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Chapter 7

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

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'In tropical systems it is possible that the effects of global climate change will be overshadowed by other, larger disturbances such as deforestation and land-use changes.' (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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7.1 Introduction

People living in the tropical Pacific have a strong affinity for rivers – an identity that is reflected in local languages[1]. On Kadavu Island in Fiji, for example, river names describe many of the traditional fishing and subsistence activities, such as:

Nubunisici – 'snail pool'	a pool where edible freshwater snails (sici) can be found;
Waidoidoi – 'doi stream'	where the bark of doi trees, a buckthorn variety (*Alphitonia zizyphoides*), can be used to tie bundles of fish together;
Wainituva – 'tuva stream'	source of tuva or derris vine (*Derris trifoliata*) roots yielding a poison used to stun and collect fish and prawns;
Nubuniura – 'pool of prawns'	*Macrobrachium* spp.;
Waikana – 'food stream'	a river known to contain edible species, a rich source of food.

Throughout the tropical Pacific, from the large rivers in Papua New Guinea (PNG), to the small streams on high islands, freshwater fish and invertebrates contribute to food security. Although the quantities harvested for subsistence are still poorly quantified[2,3] (Chapter 10), awareness of the reliance on freshwater and estuarine resources is increasing.

There is concern that the freshwater and estuarine habitats in the region that support these subsistence fisheries, by providing areas and structures where fish and invertebrates can reproduce, feed, recruit, grow and migrate, may be vulnerable to climate change. Consequently, the rich culture of people who use these rivers as part of their daily lives may also be at risk.

In this chapter, we describe the nature of freshwater and estuarine habitats in the tropical Pacific, their role in supporting fisheries, and the critical requirements needed to maintain them. We then evaluate the vulnerability of freshwater and estuarine habitats to climate change and consider the interactions between the effects of a changing climate and existing impacts on these habitats. We conclude by assessing the constraints to adaptation, the gaps in knowledge to be filled by future research, and the management interventions needed to help maintain the resilience of freshwater and estuarine habitats in the face of climate change.

7.2 The nature of freshwater and estuarine habitats in the tropical Pacific

7.2.1 River systems

The total land area of all Pacific Island countries and territories (PICTs) combined is < 0.6 million km^2, with 83% of this land in PNG and much of the remainder in the other larger islands of Melanesia. Despite their limited size, the array of about 200 high islands in the tropical Pacific, have a high diversity of river types in terms of catchment area, drainage density, annual discharge and geomorphology. This diversity decreases from west to east, in line with island size (Chapter 1). The wide range of river systems has a strong influence on the freshwater and estuarine habitats in the region, and the species of fish and invertebrates supported by these habitats. Ultimately, differences in river form account for variations in the production of freshwater and estuarine fish among PICTs.

7.2.1.1 Catchment size and drainage

Only the larger, high islands in the region have rivers of substantial length and discharge. The three largest river systems in PNG, the Sepik-Ramu, Fly and Purari, have a combined catchment area of more than 200,000 km^2. The flows per catchment area for these rivers are among the highest in the world and their catchments represent more than one-third of the area of PNG[4,5]. The larger rivers of Fiji and Solomon Islands have smaller but significant catchment areas. For example, the 3000 km^2 catchment of the Rewa River covers one-third of the island of Viti Levu in Fiji (**Table 7.1**).

Most rivers in the tropical Pacific differ, however, from those on continental land masses such as PNG, and they are characterised typically by relatively short (< 100 km), straight, steep channels with small, narrow catchments and few tributaries[6] (**Figure 7.1**). For example, Kadavu Island in Fiji has 240 separate catchments draining to the coast, but more than 90% of these are less than 3 km^2 and contain only minor channels[7].

The disparity in catchment area between rivers in PNG and those on other islands in the region highlights a clear distinction in the nature of rivers based on island size, and elevation. At the smallest extreme, Bora Bora in French Polynesia, with an area of 29 km^2 and an elevation of 727 m, is at the lower end of island size and elevation capable of producing running water[8].

Drainage networks tend to radiate outward where island geomorphology is dominated by central highlands, such as on Ambrym (Vanuatu), Rarotonga (Cook Islands) and Tahiti (French Polynesia). Where chains of volcanic peaks have created elongated islands, rivers form linear networks draining away from the mountain ranges (e.g. Pentecost in Vanuatu, Santa Isabel in Solomon Islands and Savai'i in Samoa). Intact volcanic craters develop centripetal channel networks that drain towards the centre of the crater to establish permanent freshwater lakes, such as on Ambae Island, Vanuatu.

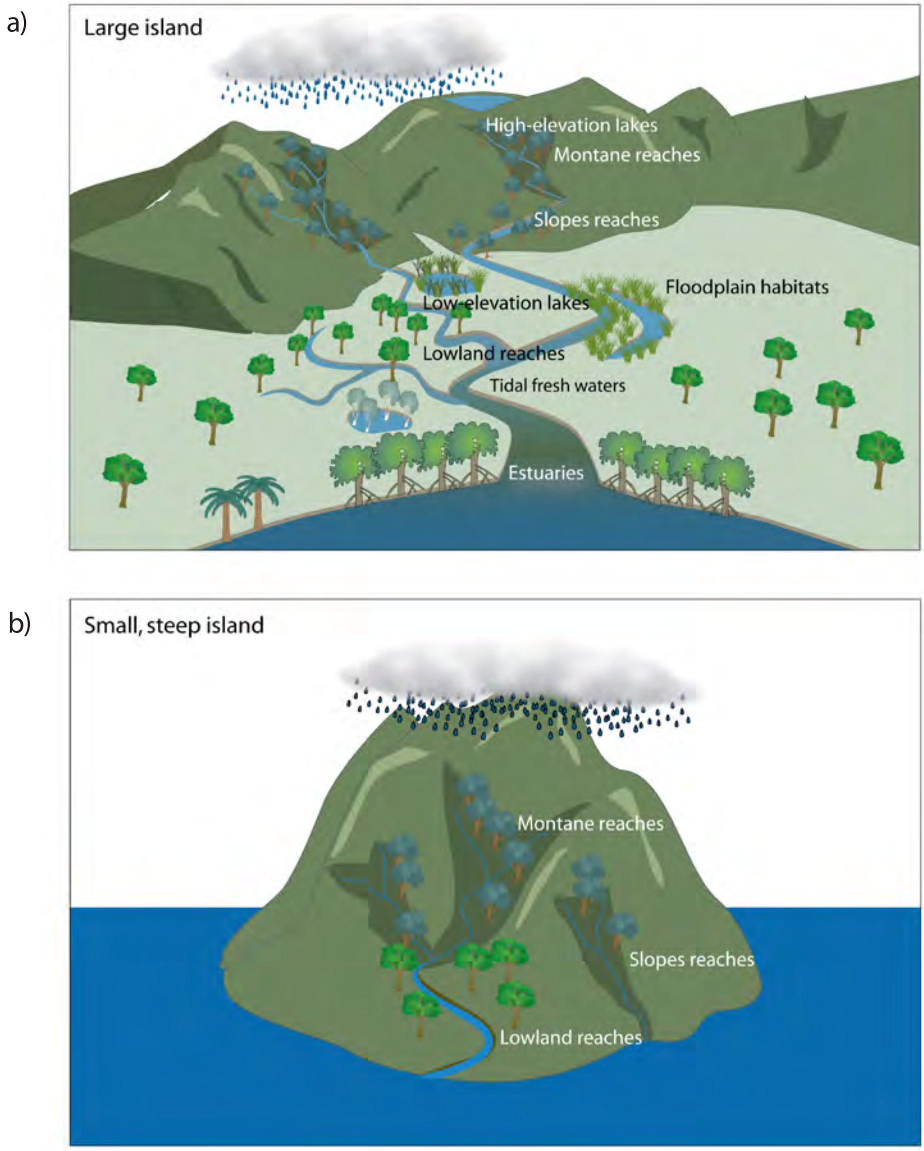


Figure 7.1 Principal freshwater and estuarine habitat types (functional process zones) in the tropical Pacific. River systems on larger islands (a) may consist of montane, slopes and lowland river reaches, and estuaries. Lakes may occur from montane regions downstream to the floodplain. Floodplains provide a diversity of wetland habitats (see text). Rivers on smaller steep islands (b) have small catchments with few tributaries, and may lack typical lowland, floodplain and estuary habitat types.

Steep volcanic islands with low permeability bedrock allow rainwater to run off to form river channels. In contrast, permeable limestone islands with low gradients enable rainwater to percolate rapidly into the groundwater rather than running off to create surface drainage channels (**Figure 7.2**). For this reason, landscapes dominated by raised coral reefs have few rivers.

Table 7.1 Largest river basins in selected Pacific Island countries and territories (PICTs), with estimates of the human populations within catchments (source: SPC Statistics for Development Programme).

PICT	Island	Largest river	Basin area (km^2)	River length (km)	Population
Melanesia					
Fiji	Viti Levu	Rewa	2918	145	98,183
	Vanua Levu	Dreketi	317	65	14,176[a]
New Caledonia	Grande Terre	Le Diahot	589	100	2500
PNG	Mainland	Sepik–Ramu	96,000	1126	339,640
	Mainland	Fly	76,000	1050	132,881
Solomon Islands	Malaita	Wairaha	486	33	160,000
	Guadalcanal	Lungga	394	50	5532
Vanuatu	Espiritu Santo	Jourdain	369	53	1229
	Efate	Teouma	91	28	3462
Micronesia					
FSM	Pohnpei	Nanpil Kiepw	7.8	10	525
Guam	Guam	Talofofo	60	12.6	4475
Palau	Babeldaob	Ngerdorch	39	15	250
Polynesia					
American Samoa	Ta'u	Laufuti	8	3	n/a
Cook Islands	Rarotonga	Avatiu	5.5	5	2600
French Polynesia	Tahiti	Papenoo	91	23	3521
Samoa	Savai'i	Sili	51	11	2270
	Upolu	Vaisigano	33	12	12,180
Tonga	'Eua	Fern Gully	2.3	2	1626

a = Entire Bua province; n/a = no estimate available.

7.2.1.2 Habitat-forming processes

As water moves through the landscape, it forms and shapes river channels and fish habitats by the processes of erosion, sediment transport, and sediment deposition. Changes in rainfall and runoff are likely to alter these habitat-forming processes, which in turn may affect the number of fish and invertebrates that can be supported.

The processes that form habitats for fish are affected by local geomorphology, which varies along rivers. In the headwaters, catchments of most rivers in the tropical Pacific are separated by narrow ridgelines. The terrain is usually rugged, with relatively impermeable volcanic rock, and channel gradients are steep, often approaching 30° or more. The coarse river bed deposits within channels are arranged in riffle-and-pool sequences. The majority of highland channels also contain large rounded boulders, and waterfalls occur frequently where resistant bedrock is exposed by erosion.

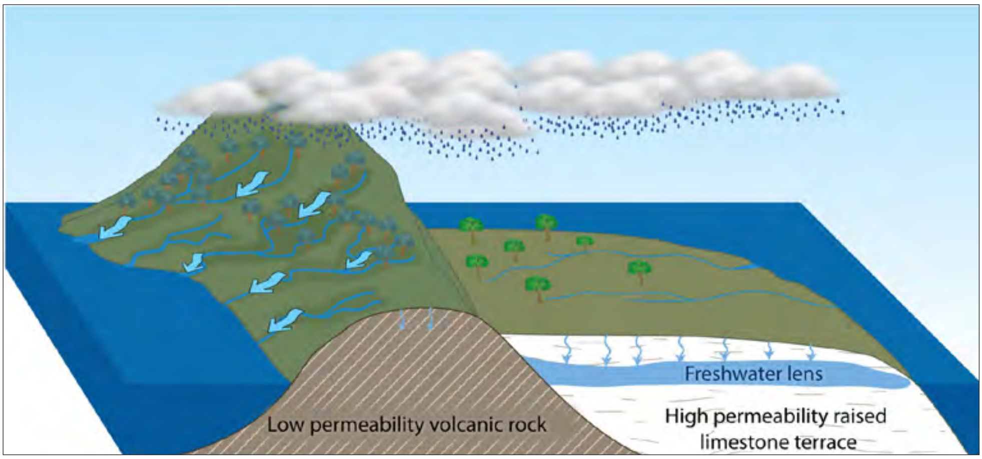


Figure 7.2 River channel density is high on steep volcanic islands because the underlying bedrock has low permeability, and rainfall runs off to form river channels. Low gradient raised coral reef landscapes have few rivers because the underlying limestone is highly permeable, allowing rainwater to percolate into the groundwater rather than forming river channels.

Deep 'down-cutting', resulting from high annual rainfall has produced a highly dissected riverine landscape on many islands. This has formed impressive gorges along some of the larger rivers[9,10], such as the Namosi Gorge on Viti Levu in Fiji. Amphitheatre-headed valleys are another common feature at the source of rivers – the Ngatoe valley in Rarotonga in the Cook Islands is a good example[11].

These characteristics, combined with small catchment sizes, promote flash-flooding, where runoff during tropical storms flows quickly into water courses, leading to rapid increases in flow.

Lower sections of river basins generally have more subdued terrain, often with alluvial terraces and floodplains or braided channels. The Fly River floodplain in PNG is the largest wetland in the region, occupying an area of 4.5 million hectares. This vast, low-elevation floodplain has promoted the formation of numerous oxbow lakes, and lateral lakes where tributaries have been blocked by accretion of deposits along the main channel. The larger rivers in PNG, Solomon Islands, Vanuatu, New Caledonia and Fiji transport large quantities of sediment and have deltas at their mouths.

Despite the humid tropical climate, most Pacific rivers have modest daily flow rates because of their small catchments. The Labasa River on Vanua Levu in Fiji is a case in point – it has a catchment area of 86 km^2 and a mean daily flow of about 3500 to 7000 megalitres per day. Most PICTs also experience distinct rainfall seasons (Chapter 2), although even the smallest rivers tend to flow year-round, except during prolonged drought. For example, Nabukavesi Creek in southern Viti Levu, Fiji, has a low but persistent flow throughout the dry season (**Figure 7.3**).

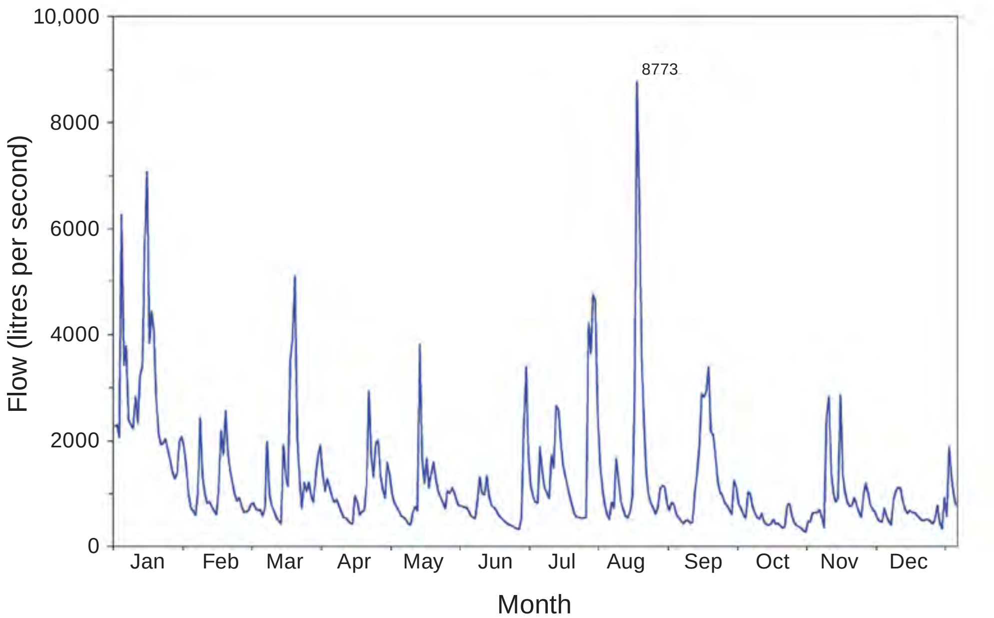


Figure 7.3 Average daily flows for Nabukavesi Creek, southern Viti Levu, Fiji, for 1995. Baseflow is maintained even during dry periods with no rainfall (source: Fiji Public Works Department, Hydrology Section).

In catchments with undisturbed natural vegetation, erosion of hill slopes is minor, and suspended sediment loads in rivers are source-limited. Bedload (sand and gravel) transport is minimal in such catchments and confined mostly to periods of high flow.

The alluvial reaches of rivers shift across valley floors as part of the natural cycle of channel migration. In the Jourdain River (Espiritu Santo, Vanuatu), for example, the lower braidplain is traversed by multiple interconnecting channels, separated by coarse gravelbars. In the lower Wainimala River, Fiji, unconfined meandering channel sections migrate by as much as 5 to 15 m per year[12,13].

7.2.2 Flow as the driver of riverine ecosystems

Flow has a dominating role in rivers – it underpins the links between environmental conditions and habitats, and influences the processes that support fish and invertebrates[14,15]. Flow transports the materials on which fish feed from upstream habitats to progressively larger habitats downstream[16]. This is an important process in the small, steep, ecologically simple rivers that dominate many Pacific islands[17].

In larger rivers, high flows connect floodplains with the main channel, and allow food and other materials to be exchanged between these two habitats[18,19]. Indeed in large floodplain river systems, the spawning, recruitment, growth and migration of fish often depend on annual or episodic flood cycles. The Fly River system is a good example of the role of lateral connections to the floodplain, and local production in the river channel, as sources of energy for aquatic food webs[20]. Floodplain habitats are particularly important for fish production in this river.

The main energy source for fish production comes from algae and microbial decomposition of plant material in upstream, channel and floodplain habitats[21,22], connected by flow, but the processes that drive food webs in freshwater rivers are a source of ongoing debate.

The dynamic nature of hierarchical habitat patches in rivers amplifies the interactions between habitats across a range of scales[23]. Changes in flow and habitats over time are just as vulnerable to climate change as these spatial roles of habitats within river catchments.

7.2.3 Hierarchical nature of riverine ecosystems

River ecosystems consist of a hierarchy of habitats at different scales (**Figure 7.4**), all of which are affected differently by climate, seasonality of climatic events, and climate variability. At the largest scale, freshwater fish that migrate between islands can link rivers across considerable expanses of ocean. Individual river systems form basins[24] that include entire catchments from the headwater tributaries downstream to the coastal environments that are influenced by freshwater discharge. At finer scales, individual habitat patches exist as snags, macrophyte beds, sandbars, pools and riffles. Each of these habitats can be further subdivided into discrete smaller patches. Accordingly, fish habitats in river systems can be considered as a hierarchy of patches at different scales over space and time[23]. The arrangement of habitat patches at any given time is influenced by interactions between adjacent patches at higher and lower levels of the hierarchy, under the dominant influence of river flow.

Larger river systems, such as the Fly and Sepik-Ramu systems in PNG, have more complex hierarchical organisation and may experience more complex responses to climate change than the simpler rivers on smaller islands.

7.2.4 Habitat templates

Fish and invertebrates have specific habitat requirements, and the pattern of habitats often represents a physical template of the species likely to occur within an area. Sections of rivers with common characteristics, such as bed gradient and sediments, have been described as functional process zones[25] (**Table 7.2**). These broadly defined zones are a useful way to consider fish habitats in freshwater and upper estuarine sections of rivers in the Pacific.

Rivers on Pacific islands can be classified into three main functional process zones[26], similar to classifications used elsewhere[27,28].

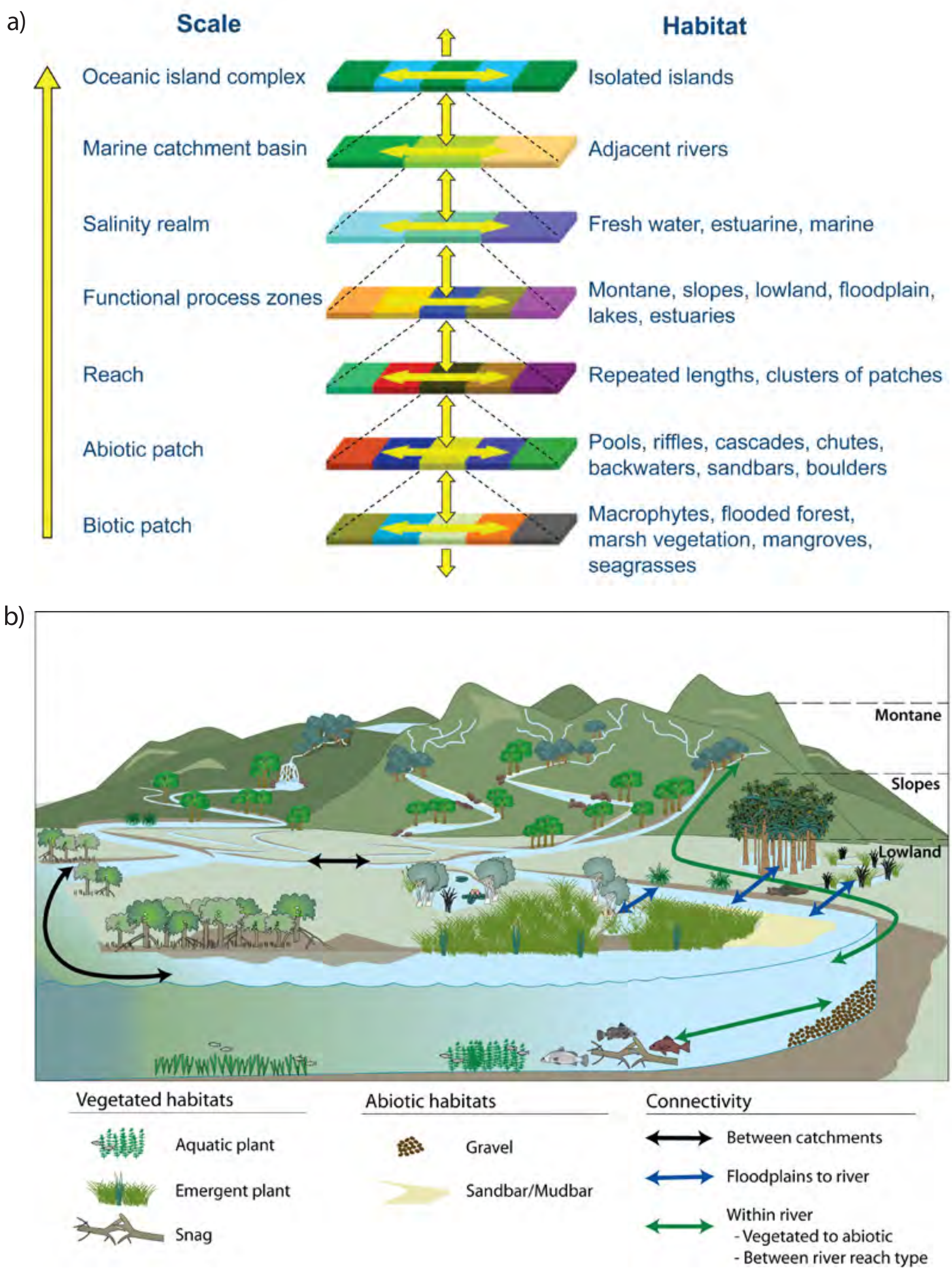


Figure 7.4 (a) Freshwater habitats are arranged hierarchically from biotic patches to entire islands, and interact with other habitats (depicted here in different colours) within and between scales; (b) vegetated and abiotic habitat patches are influenced by interactions with adjacent patches, and by larger-scale processes within river reaches, functional process zones, and marine catchment basins. Connectivity between habitats at different scales is critical for habitat use by fish.

- **Montane reaches:** > 800 m elevation, gradient commonly > 30%, and substratum mostly bedrock;
- **Slopes reaches:** > 50 m and < 800 m elevation, gradient 5–30%, with boulder, rock and gravel substrata; and
- **Lowland reaches:** < 50 m elevation, gradients < 5%, and substrata predominantly cobble, gravel, sand and fine sediments.

A further subdivision of montane reaches is required in PNG highland rivers above 1200 m, where coldwater temperatures also influence fish and invertebrates.

Each functional process zone contains a diversity of smaller-scale habitats, such as pools, runs, riffles and rapids, which tend to form a sequence according to stream gradient and flow, from rapids in steep upland reaches to slow-flowing pools in lowland reaches. Each habitat in turn contains smaller habitat patches (e.g. undercut banks, woody habitats, rocks, overhanging vegetation, plunge pools, scour holes, chutes), which provide the shelter requirements and food resources needed by different fish species (Section 7.2.3).

Freshwater lakes, floodplains and estuaries also represent distinct functional process zones. The wide range of functional process zones and habitat types in the tropical Pacific is summarised in **Figure 7.1** and **Table 7.2**, and described in more detail in Section 7.2.5.

7.2.5 Freshwater and estuarine habitats

7.2.5.1 Montane reaches

High-elevation headwaters are usually shaded by tropical rainforest, and flow from groundwater springs to form a defined channel with swift flowing water. Montane reaches are often interrupted by waterfalls, and provide fish habitat as a series of deep, slow-flowing pools and fast-flowing cascades.

Channel gradient and the height of waterfalls have a strong influence on the size and frequency of pool habitats, and the fish species that can access them[29]. Volcanic rocks are more acidic than limestone and sedimentary rocks, and produce water chemistry that is favoured by certain fish species[30,31].

Coldwater montane rivers above an elevation of 1200 m in PNG have very low fish species diversity. The lower altitudinal limit for rainbow trout, which have been stocked in the highland rivers and lakes of PNG, is 1760 m. Eels, gobies and gudgeons are the only native species inhabiting rivers above 800 m[32,33].

Table 7.2 Examples of freshwater and estuarine fish habitats in the tropical Pacific.

Habitat type	Functional process zone	Examples	Description
Rivers	Montane > 800 m elevation	Upper Jourdain River, Vanuatu	Narrow (< 5 m) constrained bedrock and boulder-strewn channel
	Slopes < 800 m and > 50 m	Papenoo River, Tahiti	Constrained channel, boulders, gravel beds, pools and cascades, length 20 km, fine sediments rapidly transported
	Lowland < 50 m	Lower Fly River, PNG	Over 846 km from the coast to Kiunga (18 m elevation), floodplain 15–20 km wide
Lakes	Large, mid-high elevation	Lake Kutubu, PNG	50 km^2 surface area, maximum depth 70 m, 800 m elevation, oligotrophic
	Small, mid-high elevation	Lake Tagimaucia, Fiji	16 ha, 5.5 m deep, 820 m elevation
	Large, low elevation	Lake Murray, PNG	647 km^2 surface area (~ 2000 km^2 wet season), maximum depth 7 m, 20 m elevation, mesotrophic
		Lake Tegano, Solomon Islands	155 km^2 surface area, maximum depth 43 m
	Small, low elevation	Kiunga Oxbow, Pangua Lake, PNG	> 8 ha on the Fly floodplain, up to 30 m deep, may connect to river via tidal channels
Flood-plains	Pools	Matevulu bluehole, eastern Santo, Vanuatu	Includes oxbows < 8 ha and smaller spring-fed blueholes (flooded dolines) in limestone terrain
	Swamp forests	Jourdain River floodplain, Vanuatu	Single species or multi-species swamp forests, e.g. *Melaleuca, Campnosperma, Inocarpus, Eugenia*
	Springs, marshes and swamps	Bonatoa peat bog, Fiji	Sedge vegetation over deep accumulations of organic material interspersed with alluvial sediments from floods
	Blocked valleys	Bossett Lagoon, PNG	4–6 m deep, intermittent, alternates seasonally between grassy floodplain, floating grasses, and limited vegetation
Estuaries	Coastal plain large estuary	Fly River estuary, PNG	Tidal range 3.5–5 m, length 100 km, prominent delta, extensive mangroves, some seagrasses, highly turbid, sand and mud sediments
	Coastal plain small estuary	Labasa River, Fiji	Tidal range ~ 2 m, length 11 km, mangroves on delta, intensively cultivated floodplain, moderately turbid from soil erosion
	Tidal river	Dagi River, west New Britain; Gumini River, Milne Bay, PNG	Tidal range 0.5–1.2 m, 100 m–2 km in length, delta variously developed, mangroves may be extensive, tidal fresh waters extensive, turbidity low

7.2.5.2 High-elevation lakes

High-elevation lakes are commonly formed as flooded craters. Lake Tagimaucia, with a surface area of 16 ha at an elevation of 820 m, is the largest lake on Taveuni Island, Fiji[34]. The vegetation around the lake is mainly swamp sedges. Other crater lakes exist in PNG (Lake Kutubu), Vanuatu (Lake Letas), Wallis and Futuna (Kikila) and Tonga (Tofua and Tao)[35]. Other highland lakes are formed by blocked valleys and basins[35]. Many of these lakes contain no fish because of their lack of connection with rivers, although some lakes have been stocked with introduced species.

7.2.5.3 Slopes reaches

Riverine slopes reaches lie at intermediate elevations below the downstream limit of the major waterfalls and rapids that characterise montane rivers, and upstream of the well-developed floodplains typical of lowland rivers. Fish habitats in this zone have intermediate channel gradients. The steep topography of many islands determines that slopes reaches are often poorly defined, and may discharge directly to the coast at waterfalls where lowland reaches and floodplains do not exist. Examples include the coastal waterfall at Katurasele on Choiseul Island, Solomon Islands, and Waitavala Stream on Taveuni, Fiji.

In contrast, the Fly River system in PNG has a well-defined slopes region, extending from an elevation of 800 m upstream of Olsobib, downstream to an elevation of 50 m near Kiunga, a distance of over 140 km. Within this section of the river, fish habitat alternates between pools 20 to 70 m wide and narrower, constrained runs, riffles and rapids interspersed with sandbars and gravelbars, sand islands and secondary channels.

7.2.5.4 Lowland reaches

Lowland coastal rivers, from an elevation of 50 m downstream to the tidal limit, typically have long, meandering channels where the river cuts across the floodplain. On smaller islands, channel width usually ranges from 1 to 25 m. These habitats are often shaded by tropical rainforest, in contrast to the larger rivers on bigger islands where the water surface is mostly exposed to sunlight. The substrate types of fish habitats in lowland reaches include silt, sand, gravel, fused rock beds and boulders.

The lowland reaches of the Fly River in PNG extend for hundreds of kilometres inland, meandering across the floodplain at an elevation of only 20 m. The channel varies from 100 to 200 m wide in the upper floodplain, increasing to more than 1000 m before reaching the upper estuary. The low gradient produces well-sorted sandy sediments, with distinctive open-water channel habitats for fish, and well-developed floodplain habitats[36].

7.2.5.5 Floodplain habitats

- **Oxbow lakes** are prominent fish habitats of the floodplain in meandering rivers. They are formed as bends in the river become cut off from the main channel. Oxbow lakes are conspicuous features of the Fly River (PNG). Oxbow lakes provide a wide range of fish habitats, from dense overhanging trees and submerged roots, to overhanging grasses, ferns and floating vegetation. Bottom sediments commonly consist of fine, sandy deposits, fine mud, and organic material, depending on the velocity of flood waters when the habitats connect to the river.

- **Swamp forests** are found in only a few PICTs[35] and provide shelter, among tree roots and trunks, for fish that can live in stagnant water. The most extensive areas occur in PNG, although other swamp forests are also found in Fiji, New Caledonia, Palau, Solomon Islands, Vanuatu and Samoa, and on a number of the high islands of Micronesia. The main trees found in this habitat may include paperbark, palms, pandanus and swamp forest vegetation associated with freshwater mangroves.
- **Freshwater marshes** usually occur in lowland areas such as the floodplains of PNG, river delta margins, behind beach ridges and in the coastal valley wetlands of Fiji[35]. In these habitats, fish shelter among the vegetation and some species spawn on vegetated surfaces. Vegetation includes grasses, reeds, herbs, sedges and ferns, often creating a peaty substrate.
- **Blocked river valleys** are characteristic of the Fly River system where sediment deposition during high flows obstructs smaller tributaries, forming large, deep off-river pools for fish. Other blocked valleys are also created when high-water levels in the Fly River stop water from draining from the broad, shallow valleys on the floodplain[37].

7.2.5.6 Low-elevation lakes

These large, relatively shallow lakes provide extensive fish habitat. The largest low-elevation lake is Lake Murray, near the confluence of the Strickland and Fly rivers in PNG at an elevation of 20 m. Despite its large surface area (647 km^2), it has a maximum depth of only 7 m during normal water levels. Lake Tegano on the island of Rennell, Solomon Islands, is the largest lake in the non-continental islands of the Pacific, with a surface area of 155 km^2 and a maximum depth of 43 m[38]. The low lakes of Tetepare Island (Lakes Bangatu and Saromana) have diverse fish communities with riparian vegetation dominated by palms and pandanus[39]. Other low-elevation lakes include the blueholes fed by springs on Santo Island, and small low-elevation crater lakes such on Ambae Island, in Vanuatu.

7.2.5.7 Tidal fresh waters

The extent of tidal fresh waters on most islands is limited because of low tidal range and steep channel gradients. Significant tidal fresh waters occur in large rivers, e.g. the Fly River, and support fish habitats such as channel pools, sand and mud banks and islands. Although the water level rises and falls with tidal movement, freshwater flow exceeds the upstream movement of saline water, maintaining freshwater habitats and preventing the establishment of estuarine vegetation. Smaller rivers such as the Rewa River on Viti Levu, Fiji, have much shorter tidal freshwater sections.

7.2.5.8 Estuaries

Estuaries are semi-enclosed tidal waters where salt water is diluted by inflowing fresh water[40]. Many estuaries in the tropical Pacific extend for distances of only a few metres in small, steep rivers[41] to hundreds of kilometres in the Fly River estuary. They are generally small and less complex than estuaries elsewhere because of the limited size of most rivers. However, the estuarine habitats of the region support a wide diversity of fish species, which can tolerate fluctuating salinity.

Several types of estuaries exist in PICTs, including coastal plain estuaries where rivers flow through low-lying floodplains, tidal rivers where freshwater flow largely prevents salt intrusion, and coastal lagoons where the entrance to the sea is partially blocked[40].

- **Coastal plain estuaries,** such as the Fly River estuary, are formed by rivers that cut a channel across deposited floodplain sediments. They have sandy or muddy sediments, often with extensive branching creek networks, and are fringed with mangrove forests and seagrass beds. These ecosystems support very productive food webs and provide nursery habitats for many species of fish. Paradoxically, these systems also provide feeding habitats for both large and small predators[42].

Dumbea River estuary, New Caledonia

Photo: Sebastien Mérion

- **Tidal rivers, or drowned river valleys,** such as the Dagi River in West New Britain, PNG, are formed as sea level rises and floods former freshwater channels. These estuaries often lack floodplains, have limited intrusion of salt water because fresh water flow dominates tidal flows, and may have long reaches of tidal fresh water. Sediments deposited by floods may form mud banks and delta islands that support mangroves, providing habitats for fish and invertebrates.

- **Coastal lagoons** are formed by some smaller rivers, such as the Vurulata River on Choiseul Island, Solomon Islands, where sediments block the mouth. These lagoons may be predominantly fresh water or brackish, depending on the volume of freshwater inflows.

Estuarine conditions, such as low or fluctuating salinities, high turbidity, and protection from wave action, often extend outside the river mouth, so that fish species in coastal habitats are often the same as those within the semi-enclosed estuary. As a consequence, the distinction between estuarine and coastal habitats, and the fisheries they support, is sometimes blurred[43].

7.2.6 Natural variability in freshwater and estuarine habitats

All freshwater and estuarine habitats are influenced strongly by river flow. Variability in flow, habitat condition, and habitat availability is a powerful force that determines the fish and invertebrate assemblages supported by each habitat[23]. Short-term variability in river flow is linked closely to rainfall because of the small sizes of catchments, and short runoff durations of rivers in the tropical Pacific, compared with continental rivers.

Similarly, seasonal river flow patterns reflect rainfall. Several PICTs in the western Pacific (e.g. PNG and Solomon Islands) do not have a distinct dry season, and river flows are relatively constant throughout the year. Guam, the Commonwealth of the Northern Mariana Islands (CNMI), and the Marshall Islands north of the equator have a distinct winter dry season. South of the equator, islands experience a distinct summer wet season, and higher islands are strongly influenced by orographic influences on rainfall distribution.

Annual variability in river flows across the tropical Pacific is also influenced on a 2- to 5-year time scale by the El Niño-Southern Oscillation (ENSO) (Chapter 2). During El Niño events, the central and eastern Pacific experiences increased rainfall, whereas islands in the western part of the region experience droughts with a virtual absence of rain for several months to 1 year (Chapter 2). Most PICTs experienced severe El Niño events in 1997–1998 and 2000–2001, when many smaller rivers and freshwater wetlands dried[37,44]. The La Niña event that followed the 2000–2001 El Niño, brought cyclones and flooding to many rivers.

River flows during the wet season are influenced by cyclones that bring intense rainfall, resulting in severe floods that can devastate freshwater ecosystems. Snail populations in the Wainibuka River, Viti Levu, were reduced from 1475 individuals per m^2 before a cyclone, to 250 individuals per m^2 afterwards[45]. Tropical Pacific rivers typically have low biodiversity, and recolonisation after disturbance can result in changes in species composition[46].

Regular flow, Tutusù River, Solomon Islands

Photo: Ron Englund

7.3 Role of freshwater and estuarine habitats in supporting fisheries

7.3.1 Use of riverine habitats by fish

The combination of functional process zones, habitats and habitat patches enable rivers and estuaries in the tropical Pacific to support a diverse range of fish and invertebrates (**Figure 7.5**). Each habitat performs multiple roles for different species and life stages[47]. Many species of fish and invertebrates are specialists, requiring particular habitat features. For example, climbing gobies are adapted to live in fast-flowing habitats such as riffles, rapids, and even waterfalls. Deeper-bodied, mid-water species, such as jungle perch *Kuhlia rupestris* and *K. marginata*[48] and mangrove jack *Lutjanus argentimaculatus* tend to live in deeper fast-flowing pools. Some gobies prefer shallow water, whereas gudgeons, and glassfish *Ambassis miops* are commonly found in river edge habitats beneath overhanging vegetation[30,31,37]. Through these associations, flow has a strong influence on fish species richness among habitats[30].

Many freshwater fish in the region have amphidromous migratory behaviour[49,50] (Section 7.3.3) and spawn in freshwater habitats. Newly hatched larvae are transported downstream to the ocean and migrate back upstream to complete their life cycle[29,51–53]. Other species encountered in fresh water are visitors from estuarine and marine habitats, such as *A. miops*, mangrove jack and trevally *Caranx papuensis* which migrate upstream into fresh water as juveniles and return to the sea later in life[54]. Milkfish *Chanos chanos* and oxeye herring *Megalops cyprinoides* can reproduce in lakes that become isolated from river channel habitats[39].

Barramundi *Lates calcarifer* occupy different habitats at different life-history stages. Juvenile barramundi migrate into the main river channel as their off-channel wetland nurseries become inhospitable in the dry season[55].

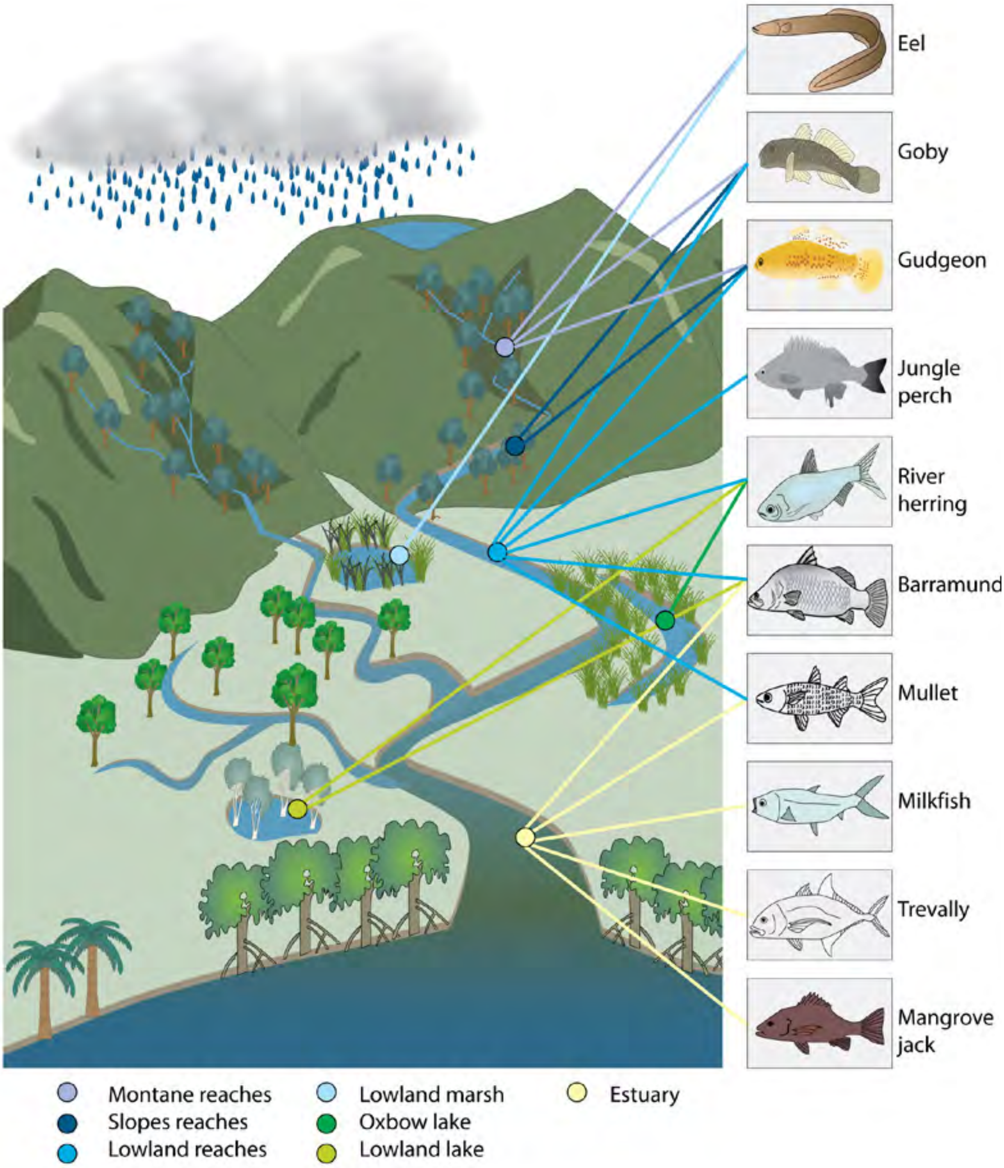


Figure 7.5 Examples of fish species that use freshwater and estuarine habitats in different functional process zones. Habitat use is not fixed for individual species. Catadromous species like barramundi migrate to sea to spawn, larvae return to coastal wetlands and move further upstream as juveniles (Section 7.3.3). Potamodromous species like river herring migrate exclusively within fresh water in the lowland river channel and floodplain habitats (Section 7.3.3).

Freshwater habitats are often discontinuous, being separated above and below waterfalls or between the main channel and floodplain habitats. For some fish species, essential habitats are sometimes separated in different catchments or occur on different islands, so that the fish need to migrate through coastal or oceanic waters to reach their required habitats. Fragmented habitats can mean that the diversity of freshwater fish is highly localised, and that even small lakes or river systems may harbour unique species. For example, the Tamavua River on Viti Levu provides habitat for half of all the endemic fish species in Fiji[56].

Connections between habitats are needed to enable fish to move between different habitats during their life cycle, particularly adults moving to spawning grounds, and recruits entering nursery habitats. This connectivity is critical to fisheries production because migration between habitats is an essential component of the life-cycles of most fisheries species in tropical rivers[57,58]. Fast flowing riffles connect pools and provide aeration, algal production, feeding and habitat areas for invertebrates and the fish that prey on them. Riffles also often provide spawning sites[59]. Slow flowing pools, in contrast, provide low-flow refuges[60], resting places for migrating fish, deposition zones for particulate organic matter and feeding areas for the large predatory fish typically targeted by fisheries.

River edge habitats provide shallow refuges for juveniles[47] and small species[61], and access to bankside vegetation[57], which provides shelter and food in the form of insects and fruit. Complex structures (e.g. fallen trees, rocks, undercut banks, and vegetated edges) are used as refuge and feeding habitats by barramundi, and by snappers (Lutjanidae)[62,63].

7.3.2 Use of off-channel habitats by fish

Off-channel habitats offer refuge during the wet season, feeding areas and spawning sites, and refuge from predators[64,65]. Many of these habitats are temporary, and dry out from time to time.

Oxbow lakes on Viti Levu, off-channel tributaries on Choiseul, and floodplain lakes on Malaita and Tetepare, each support species of fish that are rare in other habitats[30,31,39,66]. Gudgeons are commonly found near overhanging vegetation and soft mud substrate at the water's edge. Deeper waters in lakes support species such as milkfish, oxeye herring and mullet *Liza vaigiensis*[30,31,39].

Floodplain habitats of the Fly River system in PNG support 66 fish species, compared to 86 species recorded from lowland river channels[67]. Oxbow lakes, blocked valleys, and grassed floodplain habitats also support up to 46 species[37], with river herring *Nematalosa papuensis* being the most abundant species. Small species are usually more abundant in the shallower, well-vegetated blocked valleys, while the deeper oxbow lakes support larger numbers of barramundi and other predators. Twenty-three species found in riverine habitats have not been recorded in floodplain habitats[37,67].

7.3.3 Contribution of habitats to fish reproduction

Many freshwater fish species in the tropical Pacific migrate between habitats to complete their life cycles[41,50]. Depending on the species, connectivity is required between upstream and downstream freshwater habitats, river channel and off-channel habitats, and between fresh water and the sea, for successful reproduction. Since changes in flow and increasing salinity in the lower reaches of rivers are likely to occur as a result of climate change, differences in connectivity between habitats may affect fish production.

The limited availability of freshwater habitats on smaller islands dictates that the ability to migrate through the sea is an important attribute to maintain species distributions. Different migratory and reproductive strategies have evolved for this purpose.

- **Catadromous species** live in fresh water as adults and migrate to the sea to spawn. Larvae and juveniles then occupy a variety of habitats as they make their way back upstream. Examples of this reproductive behaviour are barramundi[68], jungle perch[48] and eels[69]. Larval and juvenile stages have limited swimming ability, and small environmental changes, such as low-level stream blockages, can prevent access to habitats upstream and cause populations to decline.
- **Amphidromous species** spawn in fresh water and their larvae are carried to the sea by river flow (**Figure 7.6**). Gobies and gudgeons are common amphidromous fish throughout the Pacific islands. Juveniles may spend more than 250 days at sea or in inshore waters[70,71] before re-entering fresh water. Goby larvae begin to change into their adult form once they enter a river[72]. Other common amphidromous species in the Pacific islands include six genera of atyid shrimp (*Macrobrachium),* decapod crabs (*Varuna*), and freshwater gastropods (*Neritina*)[50]. This behaviour allows species to maintain freshwater populations on islands separated by ocean[50,73].
- **Potamodromous species** migrate wholly within fresh water and complete their life cycle without going to sea. These species typically produce pelagic eggs, and migrate upstream to counter the downstream drift of eggs and larvae[66]. Examples include freshwater mullet *Cestraeus plicatilis* and river herring, which are believed to be potamodromous, based on the behaviour of the closely related *Nematalosa erebi* in Australia[74,75].

Migration between habitats is also a feature of the life-cycles of marine species that inhabit fresh water or estuaries. These species include mangrove jacks, which spawn on offshore reefs but spend their early life in fresh water and estuaries[76], penaeid shrimp with riverine nursery areas[57,77], and mangrove crabs (*Scylla* spp.), which migrate from estuaries to inshore coastal waters to spawn[78].

Irrespective of the migratory behaviour exhibited, most freshwater and estuarine fish and invertebrate species require access to a chain of connected habitats to complete their life cycle[63,76,77,79]. Rivers are the major migration corridors linking habitats[58]. The disruption of the connectivity between habitats by climatic events, such as changes in seasonal rainfall cycles, episodic floods and droughts, or changes in sea level, may limit successful recruitment.

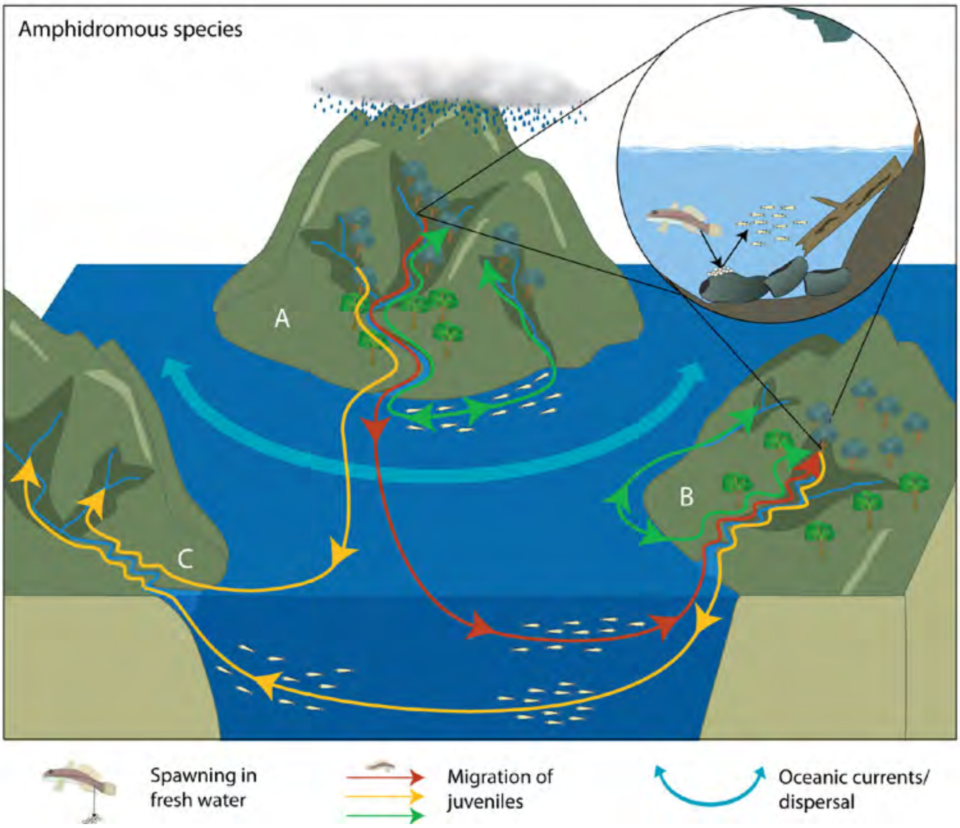


Figure 7.6 Amphidromous species may require a wide range of habitats, including all river types, estuaries, and coastal and oceanic habitats to complete their life cycles (Island A). Spawning occurs in freshwater habitats. Larvae are carried to sea by river flow, where they are transported by ocean currents (blue arrow), and develop into adults upon re-entering fresh water in the same river, adjacent rivers, or rivers on other islands (Island B). Islands without suitable spawning habitats (Island C) rely on other islands as sources of recruitment.

Freshwater habitats used for spawning and recruitment commonly experience elevated water turbidity, changes in water chemistry, and smothering by fine sediments in catchments affected by logging, mining, agriculture and urban development. Climate change has the potential to affect fish reproduction by exacerbating these threats, and by altering habitat connectivity for species that migrate within and among rivers.

7.3.4 Role of freshwater and estuarine habitats in fish growth

Four different food web pathways operate across habitats in major river systems to provide the energy sources for fish growth[20]:

1. planktivorous pathways, involving phytoplankton, zooplankton and the fish that feed on them, such as river herring;
2. epiphyte-grazer pathways, based on aquatic insects and shrimp, herbivorous fish, such as fork-tailed catfish *Arius berneyi* and mullet *Liza diadema* and predatory fish (piscivores), such as barramundi and longtom *Strongylura kreffti*;
3. terrestrial carbon pathways providing energy for species such as long tom, Papuan black bass *Lutjanus goldiei*, saratoga *Scleropages jardini* and fork-tailed catfish *Arius latirostris* and *A. leptaspis* which derive their energy from terrestrial sources, and by feeding on species such as *Macrobrachium* that ingest plant detritus; and
4. other riparian pathways, involving species such as archerfish *Toxotes chatareus* and fork-tailed catfish, which feed directly on terrestrial insects and fruits associated with streamside vegetation.

The simplified food webs from an oxbow lake and a forested reach of the Fly River channel show that fish eat a wide selection food types in different habitats (**Figure 7.7**). Changes in habitat condition such as turbidity, nutrient availability, shading by plants, extent of inundation, and flushing of detritus during flow events, influence which pathways will predominate in particular habitats at any point in time.

There are also differences in productivity between habitats in PNG; for example, barramundi grow more quickly in fresh water than in salt water[80]. Barramundi gain condition through the dry season in habitats such as oxbow lakes, when their prey are more concentrated, and lose condition in the wet season during spawning migrations[68,81].

The primary food sources for fish and invertebrates in steep gradient rivers are benthic algae growing on rocks, and low densities of attached macroinvertebrate larvae, because there is little sand to support benthic fauna. This epiphyte-grazer pathway is common in such habitats, and the herbivorous gobies living there face competition from algal-grazing molluscs[41] (**Figure 7.8**).

7.4 Critical requirements for maintaining freshwater and estuarine habitats

Flow is the primary process that shapes freshwater habitats (Section 7.2.2). Furthermore, components of the flow regime influence the nature of habitats over annual, decadal and longer time-scales[82]. Alterations in flow, as a result of changes in the timing, intensity and variability of rainfall, may therefore affect the processes that create and maintain fish habitats.

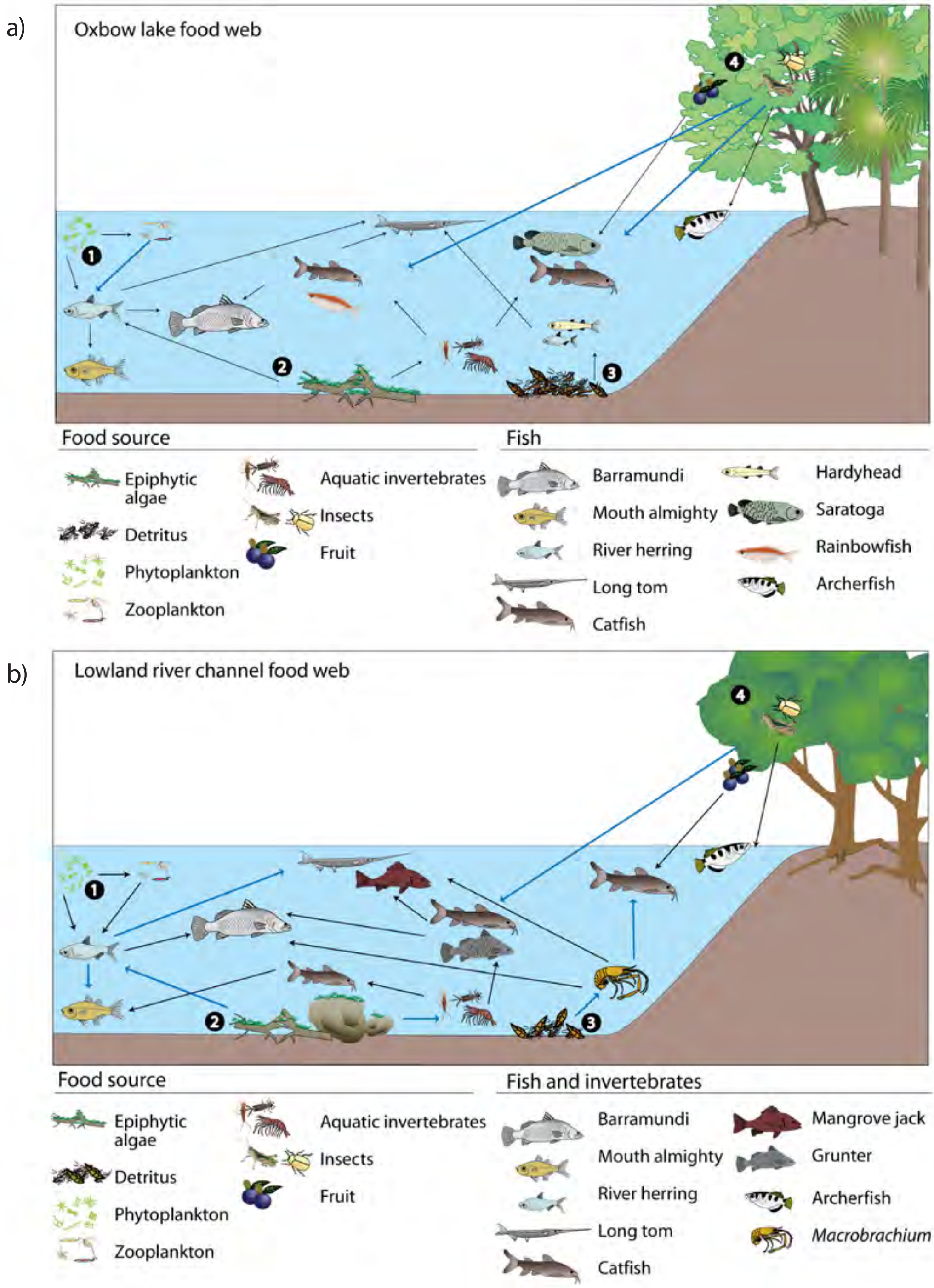


Figure 7.7 Simplified food webs typical of (a) an oxbow lake and (b) a lowland river channel in Papua New Guinea, showing energy pathways based on (1) phytoplankton, (2) algae and epiphytes, (3) terrestrial plant detritus, and (4) riparian fruits and insects[23]. Heavier blue lines show stronger relationships. Note that some fish and invertebrates harvested for subsistence are eaten by larger fish.

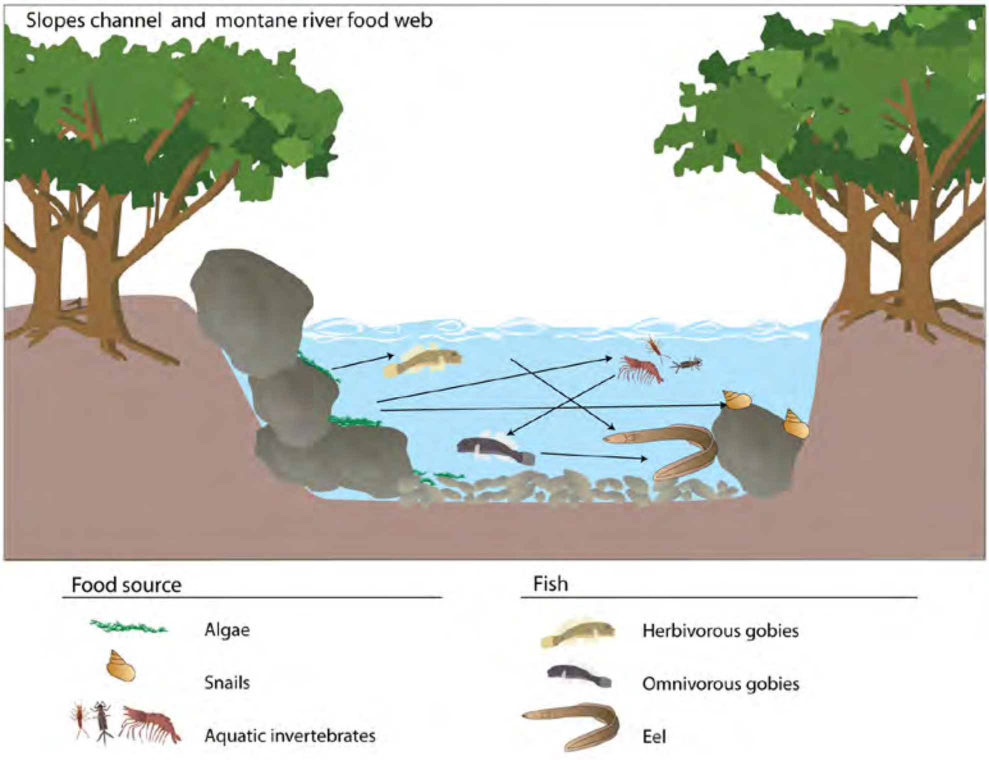


Figure 7.8 A generalised food web for habitats typical of montane rivers and the slopes reaches of rivers in the tropical Pacific.

The magnitude of river flows determines seasonal availability of habitats within river channels and floodplains, as well as providing longitudinal connectivity within the river channel, and lateral connectivity between channel and floodplain habitats. Prolonged low flows result in contraction of the river channel and reduction in the availability of habitats, whereas long-term high flows increase channel capacity and access to habitats[10].

The timing of flow determines when habitats such as gravel and macrophyte beds are available for spawning, feeding or shelter. Because growth of aquatic plants depends on the availability of both light and nutrients, macrophytes and benthic algae may experience suitable conditions for growth only at specific times of the year. Because benthic algae and macrophytes are often scoured away by high flows in rivers with pronounced wet season flows[83], the timing of flow determines the presence of vegetated habitats.

The frequency of flow events determines how often, for example, floodplain wetland habitats are refilled, how often species can enter floodplain habitats[84], and how often amphidromous larvae are carried to the sea to begin their marine migration[29].

The duration of flow events controls how long off-channel habitats are available to support rapid growth of juvenile fish before they re-enter riverine habitats[79], or migration of fish to reach upstream pools that become disconnected during low flows[29].

The rate of change in flow affects how quickly habitats become connected or disconnected, and may lead to fish becoming stranded in off-channel habitats during rapid recession of flood waters[37].

The variability and predictability of flows controls how regularly habitats connect to meet fish requirements for breeding, feeding and migration, and allow fish to synchronise their behaviour to habitat conditions. Where flows are predictable, fish may develop life-history strategies to maximise recruitment[85], such as using off-channel wetlands as nursery habitats[68], or spawning during floods to carry larvae to sea[29].

Flow is also important in maintaining estuarine habitats. The estuary of the Fly River in PNG has a daily tidal water flux about 18 times greater than the freshwater discharge[86] of 6000 m^3 per second. The funnel shape of the Fly delta, combined with the opposing freshwater and estuarine tidal flows of up to 2 m per second, produce estuarine habitats that are continuously changing.

In summary, river systems in the tropical Pacific are driven primarily by rainfall and its effect on river flow. In particular, flow is affected by seasonal patterns of precipitation, episodic events such as cyclones, and longer-term periods of high or low rainfall under the influence of ENSO (Chapter 2). Temperature also plays a role because it affects persistence of freshwater and estuarine water bodies through evaporation, as well as the suitability of habitats for individual species of fish and invertebrates (Chapter 10). The location and extent of estuaries is governed by topography, freshwater flow, tides and long-term changes in sea level.

7.5 Climate change scenarios for Pacific island river systems

Existing climate change models for the tropical Pacific emphasise the role of ocean-atmosphere interactions as forces driving island climates (Chapter 1). These models do not, however, adequately account for the ability of high islands to generate local weather patterns through cloud capture by mountains within the larger, ocean-scale climate pattern[8,87]. The spatial resolution of current climate models therefore creates uncertainty in developing projections for rainfall, runoff and river flows, all of which will shape future river and estuarine habitats.

Despite the low resolution of rainfall projections, it is likely that most rivers will receive more runoff as a result of the expected increases in rainfall of 5–20% by 2035, and 10–20% by 2100 (Chapter 2). The area receiving higher rainfall is also expected to expand towards 2100. However the southwest of the region around New Caledonia may expect a decline in rainfall of up to 20% during winter by 2100, increasing the variability of seasonal flow in the rivers there. In the southeast, French Polynesia may expect more uniform annual rainfall and river flow, with a 5–20% decrease in rainfall over summer, and a 20% increase in winter by 2100 under the A2 scenario (Chapter 2). The habitats described in earlier sections are likely to be affected by changes in flow as a result of changing rainfall patterns.

Expected increases in surface temperature of up to 0.8°C under both B1 and A2 emissions scenarios by 2035, and up to 3°C by 2100 under the A2 scenario (Chapter 2) are difficult to extrapolate directly to freshwater habitats and estuaries. Shaded rivers fed by groundwater may experience little change from present-day temperatures, whereas shallow saline wetlands exposed to the sun may warm by more than the projected increase. Actual temperatures will be driven by a combination of regional temperature changes and local conditions.

Existing models suggest that cyclones will occur in the same locations, and will become less frequent, but possibly more intense, with stronger, more damaging winds and potentially larger storm surges (Chapter 2). Projected sea-level rise (Chapter 3) will affect mainly estuaries and low-lying freshwater habitats, and will interact with altered rainfall patterns and cyclone intensity. Estuaries in lowland floodplain rivers are likely to expand inland with rising sea levels, as inundation by freshwater inflows increases during rainy seasons. Tidal movements and salinity will extend further inland. These effects will be accentuated by storm surges during any cyclones of higher intensity.

7.5.1 Direct and indirect climate change effects

Taken together, the projected changes to the climate of the tropical Pacific are expected to have profound effects on freshwater and estuarine habitats. These changes are described in more detail below and summarised in **Table 7.3**. Note, however, that due to the spatial and temporal variability in the direction and extent of projected climate change across the region, the outcomes for freshwater and estuarine fish habitats will differ according to the type and location of islands, and their local climate.

7.5.2 Effects of rainfall on river flow and habitats

Freshwater habitats are likely to be extensively affected by altered rainfall[88]. River discharge is estimated to increase by 9% in the Fly River and by 33% in the Sepik River by 2050 under the A2 emissions scenario[89], increasing further towards 2100. Higher rainfall will lead to flows of increased magnitude and duration, greater flooding, increased erosion and sedimentation downstream, and enhanced connectivity. Increased flow allows channels to cut through river bends, creating new oxbow lakes[90]. Increased flow is also expected to alter the distribution of sandbars and gravelbars[91], fill crevices among rocks and gravel, and accelerate infilling of oxbow lakes[90].

Table 7.3 Expected alterations to freshwater and estuarine fish habitats in the tropical Pacific under projected climate changes.

Habitat	Climate feature				
	Increased temperature	**Increased rainfall**	**Increased rainfall variability**	**Increased cyclone intensity**	**Sea-level rise**
Rivers	• Warming of high-elevation habitats • Warmer lowland habitats	• Greater duration of high flows • Increased depth • Greater scouring and bank collapse • Increased habitat area • Increased fallen tree habitat	• Depth and flow more variable • Greater mobility of macrophyte beds and riparian vegetation • Increased habitat variability	• Increased physical damage, erosion and sedimentation • Variable supply of woody snags	• Increased salinity in downstream pools
Lakes	• Increased stratification • Accelerated nutrient cycling and production	• Improved flushing and water quality • Increased nutrient delivery and productivity • Elevated contaminant inputs • Increased depth or stability in maximum depth	• Greater depth fluctuation • Periodic reduction in water depth	• Increased sediment, nutrient and contaminant inputs • Increased connectivity among isolated habitats	• Salinisation of coastal lakes • Increased marine connectivity
Flood-plains	• Increased production and decomposition rates • Increased evaporation and loss from small pools	• Increased river-floodplain connectivity • Increased inundation of seasonal wetlands • Increased or decreased area of shallow vegetated habitats • Increased wetland depth	• Increased variability in river-floodplain connectivity, wetland depth, area and duration • Transition to wet-dry tolerant vegetated habitats • Increased drying during droughts	• More variable connectivity of isolated wetlands • Greater physical disturbance to vegetated habitats • Increased sedimentation of floodplain • More variable habitat diversity	• Increased salinity in coastal floodplain wetlands • Loss of salt-intolerant vegetation • Expansion of mangroves into floodplain habitat
Estuaries	• Potential for inhibition of intertidal primary production	• Increased connectivity of supratidal pools • Enhanced longitudinal connectivity • Increased area with low salinity • Depth reduced by sediment deposition	• Connections to freshwater channel and freshwater pools more irregular • Increased variability in estuary area	• Increased connectivity with floodplain and upstream freshwater habitats • Increased habitat dynamics through sedimentation and scouring	• Inundation of intertidal habitats • Increased connectivity of supratidal pools and upstream habitats • Change in area subject to topography • Greater depth

Under normal conditions, the regular seasonality in flow regimes maintains a dynamic equilibrium in the mosaic of habitats. This means that as habitat features such as pool-riffle sequences or channel bars move or are lost, they will be replaced by similar features. Thus, the habitat mosaic remains relatively stable when stream power remains within a defined range.

Projected increases in rainfall under both the B1 and A2 scenarios (Chapter 2) will increase habitat availability, and the links between freshwater habitats (**Figure 7.9**), but the timing, intensity, frequency and variability of rainfall will determine which aspects of the flow regime have the strongest influence on habitat quality. Modest increases in annual flow will produce proportional increases in habitat availability, and the arrangement of habitats with respect to other habitats. The magnitude of changes will increase markedly during severe cyclones.

Reduced rainfall in the southwest Pacific by as much as 20% under the A2 scenario by 2100 in winter, and in the southeast by 5–10% in summer (Chapter 2), will reduce river flow on islands such as Grande Terre in New Caledonia and Tahiti in French Polynesia, potentially leading to a narrowing of river channels and reduced connectivity between pool habitats (**Figure 7.9**).

7.5.3 Cyclones and tropical storms

During flows from severe cyclones, stream power increases above normal levels resulting in dramatic changes in the riverine landscape[92]. If cyclones become more intense, changes such as the carving of new channels, coarse sediment transport and floodplain sedimentation will occur on a larger scale.

Cyclones typically cause high flows[93] (**Figure 7.10**) which result in dramatic changes in the freshwater habitat mosaic, such as deposits of new sediment, and re-organisation of pool-riffle sequences. Bedrock channels may be swept clear of fine materials. In lowland channels, riverbanks may collapse, meander bends may be cut off, and riverbeds scoured and filled. Cyclone Namu in 1986 caused sediment deposition up to an astonishing thickness of 8 m in rivers on Guadalcanal, Solomon Islands[94].

Increased flooding of low-lying areas is expected to provide additional aquatic habitat and enhanced connectivity between channel and floodplain areas, although potential advantages to fish may be offset if rainfall becomes unpredictable and access to floodplain habitats becomes more irregular[58].

Storm surges created by cyclones are likely to become larger as cyclones intensify, increasing exposure of floodplain and freshwater habitats to saline intrusion. Coastal lagoons protected by sand barriers may experience increased damage during cyclones, changing the salinity regime. Coastal plain estuaries and tidal rivers with topography that funnels storm surges upstream may also experience accentuated penetration of salt water.

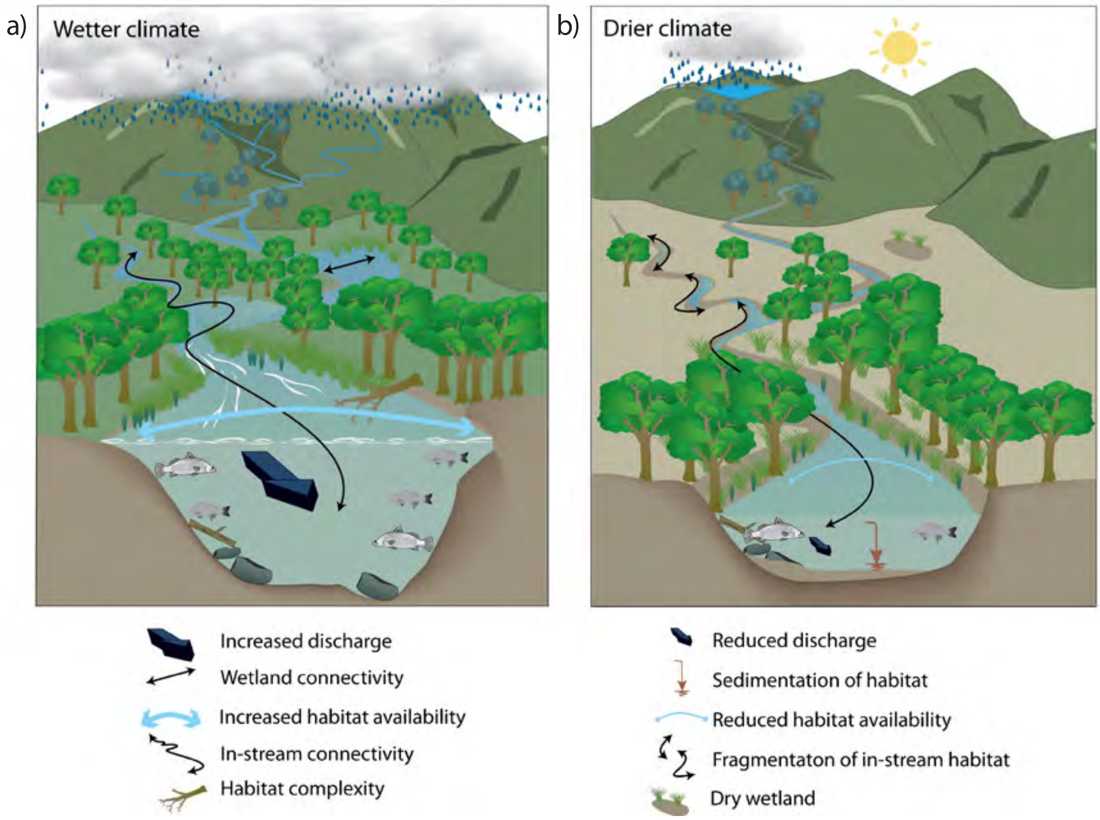


Figure 7.9 Effects of projected changes in rainfall and river flow on freshwater and estuarine habitats. (a) Wetter climates will promote increased habitat availability and diversity, increased connectivity between riverine and floodplain habitats, and expansion of floodplain wetlands. (b) In drier climates, channel habitats will contract and become shallower, with increased fragmentation of in-stream habitats and drying of floodplain habitats.

7.5.4 El Niño-Southern Oscillation events

ENSO events are projected to continue to be a strong feature of the climate of the tropical Pacific (Chapter 2), and can be expected to maintain their influence on river flow. Low flows are often associated with El Niño droughts[95] (**Figure 7.11**), which result in periods of stability and low habitat availability, for example, floodplain habitats may lose their connection to rivers, or dry completely[37]. In regions projected to have drier climates (southwest Pacific in winter and southeast Pacific in summer), reduced river flows may enable salt water to penetrate further upstream. Such intrusion has happened previously in the region, for example, during the 1997 to 1998 El Niño event in the Torassi River in PNG[96].

7.5.5 Temperature

Because of their propensity for evaporation, shallow freshwater habitats with little or no flow, such as backwaters, river edge habitats and shallow floodplain wetlands, are likely to be most vulnerable to the projected warming. The limited potential for mixing in these habitats is also expected to cause water temperatures to exceed the tolerances of many species of fish and invertebrates. Warming of coldwater rivers and lakes in the highlands of PNG will cause a contraction of these habitats to higher elevations[15] (**Figure 7.12**). Intertidal flats currently exposed to daily temperature fluctuations > 10°C might be expected to show little sensitivity to mean temperature increases of up to 0.8°C under both B1 and A2 emissions scenarios by 2035. However, projected increases of up to 3°C by 2100 may inhibit microbial production on mudflats or exceed upper thermal tolerances for infauna.

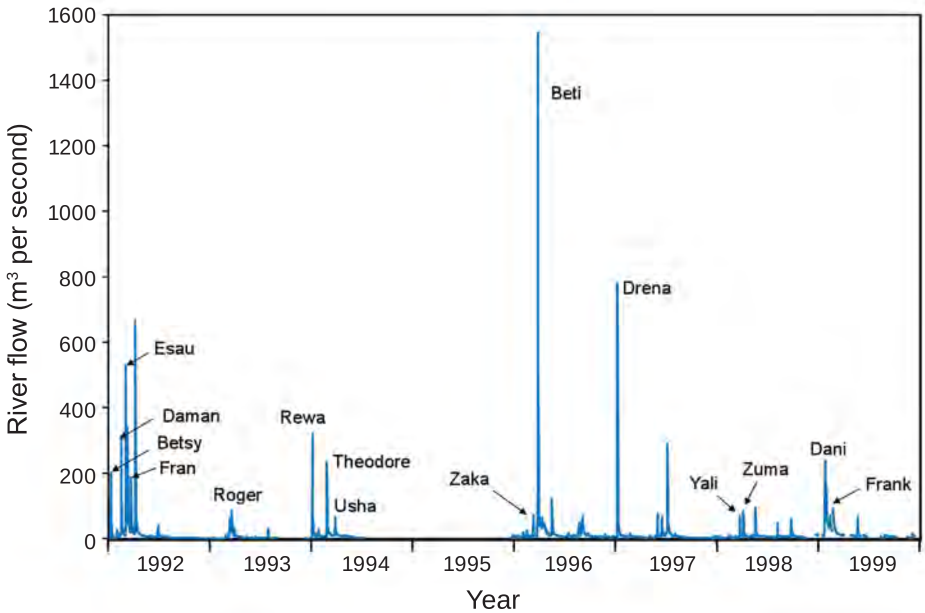


Figure 7.10 Average daily flows for the Tontouta River, New Caledonia, from 1992 to 1999. High flows caused by cyclones (named peaks) and other tropical storms (unnamed peaks) have a major role in shaping channel and floodplain habitats (source: Fiji Meteorological Service and Observatoire de la Ressource en Eau, New Caledonia)[93].

7.5.6 Sea-level rise

Intertidal estuarine habitats are particularly exposed to sea level rise[63,97]. Changes in intertidal area will be governed by local topography. Coastal plain estuaries surrounded by low-lying salt marsh, salt pan, swamps or swamp forests may increase in intertidal area. Increasing inundation of supratidal habitats will allow landward encroachment of mangroves, salt marsh and salt pan vegetation, on low-lying terrain.

Coastal wetlands will have increased depth and a higher salinity as sea level rises[35,98], leading to replacement of freshwater plants by salt-tolerant species. Under both the B1 and A2 emissions scenarios, sea-level rise is likely to be rapid, relative to the life-cycles of forest trees[99], limiting their ability to colonise new habitats. These wetlands are likely to become more variable under the combined effects of increased sea level, increased and more variable rainfall, and increasing temperatures[58].

Exposure of supratidal habitats to saline water from rising sea levels by 2035 under the B1 scenario is likely to have little impact in estuaries like the Fly River system which have a tidal range of up to 5 m[100]. But because of the low elevation of the Fly River floodplain, even the minimum projected sea-level rise of ~ 1.0 m by 2100 under the A2 scenario (Chapter 3) would inundate vegetated habitats that currently experience limited exposure to salt water (**Figure 7.13**). In contrast, supratidal habitats in estuaries with as little as 0.5 m tidal range, such as the Wagulani River in Mullins Harbour, PNG, would receive proportionally higher saline exposure. Some mangrove areas are expected to be particularly vulnerable to sea-level rise, because they are unlikely to be able to migrate landward in pace with inundation (Chapter 6).

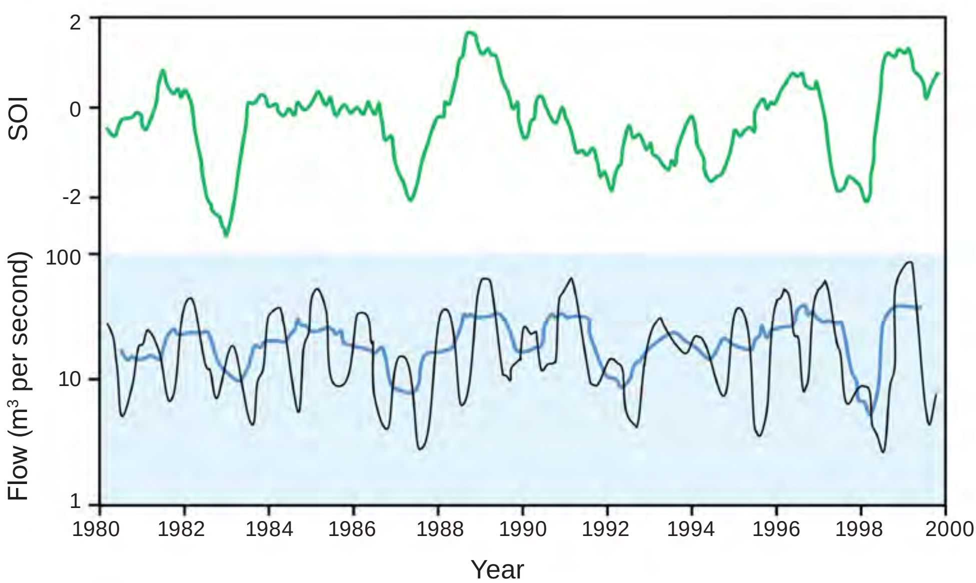


Figure 7.11 Effects of the El Niño-Southern Oscillation on river flows for the Ba River in northwest Viti Levu, Fiji. Flow seasonality (black line, 5 month running mean) reflects strong seasonality in rainfall. Low flows (blue line, 13 month running mean) correspond to low Southern Oscillation Index (SOI) periods (green line, 5 month running mean) during the drought of 1983, 1987, 1993 and 1998 (source: Fiji Public Works Department, Hydrology Section, and Fiji Meteorological Service, Terry et al. 2001)[95].

7.6 Vulnerability of freshwater and estuarine habitats

This assessment follows the approach outlined in Chapter 1, and considers the vulnerability of habitats as a function of exposure to climate change effects, their sensitivity to those changes, and the capacity of habitats to adapt to reduce the potential impact.

All habitats are exposed in a similar way to projected changes in rainfall, temperature and possibly cyclone intensity, whereas sea-level rise affects only low-lying habitats. On the other hand, the sensitivity of freshwater and estuarine habitats varies widely. In particular, differences in stream power between headwaters and tidal reaches caused by channel gradient mean that large volumes of water in lowland reaches have greater thermal stability compared with small montane tributaries. Topography can also be expected to mediate the potential impacts of climate change on riverine habitats, and the effects of mountains will influence local weather patterns. In general, as riverine habitats change from the headwaters to the sea, their relative areas and locations can be expected to adapt in different ways.

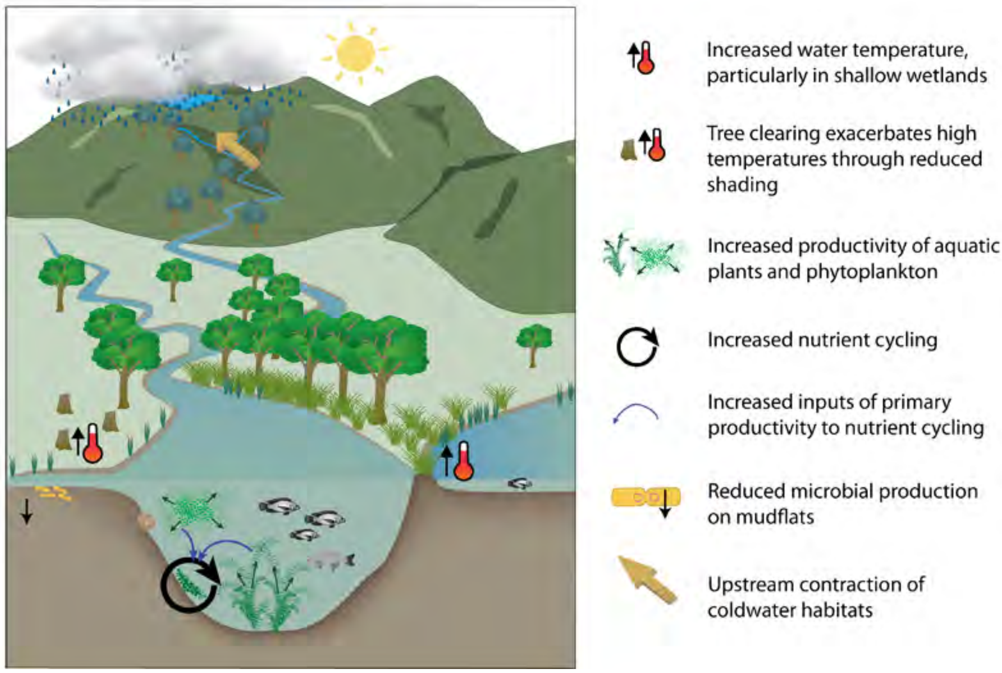


Figure 7.12 Effects of projected increases in water temperature on freshwater and estuarine habitats. Highland coldwater habitats are expected to contract upstream. Temperature extremes will be greatest in shallow floodplain habitats and intertidal flats. The greatest increases in water temperature are expected where shading of the water surface is diminished by clearing of vegetation.

7.6.1 Adaptive capacity of abiotic and vegetated habitats

Abiotic habitats such as rocks and sand respond to climate change in a purely physical way. In contrast, vegetated habitats are able to adapt to climate change because plants alter their growth rates and reproduction in response to variation in temperature, water availability, and water quality.

Abiotic habitats in rivers are influenced by climate-related events through a combination of longitudinal and lateral processes. Increased flow erodes sediments in upstream river reaches and transports them downstream where they are deposited on floodplains, within the river channel, or in the estuary, changing the shape of river habitats over time. The vulnerability of abiotic habitats is a function of exposure and sensitivity to climate change, since the habitats themselves have no adaptive capacity. Bedrock channels are largely resistant to changes in flow as a result of increased rainfall, but decreasing sediment sizes from boulders, cobbles, gravel, sand, silt and clays are progressively more sensitive to flow and require less energy to be transported downstream. Although sediment particles are unable to adapt to changes in flow or temperature, bacterial films, attached algae and macrophytes bind sediments together, making them less sensitive to changes in flow. Increasing temperature and changes in nutrient supply may affect this structural binding capacity, making sediment habitats either more or less vulnerable to changes in flow.

Vegetated habitats, such as macrophyte beds, wetland grasses, algal mats, flooded vegetation and swamp forests, have the capacity to adapt to climate change. They can do this through temperature-dependent changes in photosynthesis and growth, by responding to altered inundation patterns, or by colonising new habitats with suitable salinity. Grasses on the Fly River floodplain clearly have capacity to adapt to short-term changes in climate by colonising dry blocked valleys during El Niño droughts[37]. Mangroves are able to grow at rates similar to historical changes in sea level and sedimentation to avoid being inundated or buried by sediments[35] but may not be able to keep pace with anticipated rates of sea-level rise (Chapter 6).

As long as the quantity and quality of abiotic and vegetated habitats remain in equilibrium within a functional process zone, effects on fish and invertebrates should be restricted to local scales. But if climate change results in a net loss or gain of specific habitats, the species composition of fish and invertebrates is likely to change[23].

Photo: Nick Rains/Corbis

Macrophytes, Sivoli River, Papua New Guinea

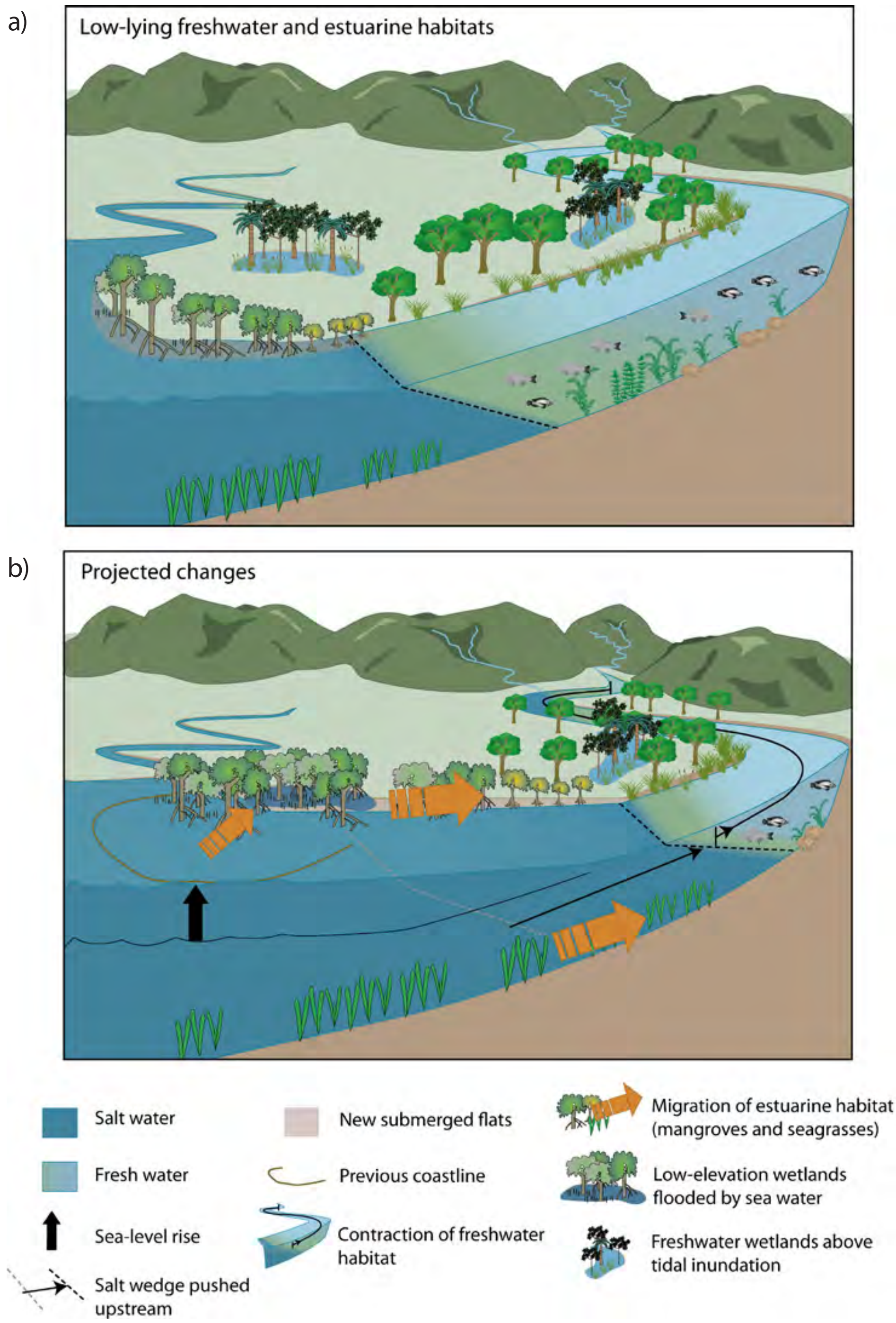


Figure 7.13 Effects of projected increases in sea level on (a) the general present-day structure of low-lying freshwater and estuarine habitats; and (b) the likely effects of sea-level rise, i.e. upstream retreat of lowland freshwater habitats and riparian vegetation, landward migration of mangroves, and salinisation of freshwater coastal wetlands.

7.6.2 Vulnerability of key habitats

7.6.2.1 Montane reaches

Exposure and sensitivity

Exposure of the montane reaches of rivers to climate change is restricted to PNG, and to small areas of Espiritu Santo (Vanuatu), Guadalcanal (Solomon Islands), Viti Levu (Fiji) and Grande Terre (New Caledonia). Nevertheless sensitivity to climate change may pose a significant risk at a local scale.

Montane reaches are principally exposed to increases in temperature, and increased flow and flow variability associated with changes in rainfall and cyclone intensity. As temperatures rise, the amount of coldwater habitat for rainbow trout in PNG will decline. Elevated temperature is likely to increase production rates of benthic algae and riparian vegetation, resulting in increased supply of organic material to the channel subject to the availability of nutrients. The accompanying increase in river flow and material washed from the catchment will also result in increased throughput of organic material. Elevated flow may increase scouring of fine sediments, resulting in small increases of substrate particle size.

Potential impact and adaptive capacity

The most extreme effects can be exemplified as a transition from clear water, with sediment-free, rocky substrata supporting low levels of algal growth, to episodic turbid water with substrata covered in fine sediments, which inhibit attachment of benthic algae. The effects of rising temperatures may be most extreme in cleared montane catchments, when runoff is warmed as it flows over exposed land. These changes are likely to reduce the amount of suitable habitat for mountain-dwelling fish.

The adaptive capacity of undisturbed catchments through enhanced vegetation growth, in response to increasing temperature and rainfall, should make montane river habitats more resilient to the impacts of climate change.

Vulnerability

Undisturbed montane rivers have low vulnerability to habitat changes resulting from increased flow, but will experience elevated water temperatures. The exception is likely to be in New Caledonia, where montane rivers are expected to be more vulnerable to channel reduction or drying, and habitat fragmentation caused by reduced winter rainfall, in addition to increased sedimentation after cyclones.

7.6.2.2 Slopes reaches

Exposure and sensitivity

River habitats in slopes reaches are common throughout the tropical Pacific, with fish penetrating well upstream[56]. These habitats are exposed to elevated temperatures, increased flow and flow variability, except in New Caledonia where river discharge is expected to decline.

In the slopes reaches of large rivers, such as the Fly and Sepik rivers, and smaller rivers, such as the Rewa and Ba rivers on Viti Levu and Papenoo River on Tahiti, elevated temperature is likely to have a modest effect by increasing production rates of benthic algae and riparian vegetation. This increase should result in improved food availability for fish species grazing on algae. Warming will be more pronounced where the water surface is not shaded by riparian vegetation. However, warming is also likely to be moderated by groundwater inflows and the extent to which groundwater is protected from increasing temperatures.

The greatest exposures in slopes reaches are from increased flow and flow variability associated with changes in rainfall and cyclone intensity. Physical habitat patches are expected to become more dynamic, with high-flow events increasing the redistribution of sediment[23]. Channels armoured by coarse sediments are likely to retain their characteristic stability, but may become more exposed to scouring where the bed is disturbed by other factors. Scouring during high flows is likely to increase channel capacity, enlarging slopes habitats by making pools deeper and wider. Where vegetation is largely intact, sensitivity of these habitats to increased runoff is likely to be low.

Potential impact and adaptive capacity

The effects on slopes habitats, and their adaptive capacity, differ between tropical and subtropical regions because of differences in projected rainfall and river flows. In tropical regions, the combination of warmer temperatures and higher rainfall is expected to increase the density of catchment and riparian vegetation, as well as aquatic macrophytes. This should expand the area of aquatic habitat, and protect rivers from erosion and sediment deposition.

In the subtropical rivers of New Caledonia, where winter rainfall is expected to decrease, baseflow is likely to have diminished capacity to transport sediment, resulting in channels contracting and becoming shallower. This is expected to result in a reduction in habitat area. Reduced flow leads to increased drying of small rivers, fragmentation of pool habitats, and increased warming. When cyclones occur, flood damage is more likely because of the combined effects of increased cyclone intensity and reduced channel capacity.

Vulnerability

Slopes reaches have low vulnerability to the expected changes in water temperature and rainfall. Transient negative effects are likely to follow cyclone damage, and diminish as vegetation recovers. New Caledonia has moderate to high vulnerability associated with the expected reduction in river flow and increased water temperature. This vulnerability arises from reduced habitat area during normal flows, and possibly greater disturbance by cyclones.

7.6.2.3 Lowland reaches

Exposure and sensitivity

Lowland river habitats are expected to warm slightly, which in isolation would result in increased growth of macrophytes, benthic algae and phytoplankton. Higher flows are expected to increase habitat area through channel expansion, although erosion stemming from increased rainfall and cyclone intensity may also expose the lowland reaches of rivers to increased turbidity and sedimentation[101,102].

Sensitivity of lowland reaches to increased rainfall and flow is expected to be low because channels already experience elevated flows regularly. Habitats are likely to become more dynamic as sand and mud banks are scoured and reformed by high flows associated with increased rainfall and more intense cyclones. Vegetated channel habitats may be sensitive to increased sediment instability and turbidity.

Downstream, lowland reaches are likely to be exposed to progressive increases in salinity caused by rising sea levels and storm surges, and changes in the distribution of primary production.

At the upstream tidal limit, greater salinity may cause suspended clay particles to flocculate and settle out of the water column during low flows. These changes are expected to increase water clarity and improve conditions for the growth of brackish water macrophytes, benthic algae and phytoplankton[100].

Lowland river reaches, Fiji

Photo: Ashley Cooper/Corbis

Potential impact and adaptive capacity

Lowland reaches are expected to be affected over a wider habitat area than upstream slopes habitats, because of their greater channel width. Lowland reaches are typically much wider than the fringing vegetation, so that the habitat area shaded by riparian vegetation and stabilised by root development is proportionally smaller than in upstream reaches. In rivers projected to have increased discharge, such as the Fly and the Sepik rivers in PNG[89], increased channel capacity caused by erosion is likely to be the dominant effect, coupled with more frequent overbank flooding and sediment deposition, and increased channel migration.

Adaptive capacity in lowland reaches will be related to the condition of vegetation on the floodplain and in the upper catchment. Vegetation reduces the rate of runoff and the potential for erosion of the river bed and banks. Where riparian vegetation is effective in protecting against bank erosion, increased discharge is expected to cause greater inundation of floodplain habitats, or scouring to deepen the channel.

Increased rainfall and warmer temperatures are likely to enhance the growth of macrophytes and riparian vegetation, thus improving the resilience of river habitats.

Vulnerability

Lowland reaches typically have low vulnerability to increased discharge, increased habitat variability resulting from extreme flows, and increased rates of channel migration. The potential negative effects of these changes are expected to be offset by greater availability of fish habitats due to increased discharge. Vulnerability of individual rivers will be determined by the combined effects of climate change and the condition of catchment vegetation. In New Caledonia, the lowland reaches of rivers are expected to be vulnerable to channel contraction stemming from reduced winter flow and increased sedimentation after cyclones, resulting in shallowing of river channels.

7.6.2.4 Lakes

Exposure and sensitivity

Lakes at both high and low elevation are exposed to increases in temperature, rainfall and possibly cyclone intensity, except in PNG where high-elevation lakes are minimally affected by cyclones because of their distance from the coast.

High-elevation lakes may be particularly sensitive to even moderate increases in temperature, which are likely to reduce the amount of suitable habitat for coldwater fish species[103]. High-elevation lakes are also sensitive to increased stratification, which may result in deoxygenation below the thermocline[103]. However, warmer lake temperatures will accelerate nutrient cycling and primary production in the pelagic zone.

High rainfall throughout most of the region means that high-elevation lakes are full of water most of the time, and higher rainfall is expected to have little effect on lake water levels. Instead, increased runoff can be expected to increase inflows and outflows from lakes, with the reduced residence time improving water quality.

Lowland lakes, such as the small but highly productive Lake Bangatu in Solomon Islands[39], will experience elevated inflows, allowing increased connectivity with the sea for amphidromous and catadromous fish species. Similar increases in connectivity are expected in larger lowland lakes, such as Lake Murray in PNG, which increases from a nominal surface area of 647 km^2 to over 2000 km^2 in the wet season. Larger increases in area and connectivity are likely to occur under wetter climate regimes, and these changes are expected to improve habitat access and quality.

Lakes in drier regions such as New Caledonia will be exposed to reduced inflows and increased evaporation, resulting in a reduction in size and increased sensitivity to warming.

Impact and adaptive capacity

The effects of climate change on lakes in the region are expected to be generally positive – most lakes will experience increased inflows to maintain habitat quality and quantity. The adaptive capacity of vegetation in intact catchments is expected to mitigate increased erosion and sediment transport under conditions of increased rainfall.

Coastal lakes may experience saline intrusion via groundwater as sea level rises, however, and increased freshwater inflows may form a freshwater layer above the saline water. Damage to coastal vegetation by cyclones may breach the narrow land barrier separating coastal freshwater lakes from the sea, transforming them into more saline habitats.

Contraction of natural and artificial lake habitats in response to reduced winter rainfall in New Caledonia under the A2 scenario is likely to occur. Littoral vegetation is expected to adapt by colonising edge habitats as the water level recedes.

Photo: Boga Figa

Lake Owa, Papua New Guinea

Vulnerability

Natural lake habitats in the tropical Pacific are likely to have low vulnerability to climate change, because the projected conditions favour processes that form or maintain lakes. However, in New Caledonia, the expected reduction in winter rainfall, and increased temperature and evaporation, make lakes highly vulnerable to climate change in drought years when summer rainfall is also reduced.

7.6.2.5 Floodplain habitats

Exposure and sensitivity

Floodplains are most extensively developed along the Fly and Sepik-Ramu rivers in PNG[35]. Elsewhere in the region, they are small in comparison, but nonetheless provide important fish habitats.

The pools, oxbow lagoons, swamp forests, marshes and blocked valleys found on floodplains are all exposed to increased temperature, higher rainfall, and more intense cyclones. Close to the coast, floodplains will also be exposed to sea-level rise, either through direct intrusion of saline water, or by the damming effects of rising tides on increased flows, forcing fresh water onto the floodplain. In the Fly River, where tidal oscillations extend upstream of the confluence with the Strickland River[104], rising sea level may lead to significant increases in inundated area, accompanied by elevated salinity intrusion during El Niño drought periods.

Greater and more regular inundation is expected to increase the area of floodplain, and enhance fish access to the range of associated habitats. Warmer temperatures are likely to increase production and decomposition rates of floodplain vegetation, leading to broad increases in productivity. However, some aquatic and riparian vegetation will be sensitive to increased water depth, and the duration of inundation. These plant species are expected to retreat into shallower habitats.

Floodplain sedimentation rates on tropical Pacific islands are among the highest in the world, in the range of 3.2 to 4.0 cm per year[105]. Increased flooding from more intense cyclones would accelerate sediment deposition on floodplains across the region.

Potential impact and adaptive capacity

Exposure to climate change is expected to increase primary production and decomposition rates, the duration and extent of connectivity among river and floodplain habitats, and the salinity of low-lying areas.

Rapid sediment deposition rates on floodplains provide an opportunity for vegetation to colonise new areas so that smothering of plants is largely transient. Slower-growing trees are presumably more likely to adapt by colonising locations less exposed to inundation and accumulation of sediment. Increased bank stabilisation by riparian vegetation offers some adaptive capacity to limit erosion and sedimentation[102].

The combination of adaptive capacity of floodplain vegetation, increased sedimentation, scouring of floodplain channels during extreme floods, and greater productivity of shallow inundated areas suggests that (1) the mosaic of floodplain habitats may be preserved; and (2) their distribution and spatial arrangement across the floodplain may become more dynamic. As floodplain grasses adapt to a wetter climate, fluctuations in the habitats they form may be accentuated between 'normal' years with increased discharge, and drought years when some habitats dry completely.

In New Caledonia, where winter rainfall is expected to decline, the effects of sedimentation on floodplains may be more marked than elsewhere, due to a decline in catchment vegetation in response to a drier climate and increased exposure to erosion.

Photo: Australian Doctors International

Floodplain habitats, Sepik River, PNG

Vulnerability

Floodplain habitats in the tropics are likely to be enhanced by increases in rainfall and water temperature and, in general, have low vulnerability to climate change. As floodplain vegetation adapts to a wetter climate, however, habitats will become more vulnerable to El Niño drought episodes. Low-lying areas of floodplain near estuaries are vulnerable to saline inundation from sea-level rise. Floodplains further upstream should be covered by fresh water more extensively as rising sea levels 'dam' the estuary and force freshwater flows laterally. Vulnerability of floodplains is greatest in New Caledonia, where the expected reductions in winter rainfall are likely to result in more frequent drying and disconnection of habitats, and increased sediment deposition during cyclones.

7.6.2.6 Estuaries

Exposure and sensitivity

Estuaries are exposed to a greater range of effects from climate change than other aquatic habitats. As the interface between fresh water and the sea, estuaries are exposed to the combined influences of climate change on rivers, and effects from the coastal environment (Chapter 6). These opposing changes have potential to create unexpected responses where they meet.

Based on the projected alterations to rivers, estuaries are likely to be exposed to moderate increases in water temperature, increases in freshwater flows and greater flow variability. Although most estuaries are also expected to extend further upstream with sea-level rise, freshwater inflows are likely to increase flushing of estuaries, resulting in greater discharge of fine sediments and greater variability in turbidity and salinity. These changes may result in increased variability in production of benthic and planktonic algae and smothering of some seagrass habitats.

Smaller estuaries on steep islands, which have intact catchment vegetation and carry low loads of fine sediment, should have low exposure to increased sedimentation. Although New Caledonia is expected to receive less winter rainfall, especially under the A2 scenario, estuaries there may experience greater variability in salinity and sediment deposition during floods and storm surges associated with stronger cyclones.

Exposure to increased water temperature is likely to vary according to the size and depth of the estuary. Small, steep, rocky estuaries in regions with tidal ranges of 1 m or less may have minimal exposure to a mixture of warmer freshwater flows and sea water. Estuaries such as the Fly River, with a large tidal range, may experience greater warming of intertidal flats, potentially inhibiting benthic production and increasing water temperature during the rising tide.

In places where sea-level rise allows inundation of extensive areas of low-lying land, the tidal regimes within estuaries can be expected to change.

Potential impact and adaptive capacity

As sea level rises, tidal movement in estuaries with a large tidal range will deliver marine sediments further upstream. This is expected to result in increased deposition and subsequent scouring of sediments during high flows[106], and a more dynamic physical habitat. The ability of macrophytes such as seagrasses and mangroves to stabilise sediment deposits will be determined by the rates of sediment delivery, scouring, and plant growth. The Ord River estuary in Western Australia provides an example of changes that might be expected elsewhere under climate change scenarios[107]. There, upstream tidal transport of marine sediments has made the estuary shallower, and formed sand banks that have been colonised by mangroves[106], forcing flood flows towards the banks. The resulting erosion has widened the estuary and much of the eroded sediment is redeposited in the channel, making the estuary even shallower and reinforcing the process.

Sea-level rise is expected to increase inundation of supratidal habitats and promote shoreward migration of the associated vegetation. Depending on location, mangroves and other estuarine plants may have a key role in the ability of estuaries to adapt to the effects of increases in freshwater flows, water temperature and sea level by enabling estuarine habitats to migrate landward at a similar rate to rising sea levels (Chapter 6).

Vulnerability

Estuarine habitats are expected to have low vulnerability to climate change because they are already exposed to great variation in freshwater inflows, temperature and salinity. On the other hand, estuaries are moderately vulnerable to sea-level rise. Where the upstream extent of estuaries is not constrained, estuarine habitats are expected to migrate landward. However, estuaries that are unable to retreat because of steep topography or other barriers are likely to be reduced in area.

Fish habitat created by mangroves Photo: Gary Bell

7.7 Interactions between effects of climate change and existing impacts

The effects of climate change on freshwater and estuarine habitats will not occur in isolation. Rather, existing environmental conditions and land use will have a strong influence on the exposure, sensitivity, adaptive capacity and vulnerability of individual habitats.

7.7.1 Effects on exposure and sensitivity

Many river catchments have been cleared of vegetation by logging, mining or agricultural activities. Cleared catchments experience accelerated erosion, which causes rivers to become more turbid. For example, on Babeldaob Island in Palau, vegetation clearing in the Ngerikil River catchment produced estuarine sediment loads 10 to 19 times higher than in the neighbouring Ngerdorch catchment, with mangroves trapping about 30% of sediments from each catchment[108]. Mining near the Ok Tedi River in PNG discharges about 80 million tonnes of waste rock and mine tailings into the river each year, increasing the fine sediment load from 3 to 5 million tonnes to 45 million tonnes per year[36] and affecting fish habitats for large distances downstream[109]. On la Grande Terre, New Caledonia, the vegetation in many catchments has been reduced, causing river channels to fill partially with coarse sediments and increasing turbidity[110]. Similar impacts are associated with forestry in Solomon Islands and Fiji[31,111,112]. In short, clearing vegetation increases the exposure of river habitats to the effects of increased rainfall[31,39,109,111].

Rivers that carry naturally high sediment loads, such as the Fly River system, appear to have low sensitivity to increased sediment delivery arising from a wetter climate. Smaller rivers appear to be much more sensitive to increased sediment, however[93,101].

Riverine habitats likely to be most exposed to sedimentation are low-gradient channels, and slow-flowing lowland reaches that become permanently turbid because of high, suspended sediment loads. Excessive deposition of sediments causes homogenisation of river habitats, by infilling pools and covering complex habitats such as rocks and macrophyte beds, creating a more uniform, rectangular cross-sectional channel profile[113].

Clearing vegetation from river banks reduces shading of the water surface, resulting in higher water temperature[114,115]. Streams with cleared catchments and banks are commonly 1 to 2°C warmer than streams with intact vegetation, and removal of riparian forest may increase water temperature by an alarming 8°C[116].

7.7.2 Effects on potential impact and adaptive capacity

Clearing of catchment vegetation has already reduced the capacity of rivers to adapt to moderate effects of climate change. The loss of adaptive capacity is roughly proportional to the percentage of catchment area cleared. However, the regenerative capacity of catchment vegetation after disturbance is likely to be enhanced by warmer air temperatures, CO_2 enrichment and increased rainfall, so that rivers are expected to recover relatively quickly from heavy rainfall or cyclone damage in the future. Where topsoil has been lost, however, vegetation will recover more slowly and exposure of rivers to sedimentation will be prolonged.

7.7.3 Effects on vulnerability

The most critical feature determining the vulnerability of river habitats to increasing temperature, and rainfall, and the possibility of more intense cyclones, is the extent of intact catchment and riparian vegetation. The ability of rivers to absorb these changes is provided through shading of the water surface by the forest canopy, and stabilisation of soils through root development (**Figure 7.14**).

In subtropical regions with drier climates, sediment inputs from cleared catchments are expected to decrease during years with normal rainfall. More intense cyclones would increase erosion and sediment delivery on a decadal scale compared to rivers with intact catchment vegetation.

Estuaries will be more vulnerable to sea-level rise where infrastructure constrains landward migration of estuarine habitats. Clearing mangroves for urban development, and construction of sea walls and similar barriers, inhibits any inherent adaptive capacity of these trees (Chapter 6). In such circumstances, the area of estuarine habitats is likely to be reduced.

The interactions between the effects of climate change and catchment conditions described here occur largely in riverine habitats, but similar conclusions apply to lakes, floodplains and estuaries. All habitats are expected to be more vulnerable to climate-related increases in erosion, sedimentation and shallowing where catchment vegetation has been managed poorly.

7.8 Integrated vulnerability assessment

7.8.1 Vulnerability of habitats

When the expected effects of higher temperatures, altered flow rates (stemming from increased rainfall, more severe droughts and more intense cyclones), and sea-level rise are integrated, all major river habitats in equatorial areas, are projected to have a low vulnerability to climate change (**Table 7.4**) Indeed these habitats are expected to expand under the influence of increased rainfall. Even in montane rivers where coldwater habitats are likely to contract, the positive effects of increased flow are expected to dominate. The associated benefits are projected to increase progressively for both the B1 and A2 scenarios until 2100 (**Figure 7.15**).

Projections for the integrated effects of temperature, altered flow rates and sea-level rise are in the opposite direction for the subtropical rivers in New Caledonia. There, freshwater habitats are projected to have a low vulnerability resulting in negative impacts by 2035 under the B1 and A2 scenarios (**Table 7.4**). By 2100, the vulnerability of subtropical freshwater habitats is projected to increase to moderate to high for B1 and A2 scenarios.

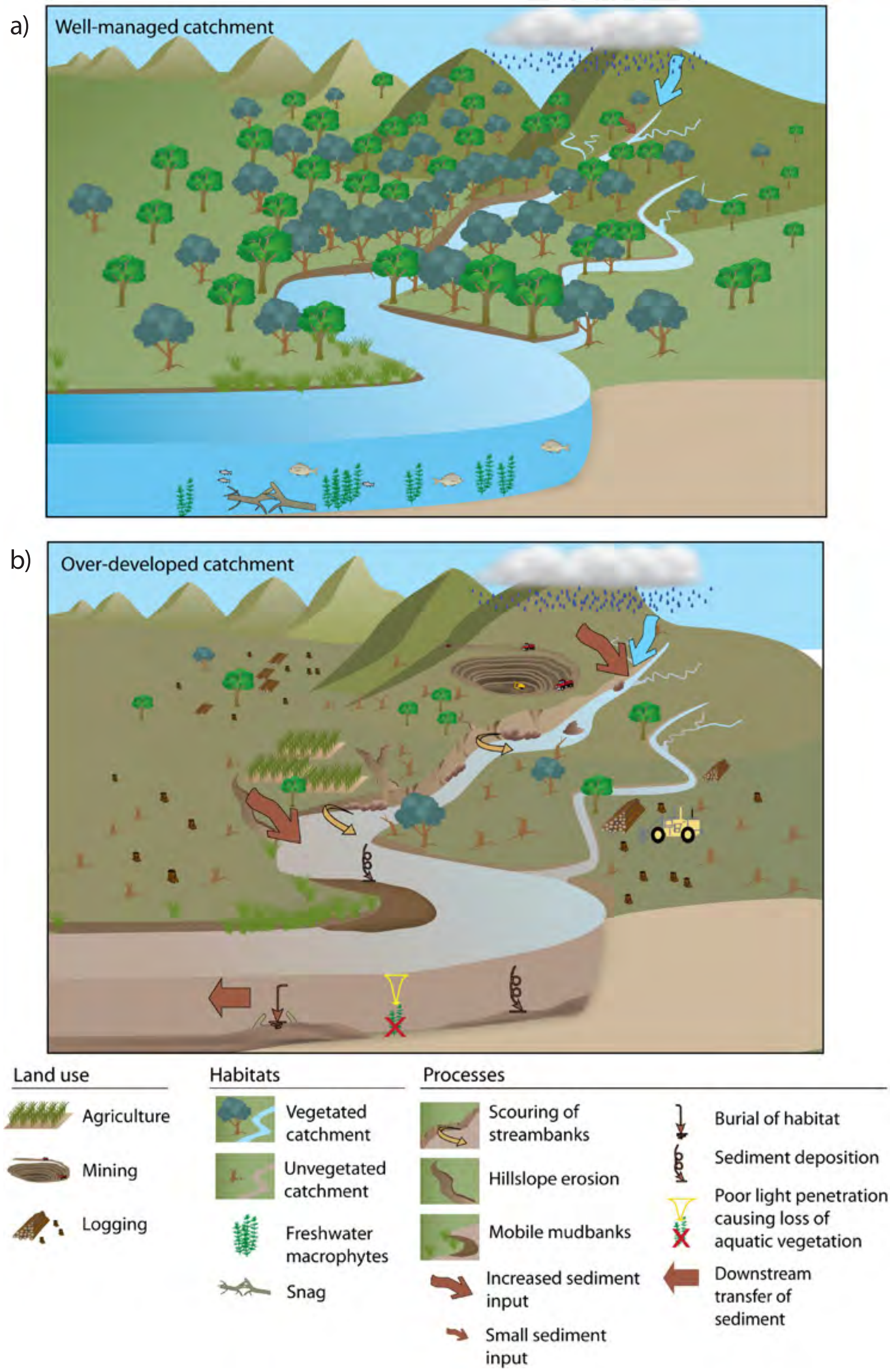


Figure 7.14 Catchments with good forest cover (a) are less vulnerable to increased temperature and rainfall, and more intense cyclones, than catchments with cleared vegetation. Erosion of hill slopes and river banks and increased burial of fish habitats by sediments (b) is much more common in rivers where vegetation has been removed from the catchment.

The vulnerability of equatorial estuaries to the combined effects of increased temperatures, greater freshwater flow and sea-level rise is projected to be low (**Table 7.4**). Unconstrained estuaries may become larger or remain the same size as they extend inland, whereas constrained estuaries may become smaller. Vulnerability to changes in habitat area, coupled with improved water quality, is projected to increase progressively until 2100 under both the B1 and A2 emissions scenarios (**Figure 7.15**).

In the subtropical estuaries of New Caledonia, vulnerability to negative impacts of increased temperature, reduced river discharge and sea-level rise is expected to be low by 2035 under the B1 and A2 scenarios (**Table 7.4**), increasing to moderate for B1 and high for A2, in 2100.

The possible positive and negative effects on all habitat types will be mediated by the way catchments are managed. Physical processes in river systems are strongly driven by the rate of runoff and river flow, which are in turn influenced by topography, geology and catchment vegetation. Where catchment vegetation has been removed excessively, the physical processes have greater effects, adaptive capacity is reduced, and the vulnerability of habitats to climate change increases (**Figure 7.16**). Catchment runoff models are required to provide more detailed assessments.

For some of the larger countries in Melanesia, climate change is projected to increase the total area of freshwater habitats substantially by 2100 (**Table 7.5**). The largest increases are likely to occur through increased inundation of floodplains. However, as indicated above, the quality of those habitats will be affected by catchment management.

7.8.2 Constraints to adaptation

Global projections for the effects of climate change on freshwater fish and their habitats[117,118] are consistent with the habitat vulnerability assessments provided here, based on projections of higher temperatures and increased river flow for most of the region (the projections for New Caledonia and the southeast Pacific are different).

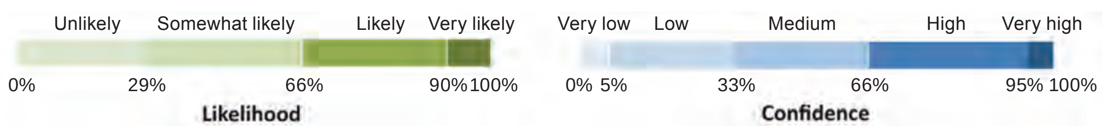
Increased river flow makes freshwater and estuarine habitats in the tropical Pacific especially likely to be affected by climate change. Where greater flows occur without excessive erosion and sedimentation, increases in availability and complexity of fish habitats are expected. Clearly, the chances of positive effects occurring are greatest in catchments with intact vegetation where sedimentation rates are relatively low[108,119]. In well-managed catchments, the adaptive capacity of natural vegetation may be sufficient to limit increased erosion of river banks and deliver benefits from increased flows. However, where natural vegetation has been removed, the inherent adaptive capacity to mitigate the damaging effects of higher rates of runoff and flow is reduced.

The primary constraint to adaptation of freshwater and estuarine habitats to climate change is, therefore, the need for development in catchments to support rapidly growing human populations, which are predicted to grow from 9.86 million in 2010 to ~ 15 million

Table 7.4 Vulnerability of freshwater and estuarine habitats to climate change under the B1 and A2 emissions scenarios for 2035 and 2100. Expected benefits (+) and negative impacts (-), in response to projected changes in surface air temperature (Temp), rainfall and sea level, are integrated to provide an overall vulnerability rating of low, moderate, or high. Ratings apply to undisturbed catchments with low levels of vegetation clearing. Disturbed catchments with high levels of clearing will experience higher vulnerabilities than indicated.

Habitat	B1/A2 2035				B1 2100				A2 2100			
	Temp	Rain-fall	Sea level	Overall	Temp	Rain-fall	Sea level	Overall	Temp	Rain-fall	Sea level	Overall
Equatorial												
Rivers												
Montane	-	+	n/a	Low	-	+	n/a	Low	-	+	n/a	Low
Slopes	+	+	n/a	Low	+	+	n/a	Low	+	+	n/a	Low
Lowland	+	+	-	Low	+	+	-	Low	+	+	-	Low
Lakes												
High elevation	+	+	n/a	Low	+	+	n/a	Low	+	+	n/a	Low
Low elevation	+	+	-	Low	+	+	-	Low	+	+	-	Low
Floodplains	+	+	+/-	Low	+	+	+/-	Low	+/-	+	+/-	Low
Estuaries	+	+	+/-	Low	+	+	+/-	Low	+/-	+	+/-	Moderate
Subtropical												
Rivers												
Montane	-	-	n/a	Low	-	-	n/a	Moderate	-	-	n/a	High
Slopes	+	-	n/a	Low	+	-	n/a	Moderate	-	-	n/a	High
Lowland	+	-	-	Low	+	-	-	Moderate	-	-	-	High
Lakes												
High elevation	+	-	n/a	Low	-	-	n/a	Moderate	-	-	n/a	High
Low elevation	+	-	-	Low	-	-	-	Moderate	-	-	-	High
Floodplains	+	-	-	Low	-	-	-	Moderate	-	-	-	High
Estuaries	+	-	+/-	Low	-	-	+/-	Moderate	-	-	+/-	High

n/a = Not applicable.



by 2035 (Chapter 1). Continued population growth and urbanisation until 2100, particularly in Melanesia, may also see increased demand for hydroelectricity generation to support economic development[15]. The extent of water resource development in the region may reduce the anticipated responses of freshwater and estuarine ecosystems to climate change in wetter regions, and intensify habitat impacts in drier subtropical islands, in line with global predictions[117].

7.9 Uncertainty, gaps in knowledge and future research

Considerable uncertainty about the projected effects of climate change on freshwater and estuarine fish habitats remains for two main reasons. Firstly, the existing climate models provide coarse-scale projections that do not reflect the effects of island topography on local climates (Chapters 1 and 2). Downscaling of these models is needed to improve forecasts of island climate, especially rainfall[ii]. Secondly, ecological understanding of rivers in the tropical Pacific is generally limited compared with knowledge of rivers elsewhere. In practice, knowledge of other rivers will need to be applied to guide adaptation processes until more is learned about our local rivers.

The global studies that have projected the effects of various climate scenarios on large river systems, including the Fly and Sepik-Ramu rivers in PNG[88], can help build knowledge of local habitats to improve confidence in the projected affects on river flows and habitat availability. These studies should also help identify the best approaches to assist freshwater and estuarine fish habitats adapt to climate change. The differences between regions mean, however, that the relevance of lessons learned from other rivers will need to be interpreted with caution.

This study has identified five main avenues of research needed to improve future assessments of the likely effects of climate change scenarios on freshwater and estuarine habitats, and the suitability of adaptation strategies. These avenues of research are listed below.

- Development and validation of ecosystem models for representative river types.
- Application of flood modelling to low-lying habitats, to improve vulnerability assessments and help evaluate options to maintain habitat availability in response to sea-level rise, and increased river flows and storm surge.
- Modelling of sediment transport, and tracing studies, to refine and target strategies to optimise vegetation in catchments.
- Quantitative inventory and mapping of river and estuary habitats, to set benchmarks for identifying changes in habitat area, quality and connectivity, and to manage their vulnerability.

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; see www.cawcr.gov.au/projects/PCCSP

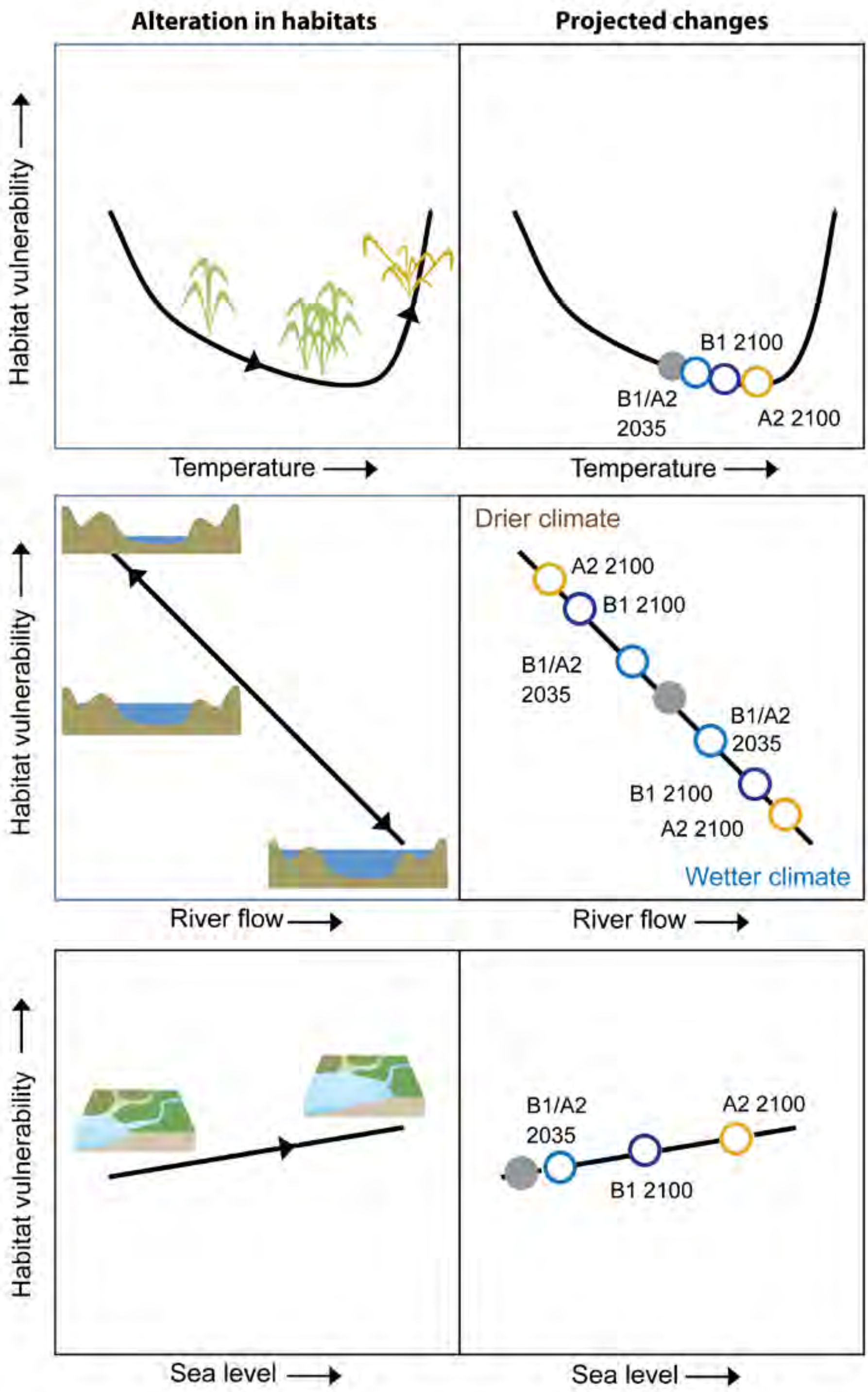


Figure 7.15 Projected vulnerability of freshwater and estuarine habitats to aspects of climate change. Left panels depict the general nature of alterations in habitats expected to occur as climate changes progressively. Arrows indicate direction of change. Right panels show relative changes projected under the B1 and A2 emissions scenarios in 2035 and 2100 compared to present-day conditions (solid circle). River flow is derived from the combined projections for rainfall, drought and possibly more intense cyclones.

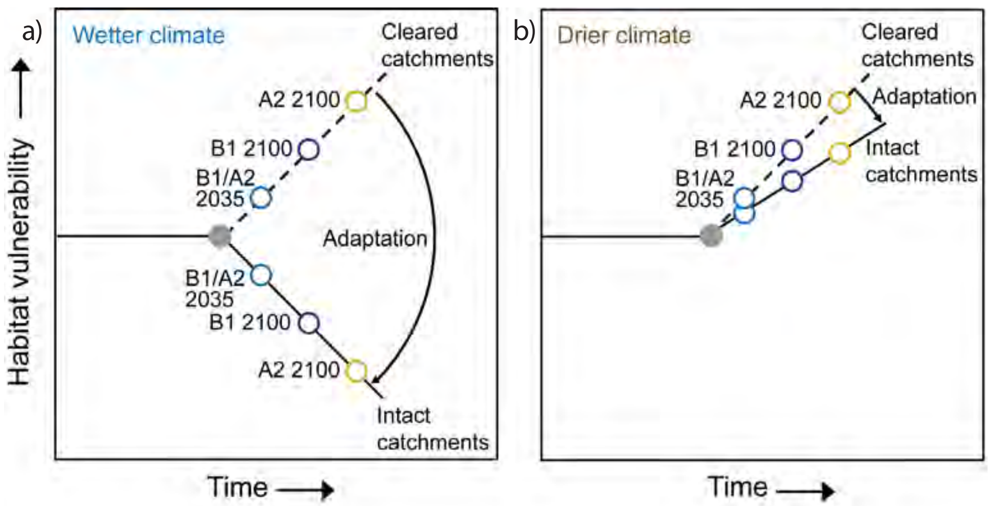


Figure 7.16 Vulnerability of freshwater and estuarine habitats in cleared catchments, and in catchments with intact vegetation, in regions projected to have (a) a wetter climate and (b) a drier climate. Regions with wetter climates have low vulnerability provided catchment vegetation is intact. Potential to reduce vulnerability through revegetation of catchments is much greater in wetter climates than in drier climates.

- Identification of the most important habitats used during the life cycles of migratory fish and invertebrate species (Chapter 10), to ensure that these habitats are included in adaptation strategies.

Due to the lack of scientific capacity in many PICTs, cooperation with regional and international institutions will be needed to complete this research, and identify and implement effective adaptation.

7.10 Management implications and recommendations

7.10.1 Habitats at greatest risk

The overwhelming outcome of this assessment is that the projected vulnerability of freshwater habitats to climate change is due largely to increases in river flow, and therefore the capacity of these habitats to adapt to climate change will depend largely on the condition of vegetation in catchments. River flows are projected to increase throughout much of the region, except in New Caledonia where rainfall may decline by up to 20% by 2100 under the A2 emissions scenario. These potential benefits will be tempered by how catchments are managed.

In their Call to Action on Climate Change in 2009[iii], the Pacific leaders identified the provision of solutions to deforestation and forest degradation as a key government response to climate change in the region. This vulnerability assessment for freshwater and estuarine habitats reinforces revegetation of catchments as a critical process.

iii Pacific Islands Forum Secretariat, Forum Communiques; www.forumsec.org.fj/pages.cfm/documents/forum-communiques

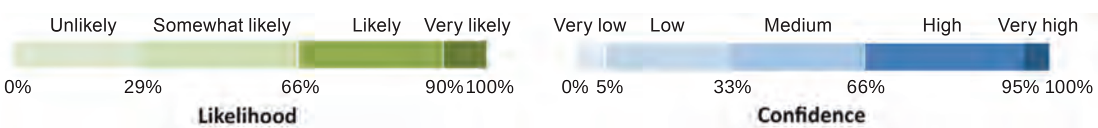
Revegetation will not only mitigate emissions and boost carbon sequestration, it will maximise the adaptive capacity of catchments to reduce the vulnerability of freshwater and estuarine habitats to the damaging effects of increased temperature, erosion, sedimentation and reduced water quality.

The single most important management recommendation, therefore, is to restore vegetation in the regions that contribute the most sediment to river networks. Because of the time needed for vegetation to become sufficiently established to reduce erosion and trap sediments, catchment rehabilitation must be an urgent priority.

Low-lying freshwater habitats are vulnerable to sea-level rise. In some cases it may be possible to prevent salinisation of critical habitats by constructing tidal barriers[120,121], but such barriers will also prevent landward migration of estuarine habitats, with the overall outcome still being a reduction in total habitat area.

Table 7.5 Estimated upper and lower ranges of projected changes in total area of freshwater habitat in selected Pacific Island countries and territories (PICTs) in 2035 and 2100. Estimates are based on projected changes in rainfall under the B1 and A2 emissions scenarios (Chapter 2), and anticipated river discharge. Confidence in projections is relatively low because local runoff conditions have not been included in the assessment. Grey cells indicate little or no change from existing habitats; blue cells indicate an anticipated increase in habitat area and availability; orange cells indicate that habitat area and availability are more likely to be reduced.

PICT	B1/A2 2035		B1 2100		A2 2100	
	Lower	Upper	Lower	Upper	Lower	Upper
Melanesia						
Fiji	-5%	5%	-5%	5%	5%	20%
New Caledonia	-5%	5–10%	-10%	5%	-20%	20%
PNG	-5%	5–10%	-5%	20%	-5%	20%
Solomon Islands	-5%	5–10%	-5%	20%	5%	10%
Vanuatu	-5%	5–10%	-5%	5%	5%	10%
Micronesia						
FSM	-5%	5%	-5%	5–10%	-5%	20%
Guam	-5%	5–10%	-5%	10%	-5%	20%
Palau	-5%	5%	-5%	5–10%	-5%	20%
Polynesia						
American Samoa	-5%	5%	-5%	5%	-5%	10%
Cook Islands	-5%	10%	-5%	10%	-5%	> 20%
French Polynesia	-5%	10%	-5%	10%	-10%	> 20%
Samoa	-5%	5%	-5%	5%	-5%	10%
Tonga	-5%	5%	-5%	10%	-5%	> 20%



Except for locations where levees are required to prevent inundation of existing urban and rural settlements, or habitats of high conservation value, structural intervention is unlikely to be justified. Where seawater exclusion is considered, comprehensive flood modelling is recommended, to identify the risks to floodplain and lowland channel habitats, and to enable alternative approaches to be identified.

Increased sedimentation as a result of higher rainfall is expected to affect water quality and channel habitats, especially those used by substrate-spawning fish and invertebrates. Effective strategies to limit sediment and associated pollutants entering rivers, such as catchment and riparian revegetation, will reduce the effects of existing catchment disturbance, and build adaptive capacity to reduce vulnerability to intense cyclonic rainfall.

El Niño drought events will cause reduced flow and habitat reduction in rivers and floodplains. Few freshwater fish in the tropical Pacific are adapted to survive in intermittent water bodies. Protection of drought refuges will enable surviving fish to recolonise habitats when normal flow conditions return.

7.10.2 Interventions to limit damage to non-vegetated habitats

It is necessary to distinguish between change, an important component of the dynamic habitat mosaic, and damage that reduces habitat quality or area. Natural channel migration, erosion, sediment deposition and infilling of wetlands typically maintain a dynamic equilibrium among habitats, so that as one habitat patch moves or is lost, another is created[23]. Damage occurs when habitat patches are lost and not replaced.

Human interventions commonly implemented to limit damage, such as stabilisation of river banks, construction of levees, floodgate systems and tidal barrages[122] may actually increase habitat damage, for example, by limiting sediment supply or accelerating erosion. Accordingly, interventions to reduce the vulnerability of aquatic habitats need to maintain the dynamic equilibrium among habitats and not seek to prevent habitat change.

Habitat dynamics can often be preserved through low-cost approaches using riparian vegetation. Assessment of local hydrological conditions, sediment dynamics, mobility of existing habitat features, and habitat quality and quantity is required before modification of natural river systems is attempted. Where habitat vulnerability is low, little can be gained by trying to prevent natural geomorphological adjustment.

In contrast, where catchment degradation has increased habitat vulnerability, targeted intervention to prevent further habitat damage is warranted. This can be achieved through revegetation of catchments and riparian areas with native species, and preventing access of livestock to riverbanks. Adoption of farming, forestry and mining practices that minimise soil loss is a key element in minimising sediment delivery to rivers[108,112,119].

Photo: Chris Roelfsema

'Gardening' on hillsides can cause loss of soil

7.10.3 Interventions to maintain vegetated freshwater habitats

Saltwater intrusion poses a threat to aquatic vegetation in lowland river reaches and floodplains. Interventions to minimise the effects of a rise in sea level of up to 1.4 m by 2100 (Chapter 3) need to be considered within the predominantly micro-tidal context of the tropical Pacific. A rise in sea level of this extent will result in extensive landward relocation of the high tide mark in many places, resulting in replacement of freshwater forests with retreating mangroves[123].

Three principal scenarios exist for vegetated freshwater habitats threatened by sea-level rise. Where topography permits, natural succession will allow vegetation to retreat inland as sea level rises. Management interventions should facilitate natural adaptation in these situations. Where the coastal zone is constrained by elevated ground, aquatic vegetation will be unable to retreat and salt-intolerant species will be lost or reduced in area. Adaptation measures will not be possible under this scenario. Where urban and rural development prevent the retreat of vegetation, adaptation to maintain habitat will require replanning the use of the landscape to allow habitat succession in conjunction with ongoing land use. Similar scenarios can be applied to vegetated floodplain habitats facing increased inundation during high flows and storm surges.

Where the effects of climate change occur more rapidly than the capacity of vegetation to adapt naturally, assisted adaptation can be planned by replanting resilient species, including mangroves (Chapter 6).

7.10.4 Management limitations

The level of legislative protection afforded to aquatic habitats varies among PICTs but is generally limited[35]. Furthermore, establishment of benchmarks for environmental change is not yet common practice. Some of these constraints are addressed by community-based management approaches, such as the Locally-Managed Marine Area Network in Fiji[35].

The Secretariat of the Pacific Regional Environment Programme identified four challenges to improving wetland management (1) limited awareness of conservation management at government and community levels; (2) insufficient knowledge to support conservation management decisions; (3) limited ability of local communities to influence wise use of wetlands; and (4) inadequate frameworks for management of natural resources and biodiversity[124]. It is also acknowledged that governments and communities in many PICTs have limited resources to reduce vulnerability to climate change.

Recognising these limitations, priorities for management include (1) increasing community education and awareness of the importance of freshwater and estuarine ecosystems to fisheries; and (2) building natural resource inventory databases to provide benchmarks for monitoring changes in habitats and the processes that drive these ecosystems. An important role of policy-making for adaptation to climate change is to ensure that developments in catchments do not compromise the ability of fish habitats to adapt.

7.10.5 Opportunities for investment to reduce vulnerability

The most critical aspects of freshwater fish habitat vulnerability to climate change are accelerated sedimentation of river channels and wetlands in disturbed catchments, and accessibility of floodplain wetlands to fish during El Niño drought events. Sedimentation risks are expected to intensify by 2035 and 2100, especially under the A2 climate scenario. However, vulnerability to these changes can be managed by early intervention.

Vulnerability of river habitats can be reduced by improved management of vegetation, and by active revegetation of cleared areas. Investment in strategic revegetation and sediment interception to prevent sediment from entering streams is a high priority[108,112].

Revegetation of entire catchments is usually not feasible, either because of the cost involved or because the land is used for food production. Targeted investment to stabilise the largest sediment sources is needed, because most sediment comes from only a small proportion of the catchment[119,125]. Establishing riparian buffer zones may also prevent mobilised sediment from entering river channels. These interventions need to be supported by environmental legislation and community awareness and compliance.

Channels can be constructed to maintain wetland water levels and sustain fish production during El Niño drought events, but the high cost of this approach restricts its use to high-value selected habitats rather than widespread application to entire floodplains. Cost-effective approaches are likely to emerge from targeted studies of vulnerable wetlands combined with local knowledge.

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