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Chapter 10

Vulnerability of freshwater and estuarine fisheries in the tropical Pacific to climate change

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'Currently, the magnitude of global climate change is such that most of its effects on freshwater fisheries could be easily masked by or attributed to other anthropogenic influences, such as deforestation, overexploitation and land use change.' (Ficke et al. 2007)[i]

i Ficke et al. (2007) Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries* 17, 581–613.

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10.1 Introduction

The freshwater and estuarine fisheries in the tropical Pacific are poorly understood compared to the oceanic and coastal fisheries of the region (Chapters 8 and 9). Yet freshwater and estuarine fisheries are more important than most people realise – catches from freshwater habitats alone contribute 4% of regional gross domestic product (GDP) derived from all fisheries resources[1]. This contribution is remarkable, given that freshwater fish habitats account for such a small proportion of the land area of Pacific Island countries and territories (PICTs), and that the land itself represents only 1.8% of the total area of the territorial waters and exclusive economic zones of PICTs (Chapter 1). Because of the predominance of high islands in Melanesia (Chapter 1), most of the freshwater fish production comes from Papua New Guinea (PNG), with significant harvests also being made in Fiji and Solomon Islands[1].

Recent preliminary estimates indicate that the total production of freshwater fish from the region is ~ 24,000 tonnes per year[1]. The significance of this production is apparent when it is compared with the total catch of freshwater fish in Australia, which is estimated to average about 300 tonnes per year for commercial fisheries[2], and around 4000 tonnes per year for recreational fisheries[3].

The estimates of freshwater and estuarine fish catches for the region are preliminary, but these catches undoubtedly form an important part of the diet for people in inland rural areas[4–6]. Indeed, freshwater fish are the most common source of animal protein for communities with access to freshwater and estuarine habitats in PNG[7]. For example, villagers along parts of the Fly River eat as much as 2 kg of fish per person each week[8]. This compares with the highest levels of per capita fish consumption (> 100 kg per person per year) by coastal communities in the region (Chapter 1)[1,9]. Clearly, any alteration in freshwater and estuarine fish production as a result of climate change has potential to affect the food security and livelihoods of people in the inland areas of the region.

In this chapter, we assess how the projected changes to surface climate (Chapter 2) and sea level (Chapter 3), and the anticipated alterations to fish habitats (Chapter 7), are likely to affect freshwater and estuarine fisheries. Because of the limited information available, and the inherent uncertainty that stems from the complex ways in which freshwater and estuarine fish interact with their habitats and other species, this chapter represents a starting point for more detailed investigation rather than a definitive analysis of vulnerability.

We begin by describing the main species of fish and invertebrates harvested from freshwater and estuarine habitats in the tropical Pacific and the ways in which they are used, and then summarise recent catch levels, status of stocks and estimates of sustainable production. To assess the vulnerability of the resources, we use the framework described in Chapter 1 to outline how the main groups of fish species are directly exposed to projected changes in surface climate and sea level, and how they are indirectly exposed through changes to the habitats on which they depend for food, shelter and reproduction. We also evaluate their sensitivity to these changes, and their capacity to adapt. These assessments are made for a low (B1) and a high (A2) emissions scenario[10] for 2035 and 2100.

We conclude by examining the gaps in knowledge and the research required to address them, and by identifying the management measures needed to reduce the negative impacts and harness the possible opportunities for freshwater and estuarine fisheries likely to be associated with climate change.

10.2 Nature and status of freshwater and estuarine fisheries

10.2.1 Main species and their uses

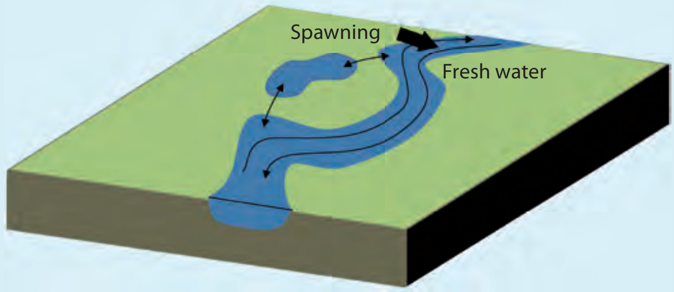
The wide variety of freshwater and estuarine habitats in the tropical Pacific (Chapter 7) supports a diverse range of fish and invertebrate species (Appendix 10.1). Several taxonomic surveys have shown that the greatest diversity and abundance of species occur on the high islands in Melanesia[4–6,11–20]. However, information on the biology of freshwater and estuarine fish and invertebrates in the tropical Pacific is limited. The best available knowledge is for barramundi *Lates calcarifer* in southern PNG[21]. The general migration patterns of various species are also reasonably well understood (Box 10.1). The most complex of these patterns occurs for the amphidromous gobies, some of which rely on transoceanic migration between islands during the larval stage to maintain distributions in rivers over wide areas of the tropical Pacific[22–25].

Surveys also reveal the prevalence of fish introduced to supplement catches of native species, or introduced illicitly or carelessly. Tilapia *Oreochromis* spp. and common carp *Cyprinus carpio* are the most widespread of the species introduced to augment production across the region and have become valued highly as food[26,27]. In PNG, a much broader range of species has become established, however (Appendix 10.2)[28–32]. In contrast to native species, the biology of the introduced species is well known, albeit from other regions.

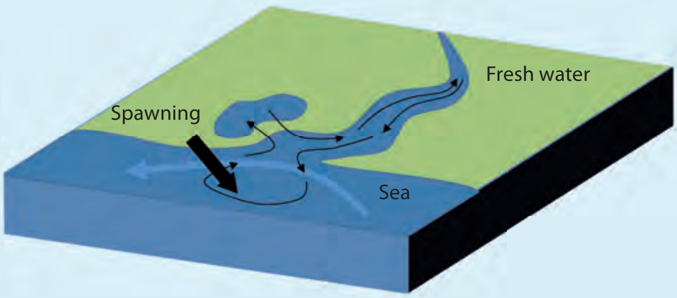
Reliable information on freshwater and estuarine fisheries in the tropical Pacific is also often lacking, and the estimates that are available (**Table 10.1**) involve a considerable amount of guesswork[1]. Nevertheless, it is evident that many of the species caught are used mainly for subsistence, and that women play an important role in these fisheries[30,33–35]. Artisanal fisheries based on the sale of catches surplus to household needs to generate income are, however, also relatively common.

Box 10.1 Migration patterns of freshwater fish in the tropical Pacific

Potamodromous species migrate wholly within fresh water and complete their life cycle without having to enter the sea. Examples in the tropical Pacific region include freshwater mullet *Cestraeus plicatilis*, which produce pelagic eggs and migrate upstream to counter the downstream drift of eggs and larvae[19]. River herring *Nematalosa papuensis* in PNG are also thought to migrate only within fresh water.



Catadromous species live in fresh water as adults and migrate to the sea to spawn. Larvae and juveniles then migrate upstream to enter fresh water. Examples of such species include barramundi *Lates calcarifer*, jungle perch *Kuhlia rupestris* and eels of the family Anguillidae.



Amphidromous species live in fresh water as adults, and spawn in fresh water. Larvae are carried to sea where they feed and grow, returning to fresh water as juveniles. The best known examples from the tropical Pacific region include gobies such as *Sicyopterus lagocephalus*, and the freshwater prawn *Macrobrachium lar*.

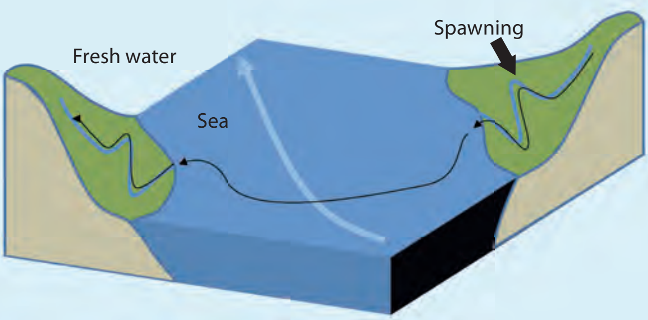


Table 10.1 Recent estimates of annual catches from freshwater fisheries in Pacific Island countries and territories (PICTs), and the estimated combined value of subsistence and commercial catches in 2007. Estimates should be considered as indicative only (source: Gillett 2009)[1].

PICT	Catch (tonnes)	Value (USD)
Melanesia		
Fiji	4146	4,287,500
New Caledonia	10	45,885
PNG	17,500	16,554,054
Solomon Islands	2000	1,464,052
Vanuatu	80	173,077
Micronesia		
FSM	1	8000
Guam	3	10,000
Kiribati	-	-
Marshall Islands	-	-
Nauru	-	-
CNMI	-	-
Palau	1	8000
Polynesia		
American Samoa	1	4000
Cook Islands	5	36,765
French Polynesia	100	488,506
Niue	-	-
Pitcairn Islands	-	-
Samoa	10	33,206
Tonga	1	1980
Tokelau	-	-
Tuvalu	-	-
Wallis and Futuna	-	-
Total	**23,858**	**23,115,025**

- Indicates that freshwater fisheries do not occur in the country or territory.

The enterprises established for commercial fisheries are limited. The most significant commercial fisheries are for barramundi in the southern rivers of PNG, and kai clams *Batissa violacea* and freshwater prawns *Macrobrachium* spp. in Fiji. In general, however, commercial fisheries for freshwater species are poorly developed in most of the tropical Pacific because the rivers are too small to sustain economically viable catches. Other fisheries based on freshwater and estuarine resources in the region are the guided recreational fishing operations for tourists in PNG, and the (often illegal and unpoliced) collection of ornamental species for the international aquarium trade[6,36].

The methods used to catch freshwater and estuarine fish and invertebrates in the tropical Pacific are usually traditional and simple. They include an assortment of woven baskets and traps, hoop nets, cast nets, gill nets, seines, hook-and-line, spears and spearguns, bow and arrow, and hand collection (Appendix 10.1) (**Figure 10.1**). Villagers in parts of PNG also divert streams to trap fish in isolated pools where they can be netted or speared[18]. Derris roots containing rotenone are crushed and applied to pools or slow-flowing waters to stupefy fish in some PICTs. Women are also skilled at catching fish, eels, prawns and freshwater clams using their hands and feet[18,37].

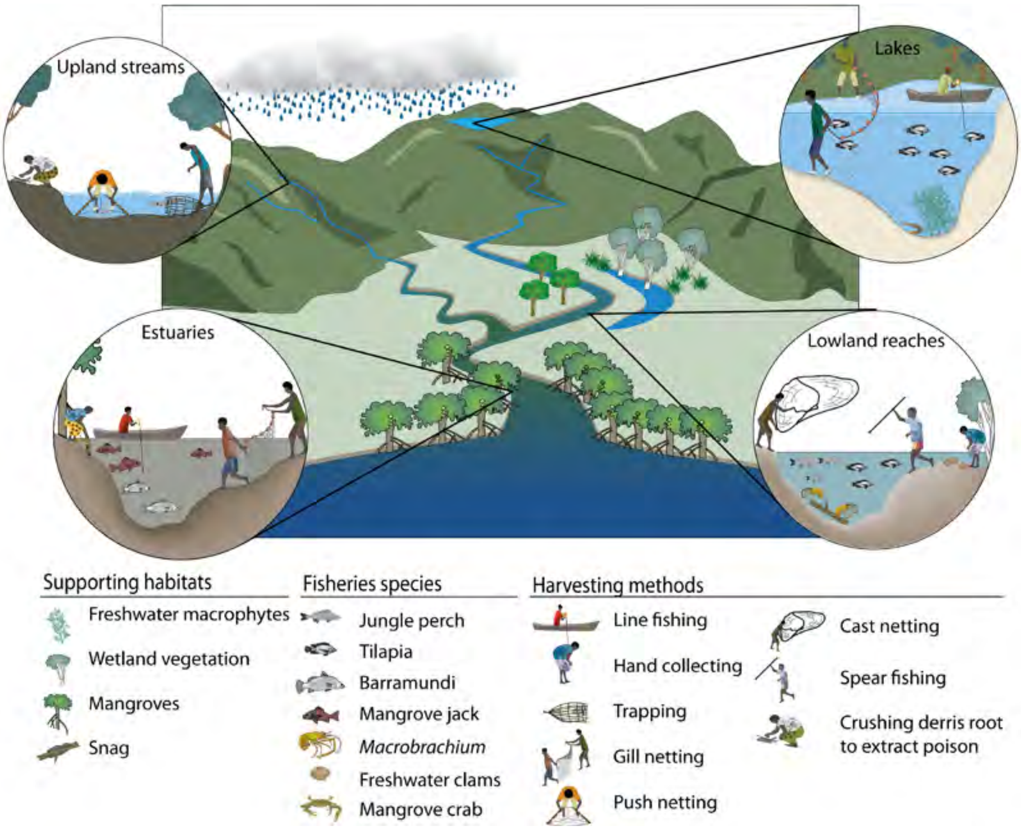


Figure 10.1 Examples of methods used to catch fish and invertebrates in freshwater and estuarine habitats in the tropical Pacific.

The most detailed accounts of freshwater fisheries come from the Fly River system of PNG[8,31,38–42]. The Sepik-Ramu River system in PNG has also been investigated for the purpose of stocking introduced species to increase production[7,28,30,33,43–45]. Yields and stock dynamics for freshwater clams (kai) in Fiji have also been documented[46]. Other fisheries, such as those for amphidromous gobies ('whitebait') returning to fresh water after their ocean migration (Box 10.1), are poorly described[47]. Overall, the most recent estimates of freshwater fish production across the region are acknowledged as crude and require validation[1]. The main native and introduced species of fish and invertebrates supporting freshwater and estuarine fisheries in the Pacific are described briefly below.

10.2.1.1 Native species

- **Barramundi** *Lates calcarifer* is the dominant species in the Fly River system in PNG, accounting for more than 30% of the total fish biomass in the river[39]. The commercial fishery began exporting barramundi caught with gill nets near the mouth and in the middle of the Fly River around Lake Murray in the 1960s[48]. Barramundi are the major predatory fish in the ecosystem and have a complex life cycle, starting as males and changing sex to become females at around seven years of age[49]. They migrate to sea to spawn in the coastal waters of southwestern PNG, and return to fresh water. Juveniles use shallow floodplain wetlands as nursery habitats.

- **River herring** *Nematalosa papuensis* make up 66% of fish numbers in the floodplain habitats of the Fly River, PNG. They are highly fecund and grow rapidly, feeding predominantly on phytoplankton and zooplankton. They are not commonly eaten, but efforts are underway to allow the fishery to expand to supply cannery and fishmeal facilities.

- **Fork-tailed catfish** *Arius* spp. are the main species caught in the Fly River subsistence fishery and are preferred by villagers over barramundi and Papuan black bass *Lutjanus goldei*[40]. The combined subsistence, artisanal and commercial yield is ~ 600 tonnes per year[40]. Fork-tailed catfish are also caught in the Sepik-Ramu River system, PNG[50].

River fisherman, Papua New Guinea Photo: Kent St John

- **Freshwater eels** *Anguilla* spp. (six species) occur in the southwest Pacific. In Fiji, eels are caught with baited lines, spears, a variety of traditional woven traps, hollow poles and cane knives, but there is no organised fishery. A small commercial eel fishery has operated in the past on Mitiaro Island in the Cook Islands[51], with catches of between 4680 and 10,400 eels per year[52].

- **Mullet** are caught in estuaries and rivers, and from reef flats and coastal waters, for subsistence and sale throughout the Pacific islands. Several species are captured, including warty-lipped mullet *Crenimugil crenilabris*, diamond-scale mullet *Liza vaigiensis*, striped mullet *Mugil cephalus*, blue-spot mullet *Valamugi seheli* and acute-jawed mullet *Crenimugil leuciscus*, using gear such as gill nets and spears. In Fiji, gill nets were banned in 1989, and have been replaced by spears as the main fishing method[26]. Mullet are exported dried, and sold fresh or salted at local markets. Mullet are highly prized in Tonga. In Vanuatu, mullet provide a significant source of protein for local communities and surplus catches are sold for income[27].

- **Goby-fry,** known as 'whitebait' – a general term applied to juvenile fish that swarm near the mouths of rivers as they re-enter fresh water – support fisheries on many islands, e.g. Tahiti and Moorea in French Polynesia. The amphidromous species of gobies harvested in these fisheries include the genera *Awaous*, *Stenigobius*, *Rhinogobius*, *Sicyopus*, *Lentipes*, *Stiphodon*, *Sicyopterus*, and *Sicydium*[23,47]. Traditional methods for catching whitebait include a variety of woven traps and baskets. Data on goby-fry fisheries are difficult to find because catches are episodic, and most of the product is eaten locally[47].

- **Flagtails**, also known as jungle perch, *Kuhlia rupestris* and *K. munda* are a highly valued food fish in Vanuatu and provide a significant source of animal protein for local communities[27]. They are also widespread in Fiji, New Caledonia and Solomon Islands, and have value as a recreational species.

- **Tropical freshwater snappers** are highly prized for food and have economic value through recreational fisheries. Prominent species include mangrove jack *Lutjanus argentimaculatus*, Papuan black bass *L. goldiei*, spot-tail bass *L. fuscescens* and Moses snapper *L. russellii*. These fish are principally marine species that visit fresh water during their juvenile and immature adult stages, although Papuan black bass are thought to live entirely in fresh water[15].

- **Freshwater clams,** known as kai, are prolific in some rivers in Fiji[53]. Kai live in sandy and muddy sediments between the upper tidal limit down to the upstream extent of saltwater penetration. They attain average densities of > 680 g per m^2 [46]. Women collect the clams with their hands and feet by wading, or occasionally, by diving[37]. In the Ba River, the commercial catch accounts for ~ 25% of the total harvest, with the remainder used for subsistence[46]. Kai are kept alive in moistened baskets and sold in markets. The meat is marinated in lime juice and eaten raw[54] or cooked in salted water, coconut cream, curried, deep fried or added to soup[26]. Commercial catches fluctuated between 1000 and 1800 tonnes per year from 1982 to 1992[26,55], suggesting a total harvest of up to 4000 to 7000 tonnes per year. In 2004, the commercial catch was ~ 2500 tonnes[1]. Meat yield is about 20% of harvested weight.

- **Freshwater prawns** *Macrobrachium* spp. and *Palaemon* spp. occur widely in the Pacific islands. The most popular native species is *Macrobrachium lar* which grows to 300 g. In Fiji, the fishery operates exclusively at an artisanal or subsistence level, with freshwater prawns usually collected by women using push nets, fine spears, traps or their hands[53]. Between 1986 and 1992, combined sales of *Macrobrachium* and *Palaemon* prawns in Fiji fluctuated between 22 and 105 tonnes per year, with *Macrobrachium* accounting for ~ 70% of the catch. In Vanuatu, up to six species of *Macrobrachium* are harvested for subsistence and by artisanal fisheries as a source of income.


Photo: Timothy Pickering

Woman selling freshwater clams in Suva, Fiji

- **Shrimp** *Penaeus merguiensis* use estuaries in southern PNG as nursery areas. The adults are caught mainly in the Gulf of Papua, where catches as high as 1000–1300 tonnes per year have been made (Chapter 9).
- **Other species** are harvested opportunistically for subsistence fisheries and occasional sale to local markets. Such species include bull sharks (Carcharhinidae), oxeye herring (Megalopidae), grunters (Haemulidae), trevallies (Carangidae), silver biddies (Gerreidae), silver moon-fish (Monodactylidae), spotted scats (Scatophagidae) and larger species of gudgeons (Eleotridae) and gobies (Gobiidae).

10.2.1.2 Introduced species

Introduced species make an important contribution to fisheries production in many PICTs. This contribution is greatest in PNG, where > 25 species have been introduced since 1949 to provide additional sources of animal protein for local people[56] (Appendix 10.2). Introduced species such as tilapia, carp and golden mahseer *Tor putitora* support important fisheries, but the environmental consequences of these introductions, including the effects on native fish stocks, have received limited attention and remain controversial[57,58].

Observed adverse effects of some stockings include declines in production of native species, damage to vegetated habitats and wetland hydrology, toxic effects from eating the eggs of snowtrout *Schizothorax richardsonii*, and bite injuries to people swimming in rivers from pacu *Piaractus brachypomus*[56]. There are also reports that pacu and an unidentified introduced species known as 'rubber-mouth' have greatly reduced the tilapia fishery in the Sepik River[56].

Walking catfish *Clarias batrachus*, climbing perch *Anabas testudineus* and striped snakehead *Channa striata* are of particular concern in PNG because of their effects on valuable fisheries species[32,38]. The catfish and climbing perch are increasing in abundance[32], and in places have largely replaced native species[42]. Climbing perch are extending their distribution southward, and have recently been recorded on Australian islands in Torres Strait[59–61]. In the Sepik-Ramu floodplains, local people attribute a decline in native fish to consumption of aquatic vegetation by pacu and Java carp *Barbonymus gonionotus*.

The main introduced species presently contributing to fisheries production and food security are tilapia and carp although many other introduced species are also used for subsistence in PNG (Appendix 10.2). Brief summaries of the contributions made by tilapia and carp are provided below.

- **Tilapia** have been introduced widely throughout the Pacific. The most common species are Mozambique tilapia *Oreochromis mossambicus* and Nile tilapia *O. niloticus*. Redbreast tilapia *Tilapia rendalli* were also stocked into the Sepik-Ramu River system in PNG. Subsistence catches of tilapia from the Sepik region have been estimated at 1500–4000 tonnes per year[44,62], accounting for 50% of the total freshwater fish catch[50]. Traditionally, most of the fishing was done by women using woven cane traps, but by the 1970s gill nets were common. Tilapia are also sold in roadside markets by women and generate a significant source of income[63]. On Bougainville Island, tilapia make up 45% of freshwater fish numbers[64], but total fish yields are low (7–12 tonnes per year) so people rarely fish for them. About 60 to 70 tonnes of tilapia were marketed each year in Fiji in the early 1990s, with additional catch consumed by subsistence fishers[26]. However, the marketed catches include fish produced by aquaculture (see Chapter 11 for recent estimates).
- **Common carp** *Cyprinus carpio* have been introduced in many freshwater systems throughout the region, both intentionally, and following escape from aquaculture facilities. In the Sepik-Ramu River system in PNG, parts of Vanuatu and Fiji, carp provide a significant subsistence fishery[7,26,27,65].

10.2.2 Recent harvest levels

Estimates of freshwater fish catches throughout the tropical Pacific (**Table 10.1**) need to be interpreted with caution. PNG is clearly the leading producer – estimates for 2007 of 17,500 tonnes per year[1] are similar to earlier figures for total annual production of 14,500 to 18,500 tonnes[66]. Catches of freshwater fish from PNG in the past are estimated to have consisted of 2.5% barramundi, 3.5% river herring, ~ 80% other freshwater fish and 14% marine fish entering fresh water (**Table 10.2**). Harvesting of river herring has strong potential, however (Section 10.2.4.2).

Fiji is the next-largest producer, with catches ranging from 1263–5921 tonnes between 2001 and 2003[1,2]. In 2007 average production was estimated to be 4146 tonnes per year (**Table 10.1**). Freshwater fisheries harvests from Fiji are remarkable because they are dominated by invertebrates – the catch consists of 85% kai, 11% *Macrobrachium* spp. and *Palaemon* spp., and 4% freshwater fish (**Table 10.2**).

Without much factual basis, the catch of freshwater fish and invertebrates from Solomon Islands has been estimated to be around 2000 tonnes per year[1]. In French Polynesia, estimates of freshwater catches vary from 50 to 100 tonnes per year[1,2], mostly freshwater fish with a small percentage of crustaceans. Estimated catches of freshwater fish from FSM and Samoa are 5 tonnes and 1 tonne per year, respectively (**Table 10.2**).

Table 10.2 Recent estimated annual catches (tonnes) of representative groups of freshwater fish and invertebrates from some Pacific Island countries and territories (PICTs)[2]. Values should be considered as indicative only of average catches.

PICT*	Group					
	Barramundi	River herring	Other freshwater fish	Marine visitors	Crustaceans	Molluscs
Fiji	-	-	124	nea	396	3024
French Polynesia	-	-	50	nea	2	nea
FSM	-	-	5	nea	nea	nea
PNG	350	480	10,814	1850	6	nea
Samoa	-	-	1	nea	nea	nea
Total	**350**	**480**	**10,994**	**1850**	**404**	**3024**

* No estimates available for Solomon Islands; - indicates that species does not occur; nea = no estimate available.

10.2.3 Status of stocks

Concern has been expressed about increasing fishing pressure on freshwater fish stocks, and the threats to production and biodiversity from mining, forestry, agriculture and invasive alien species[16,18,19,32]. Changes in estuarine environments are also thought to be affecting species that migrate between fresh water and the sea (Box 10.1)[25]. In PNG, fishery-independent surveys in the Fly River system found that mining and increased fishing effort contributed to a decrease in fish biomass of 57% to 92% upstream of the confluence of the Fly and Strickland Rivers, and that the number of fish species has been reduced by 6% to 80% since 1983[42].

Here, we summarise present knowledge of the status of the main freshwater fish and invertebrate species in the tropical Pacific. The data are patchy, however, and most reports are not recent and do not necessarily provide a reliable indicator of current trends in stocks. Based on the available data, we have categorised the status of species as 'likely overfished', 'likely fully exploited', 'likely underfished' or 'status uncertain'.

- **Barramundi:** Production in PNG peaked at 330 tonnes per year in the 1970s, but the commercial fishery in the coastal reaches of the Fly River ceased in the early 1990s when the total annual catch plummeted to 4 tonnes[67]. The decline is attributed to the combined effects of mining, overfishing and El Niño droughts[21,42,67]. After the late 1990s, catches increased again and the fishery was managed to yield more sustainable harvests of ~ 40 tonnes per year from the coastal fishery, and 170 tonnes per year from the middle Fly River system (likely fully exploited).
- **River herring:** Abundance of this species in the Fly River system has shown no consistent changes over time[42], and river herring make up ~ 40% of fish numbers and ~ 5% of biomass in riverine habitats, and > 60% of the fish caught in floodplain habitats[38,39] (likely underfished).
- **Fork-tailed catfish:** The giant catfish *Arius dioctes* is an important species in the subsistence, artisanal and commercial fisheries in the larger river systems of southern and central PNG[15]. Numbers of other fork-tailed catfish species have declined at some sites in the Fly River, with several species not recorded during recent sampling[42]. The abundance of fork-tailed catfish in the Sepik-Ramu River system has also declined, from ~ 25% of the total fish catch in the 1980s[44] to < 12% in more recent surveys[33] (likely overfished).
- **Eels:** Little is known about the status of eel populations in the region, although they are still thought to be in robust condition, given the lack of targeted commercial fisheries for the relatively modest stocks[26] and the extended seasons over which elvers enter rivers. Large upstream runs of returning elvers and glass eels, typical of temperate waters, do not occur in Fiji[53], but have not been investigated elsewhere (likely underfished).
- **Mullet:** Declining mullet catches in Fiji and Tonga have prompted changes in permitted fishing gear to allow stocks to rebuild[26,68]. Mullet harvests appear to be stable at most locations in the Fly River system, although catches of *Liza alata* have declined significantly in the middle section of the river[42] (status uncertain).
- **Whitebait:** Catches of goby postlarvae returning to freshwater habitats in French Polynesia are highly variable, ranging from 1 to 100 tonnes per year. With such large variability, the ability to detect changes in stocks is limited. However, concerns have been expressed about the decline of goby-fry fisheries as a result of habitat alteration and over exploitation throughout their range[12,25,47] (status uncertain).
- **Tropical freshwater snappers:** Stocks of Papuan black bass appear to have declined in parts of the middle Fly River system[42], but no data are available for populations elsewhere. Freshwater snappers are still regarded as common in many rivers in the Solomon Islands[18,19] and Vanuatu[27] (likely underfished).

- **Tilapia:** Stocks generally appear to be stable, or increasing in locations where they have spread only recently. In Fiji, catches increased from 6 tonnes per year prior to 1989 to 63 tonnes per year in 1993[26], but there is no recent information on tilapia stocks in the nation's rivers and lakes. In the Sepik-Ramu River system, stocks of redbreast tilapia increased soon after their introduction in the early 1990s[33] but, as mentioned earlier, populations are now being reduced as a result of predation from larger introduced species[56]. In Lake Tegano, on the island of Rennell in Solomon Islands, tilapia has yielded harvests of ~ 16 tonnes per year for many years[69,70]. Large fish are not as common as they used to be, much to the disappointment of local people. Decreasing fish size has been attributed to recent establishment of a large cormorant population, and to overfishing[71] after the introduction of gill nets (status uncertain).
- **Carp:** In the catchment of the Sepik-Ramu River system, PNG, concerns have been expressed that carp populations may become stunted unless they are fished heavily, and that red-breasted tilapia may reduce carp numbers through competition[33] (likely underfished).
- **Freshwater clams:** Catches of kai at the rate of ~ 25% of the standing stock in the Ba River, Fiji, appear to be sustainable. The traditional fishing method of wading means that kai in deeper water are not accessible to the fishery, and provide a source of unfished spawners to help maintain the population. Catches are also limited in years with high rainfall because women are unable to wade during floods[46] (likely underfished).
- **Freshwater prawns:** Catches of *Macrobrachium* spp. and *Palaemon* spp. in Fiji increased by a factor of five from 1988 to 1991, and then fell sharply in 1992, suggesting that stocks near major urban areas may have been severely overfished[26] (likely overfished in Fiji, but underfished in other PICTs).

10.2.4 Estimated sustainable production

Freshwater fish populations commonly exhibit boom-and-bust cycles linked to river flows, floods and droughts, leading to great variation in catches. Peak recruitment often occurs following major floods[72,73], whereas recruitment may fail during drought. Consequently, the large catches that can be taken after wet years are likely to be unsustainable in dry years. Nevertheless, it should be possible to manage species that do not exhibit boom-and-bust population cycles in relation to river flow, such as kai, to achieve more consistent levels of harvest.

Estimates presented here should be considered as representing sustainable production in average years, although large (sometimes an order of magnitude) increases might be quite normal for some species after wet years. A failure to reduce catches during drought when many species are most vulnerable to capture may severely inhibit population recovery after a return to normal flow conditions.

Fishing in a small stream, Papua New Guinea

Photo: Arne Hodalic/Corbis

10.2.4.1 Estimates of sustainable production

Potential fisheries yields from tropical rivers and lakes in other parts of the world have been estimated using empirical relationships between harvests and catchment area, floodplain area and surface area[74,75].

For example, fisheries production (tonnes per year) for African rivers has been estimated as:

$$\text{Yield} = 0.048 \times \text{catchment area } (\text{km}^2)^{0.93} \qquad (r^2 = 0.95)$$

In lakes and reservoirs, fisheries production in these terms has been estimated as:

$$\text{Yield} = 8.32 \times \text{lake surface area } (\text{km}^2)^{0.92} \qquad (r^2 = 0.93)$$

Freshwater habitats in the tropical Pacific tend to be much smaller, with steeper catchment gradients than those in Africa (Chapter 7), so that equations based on African rivers are unlikely to provide reliable estimates of freshwater fisheries production for the region. These equations can indicate possible yields, however, and simple measurements of catchment area and lake surface area can be used to compare potential yields among systems (**Tables 10.3** and **10.4**).

Apart from the yields from the larger rivers of PNG, sustainable catches of freshwater fish from tropical Pacific rivers are quite small. Estimates of sustainable production from five lakes and one reservoir in PNG, Solomon Islands and Vanuatu (**Table 10.4**) suggest that lakes may potentially provide larger catches than rivers. Because Lake Murray in PNG swells to > 2000 km^2 in the wet season, its potential yield may approach 9000 tonnes per year, depending on the duration of inflows.

Table 10.3 Estimated annual sustainable yield (tonnes) of freshwater fish and invertebrates from selected river systems in Pacific Island countries and territories (PICTs), based on the pooled equations for African rivers and floodplains[75]. See Chapter 7 for details of rivers.

PICT	Island	Largest river	Catchment area (km^2)	Annual sustainable yield (tonnes)
Melanesia				
Fiji	Viti Levu	Rewa	2918	80
	Vanua Levu	Dreketi	317	10
New Caledonia	Grande Terre	Le Diahot	589	18
PNG	Mainland	Sepik-Ramu	96,000	2064
	Mainland	Fly	76,000	1661
Solomon Islands	Malaita	Wairaha	486	15
	Guadalcanal	Lungga	394	12
Vanuatu	Espiritu Santo	Jourdain	369	12
	Efate	Teouma	91	3
Micronesia				
FSM	Pohnpei	Nanpil Kiepw	7.8	< 1
Guam	Guam	Talofofo	60	2
Palau	Babeldaob	Ngerdorch	39	1
Polynesia				
American Samoa	Tau	Laufuti	8	< 1
Cook Islands	Rarotonga	Avatiu	5.5	< 1
French Polynesia	Tahiti	Papenoo	91	3
Samoa	Savai'i	Sili	51	2
	Upolu	Vaisigano	33	1
Tonga	'Eua	Fern Gully	2.3	< 1

10.2.4.2 Fly River region, Papua New Guinea

The most reliable estimates of sustainable fish production from freshwater habitats are for barramundi in the Fly River[76], where a total allowable catch has been set at 260 tonnes per year for the combined coastal and inland fishery. Recent assessments suggest that the effective spawning population is large, and that recorded catches of > 170 tonnes per year from the middle Fly River system, and 50 tonnes per year from the coastal fishery, appear to be sustainable.

Sustainable yields for river herring in the Fly River system have been estimated at 18,000 to 33,000 tonnes per year[77] and 5000 to 18,000 tonnes per year[41]. These assessments included habitats that are inaccessible to fisheries, so that estimates of

5000 tonnes per year for this species may be more reasonable. Even so, this represents a significant increase in potential production compared with recent catches of < 500 tonnes per year[2]. For all species combined, potential fisheries yield for the middle Fly River system has been estimated at between 5000 and 10,000 tonnes per year[8,78].

Table 10.4 Estimated annual sustainable yields (tonnes) of freshwater fish from selected lakes in Pacific Island countries and territories (PICTs), based on the pooled equations for African lakes and reservoirs[75].

PICT	Lake	Surface area (km^2)	Annual sustainable yield (tonnes)
PNG	Murray	647	3207
	Chambri	260	1386
	Kutubu	50	304
	Yonki Reservoir	22	143
Solomon Islands	Tegano	155	861
Vanuatu	Letas	19	125

10.2.4.3 Other regions

Following the filling of Yonki Reservoir in PNG, catches of carp, Mozambique tilapia and redbreast tilapia increased by more than 50% from 40.2 tonnes per year in 1992 to 60.8 tonnes per year[30]. People living near Yonki Reservoir had no history of fishing, so that the catches may reflect both improved fishing experience and increasing stocks. Catches may approach the empirical estimate of 143 tonnes per year (**Table 10.4**).

Estimates of sustainable fisheries production from the Sepik-Ramu River system in PNG vary considerably. Initial estimates from the floodplain ranged from 3000 to 5000 tonnes per year[44], whereas subsequent estimates suggested a sustainable production of > 8000 tonnes per year[33,79]. The latter estimates are about four times greater than the empirical estimate in **Table 10.3**, and may reflect the introduction of redbreast tilapia *Tilapia rendalli*, giant gourami *Osphronemus goramy*, Java carp *Barbonymus gonionotus*, golden mahseer *Tor putitora*, chocolate mahseer *Neolissochilus hexagonolepis*, snowtrout *Schizothorax richardsonii*, Emily's fish *Prochilodus argenteus*, pacu *Piaractus brachypomus*, and other species into the Sepik-Ramu River system. The program is considered to have been successful in increasing fish catches for food production and income[57], but the environmental and social sustainability of these fisheries have not been assessed. The estimated sustainable yields of > 8000 tonnes per year may change if the introduced species ultimately have significant adverse effects on habitats, on native species, or on each other.

Sustainable production in Fiji can be estimated from catch records[26]. Mullet catches declined after a peak of > 1000 tonnes in 1988 and appeared to stabilise at a more sustainable 300 to 500 tonnes per year. Most of this catch comes from coastal waters but rivers play an important role in the life cycle of most mullet species. Decreases in freshwater prawn production after a peak of > 100 tonnes in 1991, suggests that sustainable production is likely to be 20 to 50 tonnes per year. However, fluctuations in the Southern Oscillation Index (SOI) (Chapter 2) and river flows[80] may affect natural production of freshwater prawns in any given year. Kai harvests appear to be relatively constant and sustainable at the levels described above[1,26,55].

10.3 Vulnerability of freshwater and estuarine fisheries to the direct effects of climate change

The vulnerability of freshwater and estuarine fish and invertebrates to climate change is expected to arise from the combination of (1) direct effects of changes in physical and chemical quality of the water on the survival, growth, recruitment and distribution of species, and (2) indirect effects caused by alterations to structure and complexity of the habitats that species depend on for food, shelter and reproduction (Chapter 7).

Direct effects result from projected changes in water temperature, river flow rates, salinity, dissolved oxygen and turbidity, driven by alterations in surface air temperatures, rainfall and cyclone intensity (Chapter 2), and increases in sea level (Chapter 3). These changes are expected to affect the physiology and behaviour of freshwater and estuarine fish and invertebrates, and alter the normal cues for spawning and migration.

Here we apply the framework outlined in Chapter 1 to assess the exposure of freshwater and estuarine fish and invertebrate species in the tropical Pacific to the main direct physical and chemical changes to water quality and sea level expected to occur under the B1 and A2 emissions scenarios in 2035 and 2100. We also evaluate the sensitivity of these species to these projected changes, the potential impact on these species, their adaptive capacity to reduce these impacts, and, ultimately, the vulnerability of the fish and invertebrate resources to climate change.

10.3.1 Water temperature

Exposure and sensitivity

Exposure of freshwater fish and invertebrates to projected increases in surface temperature, of 0.5–1.0°C under B1 and A2 in 2035, 1.0–1.5°C for B1 in 2100 and 2.5–3.0°C under A2 in 2100 (Chapter 2), needs to be set against the tolerance of the species to prevailing conditions, and other factors that interact with global warming to increase exposure.

Most freshwater fish and invertebrates cannot regulate their body temperature other than by selecting thermal refuges within their habitat. Increased water temperatures affect their metabolic rate, digestion, growth and muscle performance[81–84].

Freshwater fish and invertebrates that use shallow floodplain habitats in tropical regions often have upper temperature tolerances above 35°C, and some species may tolerate water temperatures > 40°C. In contrast, species that inhabit only river channels tend to occur in waters with temperature < 35°C[85,86].

Prevailing water temperatures in freshwater habitats in the tropical Pacific are typically within the range tolerated by tropical fish described above, although extreme high temperatures in floodplain habitats can kill fish. Water temperatures in the Fly River system vary between 24.8°C and 28.1°C (±3.3 SD) in channel habitats[39], and from 27.7°C (±1.4) to 33.1°C (±1.8) in floodplain habitats[38]. In Fiji, freshwater creeks have temperatures between 20°C and 26.5°C[87], whereas the range for the Rewa River is 24°C to 31°C[88]. River temperatures in Solomon Islands usually range between 24°C and 29°C, but can increase to 31°C in open pools[6] and vary between 23.5°C and 26°C[89] in forested catchments.

Increases in water temperatures of 2.5–3.0°C in flowing waters by 2100 under the A2 emissions scenario are unlikely to expose fish to lethal conditions, although sub-lethal responses may occur. Exposure to high temperatures is likely to occur more frequently in floodplain and supratidal habitats.

Exposure to the expected high temperatures could increase significantly where riparian vegetation has been cleared for other land uses (Chapter 7). For example, on the island of Babeldaob in Palau, deforestation reduced shading of the water surface by 87% and increased water temperature by 0.4°C[90]. In a more extreme case, harvesting riparian forests in British Columbia increased water temperature by up to 8°C[91].

Freshwater and estuarine fish and invertebrates in the tropical Pacific are expected to be sensitive to projected changes in water temperature in their early stages of development. Embryonic development and growth of larval fish are typically more rapid at higher temperatures[92]. Barramundi larvae reared at 31°C develop larger muscle fibres than those incubated at 26°C or 29°C, and may have enhanced swimming ability[93]. Optimal growth of postlarval barramundi occurs over a wide range of temperatures from 27°C to 36°C[94], suggesting that increases of up to 3°C may enhance survival and recruitment. However, accelerated development may mean that larvae have increased likelihood of starvation[95] before they reach their nursery habitats, resulting in lower recruitment. Elevated metabolic rates in *Macrobrachium* spp. at higher temperatures and variable salinities may alter the distribution and migratory behaviour[96] of these species.

Sex ratios may change significantly in populations exposed to elevated water temperatures – Nile tilapia exposed to 36°C resulted in subsequent generations consisting of as few as 19% females[97].

Temperature tolerances may be reduced where fish are exposed to pollutants. In Australia, temperature tolerances of silver perch *Bidyanus bidyanus*, eastern rainbowfish *Melanotaenia duboulayi* and western carp gudgeon *Hyseleotris klunzingeri* were reduced by 2.5°C to 4.3°C following chronic exposure to endosulfan and chlorpyrifos[98]. Dissolved metals also reduce the temperature tolerance of fish[99–102] and crustaceans[103,104].

Clearly, there are serious concerns that exposure of freshwater fish and invertebrates to contaminants from mine wastes, forestry and intensive agriculture may increase sensitivity to rising water temperatures.

Floodplain, Sepik River, Papua New Guinea

Photo: Robert Harding Picture Library/SuperStock

Potential impact and adaptive capacity

Mortality of fish typically increases with rising temperatures, presumably due to the greater demands for energy[105]. In general, fish with a constant weight and growth coefficient have a natural mortality of 0.57 at 25°C[105]. The projected increases of 0.5–1.0°C by 2035 are not expected to affect this estimate. Even the projected increases of up to 1.5°C under the B1 emissions scenario, and up to 3.0°C under A2 by 2100 are only likely to alter the general mortality rate marginally, increasing it to 0.58 and 0.60, respectively. Therefore, the potential impact of direct projected increases in temperature on adult freshwater and estuarine fish and invertebrates is considered to be small.

Fish eggs and larvae, which are more susceptible to the effects of heat stress, are expected to experience higher mortality more frequently in shallow habitats under both climate change scenarios, but especially under A2 in 2100. Reduced reproductive performance may also affect recruitment through changes in sex ratios[97,108].

Potential impacts due to the direct effects of higher temperatures are expected to be greatest where elevated contaminant loads and deforestation occur together. These effects should be reduced by planting riparian vegetation to increase shading of the water surface, and by improving the interception of runoff to prevent contaminants entering freshwater habitats (**Figure 10.2**).

Effects of rising temperatures are expected to be greater in freshwater lakes than in rivers, where they are likely to influence fisheries production by altering primary productivity[106]. Warmer waters can result in greater primary production in lakes and, in turn, increased harvests from fisheries[107]. For example, total estuarine and coastal fisheries landings in the Burdekin-Dry Tropics region in northern Australia are estimated to increase by 40% to 60% in the next 50 years under the A2 scenario due to the effects of temperature on primary production[107]. Nevertheless, the impact of increasing temperatures on fisheries harvests is also likely to depend on the balance between bottom-up effects (primary production), driven by nutrient availability, and the top-down effects of predation.

The distributions of species currently limited by their lower temperature tolerances are expected to expand as waters warm, especially for those species that migrate through the sea. For example, the distribution of barramundi is likely to increase southward by 800 km under the A2 scenario[109].

Potential negative impacts of higher temperatures will be ameliorated to a degree by the adaptive capacity of species. In addition to high temperature tolerances, which extend to 38.5°C to 39.0°C in barramundi, bony herring *Nematalosa erebi* and Nile tilapia[110], most species have a physiological ability to acclimate to increasing temperatures[86]. For example, zebrafish *Danio rerio* embryos reared at 33°C produce more heat shock protein to cope with thermal stress than embryos incubated at lower temperatures[111]. Carp also develop increased temperature tolerance after acclimation to temperatures of 30°C to 35°C [112]. However, the capacity of fish to adapt to increased temperature will be reduced by exposure to pollutants.

Vulnerability

The vulnerability of fish in lowland rivers and estuarine habitats to projected increases in water temperatures under the B1 and A2 emissions scenarios is expected to be low (**Table 10.5**). This assessment is based on the ability of most species to withstand fluctuating, elevated temperatures under existing conditions, combined with their capacity to adapt physiologically to projected increases in water temperature.

In contrast, fish in shallow floodplain or supratidal habitats that heat rapidly, and where prevailing temperatures are closer to their upper thermal limits, are more vulnerable to damaging warmer temperatures (**Figure 10.2**). Recruitment of species with wetland-dependent juvenile stages may be affected if cooler temperature refuges

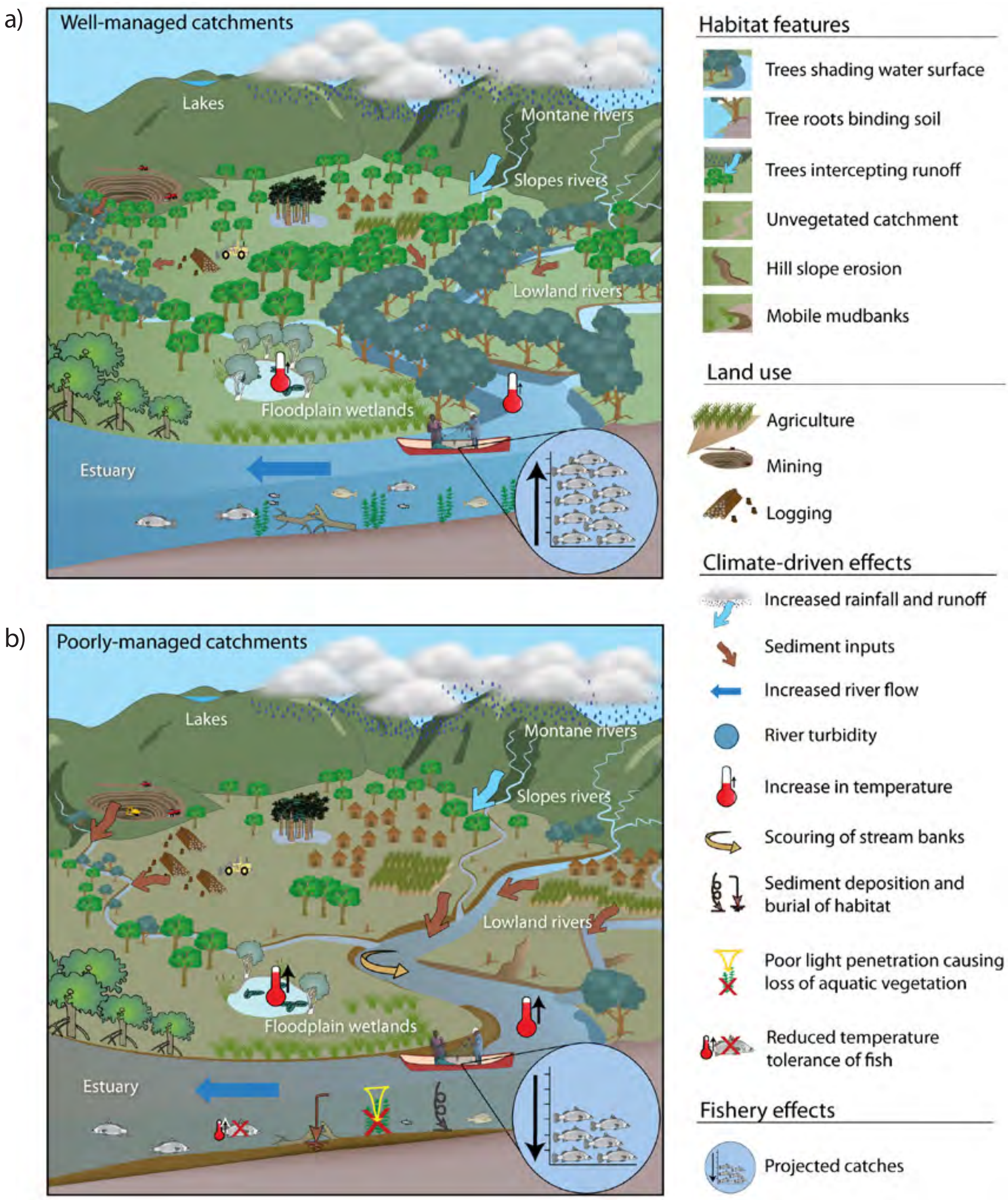


Figure 10.2 Principal effects of climate change on freshwater and estuarine fisheries in (a) well-managed and (b) poorly-managed catchments. In well-managed catchments the increase in habitat availability as a result of climate change is expected to result in increased fish catches. In poorly-managed catchments, where vegetation cover has been reduced, exposure of fish to warming and turbidity will be greater. Contaminants washed from poorly managed catchments would increase sensitivity to higher temperatures further leading to reductions in fish catches.

are not available. At high elevations in PNG, coldwater fish such as rainbow trout, snowtrout and mahseer, are vulnerable to upstream habitat contraction as temperature increases. Fisheries production is also expected to become more vulnerable to thermal stress in catchments that have been partially or completely cleared of forest, or where mining operations, intensive agriculture and forestry lead to elevated contaminant loads in rivers.

Table 10.5 Expected vulnerability, and direction of response (⇧ = higher, ⇩ = lower), of various groups (and representative species) of fish and invertebrates in Pacific Island countries and territories to the direct effects of climate change. Assessments are based on projected changes in water temperature, river flow, salinity, dissolved oxygen (O_2) and turbidity. Note that vulnerability is often projected to be different for disturbed catchments.

Group	Water temperature	River flow	Salinity	O_2	Turbidity
Catadromous species Barramundi, eels, jungle perch, mullet, oxeye herring	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments
Amphidromous species Gobies, gudgeons, *Macrobrachium* spp.	➢ L ⇧, ➢ L ⇩ at high elevation ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments
Marine visitors Snappers	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇧	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in disturbed catchments
Potamodromous species River herring, kai, carp*	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇩ ➢ M ⇩ where upstream retreat is blocked	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments
High-elevation species Rainbow trout*, snowtrout*	➢ M ⇩ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ na	➢ L ⇩	➢ M ⇩ ➢ H ⇩ in disturbed catchments
Substrate spawners Eel-tailed catfish, large gudgeons	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ M ⇩ ➢ H ⇩ in disturbed catchments
Mouth brooders Fork-tailed catfish, saratoga	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ M ⇩ ➢ H ⇩ where upstream retreat is blocked	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments
Tilapia*	➢ L ⇧ ➢ H ⇩ in disturbed catchments	➢ L ⇧	➢ L ⇩	➢ L ⇩ ➢ M ⇩ in floodplain and lake habitats	➢ L ⇩ ➢ M ⇩ in disturbed catchments

* Introduced species; H = high vulnerability; M = moderate vulnerability; L = low vulnerability; na = not applicable.

10.3.2 River flow

Exposure and sensitivity

Projected changes in rainfall, and increased intensity and variability of rainfall (Chapter 2), are expected to expose freshwater fish and invertebrates to complex changes in river flows (Chapter 7). The projected trend under the A2 scenario is for a wetter climate and increased river flows in both wet and dry seasons, producing an estimated -5% to +20% change in mean annual discharge in the western Pacific (Chapter 7). For PICTs in the east, projections under the A2 scenario are for a slight reduction in wet season flows, and increased dry season flows, changing mean annual discharge by -10% to > +20%. In contrast, for New Caledonia, wet season flows are expected to increase, with a decrease in dry season flows, producing an overall change in mean annual discharge of -20% to +20% (Chapters 2 and 7). These projections under A2 are more pronounced in 2100 than in 2035. Projected flow regimes under the B1 scenario are largely intermediate between existing conditions and the A2 scenario.

Superimposed on changes in river flow is the likelihood that more extreme flow events could become even more extreme if tropical cyclones become more intense. Although there is still no consensus about the changes to the frequency and intensity of El Niño-Southern Oscillation (ENSO) events, they will remain a feature of the tropical Pacific climate and will continue to have profound effects on river flow through droughts (Chapter 2).

Cyclones and droughts affect river flows on different spatial and temporal scales. Cyclones usually affect spatial scales of the order of ~ 100 km, whereas droughts can influence entire climatic regions at scales of 1000 km. In contrast to the short-term floods associated with cyclones, low flow conditions caused by drought often last for several years, with ecological recovery requiring even longer[113–115]. Despite the widespread expectation for higher rainfall, periods of reduced river flow may also increase under the influence of higher air temperatures and increased evaporation.

Fish in rivers and estuaries are particularly sensitive to changes in river flow, such as the magnitude, timing, frequency and duration of flow events, the rate of change in flow, and the seasonality, variability and predictability of flows[116]. Four types of river flow that affect fish are described in Chapter 7 and summarised briefly below.

- **Population maintenance flows** influence fish biomass through changing the area of available channel and floodplain habitats[117], and are related to flow magnitude measured as volume, depth or area of inundation.
- **Critical flows** trigger life history events such as migration or spawning, and are characterised by velocity and seasonal timing.

- **Habitat flows** maintain environmental quality, such as temperature, dissolved oxygen, sediment transport and substratum characteristics, and plant growth, and operate directly by scouring sediments from gravel spawning beds, or indirectly by increasing productivity of the food web. Habitat flows are characterised by volume, velocity and inundated area.
- **Stress flows** occur during extreme high or low flows, commonly associated with cyclones and El Niño drought events, and may damage fish and their habitats through high velocities, or cause habitat contraction.

Consequently, river flows affect fish directly, and indirectly through modification of habitats (Section 10.4).

Barramundi in northern Australia provide a good example of the effects of changes in river flow on riverine and estuarine fisheries, and the relationships between flow, habitat and aquatic production (Box 10.2). Populations of barramundi are expected to be sensitive to changes in river flows in PNG because the timing and magnitude of flow has a strong influence on downstream migration and spawning.

The strong relationship between river flows and abundance and catches has been well documented for many species[72,117,128,129]. It is based on interactions between seasonal habitat availability, nutrient transport, algal production, food web processes leading to increased recruitment, and cues for fish migration[74,116,130,131].

Kai clams within the lower reaches of rivers in Fiji appear to be resilient to strong flows because they burrow in sediments. However, excessively fine sediments may limit the distribution of kai by inhibiting the ability of the clams to feed using their siphons[46]. Feeding and growth of kai are presumably influenced by freshwater flows, with moderate increases in flow providing improved access to suitable habitat and food. Existing catch data are inadequate to determine whether production of kai is sensitive to changes in river flow, however.

Amphidromous species, such as *Macrobrachium* spp., reproduce in fresh water and larvae are carried by flow downstream to the estuary[132] (Box 10.1). After a larval period of 50 to 110 days, postlarvae migrate upstream[133,134] in response to freshwater flow[135–137]. Dispersal of larvae through the sea is an important life history feature for maintaining *Macrobrachium* distributions[138]. Strong flows can cause downstream displacement, but this can be balanced by increased upstream migration opportunities during high flows[139].

Larvae of amphidromous gobies may survive in fresh water for only a few days if they consume their yolk supply before reaching salt water[25]. During normal and low flow conditions, most larvae may starve to death before reaching the sea[140]. Spawning, downstream migration to the sea, and upstream return migration are cued by seasonal flow events[141], so that even small changes in flow magnitude or timing may affect survival of larvae and recruitment. Because of the long duration of the larval period,

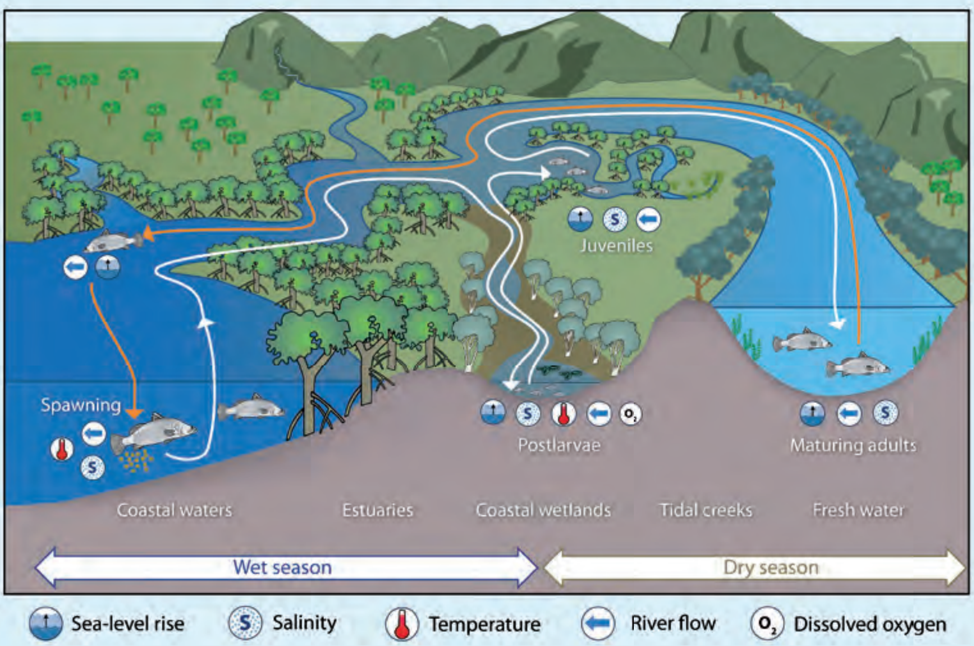
Box 10.2 Life cycle of barramundi *Lates calcarifer*

Barramundi live in coastal waters, estuaries, tidal creeks and lagoons, saltpans, floodplain wetlands and rivers with temperatures ranging from 15°C to 39°C and salinity from 0 to 40 practical salinity units (PSU). Their distribution is limited by lower temperatures and presence of permanent flowing rivers. The eggs survive salinities of 22 to 40 PSU, and early juveniles live in hypersaline flats with temperatures up to 36°C[118–122].

River flows allow adult barramundi to migrate from freshwater to coastal habitats to spawn. Early wet season flows then allow the resulting juveniles to migrate from coastal nurseries into freshwater habitats[109,118,120,123]. Towards the end of the wet season, juveniles move into permanent freshwater habitats where they mature. Growth is fastest in wet seasons with high freshwater flows and warm temperatures[124,125].

Recruitment is strongest in years with high freshwater flows during the spawning and nursery periods[126], translating into increased catches in subsequent years[75,109,125,127]. However, stress flows from severe cyclones reduce barramundi recruitment through reduced egg survival, increased predation in nursery habitats, and downstream displacement of juveniles[73], leading to lower catches in subsequent years.

Lack of flow during prolonged droughts also affects barramundi. Catches in the Fly River in PNG declined dramatically in the early 1990s when floodplain wetlands dried during an El Niño drought[38,67].



most amphidromous species are assumed to disperse widely before re-entering fresh water, but the incidence of fish returning to their natal river or island, is unknown. Goby larvae and *Macrobrachium* spp. are assisted in reaching the sea if spawning coincides with flow events. Return migrations are also assisted by flows that improve habitat continuity through cascades and pool-riffle sequences (Chapter 7).

Potamodromous species that migrate within river channels, or between channel and floodplain habitats, also fluctuate in abundance according to the magnitude and timing of freshwater flows. For example, the abundance and recruitment of bony herring *Nematalosa erebi* in Australia is reduced in rivers affected by flow regulation[142,143].

A decrease in abundance of invertebrates by > 50% occurred in the Port Curtis estuary in Queensland during the 1997–1998 El Niño drought[144]. El Niño drought elsewhere in Queensland has also caused reduced catches of fish, e.g. striped mullet *Mugil cephalus* and flathead *Platycephalus* spp.[127].

Potential impact and adaptive capacity

Modest changes in river flow may have significant effects on fish populations and catches in rivers and estuaries in the tropical Pacific. Flow accounts for 30% to 80% of variation in estuarine fishery catches in Queensland[127], and similar dependence on flow has been demonstrated in tropical riverine fisheries elsewhere[117].

Anecdotal evidence from the tropical Pacific largely supports this generalisation. Projected changes in rainfall for most PICTs are expected to enhance population maintenance flows, critical flows, and habitat maintenance flows. Provided that rainfall coincides with the timing of critical spawning, recruitment and migration behaviour, these changes are likely to result in increased populations of freshwater and estuarine fish. For barramundi, for example, increased rainfall during the low flow season is expected to provide moderate increases in habitat availability, and elevated wet season flows should increase access to shallow nursery habitats, leading to increased recruitment (Box 10.2). Stocks of other catadromous species, including striped mullet, eels, flagtails and oxeye herring are also expected to increase in response to higher rainfall and river discharge.

In contrast, elevated wet season flows in New Caledonia are likely to trigger migration and spawning of the common freshwater fish species found there, which may then be negated by reduced population maintenance and habitat flows in the dry season.

In rivers where water resource development alters seasonal flow regimes, fish typically show limited capacity to adapt to changes in flow seasonality, and decline in abundance. However, in tropical Pacific rivers where seasonal temperatures are relatively stable, fish may have a greater capacity to adapt to changes in seasonal flows as a result of climate change.

Impacts of stress flows from cyclones on riverine and estuarine fisheries are expected to be largely transient, but nonetheless may be severe in affected areas. Fish in montane habitats are adapted to cope with spate flows, and recolonisation after downstream displacement tends to be rapid[137,139]. Stress flows from cyclones are also expected to have relatively low impacts on catadromous species, amphidromous gobies and *Macrobrachium* spp., and on potamodromous species that have extensive distributions in large river systems. For such species, populations in unaffected reaches should recolonise damaged areas relatively rapidly.

Photo: Jay Dickman/Corbis

Fishing with spears in a coastal river, Papua New Guinea

Harvests of kai clams may be interrupted for longer periods during the stronger flows from more extreme rainfall events and cyclones. This outcome is expected mainly through the reduced ability of women to collect kai during high flows[46]. Indeed, most freshwater fishing operations in PICTs within the cyclone belt are expected to be disrupted for longer periods after cyclones until flood flows, debris and water quality return to normal.

The frequency and intensity of El Niño events is also expected to be important in determining the long-term population size of tropical freshwater fish species. Changes to river ecosystems[131] by ENSO and similar extreme events are likely to continue to cause variation in fishery yields from freshwater and estuarine habitats.

Vulnerability

Vulnerability of freshwater and estuarine fisheries to changes in river flow under the B1 and A2 emissions scenarios is expected to be low in the tropical western Pacific (**Table 10.5**), where fish production is projected to increase because of enhanced population maintenance flows, critical flows and habitat flows. In the eastern Pacific, annual flows are expected to increase and to become more uniform, largely through an increase in dry season flows. Rivers in this region are likely to provide increased population maintenance flows and habitat flows, but may experience a reduction in critical flows in dry years. These changes may enhance fish populations through increased habitat availability and quality, but with potentially limited recruitment.

In contrast, vulnerability of freshwater and estuarine fisheries in New Caledonia to changes in river flow is likely to be moderate to high because of lower flows and reduced habitat availability during dry seasons, with some possibility of compensation by increased critical flows during the wet season.

PICTs within the cyclone belt are expected to be more vulnerable to damaging variations in river flow because of the episodic occurrence of severe stress flows.

The anticipated positive and negative changes are projected to be less pronounced under the B1 scenario in 2035 and greatest in 2100 under the A2 scenario. In the absence of detailed studies and downscaled climate modelling, changes in fish stocks and potential yields are estimated to be approximately proportional to changes in rainfall.

10.3.3 Salinity

Exposure and sensitivity

Projected rises in sea level of 20–30 cm by 2035 under the B1 and A2 scenarios, and up to 70–110 cm and 90–140 cm by 2100 under the B1 and A2 scenarios, respectively (Chapter 3), are likely to not affect the salinity of existing freshwater and estuarine habitats uniformly. Some of the larger islands with well-developed floodplains have the highest sediment deposition rates in the world at 3.2 to 4.0 cm per year (Chapter 7), and accretion may outstrip the effects of sea-level rise so that salinity regimes do not alter significantly. Conversely, estuaries on islands that are subsiding will experience greater upstream penetration of salt water. Large river systems such as the Fly and Sepik-Ramu, are expected to have increased freshwater discharge (Chapter 7), which should counter saline intrusion to some extent. Exposure of fish to increasing salinity will, therefore, be determined by a combination of the magnitude of sea-level rise, subsidence and uplift at the island scale, and by freshwater discharge and sediment deposition at the local river scale. These processes would be affected by more severe cyclones, and by droughts associated with El Niño events.

Species likely to be exposed to increased salinity are mainly estuarine residents, marine visitors, catadromous fish such as barramundi, and amphidromous animals such as *Macrobrachium* spp. and gobies. Most of these species are expected to have little sensitivity to increased salinity, however, because of their occurrence in estuarine or salt water for at least part of their life cycle, and their ability to tolerate a wide range of salinities.

In lowland reaches of small rivers, freshwater species that are unable to retreat upstream because of steep cascades, waterfalls, or man-made barriers are expected to be exposed to higher salinities as sea level rises. Species such as sooty grunter *Hephaestus fuliginosus*, saratoga *Scleropages jardinii*, and sleepy cod *Oxyeleotris herwedenii* in these reaches have low tolerance to increased salinities. Large numbers of saratoga died in the Torassi River in western PNG during a severe El Niño event in 1997–1998, when reduced freshwater flow allowed salt water to penetrate 100 km upstream[36]. The combination of environmental stress, increased fishing pressure, and increased catchability in restricted habitats, can result in dramatic reductions of local saratoga populations. Other species, like barramundi, oxeye herring, and mullet have well-developed osmoregulatory abilities to tolerate increasing salinity.

Fishing for *Macrobrachium* in New Caledonia

Photo: Nicolas Petit

Potential impact and adaptive capacity

Variation in salinity tolerances among species produces distinct assemblages along salinity gradients in estuaries[145–148]. Changes in species composition can be expected at fixed locations in estuaries and the lower reaches of rivers as marine species penetrate further inland, and species with low salinity tolerance move upstream. For example, kai clams in Fiji live in brackish to fresh water at the upper tidal limit, and are likely to be forced to move upstream as sea level rises. Tilapia and carp, which are noted for their tolerance of low salinities, are unlikely to be affected by saline intrusion except at the downstream limit of their distributions, where they are expected to adapt by retreating upstream.

Salinity tolerances and acclimation may also be temperature dependent[149], so that interactions between altered rainfall, increased temperature, and saline intrusion may produce unexpected results for some species and locations. One possibility is that extreme cyclones may create freshwater plumes extending for large distances along the coast or to other islands to allow increased dispersal of freshwater species.

Vulnerability

Where no barriers to upstream migration occur, populations of freshwater and estuarine fish and invertebrates are likely to have low vulnerability to increased salinity stemming from sea-level rise (**Table 10.5**), although they can be expected to move upstream. Vulnerability to increased salinity is likely to be moderate in catchments where upstream migration of sensitive species is blocked. In these rivers, reduced stocks of sensitive species can be expected, but species that tolerate a wide range of salinities should remain.

10.3.4 Dissolved oxygen

Exposure and sensitivity

The availability of oxygen (O_2) in water is determined by diffusion from the atmosphere, production of O_2 by photosynthesis and consumption of O_2 by aerobic respiration. Dissolved oxygen in aquatic habitats typically peaks around dusk as a result of photosynthesis during the day, and declines overnight to minimum values in the early morning. Diel fluctuations in O_2 availability in flowing waters tend to be small because movement of the water surface promotes O_2 diffusion from the atmosphere, and mixing in the water column. In standing waters, however, large diel fluctuations in O_2 availability near the surface, and the depletion of O_2 in water layers near the bottom, can constrain fish movements, even within well-oxygenated habitats.

Oxygen solubility in water varies according to temperature, salinity and atmospheric pressure. At sea level, O_2-saturated fresh water at 20°C contains 9.09 mg O_2 per litre, but at 35°C contains only 6.95 mg O_2 per litre[150]. Respiration of most aquatic organisms increases with increasing temperature, so that an increase in temperature simultaneously increases biological O_2 demand and reduces the availability of O_2. As temperature increases, fish expend more energy in ventilating their gills[151] until the decreased O_2 availability is insufficient to meet the increased metabolic demand.

Projected reductions in O_2 availability as a result of temperature increases range from 0.08 to 0.12 mg per litre by 2035 under the B1 and A2 scenarios, equivalent to a change of 1% to 1.5% of saturation, to 0.15 to 0.23 mg per litre (1.8–2.8%) in 2100 under the B1 scenario, and 0.37 to 0.44 mg per litre (4.5–5.3%) in 2100 under the A2 scenario. These projected reductions are small compared with the changes in dissolved O_2 that occur over daily cycles as a result of photosynthesis and respiration by primary producers, or changes with depth in wetlands and lakes.

Actual changes in O_2 availability as a result of climate change can be difficult to project, and will vary greatly among habitats. For example, the rate of O_2 diffusion from the atmosphere into water is influenced by wind and wave action. Where wind turbulence increases mixing of the water column in shallow lakes, O_2 availability is expected to increase. However, in deep, stratified lakes, increased wind action under projected climate regimes (Chapter 2) is expected to bring hypoxic water from below the thermocline to the surface, resulting in reduced O_2 availability and declining fisheries production[152].

Under scenarios of higher temperatures and increased biological oxygen demand, O_2 availability is likely to decrease in some floodplain habitats. For example, growth of floating plants can form a barrier to diffusion of O_2 from the atmosphere, resulting in deoxygenation of the water column. Such declines will be offset in rivers where increased flow can be expected to maintain O_2 availability at or near saturated levels. In wetlands, fish and invertebrates are most likely to be exposed to reduced O_2 availability in water bodies with high organic loads that experience increased temperatures and drying. Fish in lakes may also experience reduced O_2 availability, depending on stratification patterns.

Species that live in flowing, well-aerated rivers typically have low tolerance to low O_2 concentrations. For example, jungle perch are rarely found in water containing less than 6.8 mg O_2 per litre[153]. In contrast, species such as snakeheads have accessory air-breathing organs that enable them to survive in wetlands when O_2 availability becomes too low to support aquatic respiration. Sensitivity of fish and invertebrate species to changes in O_2 availability as a result of climate change is therefore expected to differ depending on their preferred habitats and their tolerance to oxygen depletion.

Potential impact and adaptive capacity

Under normal conditions, the projected changes in O_2 would have negligible effects for most fish species, except for those in marginal habitats where O_2 is already limited. The effects of reduced O_2 availability may be more widespread, however, than suggested by the distribution of exposed habitats. Where shallow wetlands provide nursery habitats for species such as barramundi in PNG, reduced O_2 availability may limit recruitment. This situation may be exacerbated if predators of juvenile fish in wetland nurseries have greater tolerance of hypoxia than species valued for food. In PNG, for example, invasive alien species such as snakeheads may become significant predators of juvenile barramundi[32].

Despite their tolerance of extreme environmental conditions, barramundi in PNG are sensitive to climate effects when wetlands dry during a drought[38]. Potential for reduced O_2 availability in wetlands may then also reduce survival and recruitment in the subsequent wet season, reducing the resilience of the barramundi population to other disturbances.

Tropical fish species in habitats prone to low O_2 availability tend to be tolerant of hypoxia[151], and may have physiological adaptations such as increased blood-oxygen affinity[154], accessory air-breathing organs, and behaviours such as avoidance of hypoxic habitats or the ability to respire from the air-water interface[155]. Increased frequency of hypoxia may therefore result in fish communities dominated by hypoxia-tolerant species.

Sleepy cod *Oxyeleotris herwedenii*, Fly River, Papua New Guinea

Photo: Boga Figa

Vulnerability

Vulnerability of fish to reduced O_2 availability in riverine and estuarine habitats as a result of climate change is likely to be low under both B1 and A2 emissions scenarios in 2035 and 2100 because flowing habitats are actively aerated (**Table 10.5**). Species in habitats prone to low O_2 availability, such as floodplain and supratidal habitats, are naturally vulnerable to hypoxia (**Figure 10.2**), as is evident from fish kills following episodic O_2 depletion. However, vulnerability to hypoxia in floodplain and supratidal habitats as a result of climate change is likely to remain low under both emissions scenarios in 2035 because changes in water temperature and rainfall are relatively modest. Vulnerability of fish to hypoxia in floodplain and supratidal habitats may increase to moderate (**Table 10.5**) by 2100 under the A2 emissions scenario due to the increased likelihood of hypoxic events under conditions of more variable rainfall and increased temperature.

10.3.5 Turbidity

Exposure and sensitivity

Turbidity is caused by suspension of fine sediments in the water column. Turbid water is derived from an upstream source of fine sediment, such as the river bed or banks, or eroding hill slopes. Turbidity is also influenced by the level of catchment disturbance due to mining, forestry and agriculture, which all increase the amount of fine sediments entering rivers (Chapter 7). Catchments with intact vegetation are likely to experience little change in water turbidity as the climate changes because potential increases in sediment transport with increasing rainfall will be offset by increased growth of catchment vegetation. Catchments in which vegetation has been cleared are exposed to increased soil erosion and elevated water turbidity as rainfall increases.

In catchments with relatively intact vegetation and stable soils, transient increases in turbidity are likely to be minor under both the B1 and A2 scenarios in 2035, with potential for small increases in turbidity towards 2100 because of the increase in rainfall and runoff. However, in catchments that have been extensively cleared, the loss of soil stability and increased rainfall is expected to lead to prolonged increases in turbidity, which are likely to be more pronounced towards 2100, especially under the A2 scenario.

Most freshwater fish are relatively tolerant of the direct effects of turbidity – field evidence for direct sensitivity of fish to turbidity is rare. However, extreme suspended sediment loads > 40 g per litre can damage the gill epithelium of fish and affect respiration[156]. Also, fish species that inhabit clear waters in montane and slopes reaches of rivers, and other high-elevation habitats (Chapter 7), tend to be more sensitive to turbidity than species from lowland rivers or floodplain habitats. Lower turbidity levels that reduce light penetration may affect feeding ability of visual predators, although this is less of a problem for planktivorous fish than for piscivores[157]. Indeed, many fish species thrive in naturally turbid rivers such as the Fly River in PNG.

The fine sediments associated with turbidity can affect the availability of spawning sites[158]. However, fish species that produce pelagic eggs (e.g. barramundi, tropical snappers, carp and mullet), or which incubate eggs in their mouths (fork-tailed catfish and tilapia), are less affected by settlement of fine sediments than species with adhesive demersal eggs, such as eel-tailed catfish and gudgeons.

Fish and invertebrates are also expected to be sensitive to turbidity because it can change the habitats and food webs on which they depend (Section 10.4). Benthic primary producers are important in food webs in montane and slopes reaches of rivers, as well as lowland river channels and floodplain wetlands (Chapter 7). Highly turbid rivers typically deposit fine sediments which cover existing habitats, reducing the availability of feeding surfaces[158]. Turbidity also reduces light penetration for photosynthesis by macrophytes, phytoplankton and benthic algae.

Potential impact and adaptive capacity

Impaired feeding ability and spawning success resulting from higher levels of turbidity may reduce the abundance and growth rates of some freshwater fish species. Effects are more likely, however, via changes in primary production that drive a shift from food webs dominated by macroinvertebrate pathways to those based on zooplankton.

Such effects may result in changes in the species composition of fish communities[159]. For example, where elevated turbidity limits benthic production, species such as river herring, mullet and *Macrobrachium* spp. may be forced to rely on other food sources such as zooplankton and detritus. If alternative food sources are not available, or are in limited supply, these important species may decline in abundance, subsequently affecting predators like barramundi and spot-tail bass.

Turbid water can be expected to affect the success of visual fishing methods, such as spears, but should favour non-visual methods like gill nets and derris poisoning.

Photo: Kent St John

Cleaning fish beside a river in Papua New Guinea

Vulnerability

Vulnerability of freshwater and estuarine fish to changes in turbidity as a result of changing patterns of rainfall is expected to be low for both the B1 and A2 scenarios in 2035 and 2100 in well-vegetated catchments (**Table 10.5**). However, clearing of catchment vegetation predisposes aquatic habitats to increased turbidity with increasing rainfall intensity. Accordingly, in disturbed catchments, vulnerability of fish to elevated turbidity will be moderate under the B1 and A2 emissions scenarios in 2035 and the B1 scenario in 2100, and high under the A2 scenario by 2100. Species with demersal eggs are more vulnerable to settlement of fine sediments than species with pelagic eggs.

10.4 Vulnerability of freshwater and estuarine fisheries to the indirect effects of climate change

In addition to the direct physical and chemical changes affecting freshwater and estuarine fish and invertebrates, the projected effects of climate change on the functional process zones of rivers described in Chapter 7 are also expected to affect species that depend on the habitats in these zones for shelter, feeding and reproduction (**Figure 10.2**). Alterations to the biological components of habitats (e.g. aquatic plants and food webs) are expected as a result of increased temperatures, more variable and extreme river flows, new salinity regimes, altered oxygen availability and changes in turbidity, driven by global warming, changes in rainfall, sea-level rise, the intensity of cyclones and the continuation of El Niño events. Variations in river flow will also change the sedimentary and geomorphological characteristics of some habitats.

The scarce information on abundance and status for most freshwater and estuarine fisheries in the tropical Pacific, and the limited knowledge of the biology of these species, makes it difficult to assess the indirect effects of climate change on freshwater fisheries[160]. Overall, the projected increases in availability of shelter, feeding and spawning habitats (Chapter 7), as a result of increased flows stemming from climate change, are expected to enhance freshwater fish populations in many PICTs.

10.4.1 Vulnerability of fish and invertebrates to changes in functional process zones and freshwater habitats

10.4.1.1 Montane rivers

Exposure and sensitivity

The main fisheries species in montane habitats are introduced rainbow trout, carp and tilapia, which have been stocked in the highlands of PNG. These fish are likely to be exposed to reductions in the amount of coldwater habitat available, higher production rates of benthic algae and riparian vegetation, and increased supplies of organic material to food webs (Chapter 7). Changes in water temperature and sediment inputs are expected to be more pronounced in cleared catchments.

Sensitivity to increased water temperature and flows will be influenced by a combination of opposing effects. Coldwater species such as rainbow trout and snowtrout are expected to be affected negatively by these changes, but tilapia and carp may benefit through increased habitat availability, increased food production and faster growth. Higher rainfall may lead to increased frequency of stressful high-flow velocities, increasing the downstream displacement of fish, but prolonging connectivity to facilitate recolonisation of upstream habitats.

Potential impact and adaptive capacity

The effects of changes to the montane sections of rivers on the resident fish species are most likely to be beneficial because the projected impacts will shift habitats closer to the preferences of tilapia and carp. Production of these species is likely to increase, potentially improving the value of the fishery to local people to compensate for reduced production of coldwater species. The exception to these projections is in the montane rivers of New Caledonia, where projected habitat changes are expected to reduce fish abundance.

Vulnerability

Vulnerability of fish production in montane rivers is expected to be low (**Table 10.6**). Indeed, fish production is likely to increase slightly under the B1 and A2 scenarios in 2035 and under B1 in 2100. The increase will be more pronounced under the A2 scenario in 2100 as a result of greater warming and increased rainfall in most of the region.

In PNG, coldwater species, such as rainbow and snowtrout, are expected to decrease in abundance due to increasing temperature under the B1 and A2 scenarios in 2035 and under B1 in 2100. This vulnerability is projected to increase to moderate under the A2 scenario in 2100.

10.4.1.2 Slopes rivers

Exposure and sensitivity

The slopes reaches of rivers are projected to provide more habitats for fish and invertebrates as a result of increased rainfall and river flows (Chapter 7). Production rates of benthic algae and riparian vegetation are expected to increase, resulting in improved food availability for herbivorous fish species. Fish and invertebrates in slopes reaches, such as eels, jungle perch, tilapia, carp, gudgeons, gobies and *Macrobrachium* spp. are likely to respond positively to increased habitat area and food availability, and their production may increase. Subtle differences in physiological tolerances and species ecology are expected to allow some species to respond to environmental change more strongly than others, resulting in a change in the composition of fish communities and catches.

In New Caledonia, the fish fauna is expected to be sensitive to the projected reduction in river flow and habitat area in slopes rivers, and increased exposure to warm temperatures.

Potential impact and adaptive capacity

The low level of clearing in many PICTs will buffer slopes habitats from the effects of increasing temperatures and sediment loads from increased runoff[161]. However, intensive clearing on some islands will increase the effects of warming and erosion associated with increased rainfall. Habitats in catchments with intact vegetation will have a level of protection from the more severe effects of cyclones, and many slopes species are expected to experience only relatively modest changes in their environments. Elevated atmospheric CO_2 concentrations (Chapter 2) are likely to promote growth of riparian vegetation and benthic algae[162,163], enhancing adaptive capacity in regions with increased rainfall by increasing the stabilising effect of catchment vegetation, and providing a higher biomass of algae and detritus for consumers.

Table 10.6 Expected vulnerability, and direction of response (⇧ = higher, ⇩ = lower), of various groups (and representative species) of fish and invertebrates in Pacific Island countries and territories to the indirect effects of climate change. Assessments are based on projected changes in the quality and quantity of fish habitats. Note that vulnerability is often projected to be different in disturbed catchments.

Group	Montane rivers	Slopes rivers	Lowland rivers	Lakes	Floodplain habitats	Estuarine habitats
Catadromous species Barramundi, eels, jungle perch, mullet, oxeye herring	➢ n/a	➢ n/a	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ L ⇧ L-M ⇩ in constrained estuaries ➢ H ⇩ in NC
Amphidromous species Gobies, gudgeons, *Macrobrachium*	➢ n/a	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ n/a
Marine visitors Snappers	➢ n/a	➢ n/a	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ in coastal lakes ➢ M-H ⇩ in NC	➢ n/a	➢ L ⇧ ➢ L-M ⇩ in constrained estuaries ➢ H ⇩ in NC
Potamodromous species River herring, kai, carp*	➢ n/a	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ n/a
High-elevation species Rainbow trout*, snowtrout*, golden mahseer*	➢ M ⇩ ➢ H ⇩ in disturbed catchments	➢ n/a	➢ n/a	➢ n/a	➢ n/a	➢ n/a
Substrate spawners Eel-tailed catfish, gudgeons	➢ n/a	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M ⇩ in cleared catchments and NC	➢ n/a
Mouth brooders Fork-tailed catfish, saratoga	➢ n/a	➢ n/a	➢ L ⇧ ➢ M ⇩ in cleared catchments	➢ L ⇧ ➢ M ⇩ in cleared catchments	➢ L ⇧ ➢ M ⇩ in cleared catchments	➢ n/a
Tilapia*	➢ L ⇧ H ⇩ in disturbed catchments	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ L ⇧ ➢ M-H ⇩ in cleared catchments and NC	➢ n/a

* Introduced species; NC = New Caledonia; H = high vulnerability; M = moderate vulnerability; M-H = moderate-high vulnerability; L = low vulnerability; L-M = low-moderate vulnerability; n/a = not applicable.

Towards the upper elevation limit of slopes reaches, where the water is cooler, increasing temperatures are expected to approach the thermal preferences of species such as tilapia and carp, whereas near the downstream limit, temperatures are likely to remain within the preferred range. Fish production in slopes reaches is expected to increase due to increased food availability, and the increased metabolic rates and growth rates of fish exposed to higher temperatures.

Sampling small fish and *Macrobrachium* in Solomon Islands Photo: David Boseto

Vulnerability

Vulnerability of fish production in slopes river habitats is expected to be low (**Table 10.6**). Indeed, production is expected to increase slightly under the B1 and A2 scenarios in 2035 and B1 in 2100, becoming even higher under the A2 scenario in 2100 as a result of greater warming and increased rainfall in most of the region. However, vulnerability to drought may increase as habitats adjust to a wetter long-term climate regime, so that when droughts do occur, impacts on fish stocks may be more pronounced.

In cleared catchments, and in New Caledonia, vulnerability of fish in slopes rivers will be low to moderate because of the increased negative effects associated with exposure to reduced rainfall under the B1 and A2 scenarios in 2035, and B1 in 2100. Vulnerability will increase to moderate to high in the drier regime under the A2 scenario in 2100.

10.4.1.3 Lowland rivers

Exposure and sensitivity

Fish in lowland rivers are expected to have greater access to suitable habitat due to higher projected rainfall, accompanied by greater growth of macrophytes, benthic algae and phytoplankton, driven by elevated temperatures and concentrations of atmospheric CO_2 (Chapter 7). Higher flows should also increase the extent of aquatic vegetation as the area of wetted habitat enlarges through channel expansion. These changes should provide juvenile fish with increased shelter from predators, and greater primary production at the base of benthic food webs. However, such effects may be balanced by a reduction in vegetated channel habitats through increased sedimentation and turbidity due to the expected increases in rainfall and the possibility of more intense cyclones (Chapter 7).

Downstream lowland reaches are likely to be exposed progressively to higher salinities from rising sea levels and storm surges, causing an upstream retreat of freshwater habitats and fish species. The present suite of fish and invertebrate species is expected to be replaced by more salt-tolerant estuarine fish species.

In New Caledonia, the projections are that fish will be exposed to narrower and shallower lowland rivers as a result of reduced winter flow and episodic sediment delivery following heavy rainfall. Sensitivity to reduced habitat availability and quality is likely to result in reduced fish abundance.

Potential impact and adaptive capacity

In general, rivers with higher discharges provide more complex habitats and support a wider diversity of fish species[164]. Increased flows also promote elevated production in aquatic food webs, resulting in enhanced recruitment and fisheries production. The higher rainfall projected for the region is expected to increase discharge in the Fly River by 9%, and in the Sepik River by 33% by 2050 under the A2 scenario[165], and these changes are likely to increase further by 2100. The increased flows and resulting increases in habitat availability and primary productivity are expected to lead to greater fish abundance.

In drier regions where river flows diminish, smaller lowland river habitats will become more exposed to increasing temperatures, and salt water may penetrate further upstream because of sea-level rise and reduced freshwater flushing. Fish in these rivers are likely to have reduced ability to adapt to the combined environmental challenges compared with fish in rivers with increased flows.

The presence of invasive alien fish species creates greater uncertainty in the projections for fish production due to their potential to tolerate environmental changes more successfully than many native species. There is the possibility that native fish, and those species introduced to increase production, may decrease in abundance under climate change if they are forced into marginal habitats because of their inability to compete with invasive alien species[166], resulting in a reduction in the value of local fisheries.

Vulnerability

Vulnerability of fish in lowland rivers is expected to be low under the B1 and A2 scenarios in 2035 and B1 in 2100. In fact, the main changes are expected to be an increase in fish production as a result of greater river flow. As temperatures and river flows increase under the A2 scenario towards 2100, fish production is projected to increase further (**Table 10.6**).

Fish in lowland rivers where flows are projected to diminish, e.g. in New Caledonia, are expected to be more vulnerable to habitat reduction. In such locations, vulnerability is expected to be low in 2035 under both B1 and A2 scenarios, increasing by 2100 to low to moderate under the B1 scenario, and moderate to high for the A2 scenario.

10.4.1.4 Lakes

Exposure and sensitivity

High-elevation lakes are expected to receive increased inflows, with a reduction in residence time, that should improve water quality (Chapter 7). The projected higher temperatures are also likely to accelerate nutrient cycling and primary production in the pelagic zone. However, coldwater species in high-elevation lakes in PNG, such as rainbow trout, are expected to experience a reduction in habitat area.

Lowland lakes are also likely to receive elevated inflows, extending wet season conditions (Chapter 7), and increasing connectivity with the sea. Fish such as barramundi, river herring, mullet, tilapia and carp should have increased access to lakes and the aquatic macrophytes and food resources they provide. In New Caledonia, lakes are expected to receive reduced inflows and increased evaporation, resulting in a reduction in area and drying of exposed macrophytes.

Coastal lakes may experience increased saline intrusion from rising sea levels and storm surges, leading to replacement of freshwater vegetation with salt-tolerant species, such as mangroves (Chapter 6). This change may be balanced by increased freshwater inflows. Some freshwater fish species in coastal lakes, such as saratoga, are sensitive to saline intrusion, so that exposure to oscillations in salinity may result in these species being replaced by migratory salt-tolerant species, such as mullet and milkfish *Chanos chanos*.

Potential impact and adaptive capacity

The effects of climate change on fish in lakes are likely to vary with altitude, depth, proximity to saline habitats, wind exposure and bathymetry. In high-elevation lakes, warmwater fish species are expected to replace coldwater species, whereas in low-elevation coastal lakes, euryhaline fish species are likely to replace freshwater stenohaline species. Interactions between native fish species and introduced species may result in additional changes that are difficult to forecast, based on factors such as tolerance of hypoxia, changes in temperature and salinity, and drying of habitats. Tolerance of adverse conditions by some invasive alien species may result in them replacing native species and reducing the value of local fisheries, given that long-established introduced fish species are now valued for food. The main invasive alien species of concern occur in PNG, and include snakehead, climbing perch, walking catfish, pacu and Java carp.

Some of the species introduced to increase food supplies, such as tilapia and carp, are tolerant of more extreme environmental conditions, and are prolific breeders. The combination of elevated temperature, food availability, growth rates and habitat availability are likely to translate into increased production of these tolerant species.

Vulnerability

Vulnerability of fish production in lakes is expected to be low, with probable minor changes in species composition. Overall, small increases in fish production are expected from lakes under the B1 and A2 scenarios in 2035 and B1 in 2100. Changes in species composition and fish production should be more pronounced under the A2 scenario in 2100 as a result of greater warming, increased rainfall in most of the region, and increased saline intrusion in coastal lakes (**Table 10.6**).

In drier regions, particularly New Caledonia, fish in freshwater lakes are likely to be increasingly vulnerable to reduced inflows, and increases in temperature and evaporation, resulting in a decrease in fish production. Increased salinisation of coastal lakes is also expected. Vulnerability in such locations is projected to be low by 2035 for the B1 and A2 scenarios, increasing to low to moderate under the B1 scenario in 2100, and moderate to high under the A2 scenario in 2100.

10.4.1.5 Floodplain habitats

Exposure and sensitivity

Fish using floodplains across the region are likely to be exposed to increased inundation of floodplain habitat (Chapter 7), resulting in more productive food webs, and increases in spawning and nursery areas. Increased evaporation due to higher temperatures is likely to be offset by the greater extent and duration of inundation, and increased rainfall. Warmer temperatures, and elevated atmospheric CO_2, should also increase rates of plant growth and decomposition, leading to increases in productivity. Sensitive plant species are likely to be affected by the increased water depth and duration of inundation, and to retreat into shallower habitats. Accordingly, fish in floodplain habitats are expected to respond positively to increases in habitat area, accessibility, and productivity. These gains may be offset by sensitivity to elevated temperatures in marginal habitats and reduced O_2 availability through decomposition of organic material.

Increased deposition of sediments is likely to cause continual alteration in the spatial arrangement of floodplain habitats as aquatic vegetation disappears from some locations, and recolonises others (Chapter 7). At lower floodplain extremities, intrusion of saline water is also expected to change the distribution of aquatic vegetation. Where rising sea levels force freshwater flows onto the floodplain, exposure of floodplain fish species to changes in salinity is likely to be less severe.

In New Caledonia, the rate of sedimentation on floodplains may increase more than elsewhere because of a decline in catchment vegetation as the climate becomes drier, combined with increased erosion during more severe cyclones. Fish are expected to be exposed to reduced permanency and increased temperature in refuge habitats, reduced benthic productivity and increased sedimentation of spawning sites. Sensitivity to these changes may result in reduced fish distributions among habitats, and reduced recruitment and abundance of fish.

Potential impact and adaptive capacity

Floodplain inundation is a powerful driver of fisheries production in large rivers[130], and fish catches in the large floodplain rivers of southern PNG are expected to expand with increasing flow and water temperatures. In particular, increased discharge in the Fly River system[166] is expected to improve the availability of floodplain habitats, and increase production of barramundi, river herring and ariid catfish[38,39,109] by up to ~ 10%. Similar increases in fish production are expected in other rivers.

The magnitude of increased fish production may be influenced by the geological history of individual rivers. The Sepik-Ramu River system in PNG provides a useful case study. The vast floodplains in this system today were formed only 6000 years ago[167]. Fish species that lived in these rivers at that time lacked the adaptations common in typical floodplain species to use the newly-available habitat[44]. As a result, fish production in the Sepik-Ramu River system is substantially lower than the habitats can potentially support. Therefore, increased habitat availability stemming from the elevated river discharge in the Sepik-Ramu might produce only relatively modest increases in fish production, except for introduced species such as carp and tilapia[28,168]. The total increase in production in the Sepik-Ramu River system is, therefore, anticipated to be lower than the 33% increase in river discharge. On smaller islands with limited floodplain areas, fisheries production is still expected to increase in response to increased flows and habitat availability.

The exception to the projections for increased floodplain inundation and fish production is New Caledonia, where reduced connectivity of floodplain habitats in winter is expected to cause a decline in fish production in line with the projections made for other regions experiencing a drier climate[86,161,164].

Vulnerability

Vulnerability of fisheries on floodplain habitats to climate impacts varies among species, river systems and islands, depending on the species composition of the fishery and geological history of the location (**Table 10.6**).

Floodplain fisheries in southern PNG have low vulnerability to all the likely changes to floodplains, and are expected to provide increasing yields under the B1 and A2 scenarios, with the greatest increases in production occurring under the A2 scenario in 2100. On islands where floodplains have developed only recently, vulnerability of fish production will also be low, with the greatest benefits projected to be increased catches of introduced species, such as tilapia and carp. On steep islands with limited floodplain development, vulnerability will also be low but increases in fish production will be modest due to the limited amount of habitat available.

In New Caledonia, vulnerability of fish production associated with floodplain habitats is expected to be low in 2035 for both B1 and A2 scenarios, increasing to low to moderate under the B1 scenario, and to moderate for the A2 scenario in 2100.

10.4.2 Vulnerability of fish and invertebrates to changes in estuarine habitats

Exposure and sensitivity

Estuarine fish and invertebrates are potentially exposed to a greater range of climate change effects than species in freshwater or coastal habitats. These potential changes include the processes of water circulation and sediment transport, and rearrangement of habitats, as well as alterations to nutrient supply, food webs and connectivity between habitats[169]. Species distributions and abundances are likely to be affected by modifications in refuge habitats, feeding areas and spawning sites. Interactions between species are expected to be different, as large predators gain access to formerly shallow habitats as water depth increases.

Most estuaries are projected to extend further upstream as sea level rises, and larger projected freshwater inflows increase flushing of estuaries, resulting in greater discharge of fine sediments and variability in turbidity (Chapter 7). The combination of increased deposition and scouring is expected to produce a more dynamic habitat for fish and invertebrates. The ability of macrophytes, such as seagrasses and mangroves, to stabilise sediment deposits and provide fish habitat will be determined by the rate of sediment delivery, rate of scouring, and rate of plant growth. Greater variability in production of benthic and planktonic algae, and the occurrence and extent of seagrass and mangrove habitats, is likely to occur (Chapter 6). The adaptive capacity of estuarine vegetation is expected to allow estuarine habitats to migrate landward at a similar rate to rising sea levels[170]. Where plant communities are unable to retreat because of local topography, estuarine fish and invertebrates will experience a reduction in habitat area.

Estuarine fish and invertebrates will be sensitive to the projected positive and negative changes in habitat area, depending on local topography. Increased freshwater inflows may strengthen recruitment of many estuarine species that depend on flow cues for breeding and migration, or flow-related increases in primary production.

The sensitivity of estuarine species to expected habitat changes is likely to be greater in New Caledonia, where estuaries may experience greater variability in salinity and sediment deposition during floods associated with stronger cyclones, interspersed with periods of reduced flow and increased salinity.

Photo: Erin Michelle Smith

Children fishing in an estuary in Papua New Guinea

Potential impact and adaptive capacity

The effects of climate change on the production of estuarine fisheries will be driven by local factors that determine the relative impacts of increased river discharge and rising sea level. Sea-level rise is expected to be a persistent change with superimposed tidal oscillations, whereas changes in river flow are likely to be more episodic. The outcome of these interactions will determine whether there is an increase or decrease in the mangroves, seagrasses, intertidal flats, supratidal saltmarshes and wetlands that support estuarine fish production (Chapter 6).

Increasing river discharge is likely to increase nutrient delivery to estuaries which is expected to enhance biological productivity when combined with increasing temperature and CO_2. However, rising sea levels are projected to alter the location of salinity gradients, resulting in substantial losses of mangroves in many places, but allowing them to migrate upstream or landward in other locations (Chapter 6). Where both salinity gradients and mangroves migrate landward, increases in estuarine fish production are likely, albeit with a change in the locations where fish species with specific salinity or habitat preferences occur. Small increases in nutrient delivery are unlikely to drive changes in species composition, but catchments that deliver large increases in nutrient loads may favour the food webs of fisheries dominated by microalgae and epiphytic algae (Chapters 4 and 6). In such situations, fish catches may shift towards small-bodied, short-lived species that achieve high biomass[171].

Extreme climatic events are likely to cause transient inputs of sediments and nutrients during floods, with potential for nutrient depletion during droughts. Provided that these events are not so severe that they eliminate fish nursery habitats (Chapter 6), the effects on production of local fisheries are expected to be transient[38,72,76,109,172].

The geological record provides evidence that estuarine habitats have adapted to past shifts in climate and sea level, and display remarkable resilience to changes in the physical environment (Chapters 6 and 7). However, small estuaries that experience catastrophic habitat damage during cyclones may be severely affected. Such events are likely to cause major losses of mangroves and seagrasses through physical damage, burial by sediments or scouring during floods (Chapter 6).

The wide environmental tolerances of estuarine fish and invertebrates suggest that they will also adapt to habitat changes, and that fisheries production may increase in some areas. Nevertheless, recovery of fish habitats and stocks may be prolonged if there are no nearby sources of recruits to re-establish damaged populations. In general, barramundi are well adapted to changing environments[169]. However, there are differences in migratory behaviour and use of nursery habitats among stocks, so that future impacts on this species in PNG may differ among river systems.

Vulnerability

Vulnerability of estuarine habitats to climate change (Chapter 7), and the resulting vulnerability of estuarine fish and invertebrates, is considered to be low in most PICTs. Rather, effects on fisheries production in estuaries may be positive (**Table 10.6**). Exceptions to this trend are likely in constrained estuaries that become flooded by rising sea levels. Such locations are expected to have low to moderate vulnerability under the B1 and A2 scenarios in 2035 and under the B1 scenario in 2100, increasing to moderate vulnerability under the A2 scenario in 2100.

Other exceptions occur in estuaries with disturbed catchments that deliver elevated contaminant loads (Chapter 7). Where changes to habitats occur, and estuarine fish are exposed to contaminants, fish production is likely to be moderately vulnerable. In New Caledonia, where river discharge and habitat availability is expected to decrease, estuarine fish production may be highly vulnerable.

10.5 Integrated vulnerability assessment

10.5.1 Dominant effects

The direct and indirect effects of climate change on freshwater and estuarine fish and invertebrates (Sections 10.3 and 10.4) are expected to have differing impacts on fisheries production. Increases in average annual river flow are estimated to have by far the greatest influence because fisheries production in freshwater and estuarine habitats is linked strongly to the extent and quality of habitats[75,106,117]. The magnitude, timing, frequency, duration, variability and rate of change in river flows all influence the availability of fish habitat (Chapter 7). River flows also provide cues for fish migration, reproduction and recruitment. Therefore, altered flow regimes are expected to dominate the climate responses that drive changes in freshwater and estuarine fisheries production.

Even so, the benefits of projected increases in river flow are likely to be tempered by the other changes in surface climate and the ocean, especially where these effects interact with human activities in catchments. For example, increasing temperatures could cause modest increases in the growth rates of fish and fisheries production under adequate flow rates, but result in heat stress and lower oxygen levels in shallow habitats isolated from flows, resulting in loss of fish. The probability that higher temperature may adversely affect, rather than foster, growth of fish in slow-flowing or stagnant waters, will be increased where riparian vegetation has been removed.

The expected benefits to fish production from increased flow rates are difficult to quantify because of uncertainties in the underlying climate models and their limited ability to project changes at scales relevant to individual river systems (Chapters 1 and 2). The benefits are expected to be substantial in the tropics and negligible in New Caledonia, and to increase in proportion to projected rainfall under the B1 and A2 scenarios in 2035 and 2100. Interactions among climate change effects and human activities in catchments can also be expected to amplify or negate some of the likely benefits of increased rainfall and river flows.

The effects of climate change on the production of freshwater and estuarine fish are expected to increase in proportion to the perturbations projected under the B1 and A2 scenarios in 2035 and 2100. Primarily, changes in habitat quality, due to increased flushing, warmer temperatures, dissolved oxygen levels and turbidity, are likely to vary among habitats, and may have either positive or negative influences on the growth and abundance of fish and invertebrates. Increases in salinity associated with sea-level rise will be minor in most rivers compared with the range of salinities typically experienced by estuarine fish across the full tidal cycle.

Nevertheless, the production of freshwater and estuarine fisheries is expected to increase in most areas of the tropical Pacific because of the influence of river flow under the B1 and A2 scenarios, both in 2035 and 2100. The magnitude of changes in production will be a function of variation in rainfall, and the frequency of habitat damage by cyclones and drought. Increasing temperature could also produce a small increase in the growth rates of fish and fisheries production, which may, however, be offset in some shallow habitats by increased mortality. The vulnerability of most species groups targeted by freshwater and estuarine fisheries is projected to be low, with a realistic prospect of increased production under both scenarios by 2100, except in New Caledonia.

Fisheries for species that migrate between fresh water and the sea, such as *Macrobrachium* spp. and barramundi, may also be influenced by changes in coastal currents as a result of interactions between oceanic processes (Chapter 3) and changes to freshwater and estuarine habitats. The effects of these changes on the abundance of migratory species are difficult to estimate.

10.5.2 Projected changes in fisheries yields

Available catch estimates and projected changes to fish habitats allow only simple linear projections of fisheries yield under different climate scenarios. Averages of the upper and lower estimates for the projected changes in habitat area under each scenario (Chapter 7) indicate that production of freshwater fish and invertebrates in most PICTs may increase by up to 2.5% in 2035, by 2.5–7.5% under B1 in 2100, and by 7.5% under A2 in 2100 (**Figure 10.3**, **Table 10.7**). These estimates do not take into account changes in fishing effort or the effects of catchment alteration. The uncertainty associated with these estimates is reflected in the range of expected changes in fish production (**Figure 10.3**), which are based largely on expected variation in habitat availability (Chapter 2).

On the basis of recent catch estimates (**Table 10.1**), projected increases in production due to increased habitat availability translate into additional catches of about 1000 to 1500 tonnes per year under the B1 scenario, and about 1500 to 2000 tonnes per year under the A2 scenario, in 2100. These figures must be interpreted with caution because of the uncertainty in catch estimates[1], and the assumptions used to estimate relationships between changes in habitat availability and fisheries production.

Data on fine-scale habitat changes and habitat use are insufficient to attempt projections for individual species. However, differences in environmental tolerances and habitat requirements among species, and trophic interactions, are likely to lead to some unexpected outcomes[107].

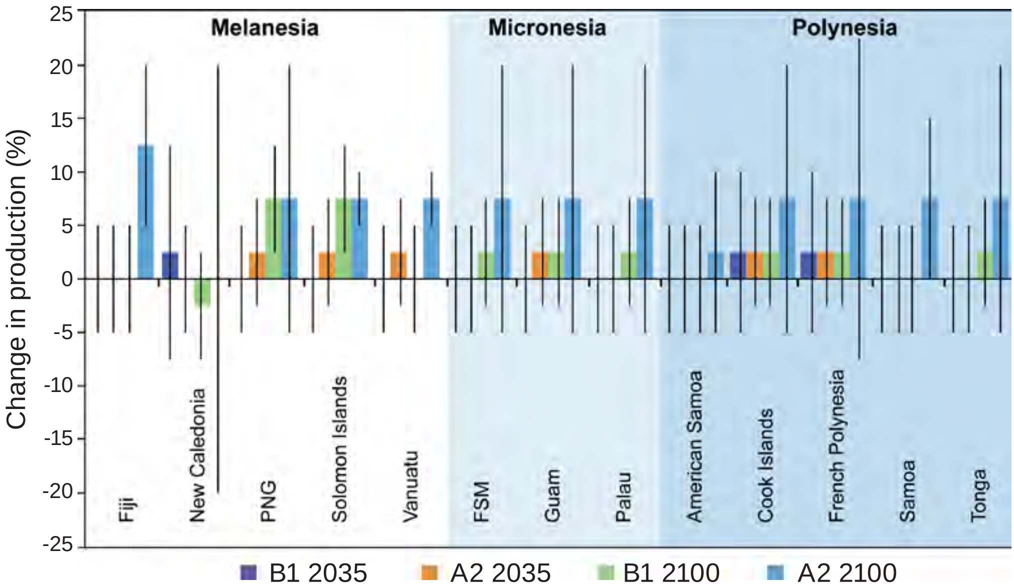


Figure 10.3 Expected changes in freshwater and estuarine fisheries production in the tropical Pacific, based on projected changes associated with rainfall and river flows. Changes in production resulting from variation in habitat quality associated with alterations in temperature, dissolved oxygen and turbidity are also expected to lie within the indicated ranges. Coloured bars indicate median expectation for each climate scenario. Vertical black bars indicate projected range of changes. These projections do not account for interactions between climate features and catchment disturbance and contaminants.

10.5.3 Projected effects on introduced and invasive alien species

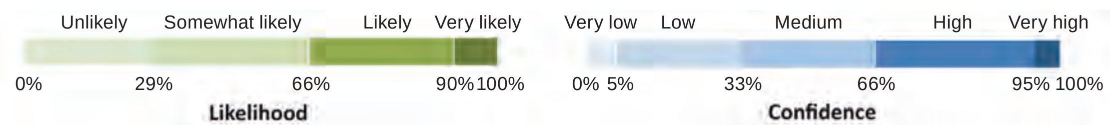
Successful introduced and invasive alien species typically have life history characteristics that allow them to thrive in disturbed environments[166]. Projected changes in habitats associated with climate change may, therefore, promote the spread of invasive alien species, and increase interactions with native species. In particular, increased river discharge may create opportunities for saltwater-tolerant invasive alien species to spread between rivers and nearby islands, leading to changes in the species composition of freshwater fisheries. Increased floodplain inundation is also likely to facilitate the spread of invasive alien species in habitats with low dissolved oxygen levels.

Carp, tilapia, snakehead, walking catfish and climbing perch are less sensitive to drought than many native species because of their ability to survive poor water quality in drying waterholes. For this reason, drying of floodplain habitats during drought, which reduces fish diversity and productivity[38,109], may create opportunities for a greater range of invasive alien species to become established in PNG.

A recent study in Australia found that a 26–34 kg reduction in carp biomass per ha resulted in a short-term increase in biomass of native fish of more than 90 kg per ha[173]. This indicates that introduced fish can sometimes reduce the total biomass available to fisheries. Greater abundance of invasive alien species as a result of climate change may therefore elevate the risk of changes in the species composition of catches, and reduced catches of target species.

Table 10.7 Projected percentage changes in annual freshwater fisheries production relative to estimated recent production[1], assessed from projected changes in habitat availability based on expected future variation in rainfall under the B1 and A2 emissions scenarios in 2035 and 2100 (Chapter 7). Likelihood and confidence values associated with the estimated changes in fisheries production are also shown.

PICT	Recent production estimates (tonnes)	Projected change (%)			
		2035		2100	
		B1	A2	B1	A2
Melanesia					
Fiji	4146	0	0	0	12.5
New Caledonia	10	2.5	0.0	-2.5	0
PNG	17,500	0	2.5	7.5	7.5
Solomon Islands	2000	0	2.5	7.5	7.5
Vanuatu	80	0	2.5	0	7.5
Micronesia					
FSM	1	0	0	0	7.5
Guam	3	0	2.5	2.5	7.5
Palau	1	0	0	2.5	7.5
Polynesia					
American Samoa	1	0	0	0	2.5
Cook Islands	5	2.5	2.5	2.5	7.5
French Polynesia	100	2.5	2.5	2.5	7.5
Samoa	10	0	0	0	2.5
Tonga	1	0	0	2.5	7.5



10.6 Uncertainty, gaps in knowledge and future research

The main source of uncertainty associated with this assessment is the extremely limited information on freshwater and estuarine fisheries resources. The sparse data on fisheries catches make it difficult to develop quantitative estimates of the likely impacts of any threat to fisheries production.

The second most important source of uncertainty is the low resolution of the global climate models used to project changes in temperature, rainfall and intensity of cyclones (Chapters 1 and 2). Downscaling of climate models to the scales of islands or catchments is needed to allow more rigorous assessment of changes in habitat availability and quality, and exposure and vulnerability of fisheries production in individual PICTs. In particular, projected changes in the quantity, intensity and seasonality of rainfall are required[ii] to estimate river flow and habitat availability.

In addition, high-quality observation networks of surface weather (Chapter 2) and river flow are needed for catchments of major rivers. This information will enable the projected changes in climate, and subsequent effects on freshwater and estuarine habitats, to be evaluated.

Because of the local importance of freshwater fisheries in PNG, fisheries production models for the Fly and Sepik-Ramu River systems are needed, based on (1) better data for catch and fishing effort, especially for subsistence fisheries; (2) improved projections of flow rates, nutrient loads, water temperature and dissolved oxygen from the downscaled global climate models described above; (3) inventories of the habitats described in Chapter 7; and (4) elevation mapping to quantify the projected changes in areas of estuaries and floodplains as sea level rises. These models will need to go beyond simple extrapolations based on habitat availability[106]. Models developed for the large rivers in PNG can then be used to inform assessments for the smaller rivers elsewhere in the region.

Empirical assessments for individual species would also help to improve the reliability of vulnerability projections extrapolated from other species or regions. Effective adaptations to maintain the production of freshwater and estuarine fisheries will also require better knowledge of the use of habitats by fish species, responses by fish to changes in habitat availability and quality, and interactions among fish species. Research on species that migrate between fresh water and the sea, which are exposed to a wider range of climate change effects than non-migratory species, is a high priority.

The benefits of species introduced for food production need to be comprehensively assessed against the potential disadvantages (Chapter 11). This assessment should identify options to increase the ways in which introduced (and invasive) species are used, and to reduce interactions with native species that are likely to be more vulnerable to climate change. Opportunities to control invasive alien species, or under-utilised introduced species, by harvesting them for use as processed or unprocessed feed for pond aquaculture, also require investigation.

10.7 Management implications and recommendations

Freshwater and estuarine fisheries production is strongly influenced by human activities in catchments that affect the quality and quantity of aquatic habitats, such as agriculture, forestry and mining. Therefore, a cross-sectoral approach to ecosystem-

ii This work is now being done for the tropical Pacific by the Australian Bureau of Meteorology and CSIRO, and partners, under the Pacific Climate Change Science Programme (www.cawcr.gov.au/projects/PCSSP) based management of freshwater and estuarine fisheries is urgently needed to maximise the opportunities, and minimise the adverse effects on production, expected to occur as a result of climate change[86].

Key challenges for cross-sectoral management are to protect undisturbed habitats to prevent further damage, and to restore degraded habitats where practical. Improved fisheries management of freshwater and estuarine resources is also essential to take advantage of the opportunities presented by climate change, and to oversee sustainable harvesting practices as demand grows to prevent overexploitation. Innovative strategies will be needed to maintain ecosystem function so that fish and invertebrates can exercise their natural capacity to adapt to climate change[86,174,175], and to manage fishing effort and gear.

Estimating future production under climate change with confidence is difficult, because of the limited information on fish catches, the meagre knowledge of the biology of most freshwater and estuarine species in the region and the habitats that support them, and the uncertainty of climate projections at the scale of islands and catchments. Nevertheless, managers need to initiate responses to projected impacts on the basis of knowledge available now, and call for support for the additional information required to improve decision-making.

In general terms, increasing the value and production of freshwater and estuarine fisheries in a sustainable way in the face of climate change will depend on (1) improving habitat management to reduce exposure and sensitivity to the changing environment; (2) building the capacity of local communities to manage habitats and fisheries resources; (3) adopting more efficient fishing and processing methods (e.g. smoking and drying), and limiting fishing effort; (4) managing threats from unwanted invasive alien species and seeking ways to benefit from those that are already established; and (5) monitoring catches and measuring the success of management interventions.

Because relatively little has been published on the management of freshwater fisheries in the region, the five categories of recommendations below are designed not only to assist PICTs to capitalise on the opportunities expected to arise from climate change, and minimise the threats, but also to identify other ways to increase production in a sustainable way.

10.7.1 Improving habitat management to reduce exposure and sensitivity to climate change

- Maximise capacity for increased fishery production by allowing freshwater habitats to expand with increasing rainfall. Options include allowing increased inundation of floodplain habitats to support fish production, and ensuring that future development does not constrain inundation patterns. This recommendation acknowledges the need for existing infrastructure to be protected from inundation where this can be justified on economic or social grounds.

- Remove or modify man-made barriers that prevent freshwater fish and invertebrates from retreating upstream as salt water penetrates into rivers with rising sea level. A survey of barriers to fish migration is needed to identify high-priority structures and cost-effective solutions. Low-cost fishways constructed with local materials may improve access to upstream habitats in places where it is impractical to remove barriers such as causeways, culverts and weirs.

- Minimise exposure of fish in disturbed catchments to increasing temperatures and sediment inputs by revegetating cleared riparian habitats to increase shading of the water surface. Revegetating cleared areas will increase the resilience of local fisheries to climate change, including cyclones, storm surges and droughts. Improved cross-sectoral governance is required to implement applicable forestry legislation where it exists, and to engage with relevant industries and local communities to encourage their participation in revegetation programs. Revegetation could provide employment for local communities. Cross-sectoral cooperation will also be required to minimise future clearing of riparian land and other important catchment areas.

- Reduce the sensitivity of fish to warmer conditions by revegetating land cleared for mining. This will help trap contaminants that reduce the tolerance of fish to higher temperatures, and reduce bioaccumulation of toxic material in fish. The cost-effectiveness of revegetation can be maximised by targeting areas that contribute most to contaminant loads in surface runoff[176]. Cross-sectoral interaction with non-fisheries agencies and relevant industries will be required to implement this recommendation.

- Engage with mining, forestry and agricultural industries to (1) identify operations that degrade freshwater and estuarine habitats, and practical, cost-effective ways to minimise these impacts; and (2) rehabilitate disturbed areas to reduce the vulnerability of freshwater and estuarine fisheries to climate change.

10.7.2 Building capacity of local communities to manage habitats and fisheries resources

- Promote innovative cross-sectoral approaches to manage small-scale fisheries[177] (Chapter 13). Local fisheries resources are often owned by communities under customary tenure, creating opportunities for villagers to manage fisheries through gear or effort restrictions, seasonal or area closures, and habitat protection or enhancement. Ownership by communities provides incentives for local-scale climate change adaptation, such as habitat protection and restoration, creating temperature refuges, or limiting catches during drought. Building local skills through co-management and community-based management to minimise vulnerability is particularly practical in communities with customary tenure of natural resources[178].

10.7.3 Adopting more efficient fishing methods and limiting fishing effort

- Regulate access to inappropriate fishing gear to avoid unforeseen interactions between increasing fishing pressure and climate change. Increasing use of monofilament gill nets, aluminium boats and outboard engines is allowing fishers to target larger areas and previously inaccessible habitats, increasing the risk of overexploitation.
- Adapt fishing methods and locations to harness the greater abundance of valuable species tolerant to the direct and indirect effects of climate change in the habitats where they occur. This approach may be particularly applicable to invasive alien species with potential fisheries value, such as snakeheads, where other forms of control are not available.
- Diversify fisheries over a wider range of species and habitats where possible. The larger rivers in PNG offer significant scope to develop fisheries for species at low trophic levels (e.g. river herring[179]), and to develop fishing methods for those floodplain habitats currently considered inaccessible. Opportunities to diversify freshwater and estuarine fisheries in many other PICTs will be limited, however, because of the small sizes of rivers and local fish stocks.
- Promote simple post-harvest methods, such as smoke curing, to increase the shelf-life of fish and fish products. Modified storage methods may also be needed to overcome the increased risk of spoilage of unprocessed fish products due to higher temperatures.

Photo: Jocelyn Carlin

Smoked freshwater fish, Papua New Guinea

10.7.4 Managing threats from invasive alien species

- Investigate ways to manage populations of low-value invasive alien species that may be favoured by climate change, to reduce negative interactions with more valuable food species. Examples may include harvesting species like climbing perch for use as fishmeal for pond aquaculture, or fish silage.
- Identify additional sources of fish to meet the need for animal protein among growing inland populations in Melanesia, particularly PNG[180]. Opportunities to develop additional freshwater fisheries are likely to be restricted to stocking new impoundments. However, responsible pond aquaculture (Chapter 11) holds promise to increase freshwater fish production for food security and livelihoods in both rural and peri-urban areas.

10.7.5 Monitoring catches and measuring the success of management interventions

- Design and implement novel and simple systems for collecting basic information on catch and effort in freshwater and estuarine fisheries to assess the effectiveness of adaptations to climate change and the sustainability of harvests. Household income and expenditure surveys or agriculture surveys, modified to include questions on freshwater fisheries, fish consumption surveys, GIS techniques and habitat classification approaches are promising tools[1,180,181].

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Appendix 10.1 Freshwater and estuarine fisheries of Pacific Islands countries and territories (PICTs)

PICT	Principal species	Main habitats	Methods of capture	Nature of fishery (and use)
Melanesia				
Fiji	Kai (freshwater clams)	Lowland rivers and upper estuaries	Hand collection	Commercial, artisanal and subsistence (sold fresh, cooked, marinated, eaten raw)
	Freshwater prawns (*Macrobrachium* and *Palaemon*)	Rivers and lakes	Push nets, hand collection, spears and traps	Artisanal and subsistence
	Eels	Lowland rivers and swamps	Hook-and-line, spears, traps	Limited subsistence
	Tilapia, carp, flagtails	Lowland rivers and lakes	Gill nets, hook-and-line, traps	Limited subsistence
	Gobies	Rivers and lakes	Whitebait traps	Limited subsistence
New Caledonia	Eels, small fish, *Macrobrachium*	Lowland rivers and lakes	Spears, traps, hook-and-line	Subsistence
PNG	Barramundi	Southern lowland rivers, floodplains, estuaries	Gill nets, traps, hook-and-line	Commercial, artisanal, subsistence and recreational
	Papuan black bass	Southern rivers and estuaries	Hook-and-line	Subsistence and recreational
	Fork-tailed catfish	Lowland rivers, floodplains, estuaries	Gill nets, traps, hook-and-line, spears	Subsistence (dried, smoked)
	River herring	Southern lowland rivers, floodplains	Gill nets, traps, cast nets	Subsistence and commercial (exploratory cannery, fish meal)
	Saratoga	Western lowland rivers, lakes and floodplains	Gill nets, hook-and-line, traps	Illegal aquarium trade and subsistence
	Tilapia and carp	Sepik-Ramu River system, lakes, reservoirs and floodplains	Gill nets, hook-and-line, traps	Subsistence and artisanal (roadside sales)
	Rainbow trout and other mountain species	High-elevation rivers and lakes	Gill nets, hook-and-line, traps	Subsistence
	Macrobrachium	Lowland rivers and lakes	Traps, cast nets, seine nets, skin diving, spears	Commercial, artisanal and subsistence
Solomon Islands	Mullet, flagtails, tropical snappers, eels, gobies and other fish	Lowland rivers and lakes	Hook-and-line, traps, gill nets	Subsistence and artisanal (local sale)
	Whitebait	Lowland rivers and lakes	Basket traps	Subsistence and artisanal (local sale)
	Tilapia	Lowland rivers and lakes	Hook-and-line, diving, gill nets	Subsistence and artisanal (local sale)
	Macrobrachium	Lowland rivers and lakes	Traps, spears	Subsistence and artisanal (local sale)

Appendix 10.1 Freshwater and estuarine fisheries of Pacific Islands countries and territories (PICTs) (*cont.*)

PICT	Principal species	Main habitats	Methods of capture	Nature of fishery (and use)
Melanesia (*cont.*)				
Vanuatu	Flagtails, grunters, snappers, silver biddies, silver moonfish, scats, mullet, eels, tilapia	Lowland rivers and lakes	Traps, hook-and-line, gill nets	Subsistence and small-scale commercial
	Macrobrachium	Lowland rivers and lakes	Traps, spears	Subsistence
Micronesia				
FSM	Eels, tilapia, *Macrobrachium*	Rivers and lakes	Hook-and-line, traps, spears	Limited subsistence
Guam	Eels, tilapia, milkfish, *Macrobrachium*	Rivers and stocked lagoons	Hook-and-line, spears, gill nets, traps	Subsistence
Kiribati	Milkfish	Stocked brackish lagoons	Gill nets	Subsistence and commercial (live bait)
Nauru	Tilapia	Ponds	Nets	Subsistence aquaculture
Palau	*Macrobrachium*	Rivers	Hook-and-line, traps, spears,	Subsistence
Polynesia				
American Samoa	Eels, gobies, flagtails, *Macrobrachium*	Lowland rivers	Traps, nets	Subsistence
Cook Islands	Eels	Lakes	Gaff, hook-and-line	Subsistence
	Tilapia	Brackish lagoons	Nets	Subsistence
	Milkfish	Stocked brackish lagoons	Nets	Subsistence
French Polynesia	Gobies (whitebait)	Lowland rivers and brackish estuaries	Basket traps	Subsistence
	Flagtails, tilapia, eels, *Macrobrachium*	Lowland rivers and brackish estuaries	Traps, hook-and-line, gill nets	Subsistence
Samoa	Tilapia, eels, *Macrobrachium*	Rivers and lakes	Traps, nets, hand collection	Subsistence and artisanal (local sale)
Tonga	Tilapia, mullet, *Macrobrachium*	Stocked lakes	Traps, nets	Subsistence
Wallis and Futuna	*Macrobrachium*	Rivers	Hand collection	Subsistence

(source: Gillet 2009, FAO 2009, Richards 1994, Amos 2007)[1,2,26,27]

Appendix 10.2 Native and introduced fish and invertebrate species harvested from freshwater and estuarine habitats in PNG

Common name	Scientific name	Habitat	Use
Fish – native			
Archerfish	*Toxotes chatareus*	L, F	S
Barramundi	*Lates calcarifer*	L, E, CW, La	S, A, C
Bream	*Acanthopagrus berda*	L, E	S
Bull shark	*Carcharhinus leucas*	L, E	S
Eels	*Anguilla* spp.	M, S, L	S
Eel-tailed catfish (5 species)	*Neosilurus* spp.	L, F	S
Fork-tailed catfish (9 species)	*Arius* spp.	L, F	S, A
Giant glassfish	*Parambassis gulliveri*	L, F	S
Gudgeons	*Mogurnda, Ophieleotris* spp.	L, F	S
Javelin grunter	*Pomadasys kaakan*	L, E	S
Long tom	*Strongylura krefftii*	L, E	S
Mangrove jack	*Lutjanus argentimaculatus*	L, E	S, A
Milkfish	*Chanos chanos*	La, L, E	S
Mullet (4 species)	*Liza* spp.	L, E, CW	S, A
Northern whiting	*Sillago sihama*	L, E	S
Oxeye herring	*Megalops cyprinoides*	L, E	S
Papuan black bass	*Lutjanus goldiei*	L, E	S, A
River herring	*Nematalosa papuensis*	L, F	S, C*
Saratoga	*Scleropages jardinii*	L	S, Aq
Sawfish	*Pristis microdon*	L, E	S
Sleepy cod (2 species)	*Oxyeleotris* spp.	L, F	S
Sooty grunter	*Hephaestus fuliginosus*	S, L	S
Spot-tail bass	*Lutjanus fuscescens*	L, E	S
Threadfin	*Polydactylus macrochir*	L, E	S
Trevally	*Caranx sexfasciatus*	L, E	S
Fish – introduced			
Brown trout	*Salmo trutta*	M	S
Common carp	*Cyprinus carpio*	L, S, F, La	S
Chocolate mahseer	*Neolissochilus hexagonolepis*	M	Sa
Climbing perch	*Anabas testudineus*	L, F, E, La	Sa
Emily's fish	*Prochilodus argenteus*	L, F	S
Giant gourami	*Osphronemus goramy*	La, F	S**
Golden mahseer	*Tor putitora*	M	S**
Goldfish	*Carassius auratus*	L, S, F	S**
Java carp	*Barbonymus gonionotus*	L, F	S
Mozambique tilapia	*Oreochromis mossambicus*	La, S, L, F	S
Nile tilapia	*Oreochromis niloticus*	La, S, L, F	S
Pacu	*Piaractus brachypomus*	L, F	S
Rainbow trout	*Oncorhynchus mykiss*	M	S
Redbreast tilapia	*Tilapia rendalli*	La, S, L, F	S
Snakehead	*Channa striata*	L, F, E	S
Snakeskin gourami	*Trichogaster pectoralis*	La, F	S**
Snowtrout	*Schizothorax richardsonii*	M	S
Walking catfish	*Clarias batrachus*	L, F, E	S
Invertebrates – native			
Giant freshwater prawn	*Macrobrachium rosenbergii*	L, F	S, A
Red claw	*Cherax quadricarinatus*	L, F	S

Habitat categories are: M = montane and high-elevation rivers; S = slopes rivers; La = lakes; L = lowland rivers; F = floodplains; E = estuaries; CW = coastal waters. Use categories are: S = subsistence; A = artisanal for sale at local markets; C = commercial; C* = potential commercial; Aq = aquarium trade; S** = of limited use for subsistence.