



Research

“We Like to Listen to Stories about Fish”: Integrating Indigenous Ecological and Scientific Knowledge to Inform Environmental Flow Assessments

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ABSTRACT. Studies that apply indigenous ecological knowledge to contemporary resource management problems are increasing globally; however, few of these studies have contributed to environmental water management. We interviewed three indigenous landowning groups in a tropical Australian catchment subject to increasing water resource development pressure and trialed tools to integrate indigenous and scientific knowledge of the biology and ecology of freshwater fish to assess their water requirements. The differences, similarities, and complementarities between the knowledge of fish held by indigenous people and scientists are discussed in the context of the changing socioeconomic circumstances experienced by indigenous communities of north Australia. In addition to eliciting indigenous knowledge that confirmed field fish survey results, the approach generated knowledge that was new to both science and indigenous participants, respectively. Indigenous knowledge influenced (1) the conceptual models developed by scientists to understand the flow ecology and (2) the structure of risk assessment tools designed to understand the vulnerability of particular fish to low-flow scenarios.

Key Words: *Daly River; environmental flow; fish ecology; indigenous ecological knowledge; indigenous fish knowledge; integration*

INTRODUCTION

Brad (scientist): Bill, why are the white tail (strawman or black mask) in the same family?

Bill (indigenous elder): Well they got a relation there, cousins, auntie and uncles.

Brad: From the dreamtime?

Bill: Yeah, from the dreamtime; they're all family. (S. E. Jackson's field notes, Flora River, 15 July 2006)

Studies that apply indigenous ecological knowledge (IEK) to contemporary resource management problems are increasing in number globally (Silvano and Begossi 2002, Silvano et al. 2008, Stephenson and Moller 2009, Bohensky and Maru 2011). As a source of fine-grained, detailed information about local ecosystem patterns and process, indigenous knowledge can be valuable for natural resource assessments, especially in those areas where extant systems of customary resource management prevail and scientific knowledge (SK) is poor or nonexistent (Fabricius et al. 2006). We adopt Berke's (2004) definition of IEK as an accumulative body of knowledge, practice, and belief about the relationships that living things, including people, have with each other that is handed down through generations by cultural transmission.

The tacit, practical knowledge gained from centuries of daily resource use is often of most interest to ecologists and resource managers (Butler 2006). Esselman and Opperman (2010), for example, surveyed the fish biology literature and concluded that indigenous fishermen have the ability to recognize taxa, behavioral traits, and spatiotemporal changes in fish assemblage composition across seasons and, in addition, can accurately

attribute causation to complex limnological occurrences. In understudied regions, some of this tacit knowledge is likely to be new to science (e.g., Morgan et al. 2002, Foale 2006, Silvano et al. 2008).

The ability to integrate IEK with SK remains a challenge (Bohensky and Maru 2011, Hill et al. 2012), not least because of the very different cognitive contexts in which indigenous people and researchers make their observations. In addition to stimulating considerable academic debate (Agrawal 1995, Wilson 2003, Butler 2006), the methodological and epistemological differences based on worldviews and approaches to investigating reality have resulted in many integration projects falling well short of both indigenous and nonindigenous expectations (Nadasdy 2005). Differences between knowledge systems do not necessarily impede integration efforts, however (Bohensky and Maru 2011). Hviding (2006:71) sees great value in partnerships that seek an understanding of similarities, differences, and complementarities between knowledge systems, arguing that "where there is contrasting knowledge, there is also potential for dialogue and convergence."

We take up Hviding's challenge to develop research partnerships across cultures by examining the similarities and differences in IEK and SK relating to the ecology of fish in a tropical catchment and consider the value of combining these knowledge sources to improve water planning and management. Fish are of significant cultural and economic value to the indigenous household economy in remote regions of northern Australia (Altman 1987, Jackson et al. 2012, Stoeckl et al. 2013), and subsistence strategies rely on ecological knowledge of seasonal fish distribution and movement (Raymond et al. 1999, Liddy et al. 2006, Woodward et al. 2012). Fish research, or "listening to stories and talking about

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fish” in the words of indigenous study participants, is an activity for which there is undoubtedly an “everyday enthusiasm” (Hviding 2006:82).

The management context for this inquiry is the determination of environmental water requirements of fish. Increasing development pressures in northern Australia have added a sense of urgency to synthesizing existing fish knowledge (Douglas et al. 2011). The ecological impacts of anthropogenic changes in river flows are currently poorly understood by the scientific community, and data available for developing environmental flow recommendations for fish are scarce or completely lacking for most tropical Australian rivers (Pusey et al. 2011). Regions like northern Australia may nonetheless have a well-developed knowledge base resident in the indigenous population (Finn and Jackson 2011). Indigenous knowledge, which can be geographically and temporally more extensive than SK (Fraser et al. 2006), may be of value for its relative empirical strength.

We therefore trialled an integrated approach to environmental flow assessment (Chan et al. 2012) that drew on indigenous knowledge as a complementary source of knowledge. Our aims were to (1) compare and contrast the scientific and indigenous knowledge of fish and flow ecology; (2) consider the benefits of integrating these knowledge sources for environmental flow assessment; and (3) outline the ethical, cultural, and logistical challenges of designing and conducting cross-cultural ecological research.

METHODS

Study area

Ecological and socioeconomic characteristics

The Daly River catchment lies in the Australian northwestern wet/dry tropics agroecological region (Fig. 1) where the natural vegetation cover ranges from eucalypt forest to low open grassland. The catchment is sparsely populated (10,000 people; Carson et al. 2009). At least 10 indigenous language groups comprise approximately a quarter of the total population and own approximately 27% of the land (Jackson 2006). The river and its catchment are in relatively good environmental condition compared to other major rivers in Australia (Chan et al. 2012). Cattle grazing is the dominant land use alongside conservation, although dryland and irrigated cropping are of increasing importance in the middle reaches of the Daly River and its major upstream tributary, the Katherine River. Small areas of the catchment are devoted to more intensive land uses such as urbanization, pasture, and agriculture.

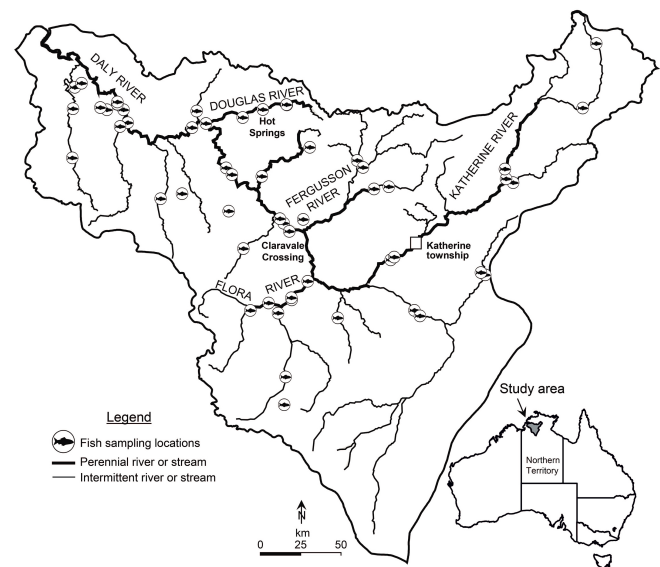
Water resource management

The Daly River has the fourth largest discharge of Australia’s tropical rivers (CSIRO 2009), and its aquifers provide relatively reliable year-round flows. Reliable groundwater reserves and relatively good soils mean that of all the Northern Territory’s (NT) regions it is most likely to be further developed for agriculture. Existing agricultural and mining industries already place pressure on the catchment’s water resources (Begg et al. 2001).

Previous environmental flow studies examined the requirements of aquatic and riparian plants, algae, and the pig-nosed turtle (*Carettochelys insculpta*; Erskine et al. 2003). However, the river

also supports more than 50 species of freshwater and estuarine fish and elasmobranchs, including some endangered and vulnerable species (Pusey et al. 2011), but fundamental knowledge of the ecology of these species, such as their distribution, habitat preferences, and breeding phenology, is lacking, and consequently, little is known about their environmental water requirements.

Fig. 1. The Daly River catchment, northern Australia, showing the fish sampling sites and locations mentioned in the text.



Indigenous land and water management

Changes in land use and settlement patterns caused by colonial and postcolonial policies have consolidated indigenous populations across north Australia, significantly disrupting subsistence strategies with consequences for health, well-being, and economic and cultural life (Keen 2003). Loss of ecological knowledge is a further consequence of the massive disruption that indigenous societies have experienced over the past 150 years.

Indigenous collective formations with traditional connections to land and water within the Daly River catchment include the Jawoyn, Wardaman, and Wagiman language groups, although there are others (see Jackson 2006). Social solidarity amongst indigenous groups is supported by common descent from shared ancestors, a sense of common traditions, and a mostly shared lifestyle nearby or on customary estates (Jackson 2006, Jackson et al. 2011). Each language-owning group has asserted its customary rights to identifiable territory under Commonwealth land rights legislation, i.e., Aboriginal Land Rights (Northern Territory Act) 1976, and, from the early 1980s, was awarded grants of freehold title to significant portions of land. Having demonstrated to the satisfaction of the Australian courts that they each share a body of knowledge about the area, claimants must also show that they are entitled to forage over the claim area, as evident in their extensive knowledge of edible food including fish, bush medicines, and natural resources.

Concern about the rapidly attenuating local knowledge base has motivated these groups to partner with scientists and undertake activities to conserve their knowledge. For instance, Wagiman (Liddy et al. 2006), Jawoyn (Wijnjorrotj et al. 2005), and Wardaman (Raymond et al. 1999) elders have published their detailed, extensive plant and animal knowledge in collaboration with linguists and scientists.

Study design

The project was primarily focused on assembling information on the ecological requirements of freshwater fish to assist decision makers to assess the risk of flow alteration scenarios for the Daly River (see Pusey and Kennard 2009, Chan et al. 2012, Stoeckl et al. 2013). We applied a multistep process that included hydrological analysis and modeling, the collection of scientific and indigenous knowledge during field trips, literature reviews, expert consultation, and environmental flow workshops for scientists, water managers, and community members.

Scientific knowledge collection

We distinguished three sources of SK about the freshwater fish: (1) new data collected by the project team during field sampling, (2) information available from past studies in the Daly River, and (3) information from other catchments in tropical northern Australia. New data collected by the project team during field sampling involved quantitative sampling of fish communities at multiple sites throughout the catchment during the early and late dry season from 2006 (see Stewart-Koster et al. 2011 and Chan et al. 2012 for a detailed description of sampling methods). This yielded information on the distribution, abundance, habitat use, diet, and influence of flow on fish communities (reported in Davis et al. 2010, 2011, 2012a, b, c, Cook et al. 2011, Chan et al. 2012, Hermoso and Kennard 2012, Linke et al. 2012, Pettit et al. 2013). Information available from past studies in the Daly River included distribution records, i.e., Museum and Art Gallery of the Northern Territory; small-scale, one-off surveys of fish distribution and abundance (Midgley 1980, Wilson and Brooks 2004); and a study of seasonal fish movements in a single tributary (D. Warfe, Charles Darwin University, *unpublished data*). Information collected from other northern Australian catchments on the habitat use, diet, and life history of some species was also sourced from Merrick and Schmida (1984), Larson and Martin (1990), Bishop et al. (2001), and Pusey et al. (2004).

Research partnerships with indigenous landowners

The project secured the consent and involvement of the three indigenous language groups, i.e., Wagiman, Wardaman, and Jawoyn, from the middle and upper sections of the Daly River during preliminary meetings in 2005. Indigenous groups were invited to join as study partners in recognition of their twin roles as custodians with local knowledge of their customary estates and as statutory landowners. Both roles generate rights and responsibilities with respect to natural resource management. Indigenous groups had a number of motivations for participating. First, a formal partnership would provide indigenous oversight of the research activity, ensuring that indigenous protocols were followed, and, in doing so, safeguard the well-being of research parties visiting indigenous lands and waters. Second, a research partnership could provide opportunities such as field-sampling activities to build the capacity of landowning groups to make well-informed decisions about water use and wider catchment

management practices. Third, it was hoped that a partnership would stem the rapid attenuation of indigenous knowledge in the region, primarily by restoring connections to customary estates. The project's heavy emphasis on field-based survey techniques would generate opportunities to visit the country; carry out management activities, such as activating dreaming and ancestral spirits; and exchange and transfer knowledge within indigenous groups, particularly, it was hoped, across generations (Smyth 2012).

The terms of the research partnership were negotiated under research agreements that established protocols for research and communication activities, promoted the sharing of benefits, and ensured protection of indigenous intellectual property. Approval for our research was granted by the human ethics committee at Charles Darwin University. From 2005, indigenous participants frequently contributed their time and knowledge to fish-sampling activities at a number of sites. Two Wagiman representatives, i.e., Mona Liddy and Lizzie Sullivan, and one Wardaman representative, i.e., Bill Harney, were members of the project's Steering Committee.

At a Wagiman Association meeting in 2011, researchers proposed the development of a scientific paper on the results of the project's indigenous knowledge component. A small writing group was then formed from amongst the Wagiman to progress the paper that was written iteratively over an extended period of face-to-face meetings. The authorship list is composed of a wider group of indigenous experts who contributed their knowledge.

Indigenous ecological knowledge collection

We used both semistructured group interviews and unstructured one-to-one interviews with indigenous participants to record their knowledge of freshwater fishes. The former was the primary method of data collection for ecological knowledge of fish species, and other information relating to language name and customary use was also recorded. Interviews were conducted at fish-sampling sites at the time of sampling to assist in identification and discussion. Fish collected during sampling were retained alive in aquaria for the duration of interviews to provide reference and were later returned alive to the point of capture.

A common series of 12 questions was put to 2 language groups at Flora River, where 7 Wardaman participated; Claravale Crossing, where 18 Wagiman participated; and Tjuwaliyn Hot Springs, where 7 Wagiman participated (see Fig. 1). At the request of the participants, interviews were conducted with each group rather than individuals, although 3 interviews were held with 2 particularly knowledgeable elders and video recorded. Questions covered a range of topics relating to aspects of fish ecology that could be impacted by altered dry-season flows, i.e., distribution and abundance, habitat preference, trophic ecology, and reproduction (see Table 1). To avoid confusion over species identifications, the systematic surveys were done only for the 15 fish species that were collected during the field research with indigenous participants and for 3 elasmobranchs that were large and easily identifiable. Field notes were taken to supplement points raised during completion of the survey sheet and to record knowledge of fish species not caught on the day of the interview.

A number of steps were taken to ensure that the information recorded was valid and accurate. First, indigenous experts were

Table 1. Similarities and differences between indigenous ecological knowledge (IEK) and scientific knowledge (SK) related to environmental flow assessments for 15 fish species from the Daly River, Northern Territory. Categories are: Congruent (=) when IEK and documented SK from either the Daly or another river system were consistent or when IEK added new knowledge that complemented or extended existing SK for the Daly River; Incongruent (≠) when IEK and documented SK are inconsistent; No knowledge (0) when there was documented SK but no IEK. The two cases for which there was no SK or IEK are shown in bold type.

Interview question	Data for environmental flow assessment	Fish species†														
		NG	BG	MAGO	BB	ST	SP	T	NC	HT	SC	GI	RC	SA	FL	
What time of year do you see them?	Seasonal variation in abundance	0	=	0	0	=	0	=	0	0	=	=	0	0	=	0
Do you see more in big floods or dry years?	Interannual variation in abundance	0	=	=	=	=	=	=	=	=	=	=	0	0	=	=
What eats it?	Predation	0	=	=	=	0	0	=	=	=	0	=	0	=	0	=
Where in the river system is it caught/found?	Distribution in river system	0	0	=	≠	=	=	=	0	=	=	=	0	=	=	=
What sorts of places are young ones caught/found?	Juvenile habitat use	=	=	=	≠	=	=	≠	0	0	=	0	=	=	0	=
What sorts of places are adults caught/found?	Adult habitat use	=	=	=	≠	=	=	≠	=	=	=	=	=	=	≠	=
Does it move to other parts of river?	Movement patterns	0	=	=	=	=	=	=	=	=	=	=	0	=	=	=
Where does it breed?	Spawning habitat	0	0	0	0	≠	≠	=	≠	=	=	=	0	0	0	=
Where does it breed?	Spawning substrate	0	0	0	0	≠	≠	0	0	0	0	=	0	0	0	0
When does it breed?	Spawning season	0	0	0	≠	=	0	=	0	≠	0	=	0	=	0	=
What does it eat?	Feeding requirement	0	=	=	=	=	=	=	=	=	=	=	0	≠	=	=
Does fish health change, e.g., fat during wet season, more disease during late dry?	Fish condition	0	0	0	0	=	=	=	0	=	0	=	0	=	=	=

†Species codes: NG = Northwest glassfish, *Ambassis sp. (cf muelleri)*; BG = Barred grunter, *Amniataba percoides*; MA = Mouth almighty, *Glossamia aprion*; GO = Golden goby, *Glossogobius aureus*; BB = Black bream, *Hephaestus fuliginosus*; ST = Freshwater stingray, *Hymantura dalyensis*; SP = Spangled perch, *Leiopotherapon unicolor*; T = Tarpon, *Megalops cyprinoides*; NC = Narrow-fronted catfish, *Neosilurus ater*; HT = Hyrtl's catfish, *Neosilurus hyrtlii*; SC = Sleepy cod, *Oxyeleotris lineolatus*; GU = Giant gudgeon, *Oxyeleotris selheimi*; RC = Rendahl's catfish, *Porochilus rendahli*; SA = Freshwater sawfish, *Pristis pristis*; FL = Freshwater longtom, *Strongylura krefftii*

initially nominated by the regional indigenous organization responsible for land management on indigenous lands. Following extensive community consultation over two years, the research team was confident that the most knowledgeable people were involved through a process of peer selection endorsed by Huntington (2000); some had demonstrated their knowledge in legal proceedings and sacred site registration processes. Second, indigenous language names were sought for those fish caught during interviews. Attribution of customary names to individual species confirmed that pertinent knowledge was directly relatable to that species. Third, on the occasion that a question yielded an uncertain response, the issue was revisited and clarified on a subsequent sampling trip or at a community meeting through a process of group review (Huntington 2000). A linguist specializing in languages from this region was contacted for confirmation of fish names.

Comparison of scientific knowledge and indigenous ecological knowledge

The SK and IEK for each question were compared and classified according to three categories: “congruent,” where IEK and documented SK from either the Daly or another river system were consistent or where IEK added new knowledge that complemented or extended existing SK for the Daly River; “incongruent,” where IEK and documented SK were inconsistent; and “no knowledge,” where there was no IEK.

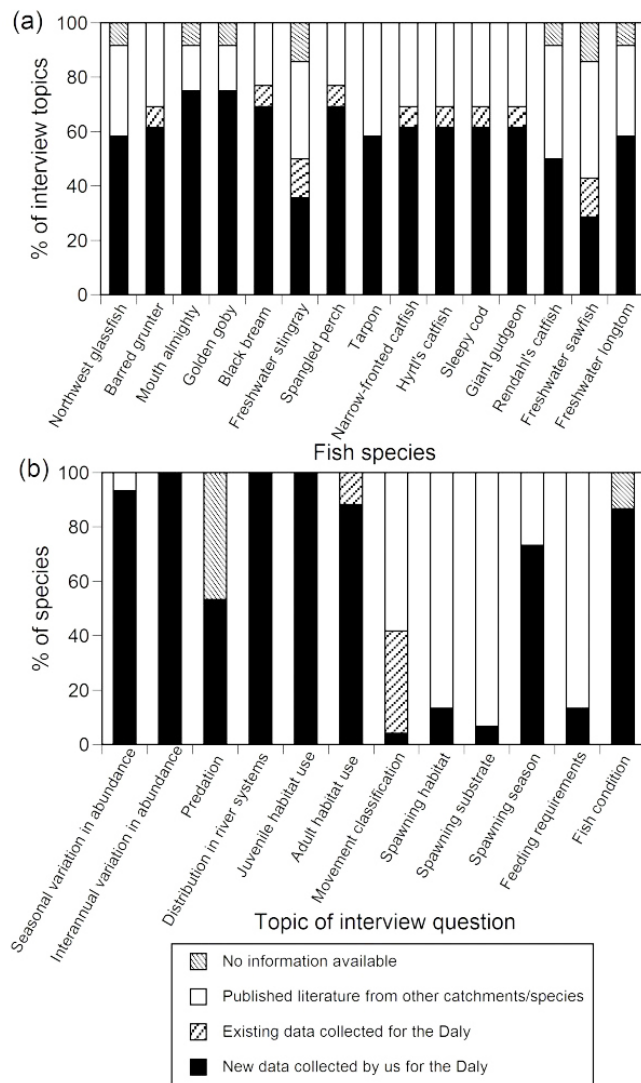
RESULTS

Sources of scientific knowledge of freshwater fish in the Daly River

Fish sampling undertaken as part of this project provided on average 59% of the SK for the 15 fish species, with relatively little information collected for freshwater sawfish (*Pristis pristis*) and freshwater stingray (*Hymantura dalyensis*), which were rarely sampled (Fig. 2a). Information from other river systems provided 31% of SK, whereas previous studies in the Daly River provided only 5% of SK and covered only 9 species (Fig. 2a). There was no SK available for 5% of responses, and this was from just 2 questions, i.e., predation (50% of species) and fish condition (< 20% of species; Fig. 2b).

The fish sampling conducted for this project provided the majority of the SK for 8 of the 12 questions related to environmental flow assessments (Fig. 2b), including 75-100% of SK on seasonal and interannual variation in fish abundance, distribution, habitat use, fish condition, and spawning season (Fig. 2b). Data collected from other river systems contributed 50-95% of the information for 4 questions related to spawning habitat, movement biology, and feeding requirements, and less than 30% for questions on seasonal patterns of abundance and spawning (Fig. 2b). Previous scientific research in the Daly only contributed to 2 questions, accounting for about 30% of the information on movement and less than 15% for adult habitat use. There was no SK on predation for half of the species or for fish condition for 15% of species.

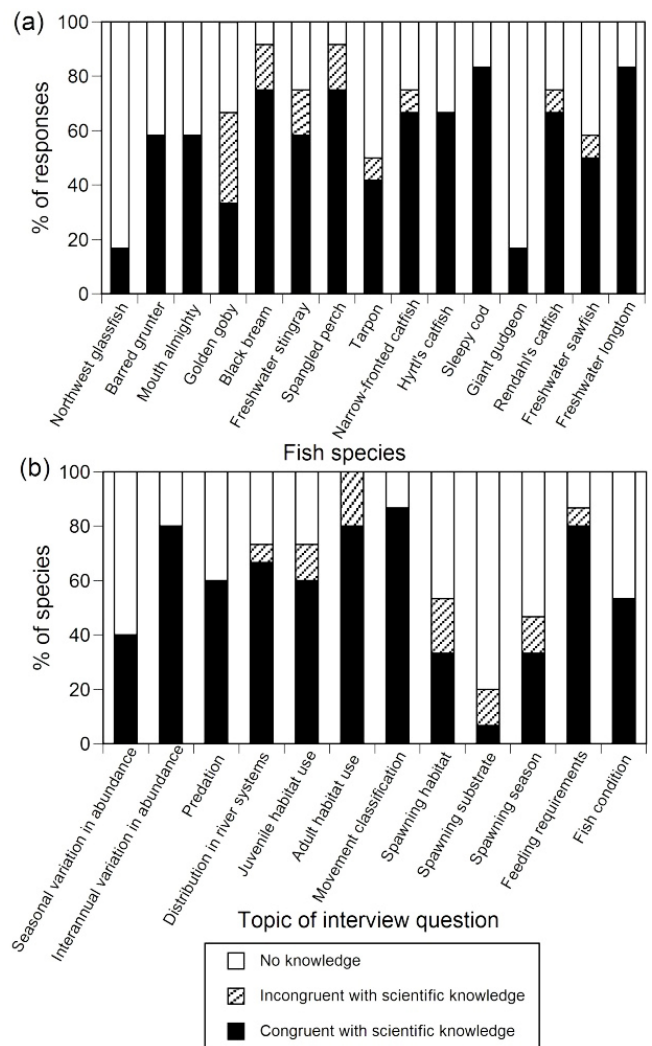
Fig. 2. Summary of scientific knowledge sources by (a) fish species and (b) topic of interview questions relevant to environmental flow assessments of fish in the Daly River. Scientific knowledge sources were categorized as no information, published literature from other catchments or closely related species, existing data collected for the Daly River, and new data collected during this study. Information is summarized for (a) each fish species (% of responses to each of the 12 interview topics) and (b) each interview topic (% of responses for each of the 15 species).



Indigenous ecological knowledge of freshwater fish in the Daly River

Systematic interviews with indigenous participants yielded 180 responses to the 12 questions, i.e., 15 species by 12 questions. Respondents had most knowledge of the fish species that were routinely caught and eaten or were easily observed, such as black bream (*Hephaestus fuliginosus*), barred grunter (*Amniataba*

Fig. 3. Summary of indigenous ecological knowledge by (a) fish species and (b) topic of interview questions relevant to environmental flow assessments of fish in the Daly River. Categories are as follows: congruent where indigenous ecological knowledge and documented scientific knowledge from either the Daly or another river system were consistent or where indigenous ecological knowledge added new knowledge that complemented or extended existing scientific knowledge for the Daly River; incongruent where indigenous ecological knowledge and documented scientific knowledge were inconsistent; and no knowledge where there was no indigenous ecological knowledge. Information is summarized for (a) each fish species (% of responses to each of the 12 interview topics) and (b) each interview topic (% of responses for each species).



percoidea), and sleepy cod (*Oxyeleotris lineolatus*; Table 1, Fig. 3a). No information was reported for about one-third (36%) of the questions, occurring most frequently in response to questions about spawning, i.e., substrate, season, and habitat; seasonal variation in abundance; and fish condition (Table 1, Fig. 3b). IEK

was congruent or extended/complemented existing SK for more than half the responses (57%; Table 1, Fig. 3b). This included knowledge of feeding requirements for 12 of the 15 species and of the predators for more than half of the species, particularly the smaller bodied fish, and habitat use for 9 of the 15 species.

Indigenous respondents frequently identified the role of predation as an important influence on the ecology of fish in the Daly River. For example, many species such as the plotosid catfishes, gudgeons (Eleotridae), tarpon (*Megalops cyprinoides*), and grunters (Terapontidae) were reported as being consumed by barramundi (*Lates calcarifer*); cannibalism was also reported to occur frequently. Predation was suggested to be important in determining the small-scale habitat use of some species, i.e., use of undercut banks as a refuge from predation. For example, the mouth almighty (*Glossamia aprion*), i.e., *Gamarl* in Wagiman language, was said to always be associated with cover, otherwise “He’d be dead ... barra would eat ‘im” (S. E. Jackson’s field notes, Claravale Crossing, 27 August 2006). Similarly, the cryptic coloration of the golden goby (*Glossogobius aureus*) was said to be important in reducing predation.

The high frequency of congruent responses likely represents a shared understanding by ecologists and indigenous fishers of what habitats fish are most likely to occur in and what they eat, the most important information for capturing fish. The case of black bream, which is a highly popular fish to eat, further illustrates this point (Jackson et al. 2012). Black bream was found to be the species ranked highest in terms of confirmed knowledge. The biology of this species is relatively well understood by science and favored as a food by indigenous participants over all others. It is also probable that the congruence of knowledge in these areas reflects the fact that some aspects of the biology of these species varies little over their geographic ranges (Pusey et al. 2004).

IEK that extended/complemented SK was most frequently reported for seasonal and interannual variation in abundance (13 species), fish condition (6 species), and movement pattern (7 species). Movement by fishes throughout the year was also heavily emphasized in conversations, and floods were seen as important in stimulating migration upstream into tributaries or into floodplain wetlands. Changes in fish condition at different times of the year were also stressed. Black bream were said to be fattest during the wet season (see also Pusey et al. 2004 for black bream in Magela Creek). Plotosid catfishes (*Libiyan/Barrhbarrin*) were fattest at the end of the wet season, whereas sawfish (*Jalamariny*) were fattest in the dry season. Sleepy cod (*Gubulu*) became sick with external sores during the dry season, especially in billabongs. IEK also provided additional information on the distribution and habitat use of several rare species, including freshwater stingray and freshwater sawfish, as well as habitat use for common species like the sleepy cod and Hyrtl’s catfish (*Neosilurus hyrtlui*; Table 1).

IEK and SK were incongruent for only 8% of responses, and these instances were mostly restricted to questions about habitat use and spawning requirements (Table 1, Fig. 3b). Of the 15 fish species that were the subject of interviews, only 2 species, black bream and golden goby, were caught in the presence of both Wagiman groups. The responses to questions about these 2 species revealed differences between groups in their level of knowledge of the goby and some inconsistencies in knowledge of spawning season, distribution, and fish condition for black bream.

In addition to the structured surveys, discussions with Wagiman and Wardaman participants about the 28 fish species that researchers collected on field trips in their absence yielded new knowledge on the large-scale distribution in the river system, for example, upper, middle, or lower reaches, for 5 species, i.e., bull shark (*Carcharhinus leucas*), fork-tailed catfish (*Neoarius graeffei*), snub-nosed garfish (*Arrhamphus sclerolepis*), black-banded rainbowfish (*Melanotaenia nigrans*), and false-spined catfish (*Neosilurus pseudospinosus*), and congruent information for 5 other species, i.e., fly-specked hardyhead (*Craterocephalus stercusmuscarum*), Ord River mullet (*Liza ordensis*), northern trout gudgeon (*Mogurnda mogurnda*), primitive archerfish (*Toxotes lorentzi*), and seven-spot archerfish (*Toxotes chatareus*). It also yielded congruent information on the spawning preferences of the lesser salmon catfish (*Neoarius leptaspis*).

DISCUSSION

Characteristics and limitations of the knowledge sources for environmental flow assessment of fish in the Daly River

The different knowledge sources used in this project have different strengths and limitations when applied to environmental flow assessments (Table 2). Before this research, there was little SK to support environmental flow assessments for fish in the Daly River. Although there was relevant SK from other river systems, most of these systems have profoundly different flow regimes from that of the Daly River, so the valid transfer of this information is uncertain. The two-year program of fish sampling was specifically designed to gather scientific data to support environmental flow assessments. It was undertaken throughout the catchment, but some sites were only visited once, and all sampling was done during the dry season. This provided the majority of SK relating to topics such as habitat use, distribution, and changes in abundance but provided no information on topics such as feeding requirements or where fish spawn; SK on these topics came primarily from other river systems.

IEK in the Daly has accrued over generations for the purpose of hunting fish for food, and it too has limitations. Some inconspicuous species were less familiar to indigenous participants, and this provided an opportunity to produce “new” knowledge and learn from research collaborations, as the case of the freshwater sole (*Leptachirus triramus*) shows. This species is small and exceedingly cryptic and was not known to Wagiman participants prior to the electrofishing fieldwork when it was located buried in the sandy river bed. Its “discovery” highlights the dynamic quality of local environmental knowledge, which is undergoing constant modification as circumstances change.

The small scale of indigenous territories or customary estates can also limit IEK (Rose 1996), and this may be particularly evident with respect to migratory species (Kennett et al. 2004). For example, in an unstructured interview, a very knowledgeable Wardaman elder reported that barramundi spawn in the upper reaches of the catchment. It is most likely that this inaccurate observation is explained by the fact that Wardaman country is very distant from the river mouth where Western science has shown conclusively that spawning of the migratory barramundi occurs (Pusey et al. 2004). Differences in observational opportunities of this kind led to Felt’s (1994) description of indigenous knowledge as partial, instrumental knowledge, which,

Table 2. Characteristics of knowledge sources used in the project and an assessment of their suitability and potential limitations for environmental flow assessment of fish in the Daly River.

Source of knowledge	Characteristics of data collection	Potential limitations for environmental flow assessments in the Daly River
Indigenous knowledge from Wagiman and Wardaman Traditional Owners	Collected over generations (> 1000 years) throughout the year, but more frequently during dry season	Collected from the Daly River for very different purposes, i.e., hunting, but some information directly relevant;
	Collected from multiple sites within clan boundary, range of stream orders, range of habitats. Covering < 100 km of river length; Very high level of taxonomic certainty	Biased toward species caught for food or bait and easily observed; recent collections biased to dry season; limited knowledge of some cryptic species; limited information for some highly migratory species for which elements of life history occur outside of language group boundaries
Field surveys conducted in the Daly River for this project	Collected over two years early and late in the dry season	Collected from the Daly River specifically to inform environmental flow assessments.
	Multiple sites covering most of the river system and a range of habitats, covering #62; 100 km of river length High level of taxonomic certainty	Biased toward species more catchable by electrofishing; no wet season information; limited interannual data; limited data on spawning habitats, feeding preferences, or movement biology
Past field surveys conducted in the Daly River	Collected over less than two years mostly during the dry season but some wet season sampling,	Collected from the Daly River for a range of purposes, e.g., distribution mapping, fish movement, but some information directly relevant for environmental flow assessments.
	Collected from a limited number of sites across river system, range of habitats but most collected from < 100 km of river length High level of taxonomic certainty	Biases depending on sampling method, mostly gill, seine, and fyke netting; limited number of sampling locations and limited interannual data.
Research from other river systems in northern Australia	Collected for up to five years during the wet and dry season, but mostly during the dry season	Collected for a range of purposes, e.g., basic ecological and life history studies, but some information directly relevant to knowledge needs for environmental flow assessments.
	Collected from multiple sites across river system, covering a range of habitats over > 100 km of river length. High level of taxonomic certainty	Sampling biases depending on method; transferability of information uncertain as most collected in rivers with profoundly different flow regimes to the Daly River

in Newfoundland, resulted in indigenous fishers being less able than scientists to detect significant declines in salmon stock size from overfishing. Although it is necessary to be aware of the limitations of these different knowledge sources, there is a growing body of literature focusing on the complementary aspects of IEK and SK and the potential benefits of integration (Silvano et al. 2008, Stephenson and Moller 2009, Hill et al. 2012).

Benefits of integrating indigenous and scientific knowledge for environmental flow assessment of fish in the Daly River

We recognized four broad types of benefits for environmental flow assessments that came from integration of the SK and IEK (Table 3). First, where SK from the Daly was congruent with IEK, e.g., distribution, habitat use, and predation, integration provided a greater level of confidence in the SK, which was based on only two years of sampling during the dry season. This was apparent for fish distributions within the river system, which is particularly important for determining locally based environmental flow targets. Although a subset of sites was sampled on six occasions, most sites were sampled only once (see Stewart-Koster et al. 2011, Chan et al. 2012). In contrast, indigenous participants were able

to draw on a much longer period of observation made over a broader range of seasonal conditions, resulting in extensions of the upstream range of estuarine species such as the occurrence of the bull shark to King River and the spotted scat (*Scatophagus argus*) to Bradshaw Creek. IEK from Wardaman participants confirmed that the snub-nosed garfish was often sighted at Flora River, representing another upstream range extension, even though it was only collected by researchers on one occasion. IEK also supported the scientific observations on habitat use. For example, results from only two years of sampling could be confirmed by Wagiman observations that the giant gudgeon (*Oxyeleotris selheimi*) commonly occurred in billabong habitats.

Second, where there was little SK from the Daly but a high level of congruence between IEK and SK from other river systems, for example, movement classification and feeding requirements, integration provided a greater level of confidence in extrapolating this SK to the Daly River. For example, indigenous participants confirmed that an observation from the Alligator Rivers (Bishop et al. 2001), i.e., that tarpon (*Lolorriying*) were often found at the junction of creeks waiting to feed on migrating fish, also applied

Table 3. Table 3. Assessment of the contribution of indigenous ecological knowledge (IEK) and scientific knowledge (SK) and the potential benefits of their integration for environmental flow management of fish in the Daly River. Assessments are based on the data from Figures 3a,b and 4a,b. IEK was assessed against existing SK available at the time of the interviews (Figure 2a,b).

Topic	Contribution of indigenous ecological knowledge (IEK)	Contribution of scientific knowledge (SK)	Key benefits of integration of knowledge sources for environmental flow assessments
Seasonal variation in abundance	No IEK for > 45% of species; IEK and SK congruent/complementary for 40% of species; No incongruent knowledge	Sampling for this project provided the SK for > 75% of species;	High level of local SK but conclusions limited because sites only sampled during the dry season. For the species for which there was IEK it provided validation of the short-term SK and/or additional information on wet season patterns. The lack of incongruence between SK and IEK provided greater confidence in both knowledge sources.
Interannual variation in abundance	No IEK for < 30% of species; IEK and SK congruent/complementary for > 75% of species; No incongruent knowledge	Sampling for this project provided the SK for > 75% of species	High level of local SK but conclusions limited because sites only sampled over two years. IEK confirmed the short-term patterns from the SK and provided complementary information for more than half of the species. The lack of incongruence between SK and IEK provided greater confidence in both knowledge sources.
Predation	No IEK for > 40% of species; IEK and SK congruent/complementary for > 50% of species; No incongruent knowledge	Sampling for this project provided the SK for 50% of species; no knowledge for 50% of species.	Moderate level of information from both knowledge sources highlighted the need for more research on many species. IEK provided validation of the use of the short term SK for about half the species. IEK from surveys and unstructured interviews highlighted the important role of predation in the Daly River and this strongly influenced the structure of risk assessment models arising from this project (see Chan et al. 2012). The lack of incongruence between SK and IEK provided greater confidence in both knowledge sources.
Distribution in river systems	No IEK for < 30% of species; IEK and SK congruent/complementary for > 60% of species; Incongruent knowledge for < 10% of species	Sampling for this project provided SK for > 75% of species	High level of local SK but based on limited sampling of each site. IEK provided validation of the SK from short-term study confirming the regular occurrence of species from sites only sampled once during this study and provided additional information that extended the range of several species. Some incongruence in knowledge highlighted the need for more research for some species, particularly migratory species.
Juvenile habitat use	No IEK for < 30% of species; IEK and SK congruent/complementary for > 60% of species; Incongruent knowledge for < 20% of species	Sampling for this project provided the SK for > 75% of species	High level of local SK but based on limited sampling of each site. IEK provided validation of the use of the short-term SK for the majority of species and additional information for a few species. Some incongruence in knowledge highlighted the need for more research on the habitat use for some species.
Adult habitat use	IEK and SK congruent/complementary for > 75% of species; Incongruent knowledge for < 20% of species	Sampling for this project provided the SK for > 75% of species	High level of local SK but based on limited sampling of each site. IEK provided validation of the use of the short-term SK for the majority of species and additional information for a few species. Some incongruence in knowledge highlighted the need for more research on the habitat use for some species.
Movement classification	No IEK for < 30% of species; EK and SK congruent/complementary for > 75% of species; No incongruent knowledge	Sampling from other river systems provided the SK for > 60% of species	Moderate level of local SK but based on limited sampling from several studies and mostly from the dry season. IEK validated the extrapolation of SK from other studies in the Daly River and from other river systems and provided additional information for several species. The lack of incongruence between SK and IEK provided greater confidence in the extrapolation of SK from other river systems.
Spawning habitat	No IEK for > 40% of species; IEK and SK congruent/complementary for < 40% of species; Incongruent knowledge for < 20% of species	Sampling from other river systems provided the SK for > 85% of species	The very low level of local SK and the moderate level of IEK highlighted the need for more research on spawning habitat in the Daly River for most species. Some incongruence in knowledge highlighted the need for caution in extrapolating SK from other river systems to the Daly River.
Spawning substrate	No IEK for > 75% of species; IEK and SK congruent/complementary for < 40% of species; Incongruent knowledge for < 20% of species	Sampling from other river systems provided the SK for > 85% of species	The very low level of local SK and IEK highlighted the need for more research on spawning substrate in the Daly River for most species. The relatively high level of incongruence in knowledge highlighted the need for great caution in extrapolating SK from other river systems to the Daly River.
Spawning season	No IEK for > 40% of species; EK and SK congruent/complementary for < 5% of species; Incongruent knowledge for < 20% of species	Sampling for this project provided the SK for > 75% of species	High level of local SK but based only on dry season sampling. The moderate level of IEK and some incongruence in knowledge highlighted the need for more research on the spawning season for many species in the Daly River and the need for caution in extrapolating SK from other river systems.

(con'd)

Feeding requirements	No IEK for < 30% of species; IEK and SK congruent/complementary for > 75% of species; Incongruent knowledge for < 10% of species	Sampling from other river systems provided the SK for > 85% of species	Very low level of local SK and with most SK based on studies in other river systems. The high level of IEK and the high level of congruence among knowledge systems validated the extrapolation of SK from other river systems to the Daly and the lack of incongruence between SK and IEK for most species provided greater confidence in both knowledge sources.
Fish condition	No IEK for > 40% of species; IEK and SK congruent/complementary for < 50% of species; No incongruent knowledge	Sampling for this project provided the SK for > 75% of species	High level of local SK but based on limited sampling of each site. The IEK provided validation of the use of SK from short term study and complemented/extended SK for some species.

to the Daly River. Whereas such information may be considered generic at the regional scale, understanding species' distributions within the Daly River catchment required more specific local knowledge, and this yielded a high level of new knowledge from indigenous responses.

Greater confidence in the veracity of project knowledge yielded practical tools of benefit to water managers. Indigenous participants' rich knowledge of fish predation and understanding of the factors influencing flow changed the scientists' conceptual understanding of the flow ecology, and this IEK was integrated into the quantitative environmental flow risk assessment using Bayesian Belief Network (BBN) predictive models (Chan et al. 2012) for two high-risk species, i.e., black bream and barramundi. IEK influenced the structure of the model in two key ways: (1) the emphasis that Wagiman participants placed on predation and the frequency with which barramundi were identified as top predators influenced Chan et al. (2012) to include predation by barramundi as an important factor in the model; and (2) indigenous responses relating to flow, particularly low-flow characteristics, provided the researchers with further impetus to include water quality as a node in the BBN models.

Without this input, researchers would not have included a predation node or emphasized its importance because the fish ecologists on the team (B. J. Pusey and M. J. Kennard), although experienced in tropical regions, had not fully appreciated the significance of barramundi predation. In addition, indigenous participants reported greater confidence in the models knowing that their knowledge had contributed to the development of the models.

Third, a finding that both IEK and SK from the Daly were limited in some circumstances highlighted the need for more information to test the validity of extrapolating from other river systems. This was particularly true for aspects of spawning ecology, e.g., spawning habitat and substrate.

Fourth, instances of incongruence either between or within the two knowledge systems highlighted the need for more research or the need for follow-up interviews. In at least one case, it appears that differences between SK and IEK may have arisen because of confusion over the identity of a particular fish. Four of the incongruent responses given by Wagiman for the golden goby were consistent with the similar-looking sleepy cod. Although Wagiman had clearly identified these as separate species, their cryptic appearance and bottom-dwelling habit mean that they are difficult to distinguish from bankside observations; hence, uncertainty over their ecology is unsurprising. Likewise, the

incongruence between different Wagiman groups relating to knowledge of golden goby and black bream warrants further investigation to identify likely reasons.

In other cases, incongruence between SK and IEK appears to have arisen from differences in the spatial scale of different knowledge sources, as described for barramundi spawning previously. Our collaboration did not work through the implications of indigenous knowledge of barramundi spawning patterns with the relevant traditional owners; however, this logical next step should be contemplated in cases where there is community interest and in which there is a sufficient degree of trust between all parties. An interesting angle to pursue would be the role of local cultural institutions in producing knowledge that might inhibit and/or enhance opportunities for sustainable management (Nurse-Bray 2003). In this case, the ontologies that are expressed frequently in local "myths" would be worthy of further examination. A number of creation stories were recounted during the project, and these included explanations of the origins of fish traits such as the shiny scales of barramundi, poisonous spines in catfish, and the distribution patterns of turtle species across the freshwater-saltwater interface. These characteristics were determined by the behavior of ancestral creator beings during a time when humans and nonhumans were beings of the same ontological kind: fish and other animals danced, walked, fought with each other, and carried out ceremonies and rituals. Acquiring knowledge from scientists who produce it through the subject-object dichotomy of Enlightenment thought (Watson and Huntington 2008) may be perceived as corrosive to the authority of indigenous experts, particularly if it conflicts with local accounts. However, it is also possible that new insights would be welcome and assimilated. Watson and Huntington's (2008:269) work on indigenous knowledge suggests that collaborative endeavors will benefit from approaches that treat such stories as "ontological assertions" rather than being dismissed as myth. Were such an approach taken, participants in a research partnership would be compelled to question what constitutes valid knowledge and what gets left out, as well as the basis for these selections.

Other benefits of integrating knowledge

In addition to enhancing the scientific understanding of fish biology and flow-ecology relationships (Stewart-Koster et al. 2011, Chan et al. 2012, Pettit et al. 2013), the research partnership generated a number of beneficial outcomes for indigenous people. First, field trips provided opportunities for people to exchange "stories about fish," including their cultural significance. Traditional owners appreciated the project's holistic approach to

identifying important cultural values and to community development (Smyth 2012). Lizzie Sullivan observed that “for many old people these research trips were the first time they had a chance to see country for a long time” (Smyth 2012:14). On-site storytelling provided an opportunity to pass knowledge on to younger generations, and audiovisual recordings were made for conservation purposes. Mona Liddy, a Wagiman elder, felt that “participation of young people instilled pride and recognition in future leaders – it strengthened their spiritual ties to country, their community and identity” (Smyth 2012:13). She also found that the process of engaging in field research was beneficial in its own right because it jogged memories relating to fish and of the country (Minutes of Project Steering Committee Meeting, 20 October 2006). These perspectives suggest that further investigation of the religious and spiritual knowledge relating to fish would be productive.

Second, community members were also engaged in the project’s knowledge transfer and adoption activities. For instance, the project funded indigenous participation at scientific conferences on at least three occasions. A poster of the fish found within the customary estates of the Wagiman language group was produced with corresponding language names. It was described by one local leader as “a lasting benefit of the project” (Smyth 2012:12). Elders reported feeling “very proud to show their achievements to the wider community and through presentations at conferences” (Smyth 2012:13). The researchers were also very pleased to see indigenous contributions toward achieving project results formally acknowledged in these ways.

Finally, the research assisted in building the capacity of a number of indigenous people to contribute to water planning and conservation management decisions. For instance, two of the authors, i.e., Mona Liddy and Lizzy Sullivan, are Wagiman representatives on the Daly River Management Advisory Committee, a multistakeholder group advising the NT water agency in the development of the *Draft Water Allocation Plan, Ooloo Aquifer* (NRETAS 2012). These representatives argued that “women especially would like to be involved in long term monitoring of water and wetlands” and that research can help them to fulfill responsibilities to manage national parks under their control (Smyth 2012:14). Wardaman participate directly in management decisions affecting the Flora River protected area, i.e., *Guwining* in Wardaman language, and they valued the opportunity to participate in research in that area. Given that indigenous people can be less equipped to learn more about fisheries than scientists because of the differences in access to technology and knowledge networks (Foale 2006), the partnership represented a valuable opportunity to provide resources and learn.

Ethical, cultural, and logistical challenges of designing and conducting cross-cultural research

In partnerships such as ours, integration of knowledge across cultures requires a critical recognition of the impacts of colonization on indigenous societies (Butler 2006). Indigenous people in the study region no longer spend most of the year living alongside the river, pursuing a lifestyle heavily dependent on fish and other aquatic species (see Kearney 1991, Raymond et al. 1999, Stanner 2010). The individuals we worked with were acutely aware that fish knowledge had been lost from their respective groups

over recent generations and that it was continuing to erode as a result of wider social changes. Confirming the language names for some fish was difficult with only one fluent Wagiman language speaker available. On a number of occasions, participants stated that they were concerned that knowledge was not being transferred across generations as it had been in the past. Jabal Huddleston’s comment illustrates this concern:

I ask those young fellas to come here and sit down (and listen) but they go away. They know a different language. The old people used to tell us. My grannie bin tell us, we like to listen to stories about fish. They’d say, “Who’s going to carry on these stories?” ... We didn’t catch up with them enough to hear those stories. (S. E. Jackson’s field notes, Chilling Billabong, 26 August 2006)

A research collaboration of this kind presents numerous challenges that can strain relationships and affect other outcomes, irrespective of the strength of researcher commitment to ethical conduct and adherence to protocols. For this reason, we will highlight a number of areas for improvement with the expectation that our experience will inform and enhance future two-way research initiatives. Like many efforts to reform research practices, we focused heavily on procedural issues (Davidson-Hunt and O’Flaherty 2007). We gave less attention to cooperative or collaborative problem framing and conceptualization, which a number of studies nominate as a critical determinant of success in knowledge integration projects involving indigenous people (Cullen-Unsworth et al. 2012, see also Casteldon et al. 2012). Had traditional owners played a stronger role in designing the research, it is likely that we would also have developed a formal mechanism for indigenous partners to review and revise drafts of findings (Koster et al. 2012) throughout the project.

The negotiation and execution of one of the research agreements required more time than any of us consider is reasonable. In one case, a bureaucratic delay of two years to execute a research agreement made it far from easy to reconcile the conflicting demands of a legally incorporated indigenous organization with the short-term funding conditions of the research project. On a more practical level, the project experienced a small number of minor difficulties characteristic of remote indigenous Australia. For example, few indigenous collaborators had bank accounts, resulting in long delays in payments to individuals. According to Mona Liddy, the difficulties that arose when attempting to confirm fish names could have been avoided had the project team included a linguist (D. Smyth, *personal communication*, 7 February 2012). These and other logistical difficulties were overcome because of the strength of the respectful and trusting relationships that were the hallmark of the collaboration.

Our experience confirms Holcombe and Gould’s (2010) observation that reliance on institutional regulation and codification alone are unlikely to generate or sustain ethical and collaborative relationship with indigenous peoples. In this case, researchers and indigenous experts embarked on a process of continual dialogue and genuine negotiation that extended beyond mere adherence to procedure. The result was a set of relationships that are likely to endure beyond the life of this project and may be applied to new and emerging problems and research goals. This approach is regarded as an indicator of success by other studies (Ballard et al. 2008, Casteldon et al. 2012, Cullen-Unsworth et al.

2012) and by traditional owners closely involved in the project: “Traditional Owners felt they had ownership of the project - there was a good balance between Traditional Owners, researchers and other stakeholders” (Smyth 2012:13).

CONCLUSION

We have described a successful research partnership that combined indigenous and scientific knowledge and trialed tools to integrate project knowledge about fish and flow ecology in the context of water planning. Project results influenced the conceptual models developed by scientists to understand the flow ecology as well as the structure of risk assessment tools designed to understand the vulnerability of particular fish to low-flow scenarios. In addition to generating knowledge that confirmed field survey results, the approach we have described elicited knowledge that was new to both scientific and indigenous participants. Some differences between indigenous and nonindigenous knowledge of fish and flows was found to exist, and this was attributed to a number of factors, including observational differences, i.e., temporal and spatial, and the methodological power of field-sampling techniques relative to the ability of subsistence fishing practices to generate knowledge of relevance to wider questions about aquatic ecology. It is difficult to apportion responsibility for any empirical gaps in indigenous knowledge to each of these factors, or indeed to the significant part that colonization is likely to have played in eroding indigenous knowledge over the past 150 years. Differences between indigenous and scientific knowledge about fish will need to be closely examined in light of the specific circumstances of each case of research collaboration. At the least, conflicting accounts highlight areas for further research to test the assumptions/strength of current SK.

For the traditional owners involved in this research, accounting for the differences between the knowledge systems is of less interest than is arresting the decline in knowledge of fish and other ecological phenomena that have accompanied rapid social and economic change. For that reason, the partnership sought to document, conserve, and revitalize indigenous fish knowledge. All parties engaged in the project saw value in pursuing opportunities to “listen to stories about fish,” thereby equipping indigenous landowners and water planners with the resources to apply new insights to contemporary land and water management problems.

Responses to this article can be read online at:
<http://www.ecologyandsociety.org/issues/responses.php/5874>

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