances the capacity to integrate water planning and conservation planning (Nel *et al*., 2011). Such a landscape-scale, ‘ecosystem values’ pproach is now being promoted elsewhere in Australia (Peake *et al*., 2011).

Case study 1: Ringarooma River catchment

The Ringarooma River catchment lies in the northeast of Tasmania and drains north into Bass Strait (Figure 1a). Annual

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rainfall is 1800 mm in the headwaters (*approx.* 1100 m a.s.l.), decreasing to around 600 mm on the coastal plains (<50 m a.s.l.). The upper catchment, used for forestry and agricultural activities, has predominantly basalt soils and the river has a rocky substrate, whereas the lower catchment has predominantly granitic soils. A history of sluice mining for alluvial tin in the lower catchment has resulted in large sand/gravel slugs dominating the substrate of the lower river and moving into a Ramsar-listed floodplain–wetland complex at the catchment outlet. The continued movement of mining sediments into the floodplain during large floods has the potential to gradually alter the hydrological connectivity of wetlands to the river in the future. Below the floodplain, the river enters a small estuary where it joins the Boobyalla River and discharges to the coast. The Ringarooma River catchment supports a human population of < 2000, mostly scattered throughout the catchment on relatively small rural holdings and in small towns such as Branxholm and Derby (Figure 1b).

The first step of the TEFF requires identifying freshwater ecosystem values (Figure 2). In Tasmania, we use the Conservation of Freshwater Ecosystem Values (CFEV) database: a GIS platform supporting a Comprehensive, Adequate and Representative analysis of ecological values from all Tasmanian freshwater-dependent ecosystems including rivers, wetlands, saltmarshes, karst, groundwater-dependent ecosystems, and estuaries across the state (CFEV, 2005; DPIW, 2008). The CFEV database provides a relative conservation value of ecosystem units (e.g. river sections and wetlands of various size classes) based on their condition and distribution in a state-wide context and is thus a systematic method for identifying and appraising the conservation value of, and management priorities for, Tasmanian freshwater ecosystems (DPIW, 2008). In addition to CFEV outputs, we conduct field surveys and use other information, such as location-specific studies and local and expert knowledge (where available), to verify the presence and condition of high priority values. In the upper Ringarooma catchment, freshwater ecosystem values of high conservation management priority include remnant rainforest vegetation communities in the riparian zones, threatened invertebrate species (e.g. the giant freshwater crayfish, *Astacopsis gouldi*), and native fish assemblages (Figure 1b; Appendix A). In the lower catchment, ecosystem values of high conservation management priority include unique and/or threatened flora and fauna associated with the Ramsar-listed floodplain–wetland complex (e.g. floodplain vegetation communities and the threatened green and gold frog, *Litoria raniformis*; Figure 1b; Appendix A).

In Step 2 of the TEFF (Figure 2), we use rainfall–runoff water balance models with multiple nodes to model natural flows across the catchment, and for the Ringarooma catchment, we conducted field studies to determine the degree of groundwater contribution where significant surface–groundwater connectivity was likely (e.g. DPIWE, 2006). Daily time series of modelled natural and current flows, and where available gauged flows, were examined using the River Analysis Package (Marsh *et al.*, 2003) to characterize natural and existing flow regime features associated with magnitude, timing, frequency, duration, predictability, and rate of change.

The Ringarooma River has a predictable seasonal flow regime with high flows over winter–spring and low summer flows (Figure 3a). Baseflow throughout the river system is substantially supported by groundwater discharge that contributes 60–70% of the total annual discharge at the outlet (DPIPWE, unpublished data). Consequently, the Ringarooma has fairly predictable flows (Table 1) and no cease-to-flow periods (Figure 3b). Approximately 23% of the mean annual flow is allocated for water use: half is abstracted from the upper catchment for agriculture and commercial enterprises; the other half is non-consumptive and supports hydro-electric power generation via a run-of-river dam on a large tributary in the middle of the catchment. Flow regime alteration due to water use is most pronounced in upper catchment tributaries during summer low flows.

To better understand surface water–groundwater interactions on the coastal floodplain, we installed an array of temporary bores in the floodplain–wetland complex (Figure 4). Water level data from the bores indicated that groundwater discharge supports water levels in many of the wetlands when flow in the river is low and wetlands are hydrologically disconnected from the river. Although the degree of connectedness is spatially variable, most wetlands are reliant on groundwater recharge from floodplain inundation during winter and spring (DPIW, 2008).

We constructed conceptual models for both the upper reaches of the Ringarooma River and the lower floodplain–wetland complex to collate and synthesize relevant flow–ecology information from both local studies and the literature, thus achieving Step 3 of the TEFF (Figure 2). The conceptual models were used to derive flow linkage tables (Table 2) that explicitly document hypothesized dependency of ecosystem values on specific features of the flow regime (e.g. spring freshes and bankfull flows), similar to the FLOWS methodology used in Victoria, Australia (DNRE, 2002). Flow linkage tables enable scientists and stakeholders to use a common language and be confident that important flow regime components have been identified using independently validated scientific studies, both from local studies and the broader literature. This is pivotal to the defensibility of the TEFF and instils confidence and acceptance by catchment stakeholders that environmental flow assessments are based on the best available evidence.

In constructing the upper reach model, we used general theoretical knowledge of fluvial processes on channel form, riparian vegetation, and habitat structure (e.g. Ward *et al.*,

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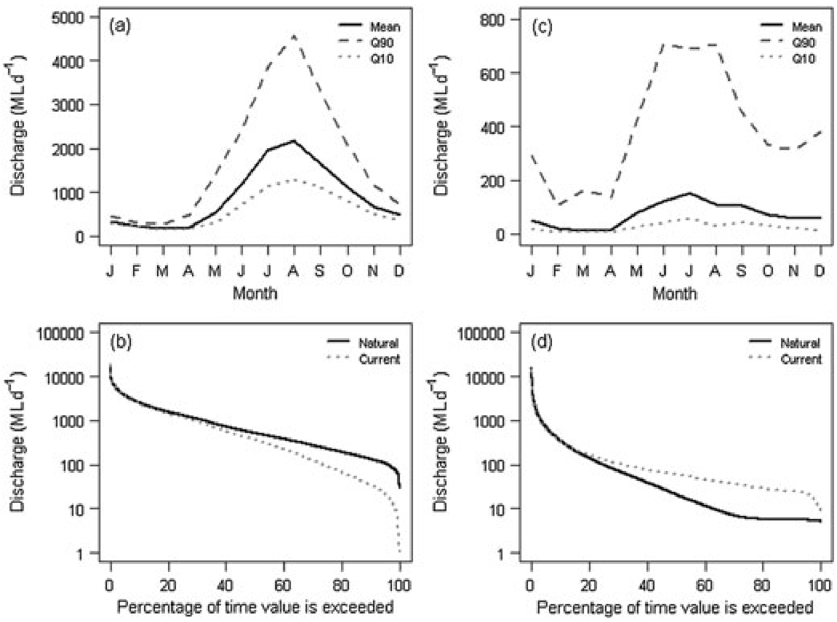

Figure 3. Monthly flow statistics (top row) and flow duration curves (bottom row) for the Macquarie River (a and b, respectively) and Ringarooma River (c and d, respectively). Monthly flow statistics were calculated using mean daily natural flow data from 1970 to 2000, derived from catchment rainfall–runoff water balance models. Mean (solid line), 10th percentile (Q10, dotted line), and 90th percentile (Q90, dashed line) monthly flows are shown. Flow duration curves were derived using modelled mean daily natural (solid line) and current (dotted line) flow data from 1970 to 2000. Modelled natural and current flow data were calibrated using gauged flow records

Table I. Flow statistics for the Macquarie River and Ringarooma River, calculated using daily time series of modelled natural flow data for 1970–2000, derived from catchment rainfall–runoff water balance models

Flow statistic	Macquarie River	Ringarooma River
Catchment area (km^2)	2700	930
Mean annual discharge (ML)	328 000	383 000
Mean daily flow (ML d^{-1})	933	1060
Flood frequency[a]		
ARI 1:5	30 000	11 000
ARI 1:20	48 000	15 500
Mean daily baseflow[b] (ML d^{-1})	222	488
Coefficient of variation	2.771	1.310
Colwell's indices[c]		
Predictability	0.207	0.509
Constancy	0.133	0.248
Contingency	0.073	0.260

ARI, annual return interval.

[a] Calculated from modelled daily flow data (ML d^{-1}) at catchment outlet and is for comparative purposes only.

[b] Estimated from gauged flow records using a three-way digital filter as described by Grayson *et al.* (1996).

[c] Colwell's indices are a measure of the seasonal predictability of environmental events (Colwell, 1974) and have been calculated using seasonal mean daily flow with 10 flow classes.

2002; Gordon *et al.*, 2004), combined with habitat-use information for instream fauna from previous studies in the Ringarooma and other rivers of the same flow regime type (DPIPWE, unpublished data). The floodplain–wetland conceptual model was guided by on-ground studies of surface–groundwater interactions in the lower Ringarooma wetland complex (DPIW, 2008) and the neighbouring Great Forester River (DPIWE, 2006), which has a similar flow regime to the Ringarooma River. Using published information in combination with on-site field studies and other local data to build conceptual models of flow–ecology relationships is in accordance with the ELOHA methodology (Poff *et al.*, 2010).

The conceptual models and linkage tables were used to derive the environmental flow objectives (Step 4 of the TEFF; Figure 2). Social and economic objectives were derived separately through the water management planning process (Figure 2). Environmental flow objectives for the Ringarooma River were to maintain the following: (i) healthy populations of native fish; (ii) diversity and abundance of macroinvertebrate communities; (iii) platypus abundance; (iv) current levels of benthic metabolism and productivity in the riverine ecosystem; (v) existing riparian and floodplain vegetation; (vi) current geomorphic character

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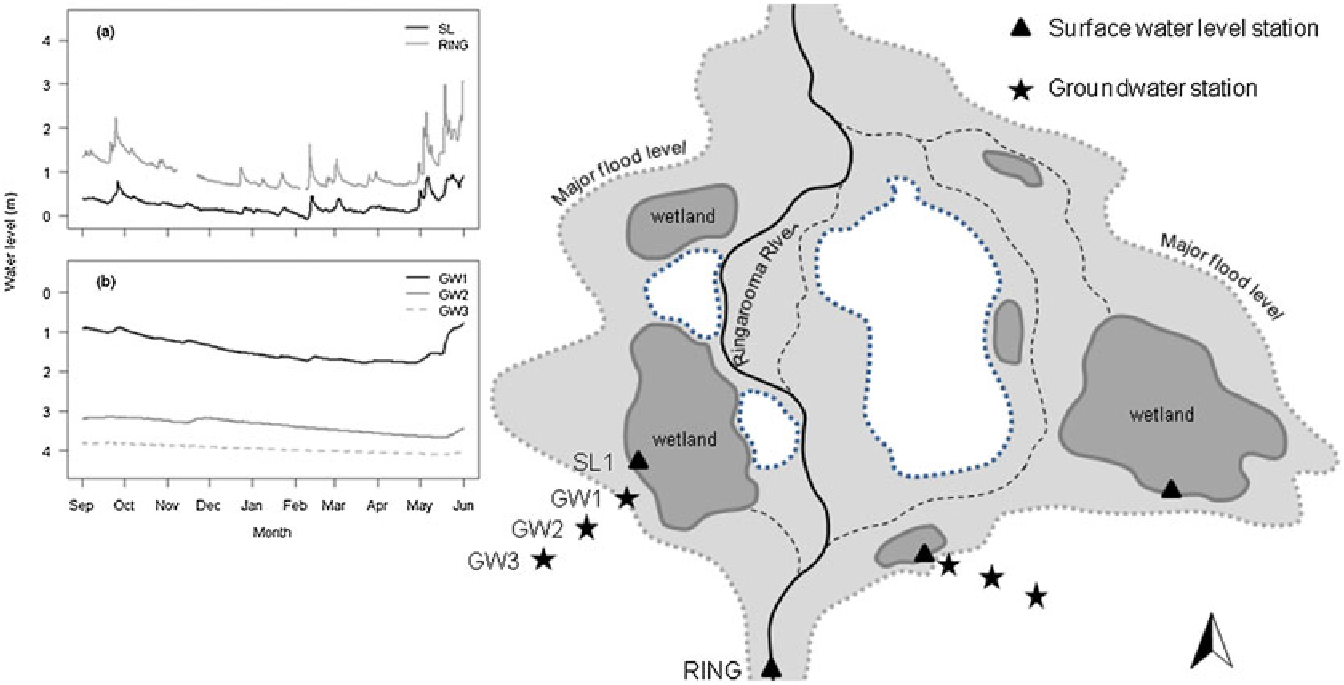

Figure 4. Schematic diagram of the lower Ringarooma River (flowing north) and its associated floodplain-wetland system. The locations of surface water (triangles) and groundwater (stars) monitoring stations are indicated, as are permanent wetlands (dark grey) and the floodplain inundation area (light grey). The insets show wetland (grey line) and river (black line) surface-water levels (top graph) and groundwater levels (bottom graph) between September 2006 and June 2007

and processes; and (vii) plant communities within floodplain wetlands. Note that these objectives were 'maintenance' rather than 'restoration' objectives, acknowledging that current and historical water use may have resulted in ecosystem changes that cannot be reversed (Harris and Heathwaite, 2012). For example, ecosystem alteration associated with

Table II. Example of a flow linkage table showing two of seven environmental objectives that guided the environmental flow assessment for the Ringarooma River Water Management Plan

Environmental objective	Process that supports the objective	Flow regime component[b]	Season	References[a]
Maintain existing riparian and floodplain vegetation communities	Wetting and drying of lateral benches in river channel	Lf, F, Bf	All year round	Britton and Brock (1994)
	Recharge of riparian and local groundwater systems	F, Bf	Winter–Spring	Winter (1999)
	Dispersal, germination, and growth of riparian and wetland plants	Lf, F, Bf, Of	All year round	Warwick and Brock (2003), Greet *et al.* (2011)
Maintain populations of native fish	Flow triggers for migration and dispersal	F, Bf, Of	Winter–Spring	Sloane (1984)
	Seasonal flow triggers for spawning	F, Bf, Of	Autumn–Winter–Spring	Koster *et al.* (2013)
	Maintenance of connectivity to enable fish passage	Lf	Summer–Autumn	Davey and Kelly (2007)
	Water levels in wetlands that provide habitat for juvenile fishes	Lf	Summer	Humphries (1995)

Note that only examples of processes supporting the objectives are shown; each objective may rely on multiple flow components. Flow regime components that influence supporting processes are identified, along with the seasons during which certain flows are considered important.

[a] Examples of supporting flow–ecology studies.

[b] Lf, low flows; F, freshes; Bf, bankfull flows; Of, overbank flows.

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mining sediments being deposited in floodplain wetlands during major floods was not addressed.

The fifth step of the TEFF, the ecosystem needs assessment (Figure 2), is not prescriptive but involves field assessments relating to the objectives and hence is generally targeted at high priority conservation values. Thus, the strategies used for the assessments are likely to vary among catchments depending on the values they contain. Examples of commonly used assessment approaches include hydraulic modelling of instream features for benthic biota, identification of barriers to fish passage, seasonal flora and fauna surveys, groundwater monitoring, substrate sediment characterization, and floodplain mapping. The ecosystem needs assessment for the Ringarooma catchment had two components that focussed on values in the upper and lower catchment, respectively. Reach-scale hydraulic models were constructed for three riverine reaches in the middle and upper catchment, and these were combined with habitat-use information for instream fauna to derive relationships between flow and instream habitat during dry months to address instream low-flow objectives. These models were also used to estimate bankfull and overbank discharge thresholds and durations, addressing riparian objectives (e.g. Table 2). In the lower reaches and floodplain wetlands, local water level and topographic data were analyzed to determine flood magnitude, timing, and duration, as well as the frequency and duration of low-flow periods that may interrupt connectivity between the river and the wetlands (DPIW, 2008).

The final step of the TEFF is to develop a series of environmental flow recommendations (Figure 2) to achieve the objectives derived in Step 5. The natural flow regime is typically used as the primary guide to satisfy the needs of the riverine ecosystem. However, it can be constrained by flow regime alterations already in place as a result of historical and current levels of water use. Recommendations in Tasmania commonly focus on the following: (i) cease-to-take flow triggers during naturally dry months that aim to maintain instream habitat and longitudinal connectivity in rivers with perennial flow regimes, or allow intermittent rivers to cease-to-flow for certain periods; and (ii) high-flow extraction rules during wet months that aim to protect the natural pattern of the high-flow regime, including systems in which the timing of flood events is unpredictable. These ‘flood harvest’ rules often include trigger thresholds, rates of extraction, and maximum durations for extraction during high-flow events. A risk assessment is coupled with the environmental flow recommendations to indicate the risk (low, moderate, or high) to specific flow components, and hence ecosystem values, under current and future flow scenarios as a result of water use and climate change.

The recommendations for the upper Ringarooma River were monthly cease-to-take thresholds during summer–autumn (when water is extracted and used directly), which aim to protect hydrological connectivity and provide adequate wetted habitat for instream biota (DPIW, 2008). Flood harvest rules for winter–spring (when water is extracted and stored in offstream dams for later use) were aimed at minimizing impacts on flood duration and rates of change in flow. Reach-specific harvest triggers approximated the 5% exceedance threshold (mean daily flow equalled or exceeded 5% of the time), with the absolute rate of abstraction not recommended to exceed one fifth of the threshold for no more than 3 days. Additionally, flood harvesting was only to be permitted during May–October when high-flow events are most prevalent. These recommendations were developed for three separate locations in the upper catchment.

The recommendations for the lower catchment and floodplain wetlands were focussed on the main river channel immediately upstream of the floodplain (DPIW, 2008). The first recommendation comprised a cease-to-take flow of 50 ML d^{-1} during summer–autumn; the threshold below which some floodplain wetlands become hydrologically disconnected from the river during dry months. Flows less than this level are extremely rare historically but have occurred more frequently in recent years as summer water use across the catchment has increased. Larger flow events in the lower river are virtually unimpacted by current water use but are required to flush wetlands impacted by dairy activity, recharge the floodplain groundwater system, and provide a mechanism for dispersal of flora and fauna. To ensure this, the second recommendation was for flood harvesting to only be permitted at flows above the 5% exceedance flow, with total abstraction not to exceed one fifth of the threshold, for not more than 5 days.

Case study 2: Macquarie River catchment

The Macquarie River is in central-eastern Tasmania and drains east then north into the South Esk River, which then flows north into Bass Strait via the Tamar Estuary (Figure 1a). Annual rainfall is low, < 600 mm, and evaporation is high at 1100 mm per annum, resulting in an annual water deficit. The upper catchment (>500 m a.s.l.) is relatively undisturbed with open eucalypt woodland on dolerite soils, whereas the lower catchment (<200 m a.s.l.) has predominantly alluvial soils and has supported livestock grazing and cropping since European settlement (early 1800s). Two significant impoundments were constructed during the 19th century to increase agricultural production and have regulated flow in the Macquarie River for more than 100 years. The Macquarie River catchment now supports a human population of about 2000, most of whom live in the towns of Tunbridge, Ross, and Campbell Town (Figure 1c).

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The relatively long history of agricultural activity in the Macquarie River catchment has resulted in widespread alteration of the landscape and a significant decline in the condition of many freshwater-dependent biophysical attributes. However, the identification of freshwater ecosystem values (Step 1 of the TEFF) demonstrated that some important remnant values persist, many of which are endemic to the catchment (Figure 1c; Appendix A). Headwater reaches with intact riparian vegetation support the endangered riparian shrub Tasmanian bertya (*Bertya tasmanica* subsp. *tasmanica*) and the endemic and threatened fish Swan galaxias (*Galaxias fontanus*). In the middle and lower catchments, freshwater-dependent values include species-rich aquatic macrophyte communities and the endemic South Esk freshwater mussel (*Velesunio moretonicus*). These values occur in large, deep riverine pools, known locally as 'broadwaters', which are unique geomorphological features of rivers in the South Esk Basin in Tasmania.

As for the Ringarooma River, we generated daily time series of natural and current flows across the Macquarie River catchment using rainfall–runoff models (Step 2) and gauged flow data. Characterization of the modelled natural flow regime demonstrated a weak seasonal pattern in the Macquarie River with persistent, often supra-seasonal, periods of low flows interrupted by large, relatively flashy floods with unpredictable timing (Table 1; Figure 3). Historically, the river is likely to have had frequent cease-to-flow periods, but the impoundments in the upper catchment (combined storage approx. 52 GL) augment and regulate low flows during summer–autumn with water releases for irrigation. The last two decades have seen increased flow variability and reductions in flow, particularly during winter–spring, thus weakening the seasonal pattern and suggesting that drier and more variable climate conditions are altering the flow regime. Currently, about 26% of the mean annual flow is allocated for consumptive water use to support irrigated agriculture, and as the upstream impoundments are fully allocated, there is increasing stakeholder pressure to allocate water from high-flow and flood events.

Conceptual models synthesizing the flow–ecology information relevant to the conservation values were constructed separately for the upper and lower river reaches of the Macquarie River (Step 3), as well as for the broadwaters that are a prominent feature of the river and support separate and unique values (Figure 5). We conducted field surveys of riparian and aquatic vegetation, and macroinvertebrate and fish communities, and combined this information with published research conducted in the catchment (e.g. Humphries, 1995) to guide the construction of the conceptual models. Similarly, the broadwater model was based on published research predominantly relating to the broadwater macrophyte communities and associated fauna (e.g. Humphries *et al.*, 1996; Warfe and Barmuta, 2006), as well as on-ground studies of groundwater inputs to littoral zones (DPIPWE, 2009), and of freshwater mussel glochidia (larvae) to determine if flow-dependent fish were favoured hosts (DPIPWE, 2009) (Figure 5).

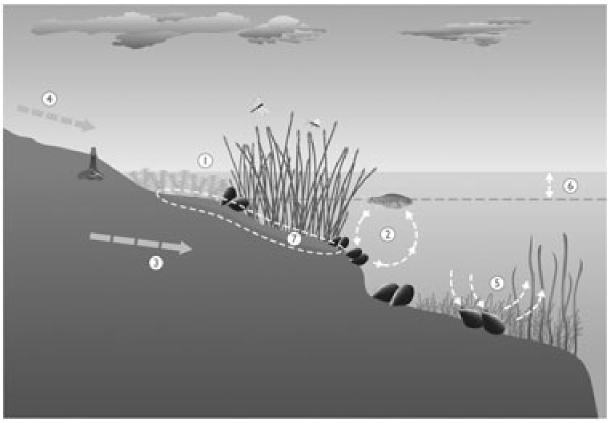

Figure 5. A conceptual ecosystem model of littoral broadwater habitats in the lower Macquarie River. Seven important attributes and processes were considered in the environmental flow assessment as follows: (1) structural habitat and biodiversity within littoral macrophyte beds; (2) fish-host life cycle requirement of endemic freshwater mussels; (3) groundwater input into the river during low flows; (4) transport of organic material and nutrients from the floodplain to the river; (5) important role adult freshwater mussels play in regulating primary production; (6) influence of water level fluctuations on littoral vegetation communities; and (7) seasonal nutrient dynamics associated with littoral macrophytes

These conceptual models, and the flow linkage tables arising from them, were then used to develop environmental flow objectives (Step 4). The objectives for the Macquarie River were to maintain the following: (i) invertebrate and floristic communities in littoral broadwater habitats; (ii) macroinvertebrate diversity and abundance in upper reaches; (iii) native fish populations throughout the river; (iv) populations of rare and threatened aquatic species including mussels; (v) remnant riparian and floodplain vegetation communities; (vi) current benthic metabolism and productivity; (vii) geomorphic character; and (viii) groundwater recharge processes.

The ecosystem needs assessment (Step 5) for the Macquarie River entailed the construction of hydraulic models for seven reaches along the length of the Macquarie River, including upper, middle, and lower reaches, and floodplain and broadwater habitats. Reaches were selected to represent the range of river channel types occurring along the river but also corresponded to 'nodes' of water management operations, ensuring environmental flows could be implemented, monitored, and managed. As for the Ringarooma River, the hydraulic models were combined with existing literature and field studies (described earlier) to derive relationships between low flows and instream habitat and to characterize bankfull and overbank discharges.

The long history of low-flow regulation for irrigation in the Macquarie River catchment meant that changing this component of the flow regime was not possible. Furthermore, current flow management mitigates poor water quality and algal blooms in the river and was considered to adequately maintain several existing ecosystem values (e.g. littoral macrophyte beds and small-bodied native fish). Therefore, no recommendations were made to alter current low-flow management practices. High-flow recommendations were made for each of the seven study reaches and were aimed at preserving inter-annual and intra-annual flow variability (DPIW, 2009). Recommended flood harvesting triggers were based on bankfull flow thresholds (equivalent to 4–18% exceedance flow depending on the reach), plus 50% of the mean rate of rise per day of events exceeding these thresholds. Using these triggers, we recommended that floodwater abstraction be permitted while flows exceed the bankfull thresholds (Figure 6). Additional triggers (equivalent to 2–6% exceedance flows) were also proposed to guide the potential future management of opportunistic extraction from larger floodplain inundation events (Figure 6).

IMPLEMENTATION OF ENVIRONMENTAL FLOWS

Summaries of important ecosystem values, the current degree of flow alteration, ecosystem conceptual models, and derived environmental flow objectives were presented to stakeholders in the Ringarooma and Macquarie catchments in scientific forums. This exercise demonstrated the process by which recommendations were developed and thereby instilled stakeholder and community confidence in the recommendations. Recommendations for water abstraction from low and high flows in the Ringarooma catchment have been integrated into a draft Water Management Plan for the catchment (DPIPWE, 2012). Water access rules in this plan are strongly aligned with the recommendations derived from the TEFF assessment and include staged flow management rules to reduce the likelihood of cease-to-take low-flow triggers being breached. In the Macquarie catchment, stakeholder concerns about the reliability of existing water allocations and other socio-economic factors have resulted in water access rules for high-flow events that only partly reflect the environmental recommendations derived from the TEFF assessment (DPIPWE, 2012). However, under this plan, water access rules will still largely protect floodplain inundation events, and total water allocations in the catchment have been capped (which will help maintain existing ecosystem values). Furthermore, the catchment stakeholders understand the environmental risks of the proposed water access rules.

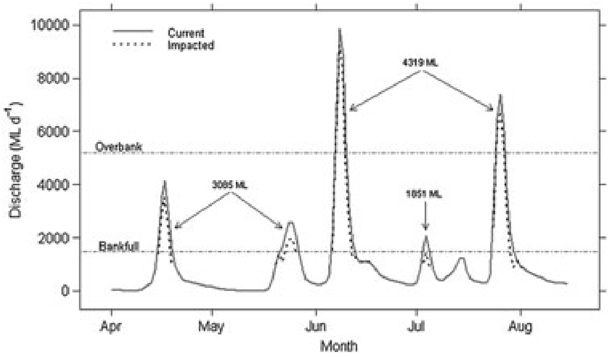

Figure 6. Example application of recommended high-flow extraction rules for the lower Macquarie River between 1 April and 15 August 2003. Modelled mean daily flow (current, solid line) and remaining flow in the river after proposed flood harvest allocations have been taken during bankfull flow events (impacted, dashed line) are shown. Impacted flow was estimated following the water abstraction rules for this site (see text for details). The bankfull and overbank levels for triggering flood allocations are indicated, as are the volumes of water in each high flow event that would be available to consumptive users

Following formal adoption of the Macquarie and Ringarooma plans, it is proposed that they be reviewed after 10 years. During operation of the plans, flows will be monitored at management nodes to ensure that flow regime objectives are being met, and field studies will assess whether consumptive water allocations have negative impacts on environmental values. Ecological monitoring in the Ringarooma catchment will address the interests of water managers, scientists and stakeholders, and will include the following: (i) assessing the condition of reaches downstream of high water use sub-catchments; (ii) examining the amount of physical habitat provided by cease-to-take thresholds across the catchment; and (iii) determining the ecological consequences of reduced flows (and increased flow variability) during summer–autumn that are associated with consumptive water use. In the Macquarie catchment, the findings of an holistic landscape monitoring programme (which is associated with planned water resource development in the catchment and includes riverine sampling) will be used in conjunction with targeted studies of river condition to access the performance of the plan. Depending on the outcomes of these and other water management activities, the environmental and consumptive water allocations may be renegotiated and implemented in a revised plan, in accordance with adaptive management protocols.

One of the strengths of the TEFF has been its capacity to improve understanding among stakeholders as to what constitutes ‘adequate water for the environment’. Past assessments using older methodologies (e.g. IFIM) predisposed stakeholders to think about environmental flows simply as ‘minimum flows’. The TEFF, like most other holistic methods, has significantly changed this perception. Catchment stakeholders now have a much better appreciation for both the complexity of the linkages between flow and ecosystem attributes and processes, and also the

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potential impact of water development on freshwater-dependent ecosystems. A critical role in this has been an increased understanding of the importance of maintaining flow variability (‘the heartbeat of the river’) and how alterations to the flow regime are likely to affect riverine ecosystems. In part, this has been greatly facilitated by the logic and transparency of the TEFF.

DISCUSSION

In the Ringarooma and Macquarie catchments, the TEFF was used to develop scientifically defensible environmental flow recommendations. These recommendations have largely been incorporated into catchment water management plans (DPIPWE, 2012a, b) and can therefore be considered a measure of the TEFF’s success. The case studies illustrate the following strengths of the Framework: (i) using catchment-specific conservation ecosystem values to define and communicate the objectives of environmental flows; (ii) using a non-prescriptive and flexible approach to incorporate catchment-specific issues; and (iii) framing recommendations to clearly illustrate linkages between flow and ecosystem values so that stakeholders and managers understand risks associated with water abstraction.

Few frameworks for assessing environmental flows have a transparent or consistent means of identifying the flow objectives. In our experience, objectives are often identified using expert input or have a focus on recreational or aesthetic values (e.g. introduced salmonid fishes; Jowett and Biggs, 2006) that are elevated to the same status as environmental values and can lead to the perception of bias among stakeholders. We found that using the outputs from a spatially explicit database of freshwater-dependent ecosystem values provided an objective and transparent means of identifying and framing objectives for environmental flows, supporting calls for better integration between environmental flow assessment and freshwater conservation planning (Nel *et al*., 2011). Such objectivity resulted in stakeholders having confidence that environmental flow objectives were not influenced by experts with real or perceived biases or conflicts of interest. Knowledge that ecosystem value was attributed in a state-wide context, with maps that clearly illustrated the spatial distribution of ecosystem values in target catchments, helped stakeholders understand that values may not occur on their property but are potentially impacted by their water use. For example, many stakeholders in the lower Macquarie River catchment were familiar with the freshwater mussel (‘they’re everywhere’) but were unaware that this species is endemic to the lower catchment and that it requires suitable fish hosts for the larval stage of its life cycle. In the headwaters of another catchment in Tasmania (not presented in this paper), the presence of a fish species that has protection under national legislation largely dictated environmental water provisions and ultimately provided ‘umbrella’ protection for a range of other freshwater values in that catchment.

The use of conceptual models complemented the presentation of catchment-specific conservation values and contributed to the implementation of the environmental flow recommendations. Conceptual models enabled the flow conditions required to maintain objectives to be explicitly visualized and clearly understood by stakeholders. For example, the conceptual models were a critical tool in communicating the importance of floods for conservation values and ecosystem processes (e.g. watering of remnant riparian forests and recharging groundwater aquifers), and therefore why floodwater harvesting should be managed. Presentation of the conceptual models provided a platform for stakeholders to ask questions of the science, scientists, and other stakeholders. This also stimulated discussion regarding how best to balance environmental needs with social and economic needs that are dependent on water development. Such a platform can also highlight where objectives may overlap. For example, during the water management planning process in another Tasmanian catchment in Tasmania (again, not presented here), it became apparent that there was limited capacity for further water allocation from low flows, but access to floodwater was able to provide both water security for irrigators and meet the water requirements of riparian vegetation and estuarine aquacultural production.

We have found the second strength of the TEFF is its non-prescriptive nature, providing flexibility to tailor its application to different catchments and to locations within specific catchments. This is a particular advantage in Tasmania, where there are many small catchments that have different issues regarding water use and flow management, and highly catchment-specific and even site-specific ecosystem values. Previous environmental flow methods used in Tasmania (e.g. IFIM; Bovee, 1982) have been unable to address the full range of catchment values or have had to rely on flow–ecology knowledge from elsewhere that may not be entirely relevant. It also resulted in a tendency to follow the same ‘recipe’ across catchments. The flexibility of the TEFF has resulted in environmental flow recommendations now being more relevant to the focus catchment, at scales relevant to water management, and therefore more acceptable to stakeholders. The TEFF’s flexibility also keeps scientists, water managers, and stakeholders open to the prospect that ecosystems change and consequently so do the management priorities for freshwater-dependent ecosystem values (Harris and Heathwaite, 2012).

The third strength of the TEFF is that framing recommendations in a manner that recognizes catchment-specific water use activities, while clearly illustrating linkages between flow features and ecosystem values, provides a transparent means by which water planning decisions can be made. Most critically, planning processes need a reasonable understanding of potential risks to the environment and stakeholder enterprises (Schofield and Burt, 2003). The TEFF does not include a comprehensive risk assessment component. We have found that comprehensive risk assessments, incorporating both environmental and socio-economic factors, are more successfully conducted during the water management planning process, in discussion with stakeholders, and that flow linkages are a useful means of identifying and quantifying the environmental risks from increased water extraction. The scientific and wider community generally accept that flow alteration is associated with ecological change and that the risk of ecological change increases with greater flow alteration (Poff and Zimmerman, 2010). However, our understanding of the magnitude, or thresholds, of ecological change that can be expected from incremental increases in water abstraction is limited. Because of this, studies at varying scales are still required to better predict environmental flow benefits (Arthington *et al*., 2010) and deal with issues of uncertainty (Harris and Heathwaite, 2012). We are currently completing research characterizing flow–ecology relationships in Tasmanian rivers with contrasting flow regimes to better understand the risks of flow alteration (DPIPWE, 2010).

Although the implementation of environmental flow recommendations can be viewed as an hypothesis test to resolve predictive uncertainty (King *et al*., 2010), post-implementation monitoring is rarely undertaken (or rarely published) with this in mind. Monitoring often tends to be limited to simply ascertaining whether the agreed-upon flow is being delivered, along with parsimonious ecological monitoring that is inadequate to assess environmental flow benefits. The benefits of environmental flows can be difficult to assess in regulated catchments where catchment activities are likely to be contributing to ecosystem condition, for example agricultural runoff, riparian land clearing, and climate change. In unregulated catchments, where water abstraction tends to increase incrementally, the focus must be on identifying water use thresholds below which ecosystem condition degrades; that is, environmental flows must act to prevent degradation in condition rather than restore condition. Providing evidence of the benefits of environmental flows in both situations is challenging (Schofield and Burt, 2003) and highlights the need for scientists to work alongside managers and stakeholders during implementation if environmental flows are to be successful (King and Brown, 2006). For example, in the Ringarooma catchment, environmental monitoring will address the concerns of stakeholders regarding the flow thresholds defined for water access rules and also test flow–ecology hypotheses that were used by scientists and water managers to develop the recommendations.

CONCLUSION

Although there are numerous methods for reaching environmental flow recommendations, there are few examples of their implementation in the peer-reviewed literature. We have drawn on our experiences in conducting environmental flow assessments across Tasmania to examine issues regarding their implementation. We conclude that spatially explicit ecosystem values provide a transparent, and therefore more acceptable, means of framing the objectives, and that a flexible approach provides a more catchment-relevant, and therefore more achievable, set of recommendations. Furthermore, communication of the scientific knowledge and framing the recommendations so they clearly illustrate flow linkages with ecosystem values enable the final decisions, and their risks, to be more clearly understood. Like restoration science, a large amount of public money is spent on environmental flow assessments (Palmer *et al*., 2005), yet the resulting recommendations and implementation can at times be a ‘dark art’. We encourage the continued publication of environmental flow recommendations and their implementation to increase our knowledge of flow–ecology responses, provide evidence of the benefits of environmental flows, and assist practitioners to share experiences and overcome difficulties with what is typically a challenging process. We also believe that it is imperative that scientists are not only involved in water planning but also in implementation, monitoring, and evaluation so that the potential benefits that can be gained from adaptive management can be realized.

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REFERENCES

Acreman MC, Ferguson AJD. 2010. Environmental flows and the European Water Framework Directive. *Freshwater Biology* **55**: 32–48. DOI: 10.1111/j.1365-2427.2009.02181.x.

Arthington AH, King JM, O'Keefe JH, Bunn SE, Day JA, Pusey BJ, Bluhdorn DR, Tharme RE. 1992. Development of an holistic approach for assessing environmental flow requirements of riverine ecosystems. In *Proceedings of an International Seminar and Workshop on Water Allocation for the environment*. The Centre for Water Policy Research, University of New England: Armidale, New South Wales, Australia.

Arthington AH, Naiman RJ, McClain ME, Nilsson C. 2010. Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities. *Freshwater Biology* **55**: 1–16. DOI: 10.1111/j.1365-2427.2009.02340.x.

Bovee KD. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. FWS/OBS-82/26. Cooperative Instream Flow Group, US Fish and Wildlife Service, Colorado, USA.

Bradford MJ, Higgins PS, Korman J, Sneep J. 2011. Test of an environmental flow release in a British Columbia river: does more water mean more fish? *Freshwater Biology* **56**: 2119–2134. DOI: 10.1111/j.1365-2427.2011.02633.x.

Britton DL, Brock MA. 1994. Seasonal germination from wetland seed banks. *Australian Journal of Marine & Freshwater Research* **45**: 1445–1457. DOI: 10.1071/MF9941445.

Brooks AJ, Russell M, Bevitt R, Dasey M. 2011. Constraints on the recovery of invertebrate assemblages in a regulated snowmelt river during a tributary-sourced environmental flow regime. *Marine and Freshwater Research* **62**: 1407–1420.

Bunn SE, Arthington AH. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* **30**: 492–507. DOI: 10.1007/s00267-002-2737-0.

Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, Jager J, Michell RB. 2003. Knowledge for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America* **100**: 8086–8091. DOI: 10.1073/pnas.1231332100.

CFEV. 2005. Conservation of Freshwater Ecosystem Values Project Database, Version 1.0 (periodic updating). Water Resources Division, Department of Primary Industries and Water: Hobart: Tasmania, Australia. Available at: https://cfev.dpiw.tas.gov.au (February 2013).

Colwell RK. 1974. Predictability, constancy, and contingency of periodic phenomena. *Ecology* **55**: 1148–1153. DOI: 10.2307/1940366.

Davey AJH, Kelly DJ. 2007. Fish community responses to drying disturbances in an intermittent stream: a landscape perspective. *Freshwater Biology* **52**: 1719–1733. DOI: 10.1111/j.1365-2427.2007.01800.x.

DNRE. 2002. FLOWS — A Method for Determining Environmental Water Requirements in Victoria. Department of Natural Resources and Environment: Melbourne, Victoria, Australia.

DPIPWE. 2009a. Macquarie River broadwater ecosystems assessment. Water Assessment Aquatic Ecology Report Series, WA 09/03. Department of Primary Industries, Parks, Water and Environment, Hobart, Tasmania, Australia.

DPIPWE. 2009b. Status of fish communities and observations on South Esk freshwater mussel (*Velesunio moretonicus*) populations in the Macquarie River catchment upstream of Lake River. Water Assessment Aquatic Ecology Report Series, WA 09/02. Department of Primary Industries, Parks, Water and Environment, Hobart, Tasmania, Australia.

DPIPWE. 2010. Tasmanian Environmental Flows (TEFlows) project technical report. Water Assessment Aquatic Ecology Report Series, WA 09/10. Department of Primary Industries, Parks, Water and Environment, Hobart, Tasmania, Australia.

DPIPWE. 2012a. Draft Maquarie River Catchment Water Management Plan. Water and Marine Resources Division. Department of Primary Industries: Parks, Water and Environment, Hobart, Tasmania, Australia.

DPIPWE. 2012b. Draft Ringarooma River Catchment Water Management Plan. Water and Marine Resources Division. Department of Primary Industries: Parks, Water and Environment, Hobart, Tasmania, Australia.

DPIW. 2007. The Tasmanian Environmental Flows Framework — technical report. Technical Report Series WA 07/03. Department of Primary Industries and Water, Hobart, Tasmania, Australia.

DPIW. 2008a. Conservation of Freshwater Ecosystem Values (CFEV) project technical report. Conservation of Freshwater Ecosystem Values Program, Department of Primary Industries and Water, Hobart, Tasmania, Australia.

DPIW. 2008b. Environmental flows for the Ringarooma River water management plan. Technical Report Series WA 08/02. Department of Primary Industries and Water, Hobart, Tasmania, Australia.

DPIW. 2009. Environmental flow assessment for the Macquarie River catchment upstream of the Lake River. Water Assessment Aquatic Ecology Report Series, WA 09/01. Department of Primary Industries and Water, Hobart, Tasmania, Australia.

DPIWE. 2006. Study to determine water requirements for McKerrows Marsh — Great Forester River. Part 4: Hydrological analysis and water resource budget. Technical Report Series WAP 05/01 Part 4. Department Primary Industries, Water and Environment, Hobart, Tasmnia, Australia.

Esselman PC, Opperman JJ. 2010. Overcoming information limitations for the prescription of an environmental flow regime for a Central American river. *Ecology and Society* **15**: 6.

Gippel G, Anderson B, Hart C, Bond N, Sherwood J, Pope A. 2009. Gap analysis and strategy development for national level estuary environmental flows policies. Waterlines Report Series No. 17. National Water Commission, Canberra, ACT.

Gordon ND, McMahon TA, Finlayson BL, Gippel CJ, Nathan RJ. 2004. Stream Hydrology: An Introduction for Ecologists, 2nd edn. Wiley: Chichester, England.

Grayson R, Argent R, Nathan R, McMahon T, Mein R. 1996. Hydrological Recipes: Estimation Techniques in Australian Hydrology. CRC Catchment Hydrology: Melbourne, Victoria, Australia.

Greet J, Webb JA, Downes BJ. 2011. Flow variability maintains the structure and composition of in-channel riparian vegetation. *Freshwater Biology* **56**: 2514–2528. DOI: 10.1111/j.1365-2427.2011.02676.x.

Harris GP, Heathwaite AL. 2012. Why is achieving good ecological outcomes in rivers so difficult? *Freshwater Biology* **57**: 91–107. DOI: 10.1111/j.1365-2427.2011.02640.x.

Hart DD, Calhoun AJK. 2010. Rethinking the role of ecological research in the sustainable management of freshwater ecosystems. *Freshwater Biology* **55**: 258–269. DOI: 10.1111/j.1365-2427.2009.02370.x.

Humphries P. 1995. Life history, food and habitat of southern pygmy perch, *Nannoperca australis*, in the Macquarie River, Tasmania. *Marine and Freshwater Research* **46**: 1159–1169. DOI: 10.1071/MF9951159.

Humphries P, Davies PE, Mulcahy ME. 1996. Macroinvertebrate assemblages of littoral habitats in the Macquarie and Mersey Rivers, Tasmania: implications for the management of regulated rivers. *Regulated Rivers: Research & Management* **12**: 99–122. DOI: 10.1002/(SICI)1099-1646(199601)12:1 < 99::AID-RRR382 > 3.0.CO;2-1.

Jowett IG, Biggs BJF. 2006. Flow regime requirements and the biological effectiveness of habitat-based minimum flow assessments for six rivers. *International Journal of River Basin Management* **4**: 179–189. DOI: 10.1080/15715124.2006.9635287.

King J, Brown C. 2006. Environmental flows: striking the balance between development and resource protection. *Ecology and Society* **11**: 26.

King AJ, Tonkin Z, Mahoney J. 2009. Environmental flow enhances native fish spawning and recruitment in the Murray River, Australia. *River Research and Applications* **25**: 1205–1218. DOI: 10.1002/rra.1209.

King AJ, Ward KA, O'Connor P, Green D, Tonkin Z, Mahoney J. 2010. Adaptive management of an environmental watering event to enhance native fish spawning and recruitment. *Freshwater Biology* **55**: 17–31. DOI: 10.1111/j.1365-2427.2009.02178.x.

Koster WM, Dawson DR, Crook DA. 2013. Downstream spawning migration by the amphidromous Australian grayling (*Prototroctes maraena*) in a coastal river in south-eastern Australia. *Marine and Freshwater Research* **64**: 31–41. DOI: 10.1071/MF12196.

Lind PR, Robson BJ, Mitchell BD. 2007. Multiple lines of evidence for the beneficial effects of environmental flows in two lowland rivers in Victoria, Australia. *River Research and Applications* **23**: 933–946. DOI: 10.1002/rra.1016.

Loch A, Bjornlund H, McIver R. 2011. Achieving targeted environmental flows: alternative allocation and trading models under scarce supply — lessons from the Australian reform process. *Environment and Planning C: Government and Policy* **29**: 745–760. DOI: 10.1068/c10142.

Marsh NA, Stewardson MJ, Kennard MJ. 2003. River Analysis Package. Version 3.0.3. Cooperative Research Centre for Catchment Hydrology, Monash University: Melbourne, Victoria, Australia.

McQuillan PB, Watson JEM, Fitzgerald NB, Leaman D, Obendorf D. 2009. The importance of ecological processes for terrestrial biodiversity conservation in Tasmania — a review. *Pacific Conservation Biology* **15**: 171–196.

Naiman RJ, Latterell JJ, Pettit NE, Olden JD. 2008. Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geoscience* **340**: 629–643. DOI: 10.1016/j.crte.2008.01.002.

Nel JL, Turak E, Linke S, Brown C. 2011. Integration of environmental flow assessment and freshwater conservation planning: a new era in catchment management. *Marine and Freshwater Research* **62**: 290–299. DOI:10.1071/MF09318.

Nui SQ, Dudgeon D. 2011. Environmental flow allocations in monsoonal Hong Kong. *Freshwater Biology* **56**: 1209–1230.

Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, Galat DL, Loss SG, Goodwin P, Hart DD, Hassett B, Jenkinson R, Kondolf GM, Lave R, Meyer JL, O'Donnell TK, Pagano L, Sudduth E. 2005. Standards for ecologically successful river restoration. *Journal of Applied Ecology* **42**: 208–217. DOI: 10.1111/j.1365-2664.2005.01004.x.

Palmer MA, Liermann CAR, Nilsson C, Flörke M, Alcamo J, Lake PS, Bond N. 2008. Climate change and the world's river basins: anticipating management options. *Frontiers in Ecology and the Environment* **6**: 81–89. DOI: 10.1890/060148.

Peake P, Fitzsimons J, Frood D, Mitchell M, Withers N, White M, Webster R. 2011. A new approach to determining environmental flow requirements: sustaining the natural values of floodplains of the southern Murray-Darling Basin. *Ecological Management & Restoration* **12**: 128–137. DOI: 10.1111/j.1442-8903.2011.00581.x.

Poff NL, Zimmerman JH. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology* **55**: 194–205. DOI: 10.1111/j.1365-2427.2009.02272.x.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: a paradigm for river conservation and restoration. *BioScience* **47**: 769–784. DOI: 10.2307/1313099.

Poff NL, Richter B, Arthington AH, Bunn SE, Naiman RJ, Kendy E, Acreman M, Apse C, Bledsoe BP, Freeman MC, Henriksen J, Jacobson RB, Kennen JG, Merritt DM, O'Keeffe JH, Olden JD, Rogers K, Tharme RE, Warner A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* **55**: 147–170. DOI: 10.1111/j.1365-2427.2009.02204.x.

Sanderson JS, Rowan N, Wilding T, Bledsoe BP, Miller WJ, Poff NL. 2012. Getting to scale with environmental flow assessment: the watershed flow evaluation tool. *River Research and Applications* **28**: 1369–1377. DOI: 10.1002/rra.1542.

Schofield N, Burt A. 2003. Issues in environmental water allocation — an Australian perspective. *Water Science and Technology* **48**: 83–88.

Sloane RD. 1984. Upstream migration by young pigmented freshwater eels (*Anguilla australis australis* Richardson) in Tasmania. *Australian Journal of Marine & Freshwater Research* **35**: 61–73. DOI: 10.1071/MF9840061.

Souchon Y, Sabaton C, Deibel R, Reiser D, Kershner J, Gard M, Katopodis C, Leonard P, Poff NL, Miller WJ, Lamb BL. 2008. Detecting biological responses to flow management: missed opportunities; future directions. *River Research and Applications* **24**: 506–518. DOI: 10.1002/rra.1134.

Stewardson MJ, Cottingham P. 2002. A demonstration of the flow events method: environmental flow requirements of the Broken River. *Australian Journal of Water Resources* **5**: 33–47.

Strayer DL, Dudgeon D. 2010. Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society* **29**: 344–358. DOI: 10.1899/08-171.1.

Tharme RE. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* **19**: 397–441. DOI: 10.1002/rra.736.

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Liermann CR, Davies PM. 2010. Global threats to human water security and river biodiversity. *Nature* **467**: 555–561. DOI: 10.1038/nature09440.

Ward JV, Tockner K, Arscott DB, Claret C. 2002. Riverine landscape diversity. *Freshwater Biology* **47**: 517–539. DOI: 10.1046/j.1365-2427.2002.00893.x.

Warfe DM, Barmuta LA. 2006. Habitat structural complexity mediates food web dynamics in a freshwater macrophyte community. *Oecologia* **150**: 141–154. DOI: 10.1007/s00442-006-0505-1.

Warwick NWM, Brock MA. 2003. Plant reproduction in temporary wetlands: the effects of seasonal timing, depth, and duration of flooding. *Aquatic Botany* **77**: 153–167.

Winter TC. 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeology Journal* **7**: 28–45. DOI: 10.1007/s100400050178.

APPENDIX A

Summary of significant flora and fauna that contribute to the high conservation value of rivers and wetlands in the Ringarooma River and Macquarie River catchments. Values were derived from the Conservation of Freshwater Ecosystem Values database (CFEV, 2005) and confirmed by field surveys

	Flora	Fauna
Ringarooma River catchment		
Upland rivers	● Branching rush (*Juncus prismatocarpus*)[b] ● Shrubby gum (*Eucalyptus ovata*) forest ● Riparian vegetation community that includes wet *Eucalyptus* species, Australian blackwood (*Acacia melanoxylon*), and southern beech (*Nothofagus cunninghamii*)	● Hydrobiid snail species (*Beddomeia* complex)[a,b] ● Giant freshwater crayfish (*Astacopsis gouldi*)[a,b] ● Fish assemblage that includes short-finned eel (*Anguilla australis*), long-finned eel (*Anguilla reinhardtii*), spotted galaxias (*Galaxias truttaceus*), pouched lamprey (*Geotria australis*), short-headed lamprey (*Mordacia mordax*), river blackfish (*Gadopsis marmoratus*), and sandy (*Pseudaphritus urvillii*) ● Platypus (*Ornithorynchus anatinus*)
Lowland rivers and floodplain wetlands	● Purple loosestrife (*Lythrum salicaria*)[b] ● Ribbon weed (*Vallisneria australis*)[b] ● Bristly knotweed (*Persicaria subsessilis*)[b] ● Native gipsywort (*Lycopus australis*)[b] ● Erect marshflower (*Villarsia exaltata*)[b] ● Coastal paperbark (*Melaleuca ericafolia*) forest community ● Scented paperbark scrub (*Melaleuca squarrosa*) ● Marginal herbland/grassland community	● Green and gold frog (*Litoria raniformis*)[b] ● Dwarf galaxias (*Galaxiella pusilla*)[b] ● Fish assemblage that includes southern pygmy perch (*Nannoperca australis*), short-finned eel (*Anguilla australis*), long-finned eel (*Anguilla reinhardtii*), spotted galaxias (*Galaxias truttaceus*), common galaxias (*Galaxias maculatus*), pouched lamprey (*Geotria australis*), short-headed lamprey (*Mordacia mordax*), river blackfish (*Gadopsis marmoratus*), Australian grayling (*Prototroctes maraena*), sandy (*Pseudaphritus urvillii*), Tasmanian smelt (*Retropinna tasmanica*), Australian mudfish (*Neochanna cleaveri*), and dwarf galaxias (*Galaxiella pusilla*)[b] ● Platypus (*Ornithorhynchus anatinus*) ● Bowlers Lagoon (fauna species-rich location)
Macquarie River catchment		
Upper Macquarie	● Tasmania bertya (*Bertya tasmanica* subsp. *tasmanica*)[a,b] ● Tunbridge buttercup (*Ranunculus prasinus*)[a,b] ● Mud dock (*Rumex bidens*)[b]	● Green and gold frog (*Litoria raniformis*)[b] ● Swan galaxias (*Galaxias fontanus*)[a,b] ● Platypus (*Ornithorhynchus anatinus*) ● South Esk freshwater mussel (*Velesunio moretonicus*)[a]
Tributaries	● Tunbridge buttercup (*Ranunculus prasinus*)[a,b] ● Curly sedge (*Carex tasmanica*)[b] ● Swamp wallaby grass (*Amphibromus neesii*)[b] ● *Melaleuca ericifolia* swamp forest community ● Hill hovea (*Hovea tasmanica*)[a,b] ● Clasping-leaf heath (*Epacris acuminata*)[a,b] ● Ellinthorpe Plains lagoon complex	● Phreatoicid isopod (*Paraphreatoicus relictus*)[a] ● Salt lake slater (*Haloniscus searlei*)[b] ● Caddis fly (*Oxyethira mienica*)[b] ● South Esk freshwater mussel (*Velesunio moretonicus*)[a] ● Platypus (*Ornithorhynchus anatinus*) ● Green and gold frog (*Litoria raniformis*)[b] ● Southern toadlet (*Pseudophryne semimarmarata*)
Lower Macquarie	● Midlands wattle (*Acacia axillaris*)[a,b] ● Clasping-leaf heath (*Epacris acuminata*)[a,b] ● Plain quillwort (*Isoetes drummondii* subsp. *drummondii*)[b] ● Slender twig rush (*Baumea gunnii*)[b] ● *Melaleuca ericifolia* swamp forest community ● Lowland *Poa* grassland ● Species-rich aquatic macrophyte assemblage	● Swan galaxias (*Galaxias fontanus*)[a,b] ● Platypus (*Ornithorhynchus anatinus*) ● South Esk freshwater mussel (*Velesunio moretonicus*)[a] ● Fish assemblage which includes southern pygmy perch (*Nannoperca australis*), short-finned eel (*Anguilla australis*), river blackfish (*Gadopsis marmoratus*), and Swan galaxias (*Galaxias fontanus*)[b] ● Caddis fly (*Ecnomina vega*)[b]

[a] Endemic to Tasmania and/or unique taxa or community.
[b] Listed under Tasmanian or Commonwealth threatened species legislation.