Catchments and Corals

Terrestrial Runoff to the Great Barrier Reef

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Foreword

The Great Barrier Reef is important to Australia for its natural, cultural and socio-economic values. The Great Barrier Reef World Heritage Area is a large area, some 350,000 square kilometres, that includes tremendous biodiversity and habitats that extend from coastal mangroves, to seagrass meadows, beautiful coral reefs and the dark depths of the continental slope. The region is host to a range of human uses such as tourism, fisheries and molecular biodiscovery. In spite of its size, the Great Barrier Reef (GBR) has many internal and external connections. Runoff from the land supplies a significant proportion of the nutrients used in the GBR ecosystem. The adjoining catchment also generates a significant fraction of Australia's national wealth through mining, sugar and beef production.

The attraction of the coastal zone is steadily rising and a substantial majority of Australians live within 100 km of the coast. The coastal areas within the GBR catchments are increasingly a desirable place to live and so the need for steady improvement in both land and reef management practices is increasing. There is very strong evidence from many parts of the world that accelerated runoff of sediment and nutrients due to poor land use practices can lead to degradation of coastal water quality and the destruction of near-shore reef ecosystems.

One of the first steps in making sure that similar degradation does not occur in the GBR is that both resource managers and the public should understand how our natural systems operate, and how humans can influence the natural world. We must understand the nature and magnitude of terrestrial and marine processes that govern water quality and the health of ecosystems in the GBR World Heritage Area.

Australia is fortunate that most of the GBR is still largely in a relatively undisturbed condition. However, because of the sheer size of the GBR, its catchment and the social and economic systems that they support, it will not be possible to make rapid changes once significant problems become apparent. Once widespread problems are obvious the time for repair will be decades to centuries. Australia has learned this lesson in the Murray-Darling River systems. Now is the time for making changes. We must understand the natural limits of the GBR ecosystem that we want to maintain and stay within them. We know that the land and sea are linked. All residents of the GBR catchment have a role in reef conservation and a stake in the benefits through their use and stewardship of the land. This book is a major milestone towards informing us all of the way this magnificent natural wonder operates.

Sir Sydney Schubert
Chairman,
CRC Reef Research Centre and Rainforest CRC

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Commonwealth Science and Industrial Research Organisation
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Great Barrier Reef Marine Park Authority
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Queensland Dept. of Primary Industries
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And of course, I thank Grace, Jane and Lauren for loaning science a husband and dad.

Acronyms

The Great Barrier Reef

GBR	Great Barrier Reef
GBRCA	Great Barrier Reef Catchment Area
GBRMP	Great Barrier Reef Marine Park
GBRWHA	Great Barrier Reef World Heritage Area

Organisations

ABS	Australian Bureau of Statistics
AGSO	Australian Geological Survey Organisation (now Geoscience Australia)
AIMS	Australian Institute of Marine Science
AUSLIG	Australian Surveying and Land Information Group (now part of Geoscience Australia)
BOM	Bureau of Meteorology
BRS	Bureau of Resource Sciences
CRC-Reef	Cooperative Research Centre for the Great Barrier Reef World Heritage Area
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GBRMPA	Great Barrier Reef Marine Park Authority
JCU	James Cook University
NLWRA	National Land and Water Resources Audit
QDPI	Queensland Department of Primary Industries
QEPA	Queensland Environmental Protection Agency
QFS	Queensland Fisheries Service (formerly the Queensland Fisheries Management Authority - QFMA)
QNR&M	Queensland Department of Natural Resources and Mines (formerly the Queensland Dept. of Natural Resources - DNR)

Chapter 1

Introduction

The Great Barrier Reef is unique. It is the largest contiguous coral reef ecosystem in the world and the largest that has ever existed [292]. Because of its sheer size, extraordinary biological diversity and relatively undisturbed state, the Great Barrier Reef (GBR) is one of the world's great natural wonders. In 1981, most of the GBR ecosystem was inscribed onto the World Heritage Register as the Great Barrier Reef World Heritage Area. It remains, by a very large margin, the largest World Heritage Area. Most foreign visitors to Australia visit the reef. Overseas and Australian reef visitors provide the base for a major regional tourism industry. The GBR is a national icon, an international biological treasure and a significant economic resource.

Photo: GBRMPA

As long as reef-building corals have lived on what is now the northeastern Australian continental shelf, they have been influenced by runoff of freshwater, sediment and nutrients from the adjacent continental land mass. The classic image of coral reefs is of a palm-fringed island surrounded by blue open ocean. Most of the world's coral reefs, however, have developed along continental and island coastlines where they are affected by terrestrial runoff. The nutrients in terrestrial runoff fertilise the

Queensland, the Great Barrier Reef and the Great Barrier Reef Catchment Area.

coastal seas from which these reefs draw their sustenance. Because of the stresses of coping with freshwater inundation and sedimentation as well as the nutrients this richer coastal environment provides, undisturbed nearshore coral reefs are among the most biodiverse in the GBR [537].

Terrestrial runoff is only one factor which has shaped the growth and evolution of coral reefs. From a global perspective, tectonic forces and climate change over geological time frames (thousands to millions of years) have driven sea level fluctuations which have been the primary natural influence on the development and survival of coral reefs, particularly those on shallow continental shelves [377, 537].

Ten thousand years ago, sea level along what is now the northeast Queensland coast was more than 100 metres below its present level [267]. The ancient GBR was only a narrow coastal fringe. Reefs and corals along the Australian continent therefore grew in habitats even more strongly influenced by land runoff than modern reefs. With the melting of the glaciers at the end of the Ice Age, sea level began rising, reaching its present height approximately 6,000 years before present. The modern GBR, built on a foundation of older reefs which formed during previous periods of high sea level, is less than 10,000 years old.

Humans have watched the growth of modern coastal coral reef ecosystems and their interaction with the land. Indigenous peoples have lived in northern Australia for at least 40,000 and quite possibly over 60,000 years [154, 178, 342, 505], fishing along the coast, gathering plants and hunting in catchments bordering the sea. These peoples watched sea levels rise and the modern GBR form on the newly inundated continental shelf. The Indigenous inhabitants were not passive occupiers of the land. Aboriginal fire use is regarded as an important factor shaping vegetation communities in northern Australia [235, 407, 472] during a period of dramatic climate change [244-247].

Nearshore fringing reefs, Cape Tribulation
Photo: GBRMPA

Timber cutting
Photo: JCU North Queensland Photographic Collection

Cattle in wetland
Photo: JCU North Queensland Photographic Collection
Reproduced with permission from the David Frederic C. Hall Photographic Collection

In the 150 years since Europeans began settling along the north Queensland coast (post 1850), there has been considerable change in the pace and scale of human land use in catchments adjoining the GBR. Early European settlement was driven by the economic rewards to be won through logging, grazing, sugarcane cultivation and mining. Since 1900, cattle grazing and farming have become the predominant land uses in the GBR catchment. These activities have led to extensive land clearing and changes in vegetation in many catchments bordering the GBR [34, 171]. Clearing and agricultural land use are now regarded to have caused a several-fold increase in runoff of sediment and nutrients into the GBR [339, 418]. Initial estimates of this increase are based on broad extrapolations of runoff and soil loss measurements from a variety of land cover and land use settings. Until recently, estimates of the amount of terrestrial sediment and nutrients running into waters of the GBR and the increase in runoff due to current and historical land use practices have not been well constrained. This lack of definition is a barrier to changing land use practices which are detrimental to the long-term health and survival of the GBR, and the sustainable use of the GBR catchment.

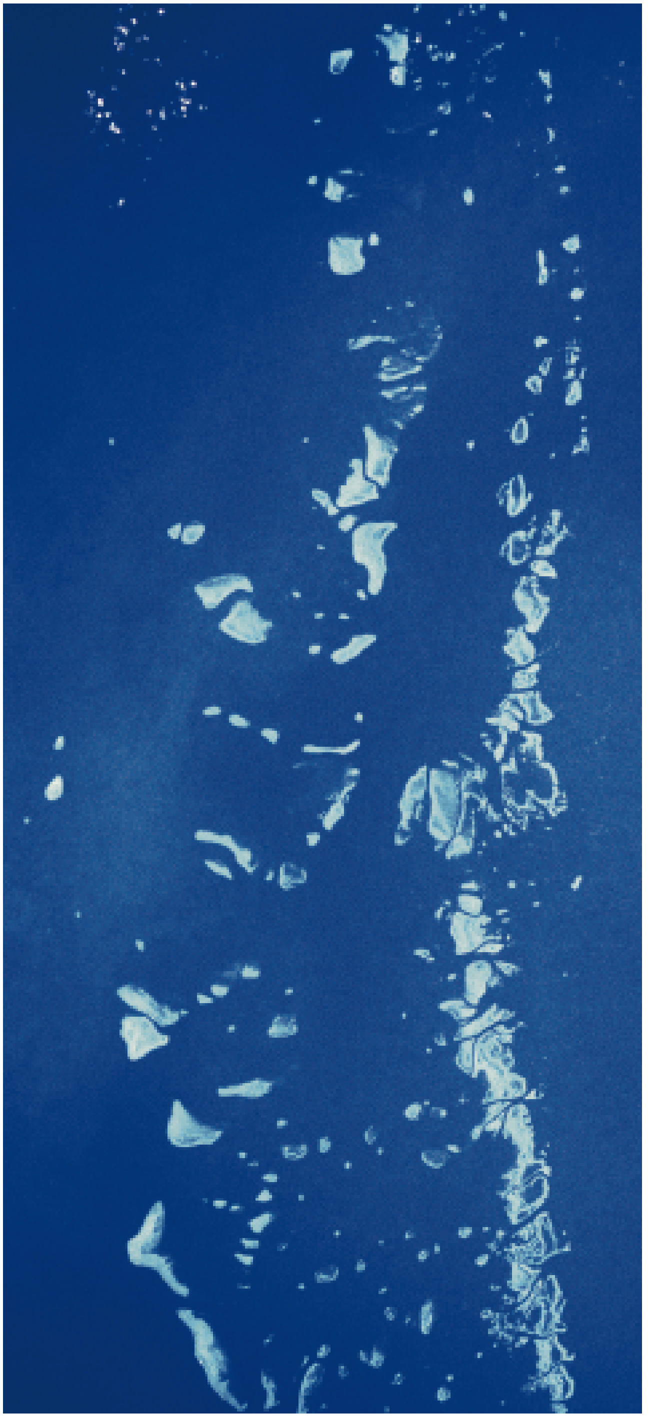
Is runoff a problem?

Why should we worry about enhanced runoff into the Great Barrier Reef if reef and coastal ecosystems have been exposed to nutrients and sediment in natural runoff for thousands, if not millions of years? The most direct answer is that reef ecosystems repeatedly exposed to too much sediment or nutrients will be disturbed and changed in ways that prevent them from returning to what we regard as a healthy and desirable state. Excess nutrients disrupt the natural balances between producers and consumers within reef and coastal ecosystems. In extreme cases, affected reefs may cease to exist as recognisable and functioning ecosystems.

There is clear evidence that coral reefs exposed to high levels of sedimentation [202, 435] or acute eutrophication [477 512, 513] deteriorate. Internationally, many coastal coral reefs have been destroyed or substantially degraded by destructive fishing practices and poor water quality caused by urban development, land clearing and de-forestation in adjacent catchments [558]. The future of these reef systems is uncertain, with many unlikely to recover to a healthy state under present conditions.

All reef-building hard corals contain tiny photosynthetic algae (zooxanthellae) which live symbiotically within the tissues of the corals and provide a significant proportion of their energy needs. The health and productivity of reef-building corals depends on a balanced relationship between the coral hosts and their algal symbionts. Normally, the coral hosts provide the zooxanthellae with a stable, sunny environment and waste products which supply most of the nutrients that the zooxanthellae require. The zooxanthellae obtain additional nutrients from surrounding waters. Coral reefs are also built by calcareous algae which secrete calcium carbonate that covers and binds the physical structure of the reef. Both calcareous algae and corals require light to survive and deposit calcium carbonate. Much of the organic matter which supports food webs in reef ecosystems is produced by ubiquitous mats of small turf-forming eukaryotic algae and cyanobacteria which grow on the bare surfaces and sediments of the reef. Extended burial by sediment kills algae and corals by cutting off light and oxygen. Less extreme, but recurrent sedimentation exacts a significant metabolic cost on corals and other animals which have to work to clean themselves [481]. If the sediment is too thick, corals and other reef organisms may exhaust themselves trying to keep clean and can die within a relatively short period [127].

Surfaces covered by fine sediment are generally unsuitable as a substrate for algal spores, larval corals and the young of other sessile reef organisms [27, 201]. As a result, coral



Hydrographers Passage and the Pompey Reef complex, (21°S) photographed by hand-held camera from a space shuttle Photo: NASA

Reef fish
Photo: B. Legg, GBRMPA

Soft coral
Photo: K. Fabricius, AIMS

reefs do not develop on fine and mobile sediments which lack a solid surface for larval settlement and adult growth.

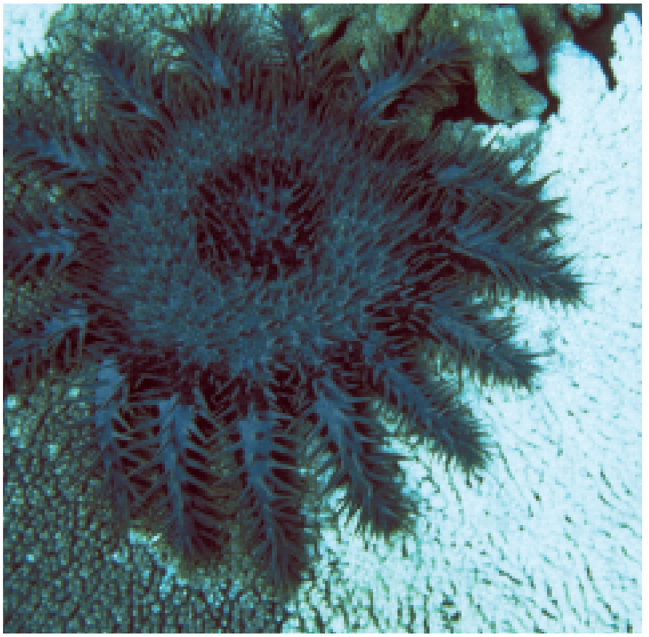
The adverse effects of excess nutrients in runoff are less obvious. All living things, including reef-building corals and algae, require nutrients to survive and grow. Nutrient concentrations in tropical coastal waters and runoff are never high enough to be directly toxic. Rather, the increased availability of nutrients alters the ecological balance between reef species which normally exist in a nutrient-limited state. The nutrients used in reef ecosystems come from a variety of sources. On a day-to-day basis, most are recycled by bacteria and other consumers of living and dead organic matter. Through rapid uptake, consumption and recycling, relatively small amounts of free nutrients can sustain high levels of ecosystem productivity. In the GBR ecosystem, nutrient losses are made up from external sources which include terrestrial runoff [144], rainfall [146], upwelled deep water from the Coral Sea [143] and fixation of atmospheric nitrogen by specialised cyanobacteria [38, 268]. Of these, terrestrial runoff is the largest nutrient source directly influenced by human activities. Until recently, estimates of the magnitude of terrestrial inputs of sediment and nutrients, and human influence on these inputs have been extrapolated from limited measurements in a few rivers and catchments.

Healthy coral reefs in coastal and continental shelf habitats tolerate the modestly enhanced levels of freshwater, sediment and nutrients delivered by natural runoff processes. There is a general view, however, that the current state of those parts of the GBR which are most directly influenced by land runoff is not what it once was. Our understanding of these changes is far from complete. Despite the considerable national and international interest in the GBR, rigorous monitoring of water quality, the state of sediment and nutrient levels in regional rivers and the health of the catchments from which they come has only been carried out at a few sites and been underway for less than two decades. From a management and conservation perspective, therefore, the important question is: "*At what level do greater inputs of sediment and nutrients from the land-based sources change the reef in ways which will jeopardise its future*?"

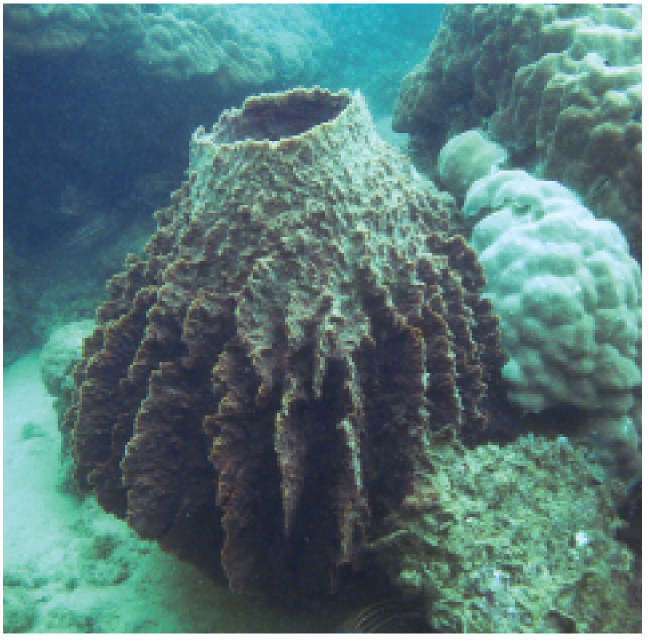
To answer this question, several types of information about the GBR and the adjacent catchment are required. Not all are currently available. In particular, we need to have robust estimates or observations of:

- the current level of sediment and nutrient inputs to the GBR;
- the extent to which inputs have changed over the last 150 years;
- the distribution of sediment and nutrients in the GBR; and
- physiological or ecological effects directly traceable to enhanced nutrient and sediment loading of tropical coastal ecosystems.

The GBR ecosystem and its adjoining catchment are a single, linked and inter-connected unit. To conserve and manage the unique and valuable features of the GBR for the long term, it is necessary to carefully manage the land and water resources of the catchment. This does not necessarily require a rigid management structure. It does require an active and committed partnership between land and reef users. The basis of this partnership is a shared understanding of how the land and sea are connected and an appreciation that land management practices which guarantee the health and future of the GBR will also guarantee the health, productivity and future of the land.



Crown-of-thorns starfish (Acanthaster planci)
Photo: AIMS



Sponge, a filter-feeder
Photo: L. Smith, AIMS

Photo: D. Wachenfeld, GBRMPA

What is the Great Barrier Reef worth?

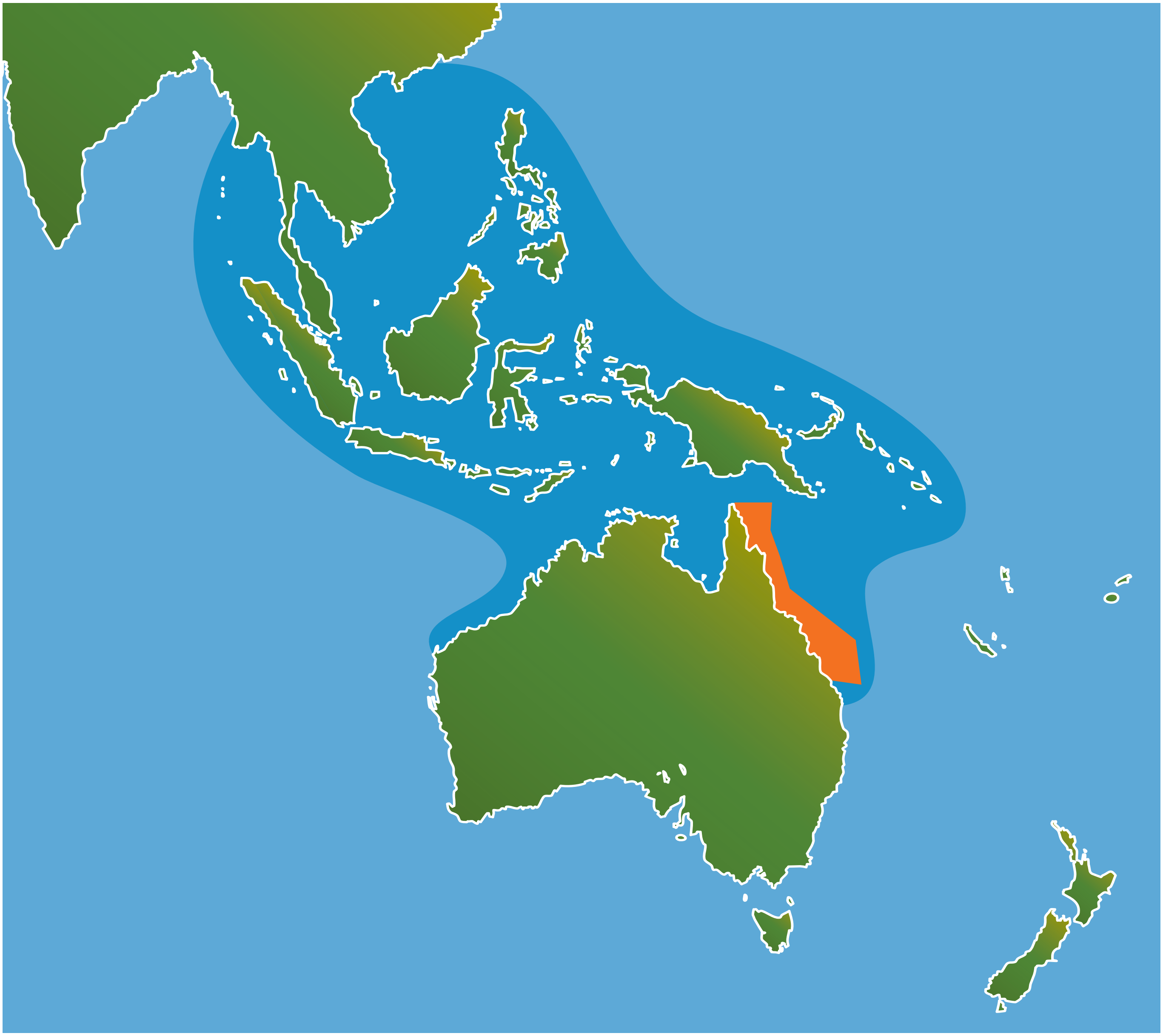
Biodiversity

The Great Barrier Reef is the largest structure created by living organisms. The GBR is part of the greater Indo-West Pacific province of high marine biodiversity. Almost all known groups of marine plants and animals that are present in the tropics exhibit their highest degree of species diversity within this broad region.

Coral reefs are the most biodiverse of shallow water marine habitats. Warm water temperatures, an abundance of solar energy to power algal photosynthesis and a complex 3-dimensional architecture offer vast opportunities for attachment, growth, feeding and concealment. Reefs provide conditions in which thousands, and likely millions, of species have evolved and now live. At this time, only a few groups of large and conspicuous organisms (e.g. hard corals, marine reptiles, birds and marine mammals) are well surveyed and described.

So far, scientists studying the GBR and adjacent coastal waters have identified:

- 350+ species of hard corals *(J. Veron, AIMS, pers. comm.)*
- 72 genera of soft corals (ca. 300-500 species; *K. Fabricius, AIMS, pers. comm.)*
- 300+ species of other cnidarians *(C. Wolff, AIMS , pers. comm.)*
- 1500+ species of fish (*GBRMPA,* 1999)
- 5000+ species of molluscs (*GBRMPA,* 1999)
- 140+ species of echinoderms (*C. Wolff, AIMS, pers. comm.*)
- 1500+ species of polychaete worms (*P. Hutchings, Australian Museum, pers. comm.*)
- 1500+ species of sponges (*C. Wolff, AIMS, pers. comm.*)
- 250+ species of ascidians (*C. Wolff, AIMS, pers. comm.*)
- 500+ species of macro-algae (*L. McCook, AIMS, pers. comm.*)
- 15 species of seagrasses (*R. Coles, QDPI, pers. comm.*)



The GBRWHA in relation to the Indo-West Pacific province of high marine biodiversity.

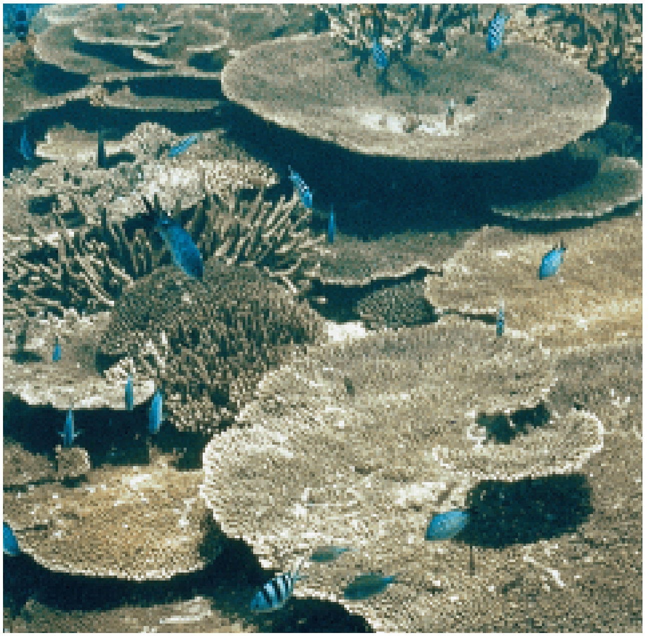


Plate and branching corals (Acropora)
Photo: GBRMPA

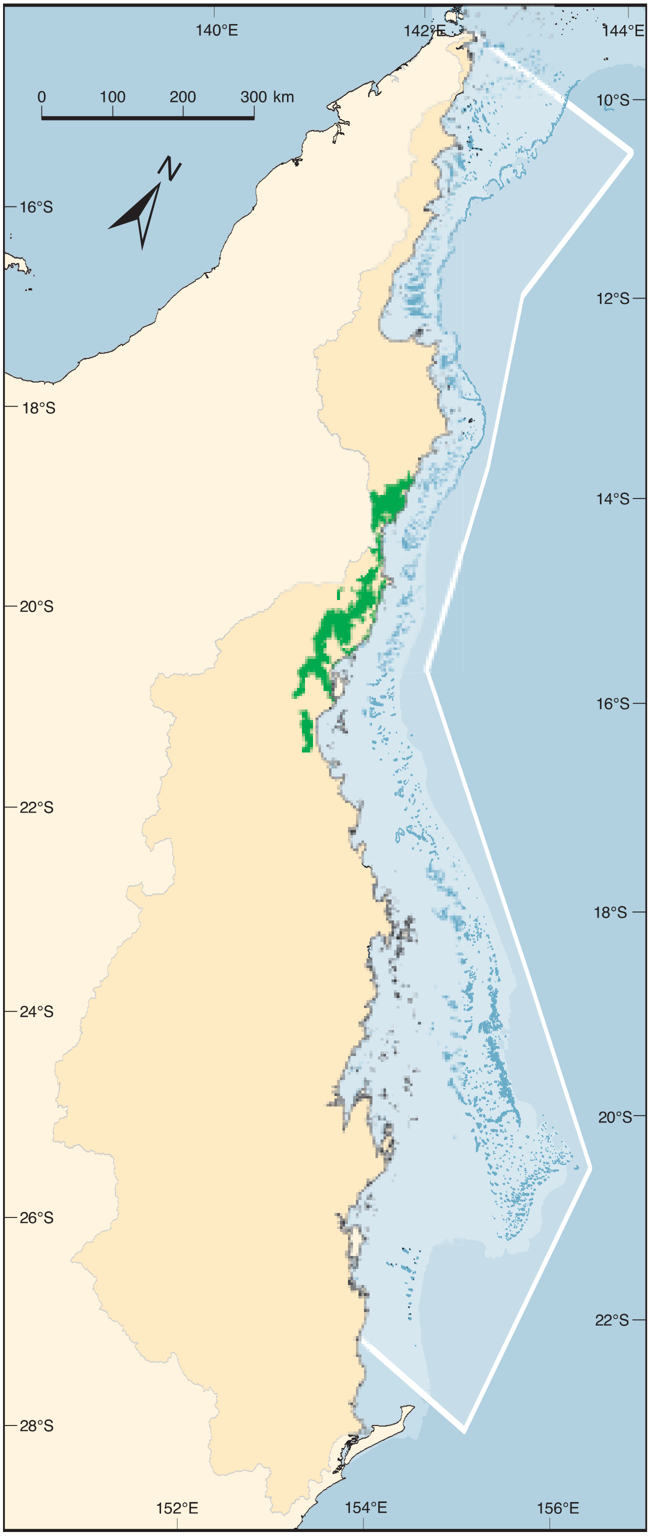
Seagrass bed
Photo: GBRMPA

- 37 species of mangroves (*N. Duke, Univ. Qld, pers. comm.*)
- 27 species of marine reptiles (sea snakes, crocodiles, marine turtles) (*GBRMPA,* 1999)
- 24 species of birds that inhabit and breed on islands (*GBRMPA,* 1999)
- 27 species of marine mammals (whales, dolphins and the dugong) (*GBRMPA,* 1999)

Most of the individuals in the above groups are large or conspicuous organisms, many live in the open and most are readily visible to the naked eye. Our understanding of the diversity of groups such as molluscs, echinoderms and macroalgae is far from complete because of limited collecting and a shortage of taxonomists to classify specimens and describe new species.

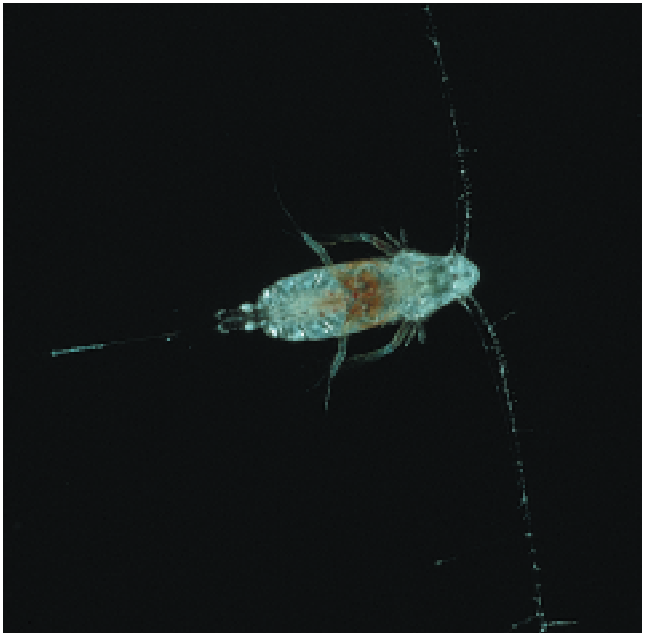
Knowledge of the smaller invertebrate organisms and micro-organisms such as worms, crustaceans, sponges, micro-algae, protozoa and bacteria is far poorer. Many of these organisms live hidden in sediments or down cracks and holes in the porous reef matrix. An unknown number of species live in close association with other species as symbionts, commensals or parasites. Many are microscopic or barely visible to the naked eye and virtually all require specialist taxonomists to identify them. Our estimates of the numbers of smaller species and genera are certainly underestimates because only a small fraction of the potential habitats within the GBR region have been carefully sampled and analysed. The taxonomy of most microbe and invertebrate groups is not well resolved. Protozoans, benthic micro-algae and bacteria, in particular, have not been widely sampled across the full range of potential microhabitats available to these groups.

The conservation value of the GBR extends beyond a simple count of species. The GBR's ecological value comes from both the close association of many species and their wide



The Great Barrier Reef World Heritage Area (white border) and Wet Tropics World Heritage Area.
Data source: GBRMPA

- *GBR World Heritage Area*
- *Wet Tropics World Heritage Area*
- *GBR catchment*



Copepod, a small crustacean which is the most common type of zooplankton in the ocean. Closely related benthic copepods are abundant in GBR sediments. Length approx 1 mm
Photo: AIMS

Nudibranch, a shell-less mollusc
Photo: L. Zell, GBRMPA

distribution throughout the GBR ecosystem [292]. At a time when many reef ecosystems throughout Southeast Asia and the Pacific Ocean have been destroyed or degraded by unrestrained and harmful fishing practices, pollution from growing coastal populations and deteriorating water quality as a result of unregulated land use [558], most of the GBR remains relatively undisturbed, remote from significant population centres and subject to limited fishing or development pressure.

The GBR is the largest reef ecosystem afforded a high degree of effective management and protection. Approximately 80% of the *ca.* 300,000 km^2 of the continental reef province bordering northeastern Australia is located within the boundaries of the Great Barrier Reef World Heritage Area. Virtually all of the World Heritage Area, in turn, is included within the Great Barrier Reef Marine Park. Recreational and commercial activities such as fishing, tourism, shipping and mineral extraction are either strongly regulated within the World Heritage Area, or in the case of mining, banned. A concerted effort has been made to set aside representative areas of the GBR for strict preservation of the natural biological communities [106].

Economic value of tourism in the Great Barrier Reef region

Because of its biological diversity, scenic beauty and favourable climate, the Great Barrier Reef is one of Australia's major tourism destinations. On almost any day, the thousands of visitors transported to islands or pontoons anchored behind outer- or mid-shelf reefs can expect to see diverse arrays of corals and fish, whether by SCUBA diving, snorkelling, glass bottom boat or from underwater viewing platforms.

The size of the GBR, the diversity of means by which tourists can visit it and the decentralised nature of the tourism industry, make it difficult to precisely estimate visitor usage of the GBR and its economic value. Prior to 1993, there was no standard method of counting reef visits.

In 1993, an Environmental Management Charge (EMC) was imposed on all daily visits to offshore locations in the GBR Marine Park to support research on and management of the reef. All offshore tourism operators maintain logbooks of passengers or reef visitors. From EMC revenues, annual numbers of reef tourism visits (visitor days) have fluctuated between 1.26 and 1.69 million (GBRMPA, 2001).

Based on surveys of the duration of stays by reef visitors and money spent during visits to the GBR region, the direct economic value of reef-associated tourism in 1997-98 was estimated as A$450 million [259]. If the costs of travel and regional economic multipliers are included, the overall economic value of GBR-focused tourism is in excess of A$1 billion. A significant proportion of this amount comes from overseas tourists.

In a broader view, the total value of tourism, associated activities and supporting business in the GBR catchment in 2001 is estimated to fall between A$4 and A$5 billion [597]. Approximately one third, A$1.4 billion, was associated with spending by overseas visitors.

Tourists at a reef pontoon
Photo: J. Oliver, GBRMPA

Economic value of commercial fishing in the Great Barrier Reef region

The Great Barrier Reef supports regionally significant harvest, line and trawl fisheries. These fisheries target prawns and other crustaceans, shellfish (e.g. scallops), reef fish (e.g. Coral Trout), pelagic fish (Spanish Mackerel) and a number of reef-associated invertebrates (e.g. Trochus, Beche-de-mer). Individual fisheries within the GBR region are managed by either the Commonwealth or Queensland governments.

Commercial fishing effort in the GBR Marine Park is monitored through the use of logbooks, which are

Prawn trawlers, Cairns
Photo: GBRMPA

maintained by most commercial operators. The quantity of fish and shellfish caught in the GBR region varies from year to year depending on fishing effort, management policies and environmental factors. The economic value of the catch depends on the mix and quantity of seafood marketed and the prevailing market price. The total magnitude and value of the commercial catch cannot be precisely estimated due to the absence of comprehensive data. Based on conservative extrapolations, the commercial fish catch from the GBR region in 1999-2000 was estimated as A$119 million [597]. Statistics published by the Queensland Fisheries Management Authority (now Queensland Fisheries Service) and Bureau of Resource Sciences (Commonwealth fisheries) indicate that the value of the GBR-based fishery has remained fairly stable over the last decade [81]. In terms of both landed tonnage (4.0-6.5 x 10^3 tonnes) and value

(A$50-80 million), prawns are the most valuable component of the commercial catch in the GBR.

Economic value of recreational fishing and boating

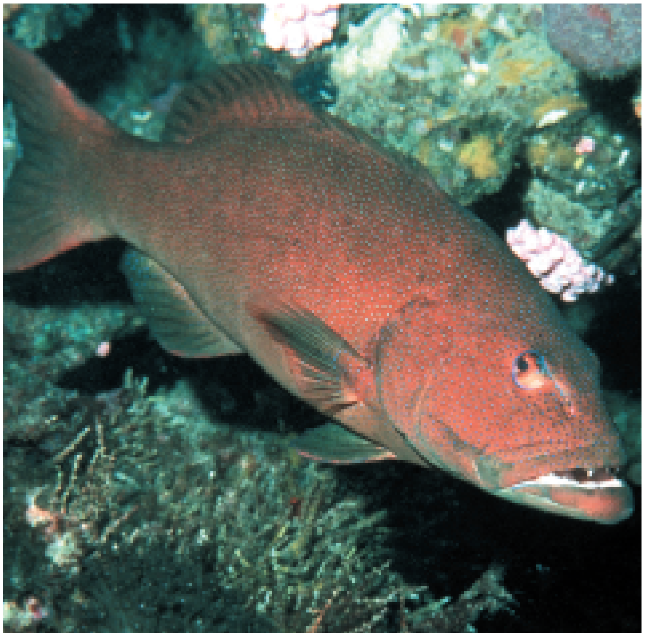
Recreational boaters and fishers in the Great Barrier Reef region spend a considerable amount of money in pursuit of their pleasure. Between 1990 and 1998, estimates of the number of private boats used in the Great Barrier Reef Marine Park have ranged between 24,000 and 45,000 [259]. Over the same period, estimated spending in the Great Barrier Reef on private boating and recreational fishing has varied from A$105 to A$120 million [259]. Total spending on recreational fishing and boating in the GBR catchment (1999-2000) has been recently estimated as A$240 million [597].

The total economic value of industries using the Great Barrier Reef

Any calculation of the economic value of tourism, fishing and boating in the Great Barrier Reef region requires a considerable number of assumptions. Direct comparisons between years are difficult because of gaps and inconsistencies in the statistical data. A recent (1996) estimate of the direct economic value of reef-based tourism, fishing and boating activities was approx. A$700 million [259]. When flow-on effects in the regional economy are also considered, the total regional "economic" value of the GBR would be on the order of A$4.6 billion [597].

Economic value of agriculture in the Great Barrier Reef catchment area

A diverse range of agricultural activities take place in catchments draining into the Great Barrier Reef. In terms of area, rangeland cattle grazing is the principal land use activity. Approximately 75 - 80% of the GBR catchment is used for grazing (QNR&M).



Coral Trout (Plectropomus leopardus)
Photo: GBRMPA

Harvesting sugarcane
Photo: C. Roth, CSIRO

Cane hauling by horse-drawn wagon
Photo: JCU North Queensland Photographic Collection

Cultivation of crops occurs on approximately 3% of the GBR catchment (QNR&M). In economic value, the principal agricultural products of the GBR catchment are beef and beef cattle, sugar, fruits, vegetables and cotton. Table 1 summarises recent (2002) estimates of the value of major crops or agricultural products produced in the GBR catchment [597].

Cattle are the most valuable agricultural product derived from the GBR catchment. The cattle are processed locally or exported live to southern Asia. Cattle numbers in statistical data collection districts most closely matching the boundaries of the GBR catchment (ABS, 1996 census) were close to 5.4 million head, up slightly from 5.2 million in 1991-92. The cattle herd in the GBR catchment makes up approximately half of the cattle in Queensland. Herd size depends on a number of factors, particularly market conditions and drought-related changes in the carrying capacity of grazing properties. Recent statistics

(2002) place the value of beef and cattle marketed from the GBR catchment in excess of A$1.25 billion [597].

Sugar is the second most valuable agricultural commodity grown in the GBR catchment. Approximately 97% of Queensland's sugar crop is grown in the GBR catchment. The area used for growing sugarcane in Queensland has increased steadily over the last century to approximately 4,400 km^2 (440,000 ha). Much of the increase in cultivated area during the last 20 years has been due to the expansion of irrigated farming in drier coastal areas such as the Burdekin River delta and the clearing of coastal lands adjacent to traditional sugar-growing areas. The economic value of the raw sugarcane to farmers and of milled sugar products varies with the crop size and the world sugar price. The 1998 sugar crop grown in the GBR catchment (35.5 million tonnes) had a value of A$1.1 billion (ABS, 2000). Because of lower production and low world sugar prices, the 2001 sugar crop had a value close to A$620 million [597].

A wide variety of fruits and vegetables are grown in coastal areas of the GBR catchment. Tropical fruits such as bananas are the primary horticulture crops in the north. In 2001, the banana crop in the GBR catchment had an estimated value of A$210 million [597]. Most of the bananas are grown in the Tully and Johnstone River drainage basins. Horticultural crops grown throughout the GBR catchment area had a total value close to A$600 million [597].

Cotton is a relatively new crop in the GBR catchment. At present, cotton farming is largely restricted to inland areas in the Fitzroy River catchment. The 1996-97, the cotton crop from the GBR catchment was estimated to have a value close to $A82 million (ABS, 2000). By 2001, the value of the cotton crop had increased to A$121 million [597].

Photo: QDPI

Bananas, Tully
Photo: M. Furnas, AIMS

Table 1. Estimated economic value of major agricultural crops or products from the Great Barrier Reef catchment. Data were obtained from the Australian Bureau of Statistics (italics) or the Productivity Commission. Dollar values are normalised to 2000-01.

	1992	1996	2000
		Millions of A$	
Beef	675	530	1,020
Sugar	550	1,080	770
Horticulture	440	556	590
Fishing	110	146	118
Total Agriculture	2,160	2,775	3,282
Cotton	*86*	*82*	121
Bananas	*205*	*149*	200
Other Fruits	*319*	*307*	
Vegetables	*111*	*114*	

19th century alluvial mining
Photo: JCU North Queensland Photographic Collection
Reproduced with permission from the David Frederic C. Hall Photographic Collection

Total economic value of agricultural products grown in the Great Barrier Reef catchment

Collectively, agricultural crops and commodities produced within the Great Barrier Reef catchment in 2000-01 had an estimated annual economic value close to A$3.2 billion. This value does not include regional flow-on effects and multipliers. Value adding through processing added approximately A$2 billion to the value of basic agricultural commodities [597].

Mining

A significant amount of mining activity takes place within the Great Barrier Reef catchment although it involves relatively little direct land use. Most of the mined commodities are exported. As with agricultural products, the economic value of mineral commodities depends both on the quantity mined and the current international price. By tonnage (ca. 120 million tonnes per year) and economic value (A$6 billion), coal from the Bowen Basin is the principal mineral extracted from the GBR catchment (QNR&M, 2000).

Gold mining primarily occurs near Charters Towers, Gympie and to a lesser extent, on Cape York Peninsula. Other mineral commodities extracted from the GBR catchment include sand and gravel, tin, limestone, base metals (copper, lead, zinc, nickel), silica and magnesite (magnesium).

There are extensive deposits of oil shale (greater than 20 billion barrels of oil equivalent) along the coast bordering the central and southern GBR near Rockhampton and Gladstone. Small mines have been developed to provide feedstock for pilot plant testing and production. As yet, no sustained commercial production of shale oil has taken place.

In terms of area, mining is a relatively small land use in the GBR catchment. Mining activity and mineral products however, are significant economic drivers for the region. Mineral processing, chiefly alumina production and aluminium smelting add approximately A$1.4 billion [597] to the value of raw minerals mined in the GBR catchment or the wider region (e.g. bauxite from Wiepa, nickel ore from New Caledonia and Indonesia, zinc and copper from Mt Isa and northwest Queensland). A large proportion of the people directly engaged in mining, the industries which support the mines, mineral processing, and their families, live in the coastal cities bordering the GBR. Mining will therefore continue to be a significant force in the economic and social development of the GBR catchment.

Kidston gold mine
Photo: GBRMPA

Estimation:

Throughout this book, I frequently use the words “estimate”, “estimated” and “estimation” to describe a derived “fact” about the Great Barrier Reef and its catchment or the process of producing such a “fact”. This is unavoidable. With large systems like the GBR and its catchment, it is logistically and financially impractical to collect the necessary range of data at enough places, frequently enough for long enough to resolve all important processes to a degree which encompasses the full range of natural variability. Reality dictates that our view of large-scale ecosystem properties must be formed and extrapolated from smaller sets of data collected at (hopefully) representative sites and times across a (again hopefully) full range of environmental conditions. These extrapolations become the “facts”.

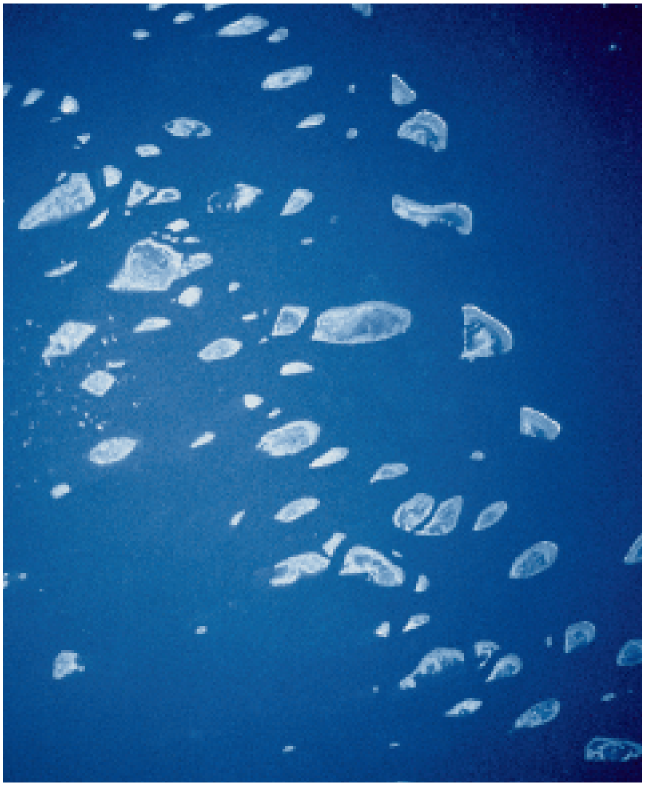
The quality of an estimate depends on the quantity and quality of available information, its suitability for the desired purpose and particularly, the underlying assumptions used to form the estimate. Rather than make unqualified statements about the magnitude of large-scale processes or phenomena, I use the term “estimate” to remind the reader of how I arrived at the result presented. In making assumptions and extrapolations, I have tried to use the best and most complete data sets available, to use them conservatively, and to the greatest extent possible, to present summaries of relevant data in figures and tables to allow the reader to see the process and outcome. Estimates always change as the information base grows, if the underlying assumptions change, or if different estimation processes are used.

Chapter 2

Geographic

and oceanographic features of the Great Barrier Reef

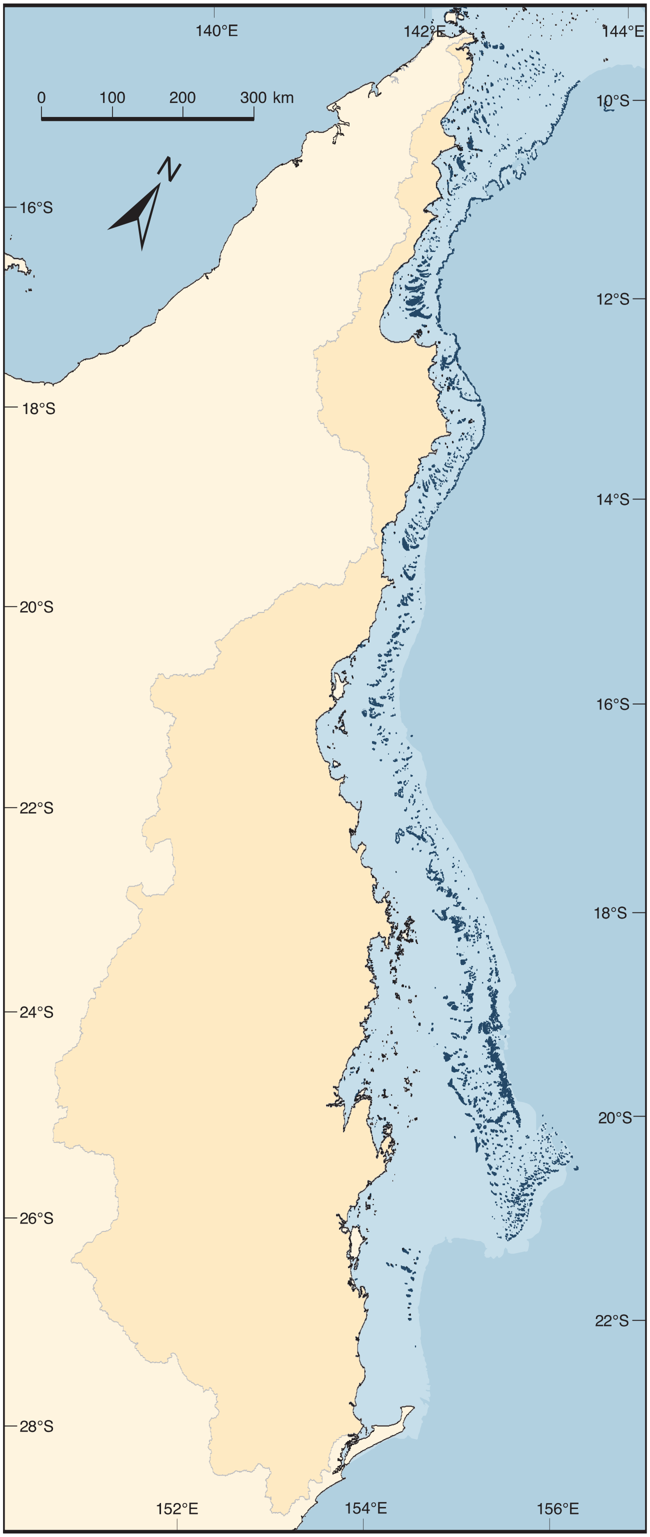
The Great Barrier Reef is the dominant marine geological feature and marine ecosystem of northeastern Australia. It consists of over 3,200 individual reefs of many types and sizes [204]. The greater GBR province [305] encompasses more than 280,000 km^2 of continental shelf between the southeastern Gulf of Papua (9°S) and Fraser Island (24° 30'S). The continental shelf varies in width between 24 km at Cape Melville (14°S) and 260 km at Cape Townsend (21°S). Seaward of the reef, the bottom deepens rapidly to over 1,000 m in the Queensland Trough. Here, the continental shelf will be taken as the seabed (including reefs and islands) between the continental shoreline (low-water mark) and the 80 m isobath.



Swains Reef complex, southern GBR
Photo: NASA

The Great Barrier Reef World Heritage Area and Great Barrier Reef Marine Park

The Great Barrier Reef World Heritage Area encompasses the northeastern Australian continental shelf from the tip of Cape York (10° 40'S) to Wreck Rock Reef (24° 19'S). The GBRWHA (345,850 km^2) includes most of the reefs which make up the GBR system. Some reefs within the greater GBR lie outside of the GBRWHA, either in the



Coral reefs within the GBR World Heritage Area.
Data source: GBRMPA

Coral reefs

Continental shelf (depth < 80 m)

GBR catchment

Free-standing platform reefs with emergent sand cays
Photo: GBRMPA

Torres Strait or the Gulf of Papua. Extending seaward from the low-water mark, the GBRWHA includes the deep continental slope bordering the seaward margin of the GBR and the western side of the Queensland Trough. The boundaries of the Great Barrier Reef Marine Park (GBRMP) largely match the boundaries of the GBRWHA. The GBRMP (343,500 km^2) is jointly managed by the Australian Commonwealth Government and the State of Queensland. A small number of coastal areas are excluded from the GBRMP and managed separately by the State of Queensland, chiefly as state marine parks, ports and reserves for future port development. There is approximately 221,200 km^2 of continental shelf within the GBRMP (water depths 0 – 80 m) [276].

Units and conversions:

Consideration of freshwater runoff and its effects at the regional, ecosystem and catchment scale involves dealing with a large range of water volumes. For consistency, I have chosen to use the following units:

1 square kilometre (km^2)	= 1,000,000 square metres	= 10^6 m^2
1 cubic kilometre (km^3)	= 1,000,000,000 cubic metres	= 10^9 m^3
	= 1,000,000 megalitres (ML)	= 10^6 ML
1 megalitre (ML)	= 1,000,000 litres (L)	= 10^6 L
	= 1,000 cubic metres (m^3)	= 10^3 m^3
1 cubic metre (m^3)	= 1,000 litres (L)	= 10^3 L

To put that into perspective, one cubic kilometre (1 km^3) of water will cover an area of 1,000 square kilometres to a depth of 1 metre. One thousand megalitres (10^3 ML) are required to cover one square kilometre (1 km^2) to a depth of 1 metre.

Instantaneous river flow or discharge is usually expressed in cubic metres per second (cumecs) or megalitres per second (ML sec^{-1}).

As far as possible, I have attempted to express concentrations or quantities of materials in mass units (grams, tonnes) which are usually used in studies of terrestrial and freshwater systems.

1 metric tonne (t)	= 1,000 kilograms	= 10^3 kg
	= 1,000,000 grams	= 10^6 g
	= 1,000,000,000 milligrams	= 10^9 mg
	= 1,000,000,000,000 micrograms	= 10^{12} µg
1 microgram (µg)	= 0.001 milligrams	= 10^{-3} mg
	= 0.000001 grams	= 10^{-6} g
	= 0.000000001 kilograms	= 10^{-9} kg
	= 0.000000000001 tonnes	= 10^{-12} t

Concentrations of materials in dissolved in freshwater or as a constituent in soils are often expressed as parts per million (ppm) or parts per billion (ppb).

1 ppm	= 1,000 ppb
	= 1 gram per tonne
	= 1 milligram per kilogram (approx. 1 litre of freshwater)
	= 1 microgram per gram (approx. 1 ml of freshwater)
1 ppb	= 0.001 ppm
	= 1 milligram per tonne
	= 1 microgram per kilogram (approx 1 litre of freshwater)
	= 1 nanogram (10^{-9} gm) per gram (approx 1 ml of freshwater)

In marine chemistry, concentrations of materials are most frequently expressed in terms of the numbers of atoms of a particular element (or molecules) per volume (litre, cubic metre) or mass (kg) of seawater. The standard unit in such cases is the mole (abbr. mol) which equals approximately 6.023×10^{23} atoms or molecules (6,023 followed by 20 zeros). The use of moles makes it easier to examine relationships and ratios between quantities of particular elements (or molecules) in biological and geochemical processes independently of their mass. The atomic (or molecular) weight of an element (or molecule) is the mass in grams of one mole of atoms (or molecules).

Molecular weights of some important nutrient elements or constituents of nutrient materials:

Hydrogen (H)	= 1.000	g per mole
Carbon (C)	= 12.00	"
Nitrogen (N)	= 14.01	"
Oxygen (O)	= 16.00	"
Silicon (Si)	= 28.06	"
Phosphorus (P)	= 30.98	"
Water (H_2O)	= 18.00	"
Carbonate ($CO_3^{=}$)	= 60.01	"

1 mole = 1,000 millimoles (mmoles, mmol)
= 1,000,000 micromoles (µmoles, µmol)

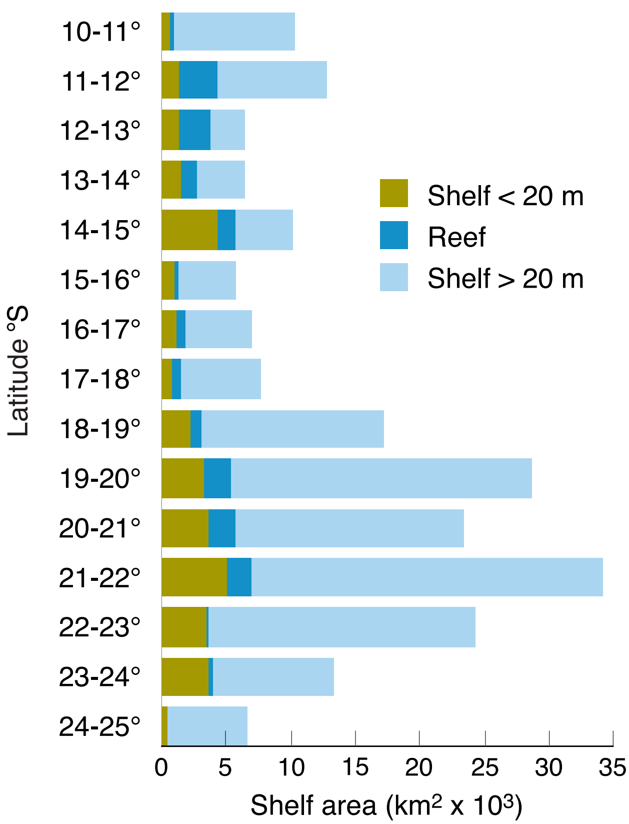
1 µmole = 0.001 millimoles (mmol)
= 0.000001 moles

Concentrations of dissolved nutrients in tropical marine and freshwaters are typically very low – usually in the range of µg per litre (µg L^{-1}) or µmoles per litre (µmol L^{-1} or µM).

The following table provides conversion factors for converting between: mole-gram, mmole-milligram, µmole-microgram.

Element	µmoles per µg	µg per µmol
Carbon	0.0833	12.00
Nitrogen	0.0714	14.01
Oxygen	0.0625	16.00
Silicon	0.0356	28.06
Phosphorus	0.0323	30.98

Ribbon Reefs near Cooktown
Photo: GBRMPA



Areas of shallow seabed (< 20 m depth), coral reefs and deeper seabed (> 20 m depth) by latitude on the continental shelf (depth < 80 m) within the GBRWHA.
Data source: Lewis, 2001

Reefs in the GBRMP

There are 3,244 catalogued coral reefs within the GBRMP (GBRMPA Reef Gazetteer). Collectively, these reefs have an area close to 20,000 km^2, or approximately 10% of the continental shelf within the GBRMP (Table 2). The number and area of reefs and the relative coverage of the continental shelf by reefs varies with latitude. The highest density of reefs is in the far northern GBR, where reefs occupy up to 40% of the shelf. Reef density is lowest off Townsville (19°S) and in the gap between the Swains Reefs and the Capricorn Bunker reefs off Gladstone (23°S). Most reefs in the GBR are free-standing platform reefs [204] located on the outer half of the continental shelf, where they rise steeply to the surface from the seabed which typically has a depth between 30 and 60 m. These outer-shelf reefs are generally immersed in clear, low nutrient waters with an oceanic character.

A significant number of reefs, however, are closely associated with the mainland or islands near the coastline. There are approximately 900 fringing reefs (27% of all reefs) within the GBRMP that border the mainland or continental islands (GBRMPA Reef Gazetteer). As an indicator of terrestrial influence, 700 reefs (21% of all reefs) are located within 10 km of the coast and 260 (8.7%) within 1 km of the coastline. The majority of the fringing reefs north of Cairns are located along the the mainland coast. Fringing reefs south of Cairns are largely associated with continental islands [204]. Compared with the offshore platform reefs, fringing reefs are smaller and relatively young. All have developed within the last 6-8,000 years following the most recent rise in sea level to its present general stage at the end of the last ice age [266]. Coastal and island fringing reefs have developed on a variety of substrates, chiefly rocky shores and headlands, algal pavements, alluvial cobble deposits adjacent to stream mouths and in a very few cases, on unconsolidated sediments sheltered by islands [266, 583].

Table 2. Latitudinal distribution of shelf area, reefs and shelf water volume in the coastal zone (water depths < 20 m).
Data source: Lewis, 2001

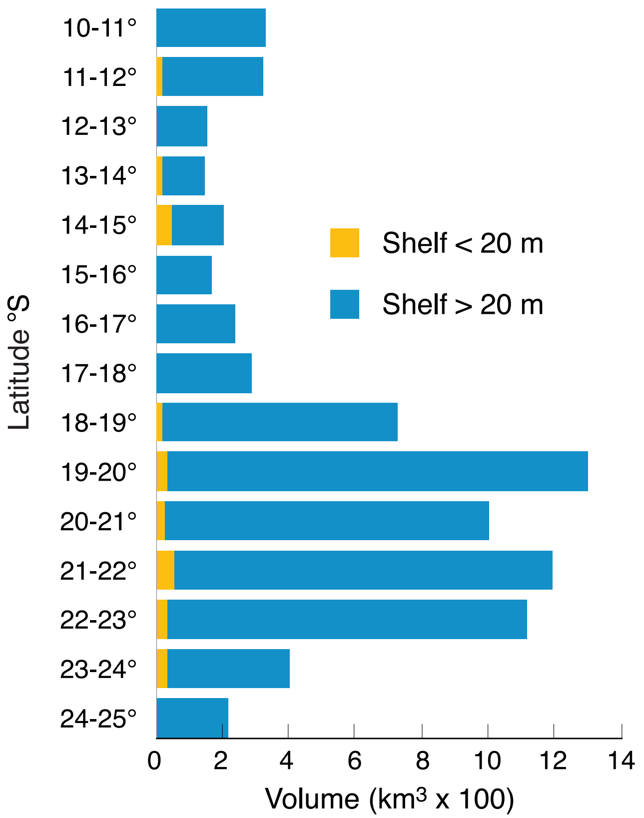
Latitude °S	Continental Shelf Area km^2	Shelf Water Volume km^3	Coastal Zone Area km^2	Coastal Water Volume km^3	Coastal Zone % area	Coastal Zone % Volume	No. reefs[1]	Reef Area[1] km^2	Reefs<10km from Coast[2]	Reef % Shelf Area	% Reefs <10 km from Coast
10-11	6,434	166	570	5.3	8.9	3.2	149	515	40	8.0	27
11-12	12,719	324	1,284	13.4	10.1	4.1	266	3,177	53	25.0	20
12-13	6,312	148	1,200	11.5	19.0	7.8	165	2,586	56	41.0	34
13-14	6,366	142	1,474	14.7	23.2	10.4	155	1,284	52	20.2	34
14-15	10,017	199	4,096	41.8	40.9	21.0	194	1,598	75	15.9	39
15-16	5,624	163	785	8.2	14.0	5.0	119	689	31	12.2	26
16-17	6,810	237	1,123	10.2	16.5	4.3	94	854	26	12.5	28
17-18	7,555	283	770	7.4	10.2	2.6	87	752	26	9.9	30
18-19	17,059	723	2,026	19.3	11.9	2.7	169	1,124	8	6.6	5
19-20	28,545	1,296	3,229	30.7	11.3	2.4	307	2,264	51	7.9	17
20-21	23,320	1,001	3,594	23.9	15.4	2.4	555	2,289	90	9.8	16
21-22	34,075	1,190	4,735	48.8	13.9	4.1	694	2,215	63	6.5	9
22-23	24,199	1,112	3,346	26.8	13.8	2.4	166	288	65	1.2	39
23-24	13,267	400	3,748	27.4	28.3	6.9	116	439	49	3.3	42
24-25	6,498	212	570	5.7	8.8	2.7	8	23	3	0.4	38
Total	**208,800**	**7,596**	**32,550**	**295.1**	**15.6**	**3.9**	**3,244**	**20,096**	**688**	**9.6**	**21**

[1] GBRMPA Reef Gazetteer
[2] GBRMPA

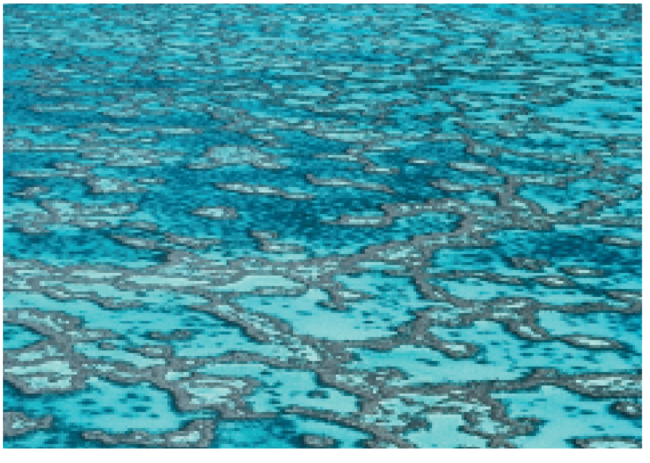
Platform and ribbon reefs near the edge of the continental shelf form a porous barrier between the shallow continental shelf and the deep oceanic waters of the Coral Sea. At the northern (9°-17°S) and southern (20-22°S) ends of the GBR, reefs block approximately 90% of the shelfbreak, restricting water exchanges between the continental shelf and Coral Sea to numerous narrow passages. In the central (17-20°S) section of the GBR between Cairns and Bowen, no consolidated shelfbreak barrier exists. Water movements between the shelf sea and the Coral Sea are therefore much less restricted.

Water volumes

The shallow shelf waters of the GBR are enclosed to varying degree by the reefs along the shelfbreak. These semi-enclosed shelf waters form a complex lagoonal habitat



Volumes of water overlying the continental shelf (depth < 80 m) by latitude within the GBRWHA.
Data source: Lewis, 2001



Extensive reef lagoon in the Pompey Reef complex, southern GBR
Photo: GBRMPA

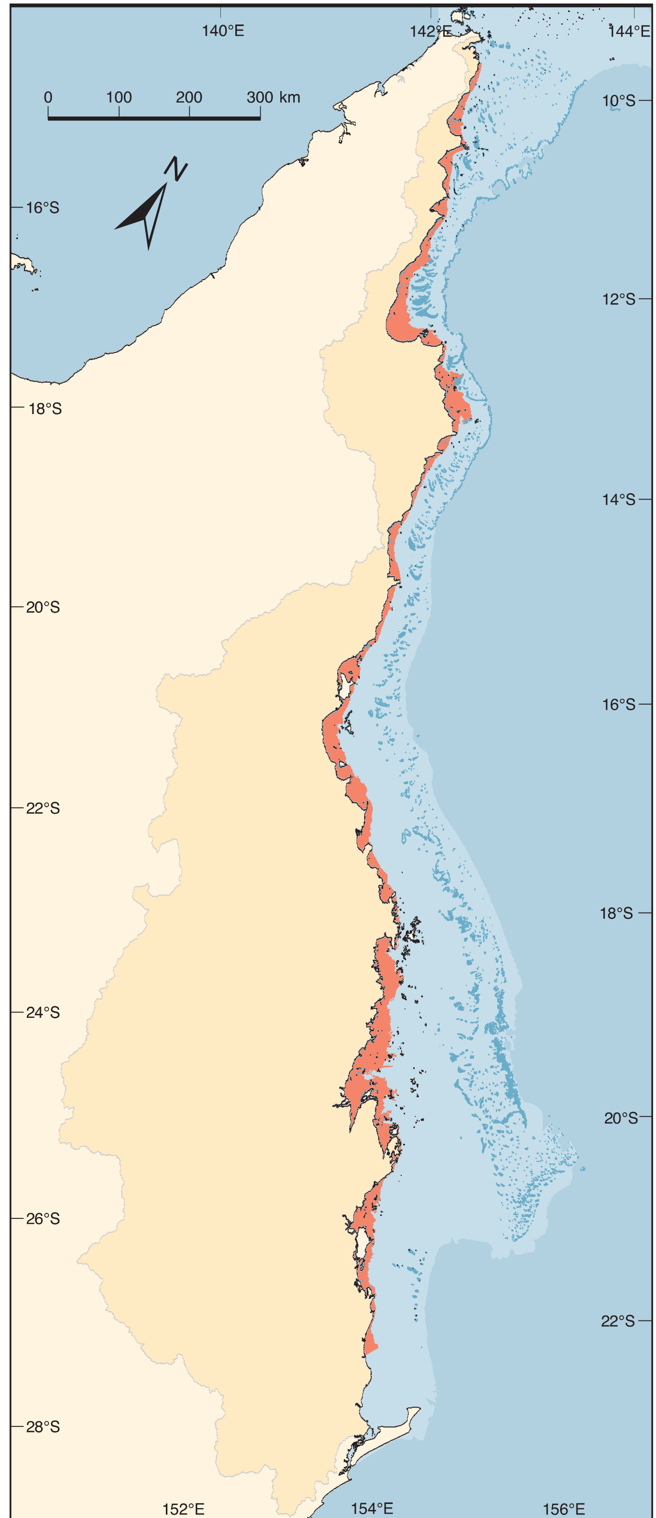
which has a total water volume of approximately 7,600 km^3 and is often referred to as the "GBR lagoon" [276]. The shelf-scale GBR lagoon should not be confused with small lagoons which are wholly or partially enclosed by individual reefs ("reef lagoons"). Most of the water in the GBR lagoon is on the outer half of the continental shelf, where water depths between reefs typically exceed 30 m. South of Cape Flattery (15°S), the continental shelf gradually widens and the GBR lagoon includes a distinct open water channel between the coast and the outer-shelf reef matrix. Water depths on the seaward side of this channel are usually greater than 30 m. To the north of Cape Flattery, reefs have formed across much of the width of the shelf, leaving only a narrow open-water channel near the coast. Coastal waters shallower than 20 m (total area = 32,550 km^2) account for 15.6% of total shelf area, but only 3.9% (295 km^3) of shelf water volume [276]. The extreme nearshore zone (depth less than 10 m) has an area of 19,300 km^2, with an overlying water volume of 97 km^3 (1.25% of shelf water volume). The nature and extent of this nearshore zone is particularly important when considering terrestrial runoff. The nearshore zone is where all river water is discharged and contains the habitats most directly affected by runoff of freshwater, sediments and nutrients from the land.

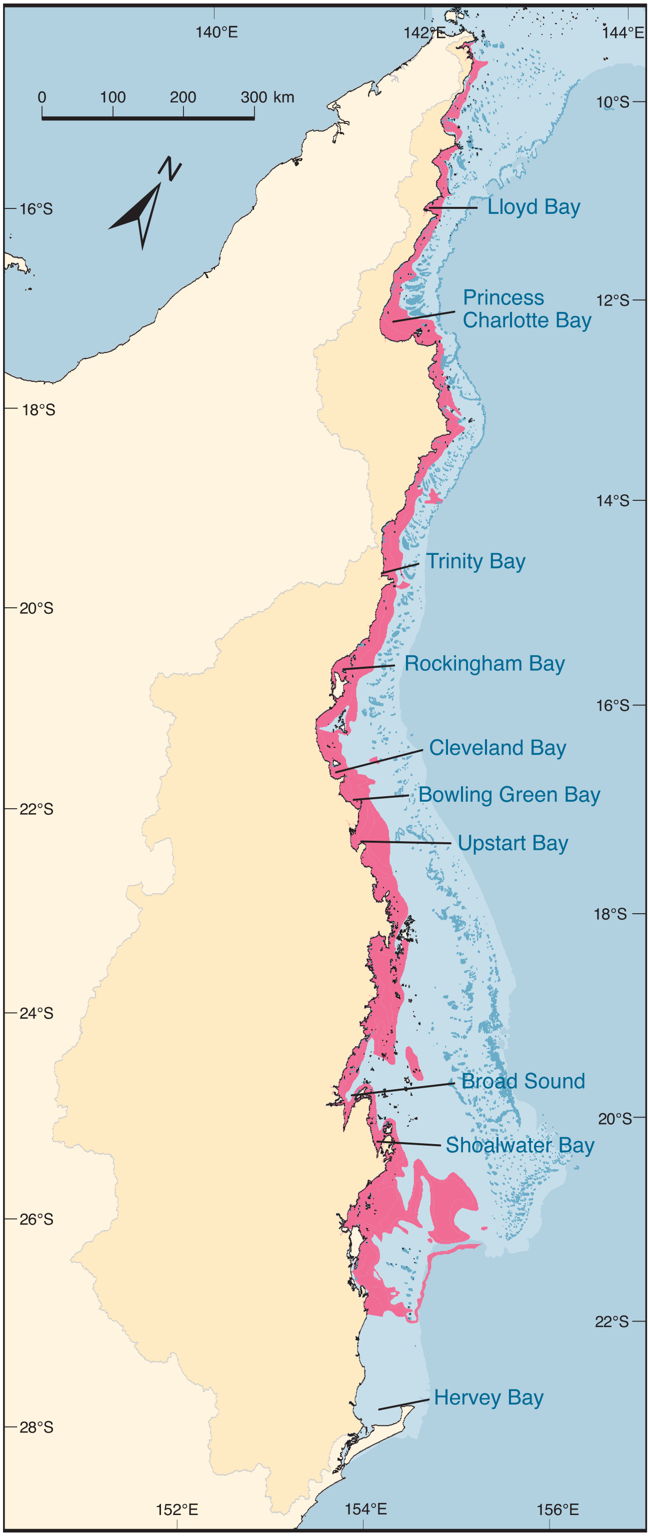
The seabed

The seabed of the GBR is largely covered by biogenic sediments derived from the calcium carbonate skeletons and concretions of reef-building corals, algae, molluscs, foraminifera and bryzoans [305, 464]. The mid-shelf lagoon floor is covered by a thin layer of mixed carbonate sediments containing relict terrigenous materials left over from the last era of exposure at low sea level [583]. Outer shelf reef sediments contain only small amounts of non-carbonate material [230, 362] believed to be mostly volcanic ash from what is now Indonesia or Papua New Guinea. The very low level of non-carbonate or non-biogenic material in outer-shelf reef sediments means that these reefs have received little if any suspended terrestrial sediment.

Coastal waters shallower than 20 m within the GBRWHA.
Data source: GBRMPA

- *Coastal waters less than 20 m*
- *Continental shelf – 20 to 80 m*
- *Reefs*
- *GBR catchment*





The distribution of terrigenous sediments ($CaCO_3$ less than 40%) within the GBRWHA.
Data source: C. Jenkins, Sydney University

$CaCO_3$ less than 40%

Continental shelf (depth < 80 m)

GBR catchment

Sediments primarily derived from terrestrial soils and rocks (terrigenous sediments) are largely restricted to a narrow nearshore band inshore of the 20 m depth contour. Sediments with a carbonate content of less than 30% cover 10,080 km^2, or less than 5% of total shelf area (C. Jenkins, Sydney University). Most of this terrigenous sediment occurs south of Townsville (19°S) where the primary sediment sources are the large dry-catchment rivers (Burdekin and Fitzroy Rivers).

Along the open coastline, the carbonate and terrigenous sediments in the nearshore zone are continually resuspended by wave action and transported northward by wind-driven coastal currents [364, 365]. Fine sediments, mostly of terrigenous origin, accumulate in northward-facing bays (e.g. Shoalwater Bay, Broad Sound, Upstart Bay, Bowling Green Bay, Cleveland Bay, Rockingham Bay, Trinity Bay, Princess Charlotte Bay, Lloyd Bay) which are sheltered from the dominant southeasterly trade winds [275, 583]. Despite this concentration process, net sedimentation rates in most northward-facing bays over the last several thousand years have been estimated at less than 1 mm $year^{-1}$. Sedimentation rates in Princess Charlotte Bay [596] have been estimated at 2-6 mm $year^{-1}$. Higher sedimentation rates (approx. 1 cm $year^{-1}$) at specific sites (e.g. Upstart Bay, southern Bowling Green Bay) are due to the proximity to a major sediment source (Burdekin River) [583].

Coastal fringing reef, Daintree
Photo: GBRMPA

Nutrients in GBR waters

The most extensive development of coral reefs occurs in tropical coastal and oceanic regions which are typically characterised by low ambient concentrations of dissolved plant nutrients, suspended inorganic particulate matter (mud), organic matter and plankton biomass. Corals and algae, the primary organic producers and framework builders of coral reef ecosystems, require constant inputs of nutrients to sustain their productivity.

Table 3. Median water column nutrient, suspended solids and chlorophyll concentrations in shelf waters of the GBR. The median is a measure of the center in a group of numbers where half are larger and half are smaller. It provides a more useful estimate of 'average' where the arithmatic average might be distorted by a few large outlying values.
– = no data.

Far Northern GBR (Cape York - Cape Flattery)				
		Inshore	**Midshelf**	**Outer Shelf**
NH_4-N	µg L^{-1}	–	–	–
NO_3-N		0.4	0.4	0.4
DON		63	62	68
PN		24	18	32
PO_4-P		<0.2	<0.2	<0.2
DOP		3	3	2
PP		3	3	3
Silicate		34	45	14
Suspended solids		800	700	500
Chlorophyll a		0.3	0.5	0.4
Central GBR (Cape Tribulation - Whitsunday Islands)				
		Inshore	**Midshelf**	**Outer Shelf**
NH_4-N	µg L^{-1}	0.4	0.1	0.1
NO_3-N		0.3	0.4	0.6
DON		76	71	75
PN		20	14	14
PO_4-P		3	3	3
DOP		<3	3	3
PP		3	2	2
Silicate		134	62	39
Suspended solids		1,700	800	500
Chlorophyll a		0.4	0.3	0.3
Southern GBR (Mackay - Gladstone)				
		Inshore	**Midshelf**	**Outer Shelf**
NH_4-N	µg L^{-1}	0.6	0.4	0.6
NO_3-N		3	1	0.7
DON		93	66	69
PN		22	21	14
PO_4-P		6	6	3
DOP		<3	<3	3
PP		3	2	2
Silicate		62	56	45
Suspended solids		3,300	1,500	600
Chlorophyll a		1.0	0.7	0.6

Marine plants and bacteria are very efficient at extracting dissolved nutrients from the large volumes of seawater that naturally flow over and through coral reefs [20-23]. A variety of particle feeders capture plankton and non-living organic matter (detritus) suspended in reef waters [184]. Specialised bacteria use the abundant sunlight to power the fixation of atmospheric nitrogen. Other bacteria in anoxic sediments remove it. At every point in the reef food web, organisms ranging from bacteria to vertebrates feed on and recycle the nutrients in biomass and detritus.

Concentrations of key nutrient elements (e.g. nitrogen, phosphorous, iron) in bio-available forms are often so low (parts per trillion) in oligotrophic reef and oceanic waters that they are difficult to measure (Table 3). These very low nutrient concentrations are due both to low rates of supply from external sources and rapid uptake by nutrient-starved algae and bacteria. Dissolved nutrient concentrations in reef waters are largely controlled by the balance between biological demand, external inputs (upwelling, river runoff, rainfall, terrestrial dust) and recycling by animals and bacteria. Demand for key nutrient elements such as nitrogen may be so high that bio-available forms (ammonium, nitrate) are recycled on time scales ranging from minutes to hours [147]. Because of this demand, nutrient inputs, from whatever source, are usually rapidly taken up and converted to biomass by fast-growing phytoplankton and bacteria [102, 141]. This biomass adds to the stock of particulate organic matter in reef waters.

Within the GBR, dissolved nutrient, particulate matter and plankton biomass concentrations are typically higher close to the coast. This difference is due to the input of nutrients and sediment from the land, wave driven resuspension of shallow sediments and the continual remineralisation of organic matter produced in coastal waters and sediments. The cross-shelf concentration differences are not large under normal, non-disturbed

Forms of major nutrients in GBR waters:

NH_4^+ — Ammonium – The most easily utilised form of fixed N. It is also the principal form of N excreted by animals and bacteria. Plants and bacteria can directly use ammonium to synthesise amino acids and other N-containing compounds. Because of high demand, concentrations are usually very low (parts per trillion)

NO_3^- — Nitrate – The most stable form of fixed N in oxygenated seawater. Produced by specialised bacteria (nitrifiers) from ammonia. Readily taken up by plants and bacteria, but usually only after most ammonium is used up. Conversion to usable ammonium in cells requires significant amounts of cellular energy. Concentrations are usually low because of high demand for any type of bio-available fixed N.

NO_2^- — Nitrite – A biochemical intermediate between nitrate and ammonium. Produced during nitrification. Concentrations are usually low due to low production and release under most circumstances.

DIN — Dissolved Inorganic Nitrogen – Summed concentration of ammonium, nitrite and nitrate.

DON — Dissolved Organic Nitrogen – N incorporated into organic matter which passes through an ultra-fine filter (pore size <0.5 µm). Some N-containing small organic molecules (urea, amino acids) can be utilised by bacteria and algae. Most DON, however, is only accessible to bacteria that can break down complicated organic molecules.

PN — Particulate N – N in biomass, dead organic matter or attached to inorganic particles which can be collected by an ultra-fine filter (pore size<0.5 µm).

PO_4^{3-} — Phosphate – The principal soluble inorganic form of P. Animals and bacteria excrete most of their P as phosphate. Readily utilisible by plants and bacteria. Phosphate ions readily bind to a range of minerals (e.g. clays) and form insoluble minerals in carbonate sediments (e.g. apatites).

DOP — Dissolved Organic Phosphorus – P incorporated into organic molecules and inorganic particles passing through an ulta-fine filter (pore size <0.5 µm). Many types of plants and bacteria secrete enzymes which convert DOP to soluble phosphate for uptake.

PP — Particulate Phosphorus – P in biomass, dead organic matter or attached to inorganic particles which can be collected by an ultra-fine filter (pore size<0.5 µm).

Si — Silicate – Required by some microalgae (diatoms) to build cell walls. High concentrations are found in river waters. Rarely limiting in GBR waters.

S — Sulfur – An essential element for key amino acids in proteins. Very abundant as sulfate ($SO_4^{=}$) in oxygenated seawater. Converted to sulfide ($S^{=}$) in anaerobic sediments.

Trace Elements: (iron – Fe, copper – Cu, zinc – Zn, molybdenum – Mo, cobalt – Co, manganese – Mn, nickel – Ni, magnesium – Mg, boron – B, selenium – Se) Elements required in very small amounts for the function of specific enzymes. Only directly available to algae and bacteria. Concentrations are typically very low in seawater, but are usually adequate for growth. In some cases, (e.g. iron), low concentrations of soluble, bio-available forms limit productivity. Metal bio-availablity in seawater and freshwater is often controlled by interactions between largely insoluble ions and dissolved organic matter.

Forms of major nutrients in GBR catchment soils:

NH_4^+ — Ammonium – The most easily utilised form of fixed N in soils. Excreted by soil animals, bacteria breaking down soil organic matter, and the breakdown of fertilisers (e.g. urea). Can bind to clay minerals in some soils. In alkaline (high pH) soils, ammonium is converted to ammonia gas (NH_3) which is lost to the atmosphere (volatilisation).

NO_3^- — Nitrate – The most stable form of fixed N in oxygenated soils. A component of some fertilisers and is produced in situ by specialised bacteria (nitrifiers). Readily taken up by plants and bacteria. Nitrate does not bind to most soils and can be readily leached from soils or to groundwater by soil water runoff or infiltration. In anaerobic soils or sub-zones, can be converted to N_2 gas by specialised bacteria (denitrification).

DON — Dissolved Organic Nitrogen – Soil water N incorporated into soluble organic matter. Primarily utilised by bacteria that can break down complicated organic molecules.

PN — Particulate N – N in biomass, dead organic matter or attached to inorganic particles.

PO_4^{3-} — Phosphate – The principal soluble inorganic form of P in soil water. Phosphate ions readily bind to a range of minerals (e.g. clays) and form insoluble minerals. Most inorganic P in soils exists in a bound state.

DOP — Dissolved Organic Phosphorus – Soil water P incorporated into soluble organic molecules. Many types of plants and bacteria secrete enzymes which convert DOP to soluble phosphate for uptake.

PP — Particulate Phosphorus – P in biomass, dead organic matter or attached to inorganic particles. Most soil P is bound to soil particles.

Si — Silicate – Required by some plants (grasses) to build cell walls. High concentrations are found in soil waters.

S — Sulfur – An essential element for key amino acids in proteins. Usually occurs as sulfate ($SO_4^=$) ions.

K — Potassium – Required for plant growth. Abundant in marine waters.

Ca -— Calcium – Required for plant growth. Abundant in marine waters.

Trace Elements: (iron – Fe, copper – Cu, zinc – Zn, molybdenum – Mo, cobalt – Co, manganese – Mn, nickel – Ni, magnesium – Mg, boron – B, selenium – Se) – Elements required in very small amounts for the function of specific enzymes. Concentrations are typically very low in soil water, but much higher than in marine waters. Runoff is the major source of trace elements in coastal waters.

conditions, but they are persistent. North-south differences in nutrient, suspended particulate matter and plankton biomass concentrations also exist, but are often less pronounced than cross-shelf differences [144].

The biomass of plankton in reef waters is usually constrained by the limited availability of bio-available nitrogen and to a lesser degree, phosphorus [142]. Even under low-nutrient conditions, phytoplankton and bacteria in reef waters can grow at rapid rates, but only for very short periods of time. As they do so, they are consumed by grazers at similar rates. Dissolved stocks of bio-available nitrogen and phosphorus are usually only sufficient for one or at most, a few days growth. Continual growth of corals, algae, phytoplankton and bacteria are sustained by continuous consumption, remineralisation and recycling of nutrients. The generally larger stocks of nutrients in dissolved organic (DON and DOP) and particulate (PN, PP) forms are only available to phytoplankton and other algae after much slower mineralisation by bacteria.

Away from the shallow nearshore zone, GBR waters are usually characterised by low to very low concentrations of suspended particulate matter [183, 264]. Suspended matter in reef and coastal waters includes fine inorganic particles (clays, carbonates) derived from resuspension of coastal and reef sediments, living plankton and detritus from a variety of sources. Suspended particles of non-living organic matter can form larger aggregates ("marine snow") which also contain a range of living organisms and inorganic matter [9]. On the mid- and outer-shelf, concentrations of suspended matter are typically less than 1 mg L^{-1}. Suspended matter concentrations in coastal and nearshore waters span a much wider range, from < 1 mg L^{-1} to several 100s of mg L^{-1} depending upon water depth, wave activity and the type of bottom sediments [264]. The higher suspended matter concentrations (greater than 10 mg L^{-1}) are usually short-lived, but occur frequently in shallow nearshore waters.

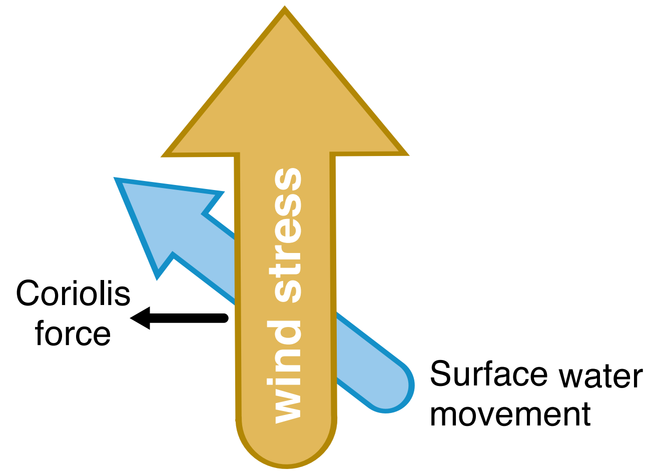
The normally low concentration of suspended particulate matter (living and dead) is the principal reason for the high transparency of tropical reef and oceanic waters. Along the seaward margin of the GBR, light can penetrate more than 100 m, allowing plankton, algae and corals to grow over a wide depth range. This range is greatly reduced in turbid or nearshore waters [140, 512].

Salinity

Surface waters of the western Coral Sea and GBR typically have a salinity close to 35‰ (35 parts per thousand or 35 g of dry inorganic salts per kg of seawater). During the dry season, salinities in coastal waters may reach 36‰ as a result of evaporation. Substantial decreases in surface salinities (less than 33‰) only occur during major flood events and following extensive periods of rainfall associated with cyclones or monsoonal rains.

Currents and mixing

The waters of the GBR are never still. The push of winds and the relentless pull of gravity drive currents which flow along and across the continental shelf. On a day-to-day basis, tides cause most water movement in the GBR [573]. Tidal currents typically flow back and forth across the shelf with velocities in open waters ranging up to 60, but usually less than 30 cm sec^{-1}. Over a daily tidal cycle, volumes of water ranging from 0.03-0.07% of the shelf water volume move on and off the continental shelf. As tidal currents flow over and around reefs, bottom friction and the displacement of flowing water by reefs set up horizontal and vertical eddies which mix the shelf waters [573]. The scale of mixing caused by tidal currents moving about reefs, islands and other topographic features is often difficult to comprehend. For example, a circular reef 2 km in diameter, surrounded by water 30 m deep with a tidal current of 0.5 knot (1 knot = 1 nautical mile $hour^{-1} \approx 0.5$ m sec^{-1}), displaces a volume of water (approx. 15,000 m^3 sec^{-1}) similar in magnitude to the average discharge (18,000 m^3 sec^{-1}) of the Mississippi River, the world's fifth largest



Wind stress, the Coriolis Force and their combined effect on surface water movement in the Southern Hemisphere. Surface waters are deflected to the left of downwind.

river. This displaced flow is more than six times the time-averaged annual river discharge rate into the GBR.

Tidal currents in the central and southern GBR are embedded within larger flows on the continental shelf driven by the East Australian Current (EAC) in the Coral Sea [594]. The southward flowing EAC begins between 15°S and 17°S, (Lizard Island-Cairns) following the bifurcation of the westward flowing South Equatorial Current against the GBR [12]. Most of the EAC flows along the outer edge of the continental shelf at an average speed of 30 cm sec^{-1} (26 km day^{-1}) [11]. Small changes in the slope of the sea surface set up by the EAC cause shelf waters to flow southward as well. The speed of this shelf current varies with the strength of the EAC and flow restrictions caused by reefs [573]. Current speeds in open waters of the central GBR range up to 55 cm sec^{-1} (48 km day^{-1}) [11, 75, 573, 579], but are usually less than 30 cm sec^{-1}. In the far-northern GBR, the dense reef matrix inhibits significant longshore flow. North of Cape Melville, non-tidal flows are overwhelmingly driven by the winds [580].

During the summer, interactions between northerly winds and the EAC cause episodic upwelling of cool, nutrient-enriched Coral Sea water along the seaward margin of the GBR [13, 143]. While some degree of upwelling occurs along most of the length of the GBR, the largest events observed to date occur in the central GBR where the reef matrix is relatively open. During these events, water from the Coral Sea intrudes inshore along the bottom. In most cases, intruded water stays on the outer half of the shelf, but occasionally large intrusions can extend across the shelf to within a few kilometres of the coast [143]. Limited upwelling occurs through the narrow passes which separate shelfbreak barrier reefs of the far northern and southern GBR [498, 575], but large cross-shelf intrusions are blocked by the dense wall of shelfbreak reefs. In the central GBR (16-19°S), intrusions are estimated to inject 3-30 tonnes of nitrogen and 0.4-4.4 tonnes of phosphorus

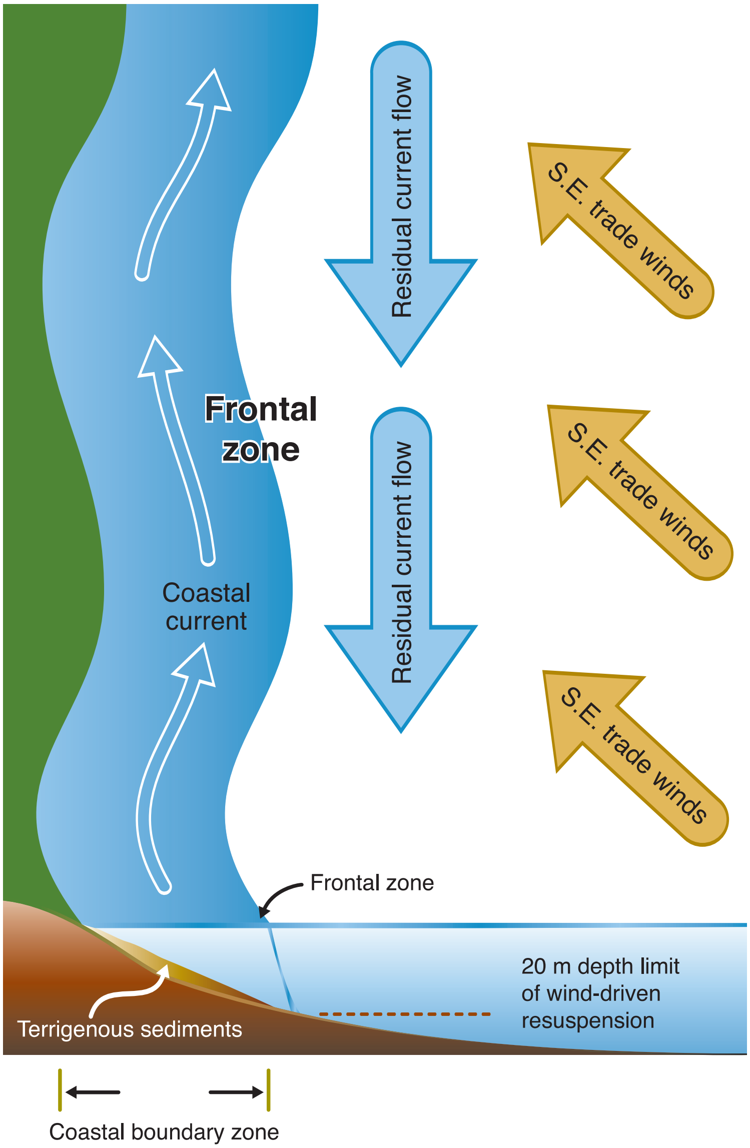


Illustration of the relationship between wind stress, wind-driven coastal currents, the inner-lagoon frontal zone and cross-shelf distribution of terrigenous sediments in the GBR.

per km of shelf each year depending on the number and magnitude of upwelling events [143].

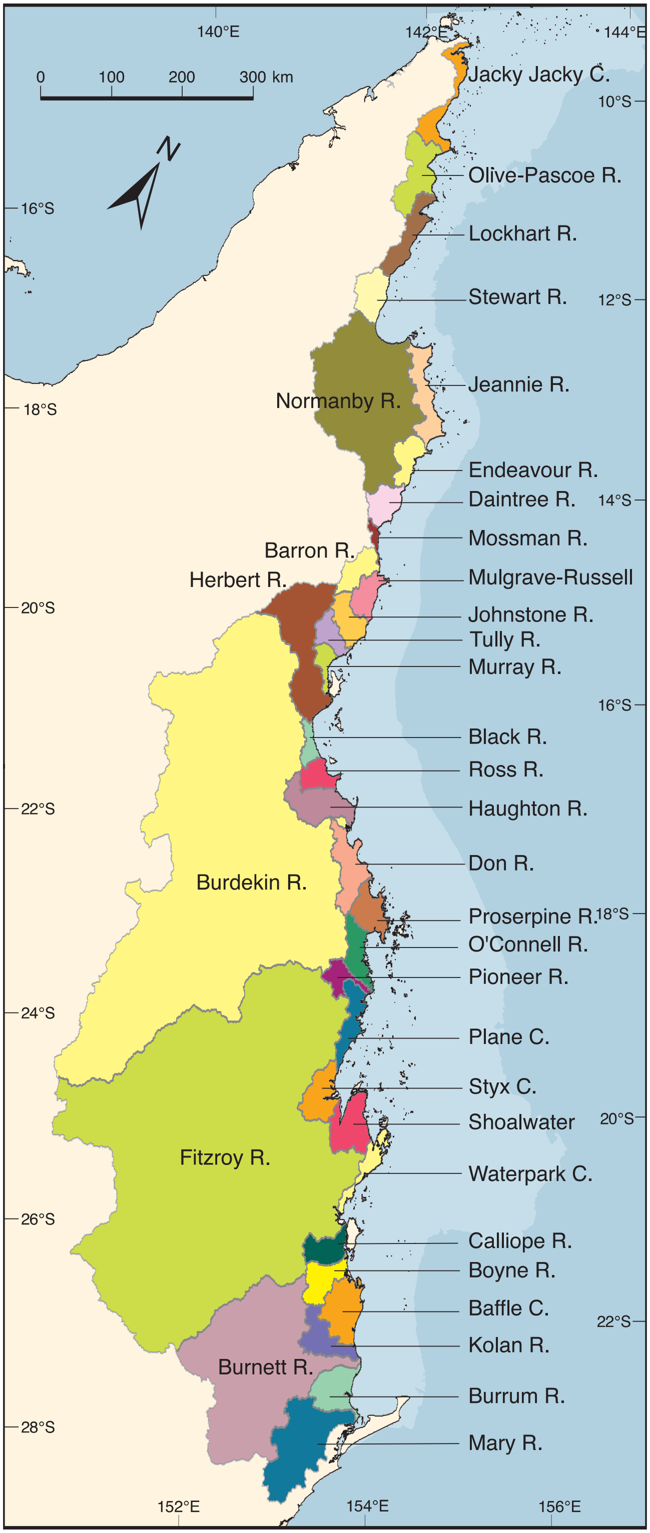
Winds strongly influence the movement of water within the GBR. For much of the year, persistent southeasterly trade winds blow throughout the GBR region. Friction between the winds and the sea surface drives a north and west-flowing movement of surface waters. This wind-driven flow runs against the southward flow caused by the EAC. In deeper outer shelf waters, a two layered flow regime may develop, with a wind-forced surface layer overlying a south-flowing near-bottom layer [13]. In shallow coastal waters, the influence of the wind extends to the bottom, leading to the development of a north-flowing coastal current [249, 365]. This coastal current is the primary mechanism which moves sediment northward along the coast [275]. Differences in water speed and direction (shear) between the north-flowing inshore current and deeper shelf waters in the GBR lagoon lead to the formation of a boundary (or front) between coastal and lagoonal waters [249]. The shear zone between the shallow coastal boundary zone and the deeper GBR lagoon acts as a barrier to the offshore movement and mixing of coastal waters. The presence of the coastal boundary zone and the rate of cross-shelf mixing varies with the local bathymetry, wind strength and duration of appropriate southeasterly winds. The shear zone is only present when northward wind stress from the southeasterly trade winds is sufficient to overcome the southward residual current. The most important consequence of wind-driven flow along the coast and the formation of a coastal boundary zone is that river waters and transported materials can be trapped in the narrow coastal band, accentuating their impact on nearshore ecosystems.

Catchments draining into the Great Barrier Reef

The Great Barrier Reef receives runoff from the catchments of eastward-draining rivers and streams between Cape York and Fraser Island. Rivers and streams on the mainland have a combined catchment area of 423,070 km^2, approximately twice the area of the GBR continental shelf (Table 4). Streams on continental islands within the GBRWHA drain catchments with an area of 1,070 km^2. These ungauged island streams are small and most are ephemeral, draining largely unmodified catchments. In this book, only runoff from the mainland catchments is considered. Collectively, these catchments comprise the Great Barrier Reef Catchment Area (GBRCA).

The GBR catchment encompasses 25% of the State of Queensland and 5.6% of the Australian continental landmass. On the ground, the western boundary of the GBR catchment is often not well defined due to flat local land relief. Streams arising west of the divide flow into the Gulf of Carpentaria, the Lake Eyre basin and the Murray-Darling River system.

The GBR catchment varies considerably in width. Near Cairns (17°S), the coastal mountain range forms the

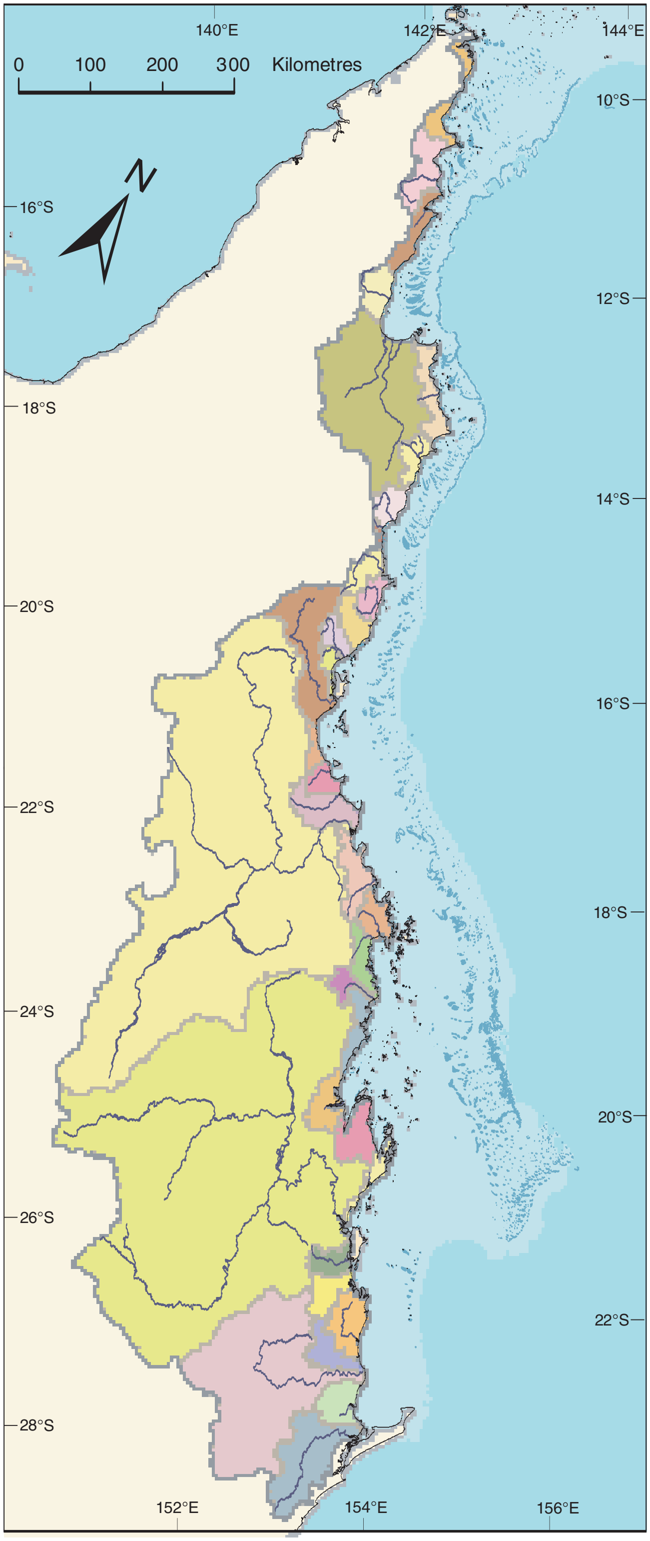


Mainland drainage basins of the GBRCA
Data source: QNR&M

Table 4. Summary statistics for the major mainland drainage basins of the GBR catchment. Average rainfall was calculated from the long-term average isohyet distribution within basin boundaries. Basin areas and gauged runoff (1968-1994) were obtained from the Queensland Dept. of Natural Resources & Mines. Rainfall data was obtained from the Bureau of Meteorology.

Basin Name	Basin No.	Area	%	Annual Runoff			Average Annual		%	Adjusted
			Gauged	Average	Max	Min	Rainfall	Runoff	Runoff	Runoff Volume
		(km^2)			(km^3)		mm	mm		(km^3)
Jacky-Jacky C.	101	2,963	0				1467		(36)	1.56
Olive-Pascoe R.	102	4,179	31	3.71	7.14	0.27	1187	888	75	3.71
Lockhart R.	103	2,883	0				1225		(55)	1.94
Stewart R.	104	2,743	17	1.21	2.30	0.01	1222	441	36	1.21
Normanby R.	105	24,408	33	4.95	17.49	0.60	1185	203	17	4.95
Jeannie R.	106	3,637	19	1.54	4.69	0.13	1344	423	32	1.54
Endeavour R.	107	2,104	28	1.82	4.92	0.44	1939	865	45	1.8
Daintree R.	108	2,192	39	1.26	3.52	0.11	2492	575	23	1.26
Mossman R.	109	466	12	0.59	1.21	0.18	2208	1,265	57	0.59
Barron R.	110	2,136	89	0.81	2.66	0.16	1453	279	19	0.81
Mulgrave-Russell R.	111	1,983	48	3.64	7.21	1.32	3016	1,836	61	3.64
Johnstone R.	112	2,325	59	4.67	9.12	1.65	2996	2,009	67	4.67
Tully R.	113	1,683	88	3.29	5.37	1.24	2855	1,954	68	3.29
Murray R.	114	1,107	14	1.06	2.60	0.38	2098	958	46	1.06
Herbert R.	116	9,843	87	4.01	11.99	0.53	1506	407	27	4.01
Black R.	117	1,057	33	0.38	1.54	0.00	1530	360	23	0.38
Ross R.	118	1,707	56	0.49	3.37	0.01	1027	287	28	0.49
Haughton R.	119	4,044	68	0.74	3.18	0.02	888	183	21	0.74
Burdekin R.	120	130,126	100	10.29	54.46	0.52	727	79	11	10.29
Don R.	121	3,695	16	0.75	3.66	0.00	1045	203	19	0.75
Proserpine R.	122	2,535	13	1.08	3.95	0.02	1360	426	31	1.08
O'Connell R.	124	2,387	30	1.54	4.19	0.07	1469	645	44	1.54
Pioneer R.	125	1,570	92	1.19	5.15	0.00	1385	758	55	1.19
Plane Creek	126	2,539	19	1.49	4.97	0.05	1125	587	52	1.49
Styx R.	127	3,012	0				1010		(52)	1.58
Shoalwater	128	3,605	0				975		(52)	1.83
Waterpark C.	129	1,835	13	1.11	2.68	0.23	860	605	70	1.11
Fitzroy R.	130	142,537	95	6.08	23.22	0.18	735	43	6	6.08
Calliope R.	132	2,236	58	0.3	1.08	0.02	790	134	17	0.30
Boyne R.	133	2,590	88	0.29	2.40	0.00	968	112	12	0.29
Baffle C.	134	3,996	37	0.78	3.03	0.08	893	195	22	0.78
Kolan R.	135	2,901	80	0.41	2.10	0.02	1065	141	13	0.41
Burnett R.	136	33,248	98	1.15	6.37	0.12	763	35	5	1.15
Burrum R.	137	3,358	14	0.55	2.36	0.03	766	164	21	0.55
Mary R.	138	9,440	50	2.72	9.27	0.26	1174	288	25	2.72

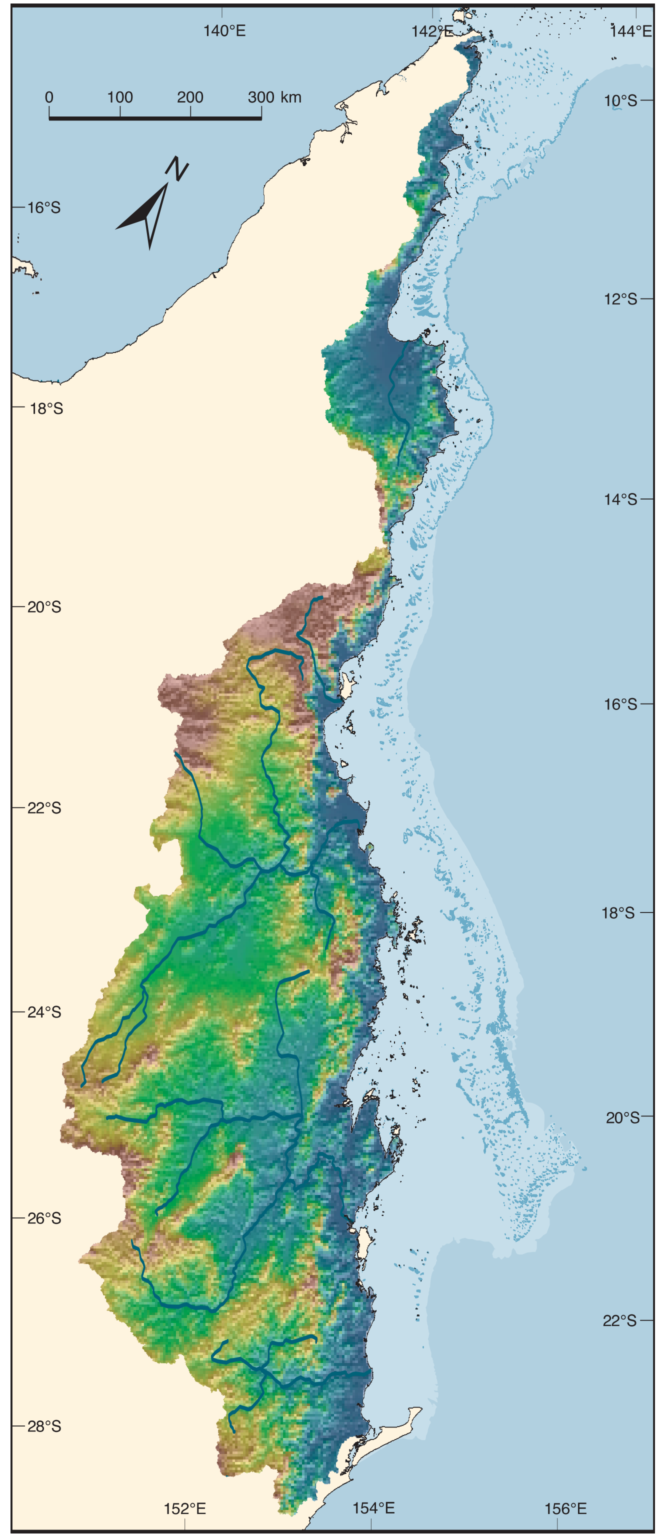
* 1 cubic km (km^3) = 1 billion (10^9) m^3 = 1 million MegaLitres (10^6 ML)

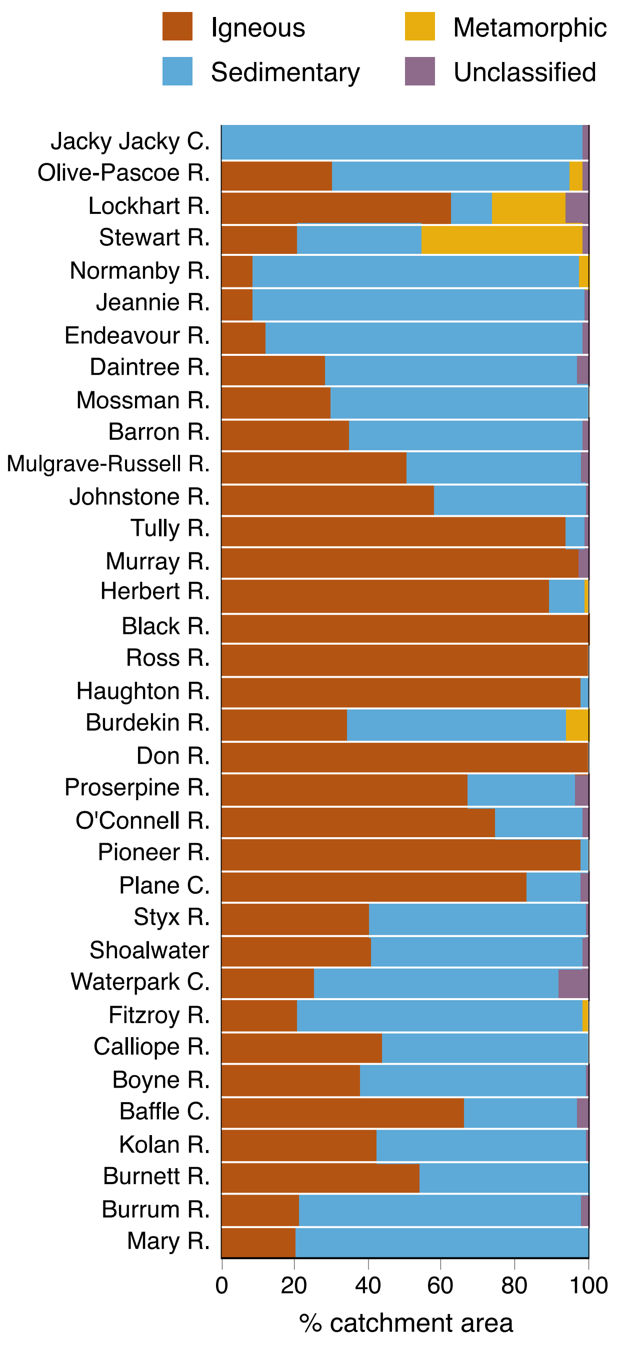


Gauged rivers of the GBRCA
Data source: AUSLIG

The topography of the GBRCA
Data source: AUSLIG

Height above sea level





Relative extent of major bedrock types underlying drainage basins of the GBRCA.
Data source: AGSO

continental divide and the GBR catchment is only tens of kilometres wide. To the south, in the catchment of the Fitzroy River, the GBR catchment extends nearly 450 km inland. The southern end of the GBR catchment encompasses part of a broad low-relief highland region, the Central Highlands.

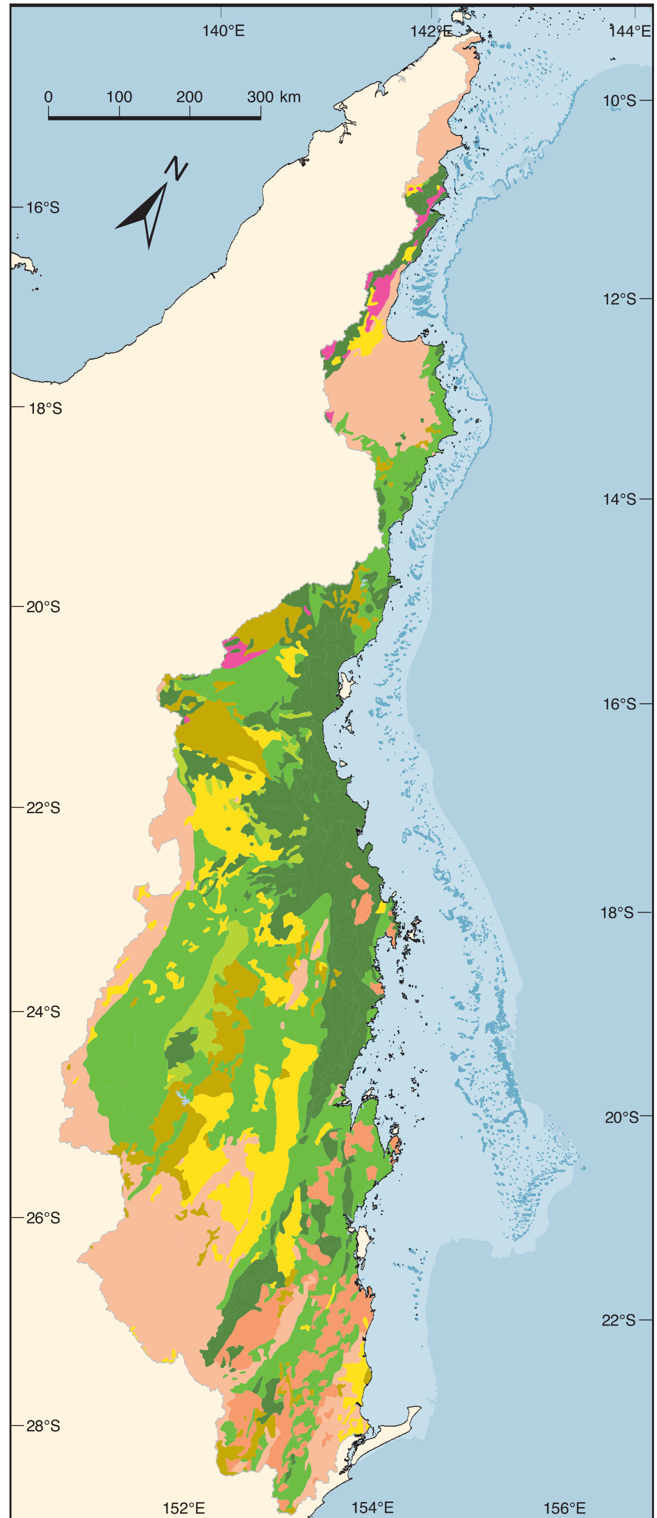
Catchments and drainage basins

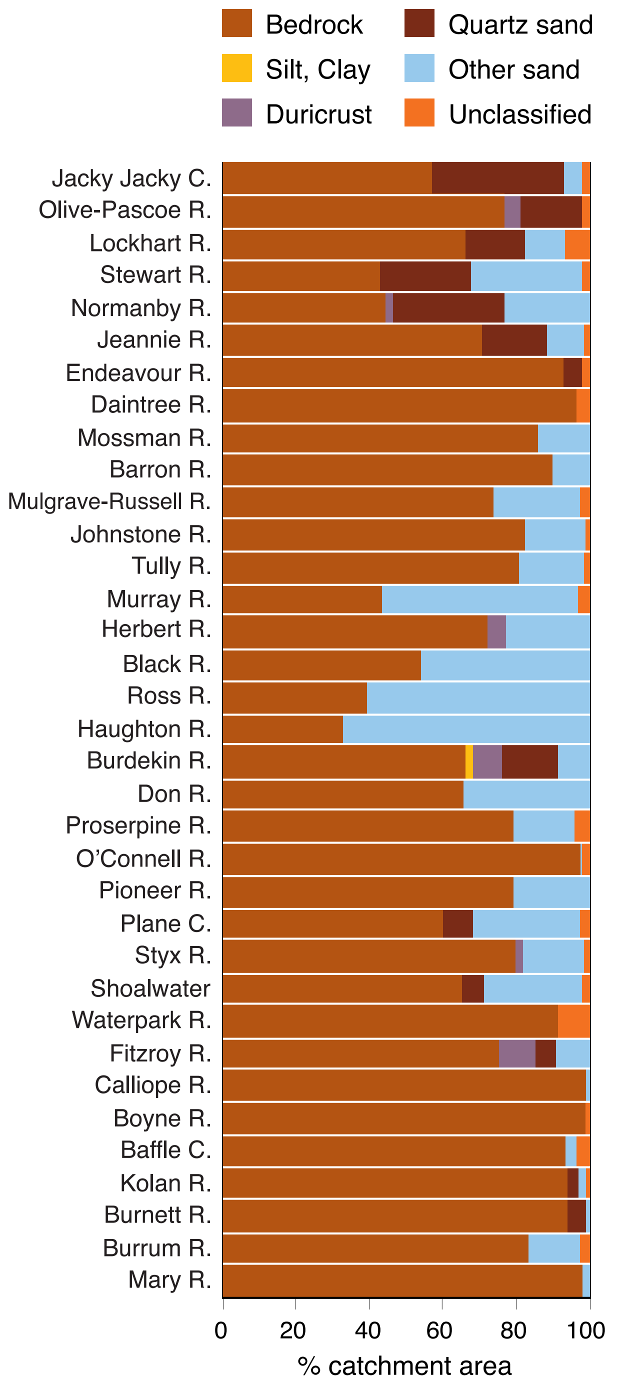
Approximately 30 significant rivers and many hundreds of small, usually ephemeral streams drain into coastal waters of the GBR. For statistical purposes, the catchments of these rivers and streams have been aggregated into 35 drainage basins separated by natural topographic boundaries (QNR&M). Unless stated otherwise, these basins will be used to calculate estimates of land cover, land use and runoff to the GBR. Areas of individual drainage basins range from 466 km^2 (Mossman River) to 142,537 km^2 (Fitzroy River). Most of the basins are small. Only seven exceed 5,000 km^2 in area. The two largest drainage basins, which contain the Burdekin (130,126 km^2) and Fitzroy River systems, account for 64% of the total area of the GBR catchment.

Measurement of water discharge into what is now the Great Barrier Reef World Heritage Area began in 1910. By 1924, river heights were measured daily in 10 river systems (Mary, Burnett, Fitzroy, Pioneer, Don, Burdekin, Herbert, South Johnstone, Mulgrave, Barron) around which the timber, mining, sugar and beef industries were developing. A major expansion of the stream gauging network took place in the 1950s to provide information on state water resources. This expanded network was maintained until the early 1990s, when gauging stations on many smaller rivers and streams were decommissioned. The most complete set of discharge measurements was recorded between 1968 and 1994. During this 27-year period, daily water heights were measured in 54 rivers and streams discharging directly into the GBRWHA. One or more of these gauged streams are located in 31 of the

The distribution of major bedrock types within the GBRCA.
Data source: AGSO

- *Cainozoic Igneous*
- *Cainozoic Sedimentary*
- *Mesozoic Igneous*
- *Mesozoic Sedimentary*
- *Paleozoic Igneous*
- *Paleozoic Sedimentary*
- *Paleozoic Metamorphic*
- *Precambrian*





Relative extent of superficial geological covers underlying soils in drainage basins of the GBRCA.
Data source: AGSO

35 mainland drainage basins. The proportion of individual drainage basins covered by the catchments of gauging stations varies considerably, from less than 12% (Mossman River) to nearly 100% (Burdekin River). Overall, gauged sub-catchments with an aggregate area of 345,260 km^2 encompass 81% of the total GBR catchment.

Geography

The major topographic feature of the GBR catchment which influences runoff is the range of hills and low mountains which extends parallel to the coast for the length of the GBR. This range, sometimes referred to as the Great Escarpment [356], separates the narrow coastal plain from the inland parts of the Burnett, Fitzroy and Burdekin catchments, and upland regions such as the Einasleigh Uplands, Desert Uplands and Atherton Tablelands which comprise the inland sections of the Barron, Herbert and Burdekin River catchments. The coastal range determines the size and topography of the smaller drainage basins along the coast. Most of the hills and mountains forming the coastal range are less than 1,000 m in height. The two highest peaks in Queensland, Mount Bartle Frere (1,612 m) and Bellenden Ker (1,593 m) are located in the coastal range between Innisfail and Cairns.

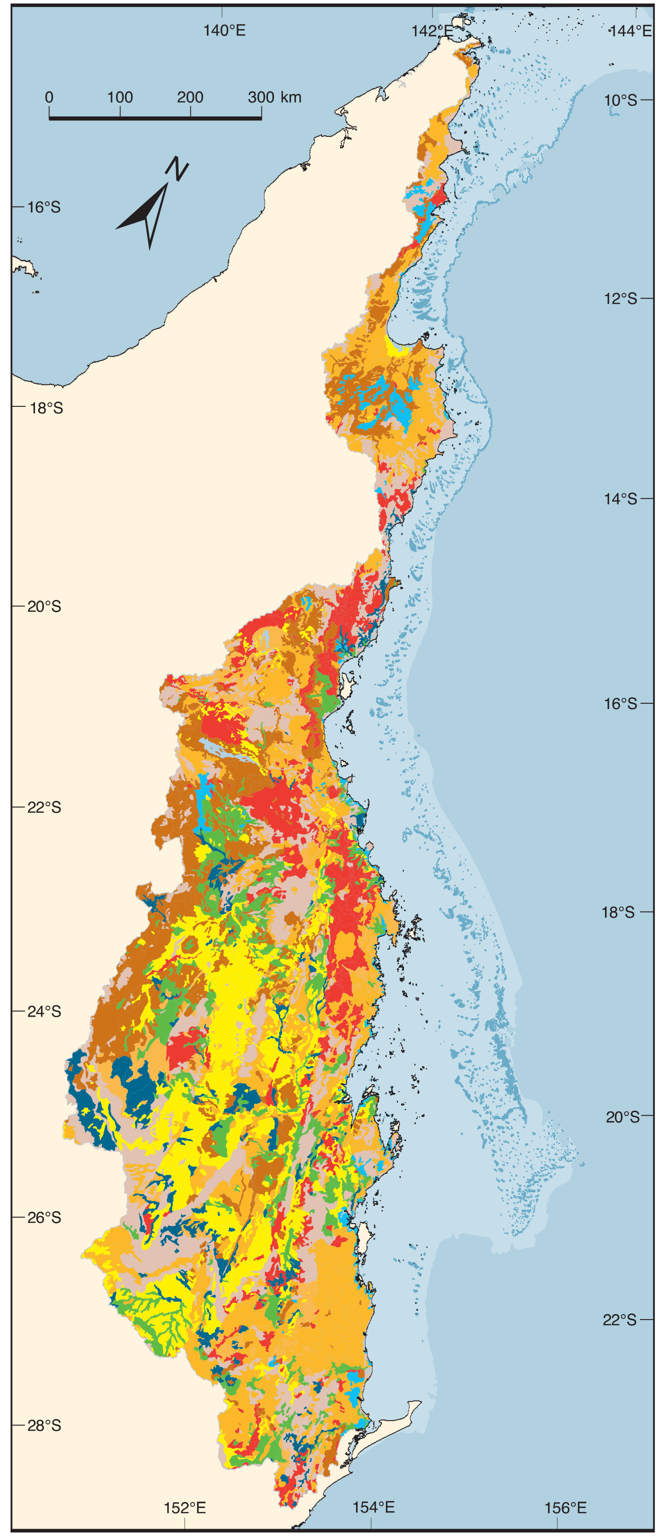
The distribution of rainfall within the GBR catchment (Chapter 5) is largely related to the presence and height of the coastal range. At several places (e.g. Cairns to Cooktown), sections of the coastal range lie along the coast without any significant coastal plain. There are a number of gaps in the range through which the Fitzroy, Burdekin and Herbert Rivers drain extensive inland catchments.

Geology

The hills and mountains which form the coastal range are the eroded remains of an epoch of mountain building and continental accretion during the Paleozoic era (545-245 million years before present-MYBP) [198, 425]. This mountain

The distribution of major soil types within the GBRCA.
Data source: CSIRO

- *Alluvial Soil, Lithosol, Sand*
- *Black Earth, Brown Clay, Grey Clay*
- *Gleyed Soil, Humic Gley*
- *Krasnozem, Euchrozem*
- *Prairie Soil*
- *Podzol, Red Podzolic, Yellow Podzolic*
- *Red Brown Earth, Red Earth, Yellow Earth*
- *Solodic Soil, Solodized Solonetz*



Major soil groups of the Australian Soil Classification in relation to the Australian Great Soil Groups
Source: NLWRA

Australian Soil Classification	Australian Great Soil Group
Supracalcic Calcarosol	Solonised Brown Soil
Calcic Calcarosol	Grey-Brown Soil
	Red Calcareous Soil
	Solonised Brown Soil
Red Chromosol	Red-Brown Earth
	Non-calcic Brown Soil
	Red Podzolic Soil
Brown Chromosol	Brown Podzolic Soil
	Lateritic Podzolic Soil
Red Dermosol	Red Podzolic Soil
Red Ferrosol	Krasnozem
	Euchrozem
Red Kandosol	Red Earth
Yellow Kandosol	Yellow Earth
Brown Kandosol	Yellow Earth
Red Kurosol	Red Podzolic Soil
	Soloth
Brown Kurosol	Grey-Brown Podzolic
	Soloth
Semiaquic Podosol	Humus Podzol
Red Sodosol	Solodized Solonetz
	Solodic Soil
Grey Sodosol	Solodized Solonetz
	Solodic Soil
Black Sodosol	Solodized Solonetz
	Solodic Soil
Orthic Tenosol	Earthy Sand
Black Vertosol	Black Earth
	Black Clay
Grey Vertosol	Grey Clay
Brown Vertosol	Brown Clay

Table 5. Areas of major bedrock types in drainage basins of the Great Barrier Reef catchment.
Data source: AGSO, 1999

Basin Name	Basin Area km^2	Igneous km^2	%	Sedimentary km^2	%	Metamorphic km^2	%	Unclassified km^2	%
Jacky Jacky C.	2,963	6	<1	2,902	98			55	2
Olive-Pascoe R.	4,179	1,277	31	2,686	64	132	3	85	2
Lockhart R.	2,883	1,813	63	311	11	575	20	185	6
Stewart R.	2,743	574	21	909	33	1,207	44	53	2
Normanby R.	24,408	2,110	9	21,608	89	686	3	4	<1
Jeannie R.	3,637	321	9	3,266	90			51	1
Endeavour R.	2,104	255	12	1,816	86			33	2
Daintree R.	2,192	620	28	1,498	68			74	3
Mossman R.	466	140	30	325	70			2	<1
Barron R.	2,136	750	35	1,351	63			35	2
Mulgrave-Russell R.	1,983	1,008	51	933	47			42	2
Johnstone R.	2,325	1,352	58	949	41			25	1
Tully R.	1,683	1,587	94	76	4			21	1
Murray R.	1,107	1,077	97					30	3
Herbert R.	9,843	8,823	90	885	9	93	1	42	<1
Black R.	1,057	1,057	100					0	<1
Ross R.	1,707	1,700	100					6	<1
Haughton R.	4,044	3,963	98	55	1	8	<1	19	<1
Burdekin R.	130,126	44,829	34	76,726	59	8,560	7	13	<1
Don R.	3,695	3,692	100					3	<1
Proserpine R.	2,535	1,705	67	737	29			93	4
O'Connell R.	2,387	1,794	75	547	23			46	2
Pioneer R.	1,570	1,542	98	24	1			4	<1
Plane C.	2,539	2,124	84	360	14			54	2
Styx R.	3,012	1,223	41	1,753	58			32	1
Shoalwater	3,605	1,474	41	2,065	57			66	2
Waterpark C.	1,835	466	25	1,217	66			153	8
Fitzroy R.	142,537	29,749	21	110,121	77	2,482	2	188	<1
Calliope R.	2,236	990	44	1,243	56			4	<1
Boyne R.	2,590	984	38	1,581	61			25	1
Baffle C.	3,996	2,646	66	1,213	30			137	3
Kolan R.	2,901	1,240	43	1,634	56			26	1
Burnett R.	33,248	17,983	54	15,252	46			13	<1
Burrum R.	3,358	713	21	2,574	77			71	2
Mary R.	9,440	1,904	20	7,511	80			25	<1
Total	**423,070**	**143,492**		**264,127**		**13,741**		**1,714**	
% GBR Catchment		**33.9**		**62.4**		**3.2**		**0.4**	

Table 6. Surface geological cover underlying soils in drainage basins of the GBRCA.
Data source: AGSO, 1999

Basin Name	Basin Area	Bedrock	Clay, silt	Duricrusts km^2	Quartz sand	Other Sand	Unclassified
Jacky Jacky C.	2,963	1,682			1,055	171	55
Olive-Pascoe R.	4,179	3,200		196	698		84
Lockhart R.	2,883	1,895			466	337	185
Stewart R.	2,743	1,165			685	840	53
Normanby R.	24,408	10,738		664	7,261	5,741	4
Jeannie R.	3,637	2,564			642	381	50
Endeavour R.	2,104	1,954			117		33
Daintree R.	2,192	2,105				12	75
Mossman R.	466	399				66	1
Barron R.	2,136	1,914				220	2
Mulgrave-Russell R.	1,983	1,457				483	42
Johnstone R.	2,325	1,908				392	25
Tully R.	1,683	1,353				310	20
Murray R.	1,107	480				597	30
Herbert R.	9,843	7,077		494		2,231	42
Black R.	1,057	566				491	0
Ross R.	1,707	667				1,034	7
Haughton R.	4,044	1,317				2,708	18
Burdekin R.	130,126	86,497	1,623	11,183	19,248	11,565	11
Don R.	3,695	2,412				1,281	3
Proserpine R.	2,535	2,008				433	93
O'Connell R.	2,387	2,323				18	46
Pioneer R.	1,570	1,240				326	4
Plane C.	2,539	1,520			208	757	54
Styx R.	3,012	2,392		56		528	36
Shoalwater	3,605	2,337			222	980	66
Waterpark C.	1,835	1,683				0	152
Fitzroy R.	142,537	106,725	44	14,942	7,404	13,375	47
Calliope R.	2,236	2,201				31	4
Boyne R.	2,590	2,565					25
Baffle C.	3,996	3,719				140	137
Kolan R.	2,901	2,722			81	72	26
Burnett R.	33,248	31,089			1,714	433	13
Burrum R.	3,358	2,792				495	70
Mary R.	9,440	9,210			47	158	25
Total	**423,070**	**305,876**	**1,667**	**27,535**	**39,849**	**46,605**	**1,539**
% GBR Catchment		72.3	0.4	6.5	9.4	11.0	0.4

building was followed by a long period of erosion and subsequent episodes of uplift and mountain formation during the Mesozoic (245-65 MYBP) and Tertiary (65-2 MYBP) ages. The granitic basement rocks that form a significant portion of the coastal range are largely of Paleozoic age. Small outcrops of older rocks are found at a number of inland sites, e.g., near Charters Towers. There are metamorphic rocks, mostly of Paleozoic age, at several places in the coastal range, largely in the hinterlands of catchments on Cape York Peninsula.

The coastal plain and underlying sediments of the adjacent continental shelf are mostly formed of alluvium derived from the erosion of the coastal mountains.

Several episodes of volcanic activity have occurred as a result of tectonic activity associated with Australia's general northward movement and the formation of Papua New Guinea. Eruption cones, craters and sometimes extensive surface outflows of basalt which range in age from <15,000 to 65 million years are the remains of this activity. Volcanic features are located throughout the northern GBR catchment. The youngest are located in the upper Burdekin, Herbert, Tully and Barron River catchments [483].

Basement rocks west of the coastal ranges are mostly of sedimentary origin with scattered intrusions and outcrops of igneous rocks [474]. The deeper sedimentary rocks in these basins are largely of Paleozoic age (545-245 MYPB), with overlying layers of younger sediment (to <2 MYBP). These sediment layers were formed when extensive shallow seas covered the region. Large deposits of coal occur throughout the Bowen Basin which extends south from Collinsville (20°S). These coal deposits formed during epochs when the shallow seas retreated or as part of deltaic formations along the sea margin. The coal deposits are accessible to surface mining at a number of locations, forming the basis for Queensland's most valuable export industry.

The Normanby River basin on Cape York Peninsula is underlain by extensive sandstones of Mesozoic (245-65 MYBP) to Tertiary (1.8 MYBP) age [351]. Large fields of silica sand dunes form the coastline on Cape York Peninsula at several locations (Cape Flattery – 15°S, Temple Bay - 12°S). The source material for these dunes is unresolved. One possibility is that they were formed by weathering and erosion of the underlying sedimentary rocks. Alternatively, the sand may have been derived from sedimentary rocks underlying the now submerged continental shelf.

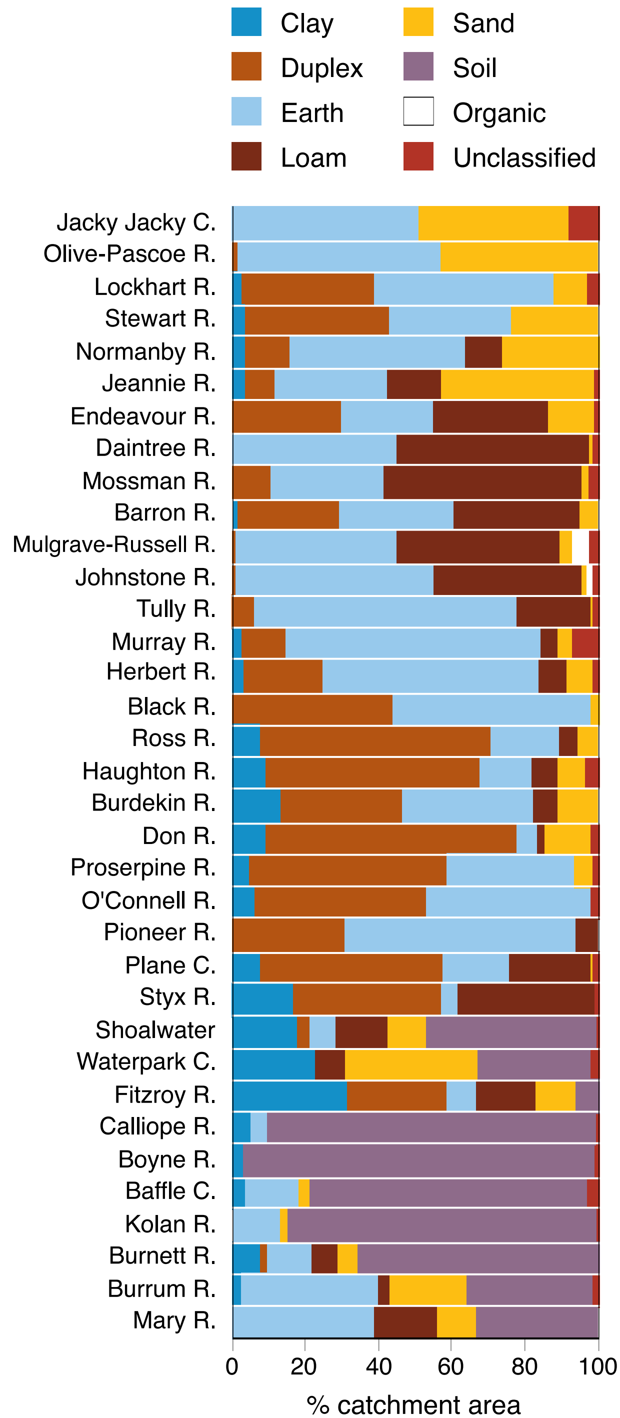
On an area basis, 62% of the basement rocks underlying the GBR catchment are of sedimentary origin, 34% are igneous and 3% metamorphic.

Modern soils of the GBR catchment have developed on a variety of geologic surfaces (Table 6). These include bedrock, silt and clay, sand or alluvial materials and several types of laterites or oxide crusts (duricrusts). Many of these landscapes are of great age [98].

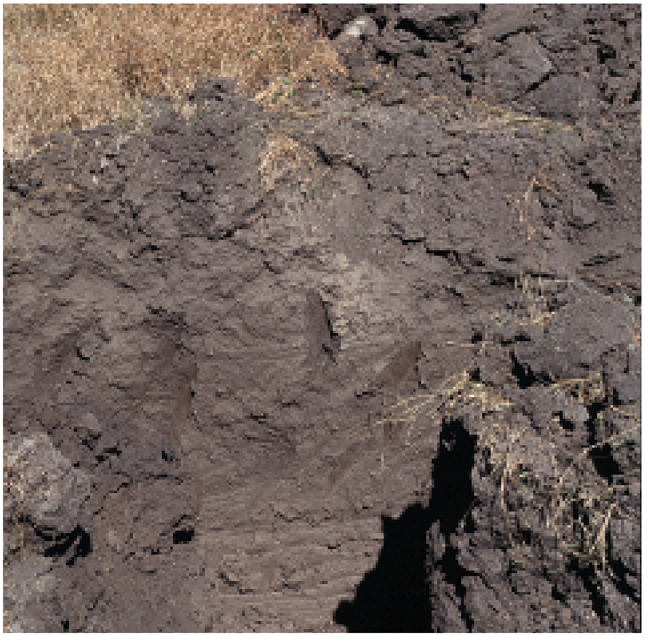
Soils

There is a great diversity of local soil types within the GBR catchment [219, 360]. The distribution of local soil types is determined by the regional geological and topographic setting, local and upstream bedrock, rainfall and the local erosional or depositional history. Soil nutrient availability is closely related to soil type and vegetation cover. Over large areas, local soil types can be amalgamated into broader categories (Table 7; Table 8). With appropriate caution, these major soil groups are a useful basis for estimating basin-scale soil properties such as erodability [280] and nutrient content [478]. Specific vegetation communities such as brigalow or rainforest are often associated with particular soil types within a regional setting [454].

The relative distribution of soil types in the GBR catchment varies with catchment. There are significant



Relative extent of major soil structural types in drainage basins of the GBRCA.
Data source: CSIRO



Clay soil
Photo: P. O'Reagain, QDPI

Duplex soil
Photo: C. Roth, CSIRO

Cracking clay soil
Photo: QDPI

areas of earth-structured soils (red and yellow earth) in almost all catchments. Sandy soils are most prominent in catchments on northern Cape York Peninsula. Soils with a well-defined layered structure (duplex soils) dominate in catchments of the southern Cape York Peninsula and the dry Burdekin and Fitzroy River catchments bordering the central and southern GBR. Loam soils are most prevalent in the small wet-tropical catchments bordering the central GBR.

The clay and duplex soils underlying the formerly extensive brigalow and eucalypt woodland communities of inland central Queensland are particularly important [180]. A large proportion of the native (pre-1850) vegetation communities growing on these soils has been cleared for grazing purposes. Krasnozem and related red or yellow earth soils derived from weathered basaltic rocks are dominant in the wet tropics bordering the central GBR.

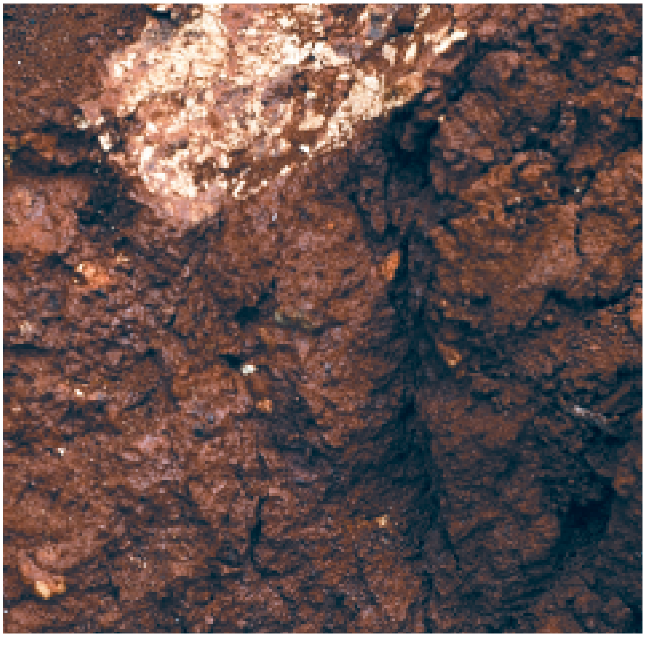
Sugarcane, horticultural crops and perennial pastures are grown on these naturally rich soils.

Duplex (25%) and earth-type soils (25%) account for nearly half of the area of soil cover throughout the GBR catchment (Table 9). Duplex (34%) and earth-type (36%) soils cover most of the Burdekin River catchment. The Fitzroy River catchment contains the greatest extent of clay soils (31%), as well as extensive areas of duplex (27%) and loam (16%) soils. Overall, clay soils cover approximately 16% of the GBR catchment. Loam soils and sandy soils cover 11% and 12% of the GBR catchment, respectively.

Most surface soils of the GBR catchment are highly weathered. This weathering reflects the great age of the landscapes in many locations, high seasonal rainfall and high soil temperatures. Weathering over a long period leads to dissolution and leaching of soluble nutrient ions and silicate materials from the soil profile. After long periods of leaching, laterite crusts (duricrusts) and sub-surface layers may develop. Laterites are nutrient-poor tropical soils primarily formed of insoluble iron and aluminium oxides. Surface laterite crusts or sub-surface layers can have a significant effect on the infiltration of water into and through soils.

In tropical soils, elevated temperatures greatly accelerate the microbial breakdown of soil organic matter. The organic content of soil is a primary factor influencing its structure, nutrient content and permeability. The highest concentrations of soil organic matter, nitrogen and phosphorus in soil profiles are usually found near the surface. In cultivated soils, fertiliser nutrients also contribute substantially to near-surface enrichment. Plant root development and soil biological activity are concentrated in the surface horizon. The surface layer of soil is the most prone to disturbance from fire, agricultural tillage and erosion. In the absence of fertiliser inputs, the accumulation and bioavailability of

Yellow Earth soil
Photo: P. O'Reagain, QDPI



Krasnozem soil
Photo: C. Roth, CSIRO

Table 7. Distribution of soils in Australian Great Soil Groups by drainage basin.
Data source: CSIRO, 1999

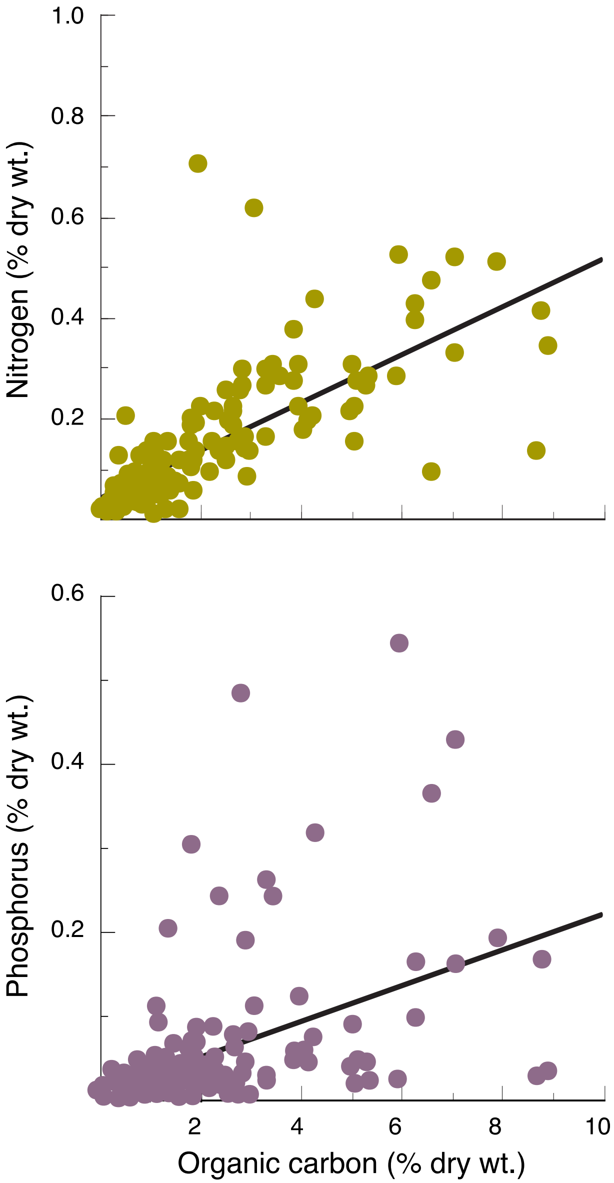
Basin Name	Basin Area km^2	Alluvial Soil	Lithosol	Sand	Black Earth	Brown Clay	Grey Clay	Prairie Soil	Gleyed Soil	Humic Gley	Krasonzem km^2	Red Earth	Red Brown Earth	Yellow Earth	Rendzinas	Solodic Soil	Solodized Solonetz	Soloth	Red Podzolic	Yellow Podzolic	Podzol & Minor	Unclass.
Jacky-Jacky C.	2,963	17		777								381		84						1,048	416	239
Olive-Pascoe R.	4,179	1,266	7	119					564		114	653		120						949	364	24
Lockhart R.	2,883	57		193					570	64	511			792						599	14	82
Stewart R.	2,743	237	153	79						80	4	709		208					77	1,013	171	11
Normanby R.	24,408	661	2,428	30	19		491		2,585		447	6,496		673						4,826	5,474	280
Jeannie R.	3,637	9	657	810					2	123	99	90		15						1,225	575	33
Endeavour R.	2,104	189	423	78							165	53						43		939	201	14
Daintree R.	2,192	836	160					177	10		974											36
Mossman R.	466	198						64	17		127								51			10
Barron R.	2,136	427	127					14	88		567								81	797		35
Mulgrave-Russell R.	1,983	586						358			612	263				24						141
Johnstone R.	2,325	614						353			1,259					31						68
Tully R.	1,683	87	9					253	75		821	48		266		102						23
Murray R.	1,107	53						42	95	7	471	188		16		30				115		89
Herbert R.	9,843	469	853		264				146	22	2,256	2,993		195		1,119			155	1,102	149	121
Black R.	1,057	18									130	446				8			32	422		
Ross R.	1,707	199					13		41	110	89	187				87			123	855		4
Haughton R.	4,044	707	32				223	202	12	123	565	46		28		232			8	1,731		134
Burdekin R.	130,126	5,434	11,504	1,030	4,668	1,334	10,751	3,839	1,092		17,179	19,199	257	18,118	22	12,896	119	145	7,582	11,807	2,250	900
Don R.	3,695	298			150		23	43	28	153	1,925			0		638				369		69
Proserpine R.	2,535	81	8					1	50	109	363					304			628	955		37
O'Connell R.	2,387	11	7							140	453					35			722	978		41
Pioneer R.	1,570	0	8								786					26			235	513		2
Plane C.	2,539	20	313				12			177	268	10				0			234	1,476		28
Styx R.	3,012		492		6		386			106	237	124				209				1,410		42
Shoalwater	3,605		638		139		358	15		132	88	197		34		393		25		1,560		26
Waterpark C.	1,835		373	280				68	117	293						29				475	152	50
Fitzroy R.	142,537		16,089	12,705	16,177	5,653	20,653	11,934	247	326	8,872	7,803	28	338	1,199	11,989		968	4,156	23,266	72	64
Calliope R.	2,236		12							112	91									2,001		19
Boyne R.	2,590		1	7						73		1							1	2,476		31
Baffle C.	3,996	8		106						139		15								3,589		139
Kolan R.	2,901	39		13						23		39								2,768		19
Burnett R.	33,248	5	3,940	79	1,712	37	313	1,269	141	19	2,431	1,096				3,250		1,148	3,165	14,384	234	27
Burrum R.	3,358		555	97					648		209	69				188		22		1,260	231	79
Mary R.	9,440		2,581					1,067	209		1,398	116		665		505		34	390	2,445	15	15
Total	423,070	12,525	41,370	16,402	23,134	7,024	33,224	19,700	6,735	2,332	43,510	41,221	284	21,554	1,221	32,093	119	2,385	17,638	87,352	10,318	2,932
% of GBRCA		3.0	9.8	3.9	5.5	1.7	7.8	4.6	1.6	0.6	10.3	9.7	0.1	5.1	0.3	7.6	0.0	0.7	4.2	20.7	2.4	0.7

Table 8. Areas covered by dominant soil structural types within drainage basins discharging into the Great Barrier Reef region. Areas were calculated from of major soil units given in the "Soils of Australia" digital map. Individual map units units aggregated under dominant soil types may contain a variety of minor soil types in smaller patches.
Data source: CSIR0, 1999

Basin Name	Basin Area km^2	Clay	Duplex	Earth	Loam	Sand km^2	Red Soil	Brown Soil	Yellow Soil	Organic	Unclass-ified
Jacky Jacky C.	2,963			1,514		1,210					239
Olive-Pascoe R.	4,179		67	2,333		1,756					23
Lockhart R.	2,883	64	1,061	1,411		264					82
Stewart R.	2,743	87	1,090	922		640					5
Normanby R.	24,408	788	3,095	11,649	2,401	6,472					2
Jeannie R.	3,637	123	314	1,117	513	1,538					33
Endeavour R.	2,104		634	526	651	279					14
Daintree R.	2,192			984	1,150	23				11	25
Mossman R.	466		51	144	247	14					10
Barron R.	2,136	30	602	670	722	105					7
Mulgrave-Russell R.	1,983		24	875	868	75				8458	
Johnstone R.	2,325		31	1,259	918	49				22	46
Tully R.	1,683		102	1,210	328	20					22
Murray R.	1,107	22	144	770	42	53					75
Herbert R.	9,843	286	2,182	5,821	681	751					121
Black R.	1,057		464	574		18					0
Ross R.	1,707	123	1,086	323	73	98					4
Haughton R.	4,044	345	2,391	570	277	327					134
Burdekin R.	130,126	16,775	44,078	46,205	8,439	14,090	537				2
Don R.	3,695	326	2,550	217	43	472	19				69
Proserpine R.	2,535	109	1,387	875	8	118	2				37
O'Connell R.	2,387	140	1,128	1,060	7	11					41
Pioneer R.	1,570		490	987	91	0					2
Plane C.	2,539	189	1,282	454	551	35					28
Styx R.	3,012	499	1,222	135	1,115						42
Shoalwater	3,605	628	142	256	491	410	25		1,627		26
Waterpark C.	1,835	415		7	138	681	29	54	468		44
Fitzroy R.	142,537	44,381	39,090	11,563	22,507	16,839	4,066	594	3,434		63
Calliope R.	2,236	112		91	12				2,001		19
Boyne R.	2,590	73		1	1	7	1		2,476		31
Baffle C.	3,996	139		604		114			3,000		140
Kolan R.	2,901	23		370		52			2,437		19
Burnett R.	33,248	2,463	751	4,019	2,285	1,981	4,313	253	17,176		6
Burrum R.	3,358	89		1,263	84	730	208		924		59
Mary R.	9,440	31		3,662	1,554	1,042	625	129	2,382		150
Total	423,070	68,260	105,458	104,440	46,197	50,275	9,825	1,030	35,925	116	1,544
% GBR Catchment		16.1	24.9	24.7	11.0	10.9	2.3	0.2	8.5	0.03	0.4

Table 9. Areas of major soil types and relative coverage of the GBRCA. Data were extracted from the digital version of the Atlas of Australian Soils (CSIRO, 1999)

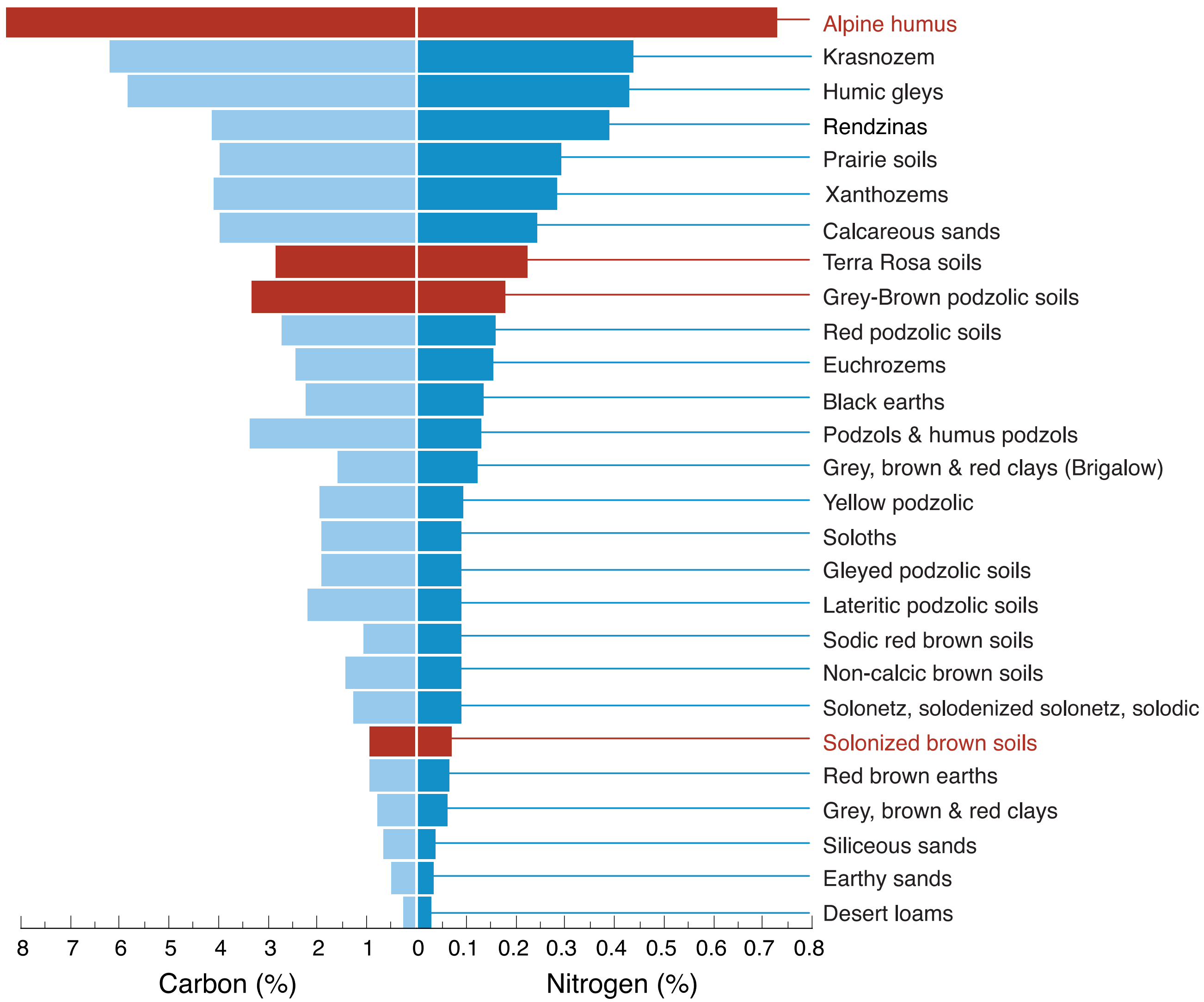
Soil Type	Area (km^2)	% of GBRCA
Clays	68,260	16.1
Duplex	105,458	24.9
Earths (Red, Yellow)	104,440	24.7
Loams	46,197	11.0
Sands	50,275	11.9
Soils (Red, Brown Yellow)	46,780	11.0
Organic	116	0.03
Unclassified	1,544	0.4
Total	**423,070**	



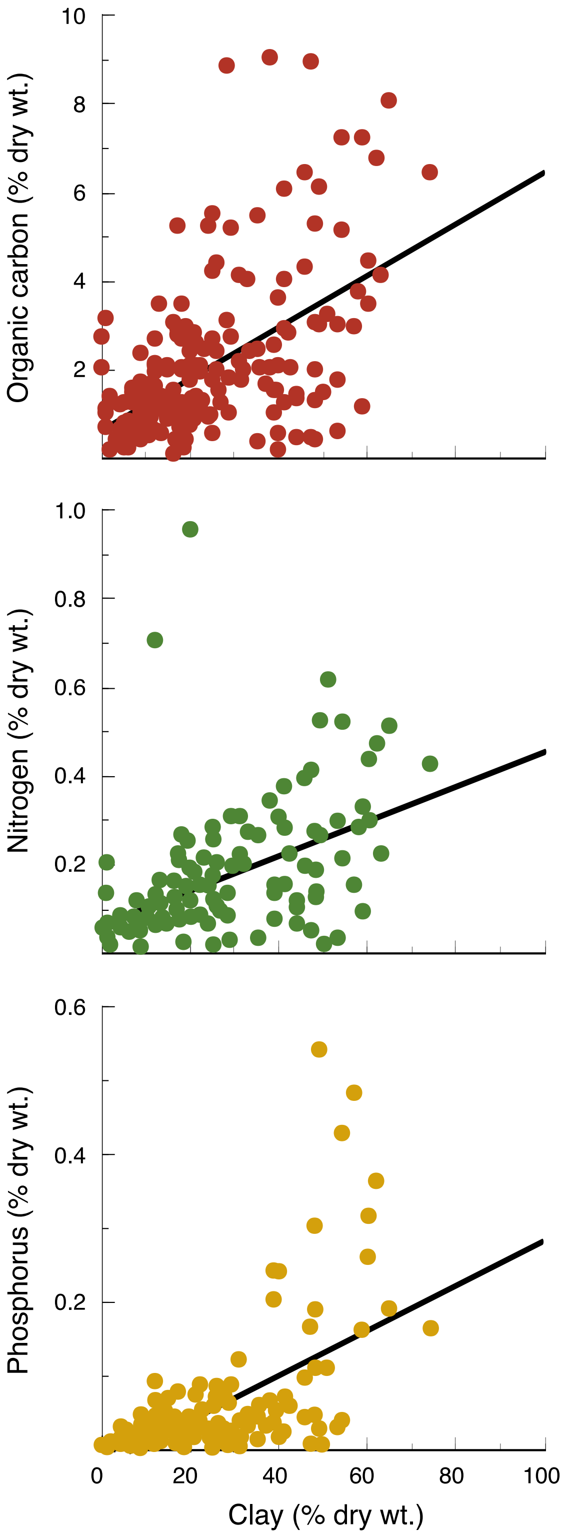
The nitrogen (top) and phosphorus (bottom) content of surface soils in the GBRCA in relation to soil organic carbon content. Data source: QNR&M, QDPI, CSIRO soil reports (various)

nutrients in the surface layer of soil is primarily related to biological activity. Concentrations of soil nitrogen [260,478], and to a lesser extent, phosphorus [383], are positively correlated with soil organic carbon content. The organic content reflects local deposition and burial of litter from overlying vegetation, root growth and death, microbial mineralisation of non-living organic matter by bacteria and fungi, and biological activity of larger soil animals (e.g. termites, worms).

Clay makes up approximately 25-30% of the dry mass of most near-surface soils collected from central and southern GBR catchments (Table 10). In some cracking clay and krasnozem soils, the clay content can exceed 70%. The organic carbon, nitrogen and phosphorus content of soils throughout the GBR catchment are broadly correlated with the clay content. Clay is comprised of very small (less than 2 µm), sheet-like particles of aluminosilicate. Although the individual clay particles are small, the clay particles in a given mass of soil have an enormous surface area. A wide range of organic and inorganic ions bind to clays in soils and sediments. Some ions (e.g. PO_4^{3-} bind strongly to aluminium and iron oxides in soils [384] and freshwater sediments [373]. As a result, soils with a high iron and aluminium oxide content (e.g. krasnozems), have the capacity to adsorb and hold large amounts of



The average carbon and nitrogen content of surface soils in Australian Great Soil Groups. Blue bars indicate soil types found within the GBRCA. Soils samples (n=3014) were collected throughout Australia. Of these, 1944 are from unfertilised Queensland sites.
Data replotted from Spain et al., 1983



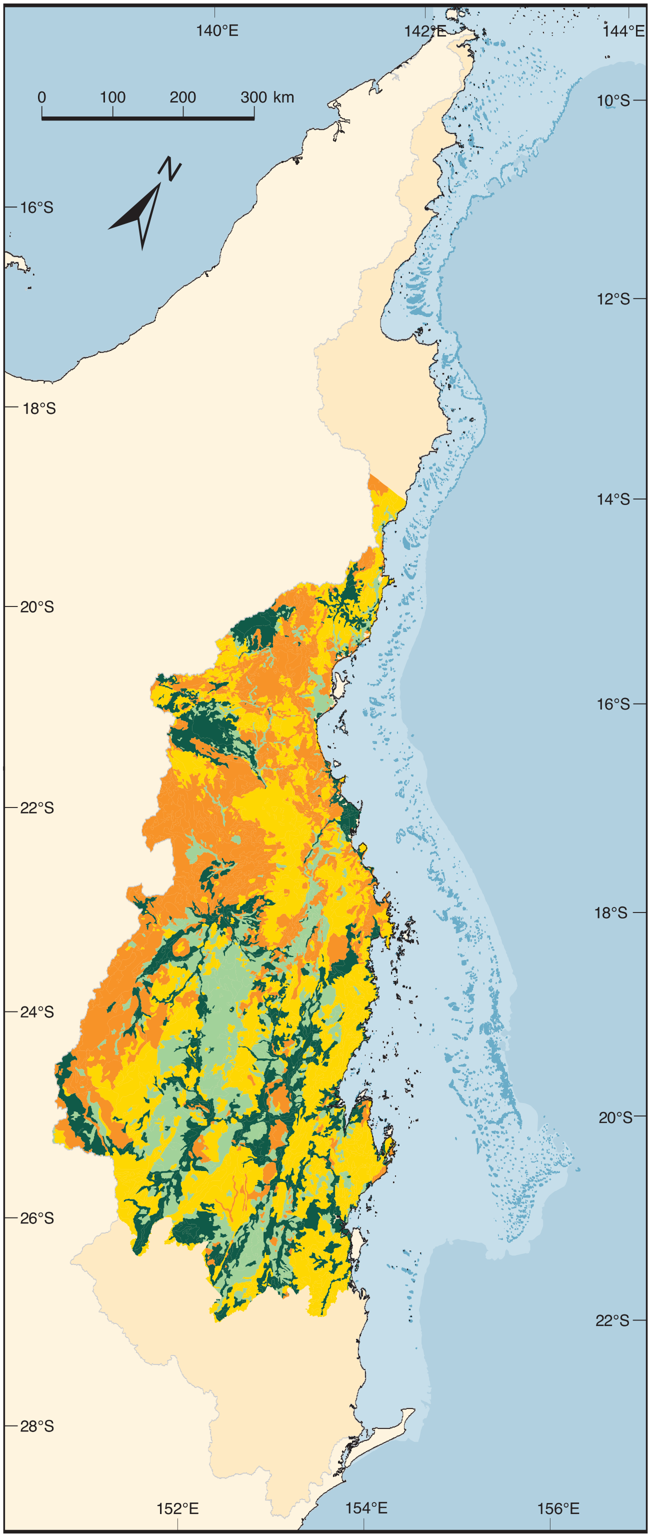
phosphate [332, 416]. In such soils, only a small proportion of the phosphorus is present as soluble phosphate ions, available for leaching or rapid plant uptake [333]. The majority of soils in inland sections of the GBR catchment have a low phosphorus binding capacity and are generally nutrient depleted [5], although alluvial soils along watercourses can have much higher phosphorus contents (Table 11). Other ions (e.g. NO_3^-) do not bind to clay particles under normal surface soil conditions and percolate freely downward into the underlying groundwater [53, 401, 402].

Soil clay content influences nutrient and sediment runoff in a variety of ways. Clay soils are characterised by low permeability once saturated. Rainwater falling on saturated and low-permeability clay soils will then run off as surface flow. Bare clay surfaces may slake when wet, forming hard, impermeable surface seals after they dry [340]. While they retain moisture, clay soils are structurally more cohesive than other soil types, particularly sandy soils and resist erosion [388]. The erosivity of soils depends on the proportion of very small (< 125 μm) unconsolidated particles or soil aggregates [280]. Even when disturbed or naturally fragmented, larger aggregates of clay resist erosion [388]. Once fully dispersed and suspended in floodwaters, however, clay particles tend to remain in suspension and are readily transported out of small and large catchments in both surface runoff and streams. Most of the turbidity in surface runoff and in river water during floods comes from suspended clay particles. The proportion of eroded soil that actually reaches the stream network through overland flow (the delivery ratio) is sensitive to the quantity of clay minerals suspended in runoff water. Larger eroded soil particles (sand and gravels) remain close to their source [90], forming and reforming alluvium deposits on hillslopes and within drainage

Relationships between the organic carbon, total nitrogen, total phosphorus and clay content of surface soils collected throughout the GBRCA.
Data source: QNR&M, QDPI, CSIRO soil reports (various).

Table 10. The average (± 1 standard deviation) clay, organic carbon, nitrogen content of surface soil samples collected in the GBRCA. Data compiled from many literature sources (QNR&M, QDPI, CSIRO).

Basin Name	Clay	Organic C	Total N % Dry Wt.	Total P
Jacky-Jacky C.	10±8	0.7±0.3	0.07±0.08	0.095±0.134
Olive-Pascoe R.	7±6	0.9±0.7	0.05±0.04	
Lockhart R.	2	0.8±0.8	0.04±0.05	0.005±0.008
Stewart R.	16±18	1.0±0.6	0.05±0.02	0.043±0.055
Normanby R.	31±24	1.1±0.8	0.08±0.12	0.074±0.122
Jeannie R.	27±19	1.3±0.8	0.07±0.05	0.026±0.012
Endeavour R.	27±19	1.3±0.8	0.07±0.05	0.026±0.012
Daintree R.				
Mossman R.				
Barron R.	38±22	3.5±2.3	0.24±0.17	0.128±0.116
Mulgrave-Russell R.				
Johnstone R.	32±20	3.7±4.1	0.25±0.19	0.090±0.125
Tully R.	26±18	3.3±2.1	0.20±0.15	0.052±0.089
Murray R.				
Herbert R.	20±14	1.4±0.9	0.11±0.08	0.033±0.029
Black R.	12±5	1.1±0.7	0.10±0.04	0.019±0.018
Ross R.	10±6	1.2±0.3	0.08±0.03	0.014±0.005
Haughton R.	24±16	1.1±0.4	0.07±0.02	0.036±0.021
Burdekin R.	31±24	1.2±1.0	0.09±0.09	0.077±0.262
Don R.	18±14	0.9±0.6	0.07±0.04	0.034±0.031
Proserpine R.	16±12	1.6±0.7	0.10±0.05	0.030±0.022
O'Connell R.				
Pioneer R.	22±13	1.5±1.1	0.12±0.11	0.036±0.031
Plane C.				
Styx R.				
Shoalwater				
Waterpark C.	20±12	2.4±1.3	0.14±0.08	0.044±0.032
Fitzroy R.	46±18	1.3±0.6	0.09±0.05	0.042±0.025
Calliope R.	24±15	2.1±0.9	0.14±0.06	0.054±0.042
Boyne R.				
Baffle C.				
Kolan R.				
Burnett R.	32±21	1.8±0.9	0.14±0.09	0.075±0.057
Burrum R.				
Mary R.	27±15	2.4±2.1	0.13±0.12	0.044±0.030



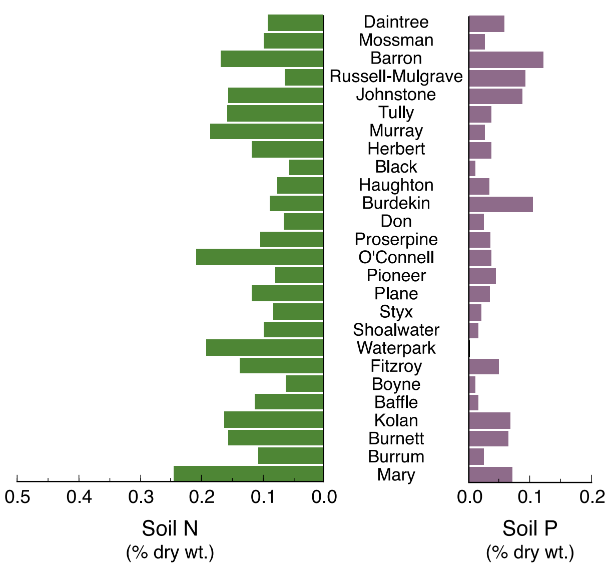
The bicarbonate-extractable phosphorus content of pasture soils within the central GBRCA.
Data source: QNR&M, Ahern et al., 1995

0 – 4 ppm
4 – 8 ppm
8 – 16 ppm
> 16 ppm
GBR catchment, unmapped

Table 11. Relative distribution of soil phosphorus status in the central GBRCA.
Data source: QNR&M, 1999; Ahern *et al.,* 1995

Catchment	Catchment area	Catchment classified		Bicarbonate extractable P in classified soils mg P kg^{-1}				
				<4	4-8	8-12	12-20	>20
	km^2		%			km^2		
Daintree R.	2,192	1,783	81	164	1,467	141		11
Mossman R.	466	460	99	78	320	62		
Barron R.	2,136	2,136	100	998	735	8		389
Russell-Mulgrave R.	1,983	1,930	97	55	1,290	356		229
Johnstone R.	2,325	2,280	98	139	898	353		
Tully R.	1,683	1,660	99	242	999	253		166
Murray R.	1,107	1,037	94	515	456	42	7	17
Herbert R.	9,843	9,726	99	5,247	2,208	1,373	21	877
Black R.	1,057	1,057	100	765	272	20		
Ross R.	1,707	1,703	100	1,078	342	68	188	27
Haughton R.	4,044	3,916	97	1,906	1,151	16	433	410
Burdekin R.	130,126	130,121	100	61,664	32,699	9,021	13,940	12,797
Don R.	3,695	3,629	92	884	2,199	172	292	83
Proserpine R.	2,535	2,510	99	1,288	954		212	55
O'Connell R.	2,387	2,359	99	497	1,274	11	137	440
Pioneer R.	1,570	1,569	100		1,111	37	17	403
Plane C.	2,539	2,519	99		2,266	69	185	
Styx R.	3,012	2,976	99	124	1,734	40	776	301
Shoalwater	3,605	3,586	99	338	2,149	486	613	
Waterpark C.	1,835	1,793	98	246	1,101	156	290	
Fitzroy R.	142,537	117,026	82	8,662	47,724	16,362	34,000	10,278
Calliope R.	2,236	2,222	99	2	1,635		199	386
Boyne R.	2,590	2,485	96		2,189	8	71	217
Total	**327,210**	**300,484**		**84,728**	**105,707**	**28,914**	**51,382**	**27,075**

Cattle in woodland pasture
Photo: M. Furnas, AIMS



The average total nitrogen and phosphorus content of surface soil samples collected in drainage basins of the GBRCA.
Data source: QNR&M data reports, various

networks while suspended clay particles are rapidly transported out of the catchment with flood waters.

The average total nitrogen and phosphorus content of surface soils in the GBR catchment is close to 0.15 and 0.05% of dry soil weight (1500 and 500 parts per million), respectively (M. Grundy, QNR&M). Variations in composition exist between and within catchment due to the nature and distribution of local soil types and where soil sampling was carried out. Overall the chemical properties of very few soils in the GBR catchment have been analysed.

Most soil sampling to date has been carried out in current or prospective agricultural areas, though most samples have been taken from non-fertilised soils [478]. The average soil clay, nitrogen and phosphorus values shown in Table 10 do not fully reflect the spatially averaged soil nutrient content or importantly, the nutrient content of soils most likely to be eroded from catchments. Soil nutrient content varies with the parent rock or source of the soil, the size distribution of soil particles, organic matter content and the soil's surface charge (ion holding) characteristics [157]. Most of the nitrogen in soils is part of organic matter [260] and to a lesser extent as ammonium ions bound to soil particles [63]. Phosphorus is largely present as a constituent of soil minerals or as inorganic ions bound to soil particles [333]. The usually small percentage of readily bio-available phosphorus is also associated with the organic material in the soil [383].

The most extensive soil fertility mapping in the GBR catchment to date is for phosphorus in soils of north and central Queensland, encompassing most of the Fitzroy, Burdekin and Herbert River drainage basins [5]. Approximately 28% of surface soils in this area are characterised by very low phosphorus availability (< 4 mg of nominally bio-available phosphorus per kg of dry soil). An additional 36% contains only 4-8 mg of bio-available phosphorus per kg of dry soil. Soils with higher bio-available P levels (greater than 20 mg P per kg dry soil) are concentrated around basaltic parent rocks and in alluvial floodplain soils along major rivers. Detailed mapping of soils and soil nutrients has been carried out in a number of coastal floodplains either used for or projected to be used for intensive agriculture. This intensive mapping shows considerable fine-scale variation in soil properties and potential fertility, but overall, soil nitrogen and phosphorus concentrations are roughly similar to those derived from broadscale soil sampling.

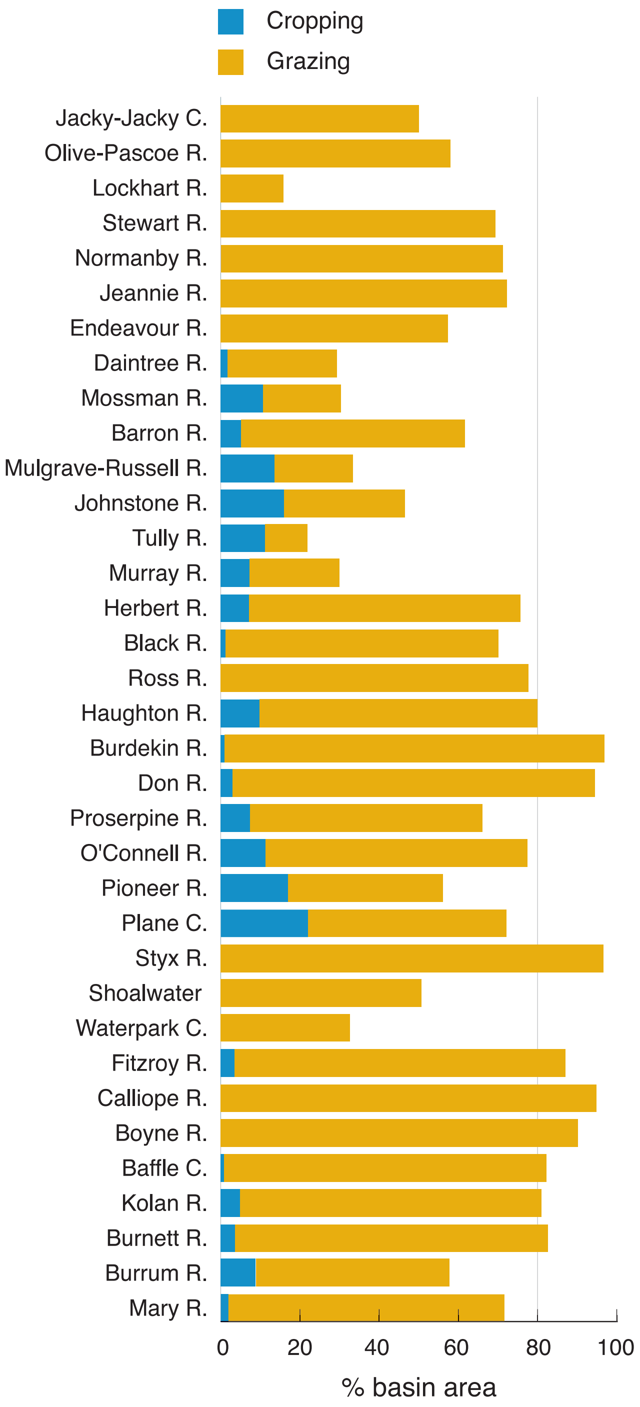
Human populations of the GBR catchment

About 1.1 million people live within the boundaries of the GBR catchment (ABS, 2000). The resident population has increased from 919,000 in 1991 at an average annual growth rate of 2.2%. Approximately 42% of the people live in six coastal urban centres (Cairns, Townsville, Mackay, Rockhampton, Gladstone, Bundaberg) with populations in excess of 25,000 (Table 12). This proportion has not changed markedly over the last decade (43% vs 42%).

The non-urban population of the GBR catchment lives in smaller regional centres, rural towns and on agricultural properties. The highest non-urban population density is found at the southern end of the GBR catchment in the coastal regions bordering Hervey Bay (Burnett, Burrum

Table 12. The population of major urban centres in the GBRCA, ABS statistical districts in which they are located, populations recorded in 1991 and 1998 and rates of population growth in the census district. Data source: ABS, 2000

Centre	ABS Distcrict	1991	1998	% Ann. Growth
Cairns	Far Northern	92,630	118,843	3.6
Townsville/Thuringowa	Northern	114,063	124,876	1.3
Mackay	Mackay	63,584	74,122	2.2
Rockhampton	Fitzroy	60,067	59,697	-0.1
Gladstone	Fitzroy	24,983	27,220	1.3
Bundaberg	Wide Bay	41,790	44,055	0.8
GBRCA		919,300	1,074,200	2.2



Proportions of drainage basins used for cropping and grazing. Data source: BRS, 2000

and Mary River basins). In contrast, few people live on Cape York Peninsula. The net growth rate of urban populations in GBR catchment has been somewhat slower than that of the non-urban population, though some cities such as Cairns, have had high growth rates over the last decade, largely as a result of tourism and lifestyle-related development.

Land use in the GBR catchment

The land within the GBR catchment is used for a variety of purposes (Table 13). Agriculture, particularly grazing, is the major human land use. Significant areas of land are also set aside for conservation purposes in reserves and national parks (Table 14). Only a very small proportion of the total area of the GBR catchment is used for mining, urban and suburban development and tourism facilities.

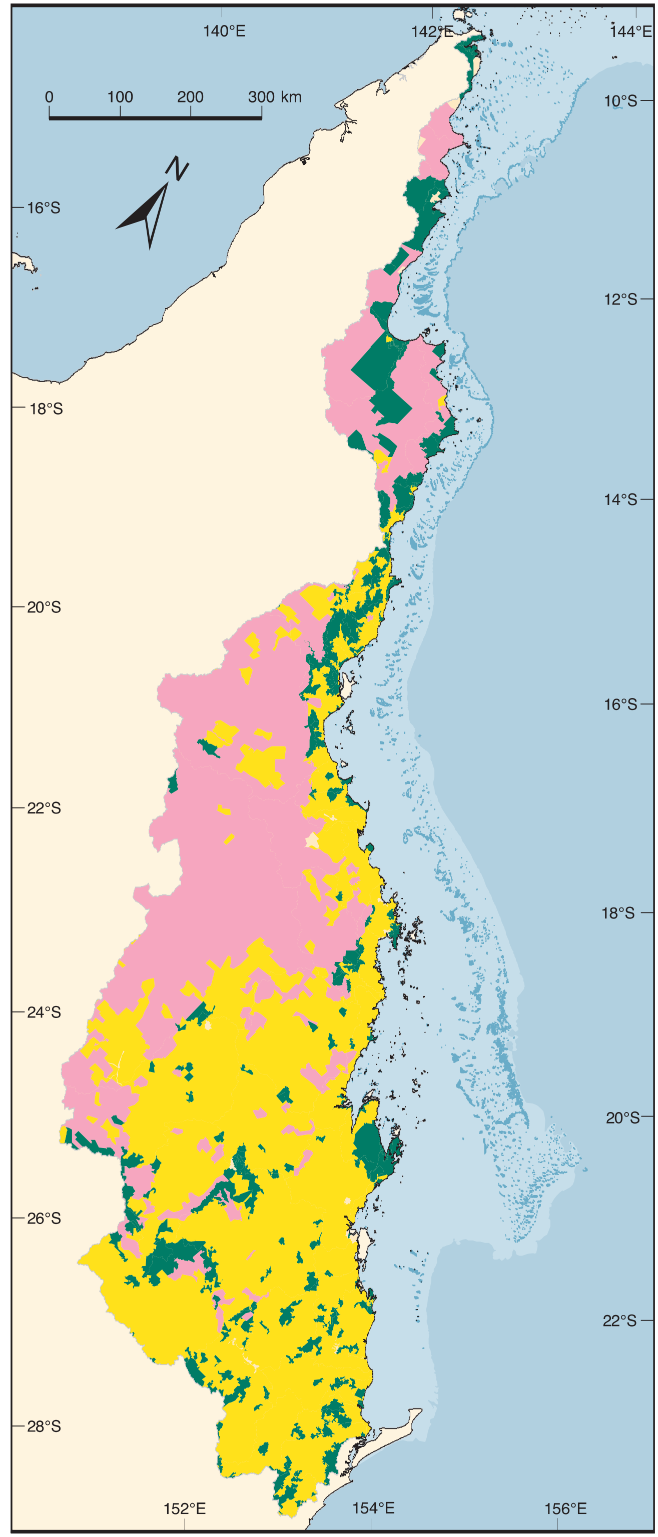
Agriculture

By area, rangeland cattle grazing is the principal land use in the GBR catchment. The cattle industry is largely based on open range grazing in cleared or woodland paddocks with native or sown pasture grasses. Cattle are grazed in all basins of the GBR catchment, although in a few (e.g. Russell-Mulgrave River), the area devoted to grazing is relatively small because cleared land is more profitably used for other purposes.

Most of the grazing land in the GBR catchment is or once was *Eucalyptus* or *Acacia* woodland. The total land area within individual catchments used for grazing purposes at any time is difficult to estimate because some nominal grazing areas are only used intermittently. Grazing may co-occur with other land uses (e.g. forest reserves) and within lands allocated for grazing, some areas may not be used because of unsuitable topography (steep slopes) or groundcover (rocks). The area of freehold and leasehold land within the GBR catchment (357,000 km^2 – 84% of the GBR catchment) which is not used for cropping, forestry, urban areas or other purposes can be taken as

Freehold and leasehold land tenure in the GBRCA.
Data source: GBRMPA

- *Freehold*
- *Leasehold*
- *Protected*



the upper limit to the extent of grazing land. Alternative estimates of grazing land put the total at a lower level – 321,000 km^2 (76% of the GBR catchment) [418].

After grazing, forestry (29,300 km^2) is the second largest "agricultural" land use in the GBR catchment. The area of forest being actively harvested at any one time may be small, but significant areas within particular drainage basins have been set aside for forestry purposes [418]. The proportion of individual drainage basins allocated to protected World Heritage Areas, State Forests or Forestry Reserves ranges from 62% (Tully River) to nil (Jacky Jacky Creek, Olive-Pascoe Rivers, Jeannie River, Don River). The forest cover of eight drainage basins exceeds 25% of basin area, while forest cover is < 1% in seven basins. Forestry-associated disturbances within catchments that affect runoff include the removal of trees, destruction of undergrowth and the construction of infrastructure (e.g. logging tracks and roads) to remove logs from the forest area [100, 101, 159, 163]. In high-rainfall tropical areas, poorly designed and constructed logging or farm roads and other infrastructure can be a major source of eroded soil washing into coastal waters [202].

By cultivated area and economic value, sugar is the most important crop grown in the GBR catchment. Since 1900, the area of cane harvested has increased from 0.2 km^2 to over 4,400 km^2, approximately 1% of the GBR catchment. Sugarcane is now cultivated in 19 of the 35 mainland drainage basins. Most of the sugarcane is grown on the coastal plain, east of the coastal mountain range. Some sugarcane is also planted on the Atherton Tablelands and in the headwaters of the Mitchell River catchment. Overall, over 5,000 km^2 of land has been assigned for sugarcane cultivation [597]. Most, but not all of this land has been cleared. In recent years, there has been limited switching to alternative crops in some catchments (e.g. banana cultivation in the Tully and Johnstone River basins) due to the low market price of sugar. Within individual drainage basins, the proportion of land used to grow sugarcane ranges from 0.2% (Burdekin River) to over 20% (Plane Creek). Land usage for sugar cultivation exceeds 1% of total basin area in seventeen basins and 10% in six (Mossman, Russell-Mulgrave, Johnstone, O'Connell, Pioneer Rivers and Plane Creek). In lowland areas of the wet-tropical catchments, much of the land cleared for sugar cultivation was originally lowland rainforest. Only a small proportion of the original rainforest remains [169, 553, 554]. Recent (post-1960) expansions of the sugar industry have largely been in sections of the coastal plain dominated by *Melaleuca* and *Eucalyptus* woodlands, where irrigation of the crop is often necessary. In particular, recent expansion of sugarcane cultivation in the Burdekin and Haughton River drainage basins has largely been based on irrigation with ground water and stored water from the Burdekin Falls Dam.

Woodland pasture
Photo: M. Furnas, AIMS

Other crops

A variety of other crops are cultivated throughout the GBR catchment. After sugarcane, dryland grain cropping, largely in inland areas of the southern dry catchments bordering the southern GBR (Fitzroy and Burnett Rivers) is a major land use.

Cotton is farmed on 280 km^2 of the Fitzroy and Burnett River basins [597]. While the area of cotton cultivated is not large relative to the GBR catchment, inland cotton cropping is dependent on large-scale water storage, irrigation and significant levels of fertiliser and pesticide use. The withdrawal and storage of irrigation water from inland reaches of rivers can have a major effect on catchment environmental flows and the downstream movement of eroded soils, nutrients and pesticides.

Clearing coastal forest for cane cultivation
Photo: C. Roth, CSIRO

Land use for other crops in the GBR catchment is relatively small or may vary from year to year. Within individual catchments, however, the area of specific crops may be

Table 13. Agricultural land use in the Great Barrier Reef Catchment Area. Data source: Rayment and Neil (1997). - = no data

Basin	Area km²	Timber	Aqua-culture	Horti-culture	Other Cropping km²	Sugar	Total Cropping	Grazing	% Basin Area Timber	% Basin Area Cropping	% Basin Area Grazing
Jacky Jacky C.	2,963	-		-	-	-	-	-	-	-	-
Olive-Pascoe R.	4,179	-		-	-	-	-	-	-	-	-
Lockhart R.	2,883	376	-	-	-	-	-	-	13	-	-
Stewart R.	2,743	766	-	-	-	-	-	-	28	-	-
Normanby R.	24,408	407			35.5		35.5	-	2	0.1	-
Jeannie R.	3,637	-	-	-	-	-	-	-	-	-	
Endeavour R.	2,104	330	-	-	-	-	-	-	16	-	-
Daintree R.	2,192	803		0.9	0.6	38.3	39.8	569	37	1.8	26
Mossman R.	466	127		0.3		49.0	49.3	219	27	10.6	47
Barron R.	2,902	831		12.0	91.1	45.8	148.9	1,040	29	5.1	36
Mulgrave-Russell R.	1,983	346		3.0	0.4	264.6	268.1	786	17	13.5	40
Johnstone R.	2,325	613		20.7	4.9	344.8	370.5	969	26	15.9	42
Tully R.	1,683	1,031		25.9		162.2	188.1	350	61	11.2	21
Murray R.	1,107	362		10.0	0.3	69.5	79.9	337	33	7.2	30
Herbert R.	9,843	991		0.0	36.5	668.6	705.0	7,202	10	7.2	73
Black R.	1,057	220		0.0	4.8	7.6	12.3	728	21	1.2	69
Ross R.	1,707	48	-	-	-	-	-	-	3	-	-
Haughton R.	4,044	30		13.1	5.5	379.6	398.2	2,701	1	9.8	67
Burdekin R.	130,126	1,219		13.0	986.9	259.7	1259.6	123,107	1	1.0	95
Don R.	3,695	0		1.9	64.6	42.8	109.3	3,552	0	3.0	96
Proserpine R.	2,535	232		0.0	0.2	186.8	187.0	1,858	9	7.4	73
O'Connell R.	2,387	188		0.0		270.8	270.8	1,720	8	11.3	72
Pioneer R.	1,570	354		0.0	0.7	266.7	267.5	723	23	17.0	46
Plane C.	2,539	136		0.0		560.7	560.7	1,800	5	22.1	71
Styx R.	3,012	51	-	-	-	-	-	-	2	-	-
Shoalwater	3,605	8	-	-	-	-	-	-	0	-	-
Waterpark C.	1,836	196	-	-	-	-	-	-	11	-	-
Fitzroy R.	142,537	9,820		15.3	4991.3		5006.6	133,560	7	3.5	94
Calliope R.	2,236	162	-	-	-	-	-	-	7	-	-
Boyne R.	2,590	332	-	-	-	-	-	-	13	-	-
Baffle C.	3,996	477		3.5	14.3	15.4	33.2	2,930	12	0.8	73
Kolan R.	2,901	381		1.5	6.6	134.1	142.1	2,354	13	4.9	81
Burnett R.	33,250	4,874		36.5	888.4	265.2	1190.1	26,487	15	3.6	80
Burrum R.	3,361	900		0.7	2.7	293.9	297.3	1,784	27	8.8	53
Mary R.	9,440	2,734		2.9	60.5	115.2	178.6	6,192	29	1.9	66
Total	**423,070**	**29,294**	**5**	**178.2**	**7,178**	**4,441**	**11,797**	**320,945**			
% of Total		**6.9**	**<0.01**	**0.04**	**1.7**	**1.0**	**2.8**	**75.7**	**6.9**	**78.6**	**75.9**

Table 14. National Estate, Forest Reserve and Defence Reserve areas in the GBRCA.
Data source: GBRMPA, QNR&M

Basin Name	Basin Area	National Estate	Forest Reserve Km^2	Defence Reserve	Other Reserve
Jacky Jacky C.	2,963	604			604
Olive-Pascoe R.	4,179	189			189
Lockhart R.	2,883	301	376		676
Stewart R.	2,743		766		766
Normanby R.	24,408	5,197	407		5,604
Jeannie R.	3,637	429			429
Endeavour R.	2,104	37	330		368
Daintree R.	2,192	693	785		1,478
Mossman R.	466	80	127		206
Barron R.	2,902	40	831		871
Mulgrave-Russell R.	1,983	573	346		919
Johnstone R.	2,325	279	613		892
Tully R.	1,683		1,031		1,031
Murray R.	1,107	334	362		696
Herbert R.	9,843	642	991		1,633
Black R.	1,057	78	220		298
Ross R.	1,707	240	48	89	377
Haughton R.	4,044	314	30		344
Burdekin R.	130,126	960	1,219		2,179
Don R.	3,695	80			80
Proserpine R.	2,535	310	232		542
O'Connell R.	2,387	109	188		297
Pioneer R.	1,570	127	354		481
Plane C.	2,539	74	136		210
Styx R.	3,012		51		51
Shoalwater	3,605		8	1,617	1,625
Waterpark C.	1,835		196	791	987
Fitzroy R.	142,537	3,647	9,820	276	13,743
Calliope R.	2,236		162		162
Boyne R.	2,590		332		332
Baffle C.	3,996	148	477		625
Kolan R.	2,901		381		381
Burnett R.	33,248	52	4,874		4,926
Burrum R.	3,358	193	900		1,092
Mary R.	9,440		2,734	1	2,734
Total	**423,836**	**15,727**	**29,328**	**2,773**	**47,828**
% GBR Catchment		**3.7**	**6.9**	**0.7**	**11.3**

Cleared pastureland, upper Tully River floodplain
Photo: M. Furnas, AIMS

significant, with resulting implications for soil erosion and fertiliser use. For example, banana cultivation in the wet-tropical Tully and Johnstone River basins has increased nearly 10-fold (9.5 km^2 to 85 km^2) during the last 25 years. Largely because of the higher economic returns these catchments are now the centre of the Queensland banana industry . Much of this land was previously used for pasture or sugaracane cultivation. Land used for banana farming receives more fertilisers (250-485 kg N ha^{-1} per year) than land used for sugar (ca. 120 kg N ha^{-1} per year). Soils in banana paddocks are generally kept cleared, exposing them to accelerated erosion during periods of high rainfall. Bananas can also be grown on steeper lands which are less suitable or unsuitable for mechanised sugar cultivation with attendant erosion risks in high rainfall areas.

Vegetable (tomatoes, potatoes, maize) and horticultural cropping (e.g. mangos, pineapples, other tropical fruits) takes place on approximately 450 km^2 within the GBR catchment. Most of these crops are grown on the coastal plain in relatively flat country. Horticultural crops receive fertilisers at a variety of rates depending on the crop, location and soil type [251]. These rates, however, are typically much higher than for sugar [414, 417].

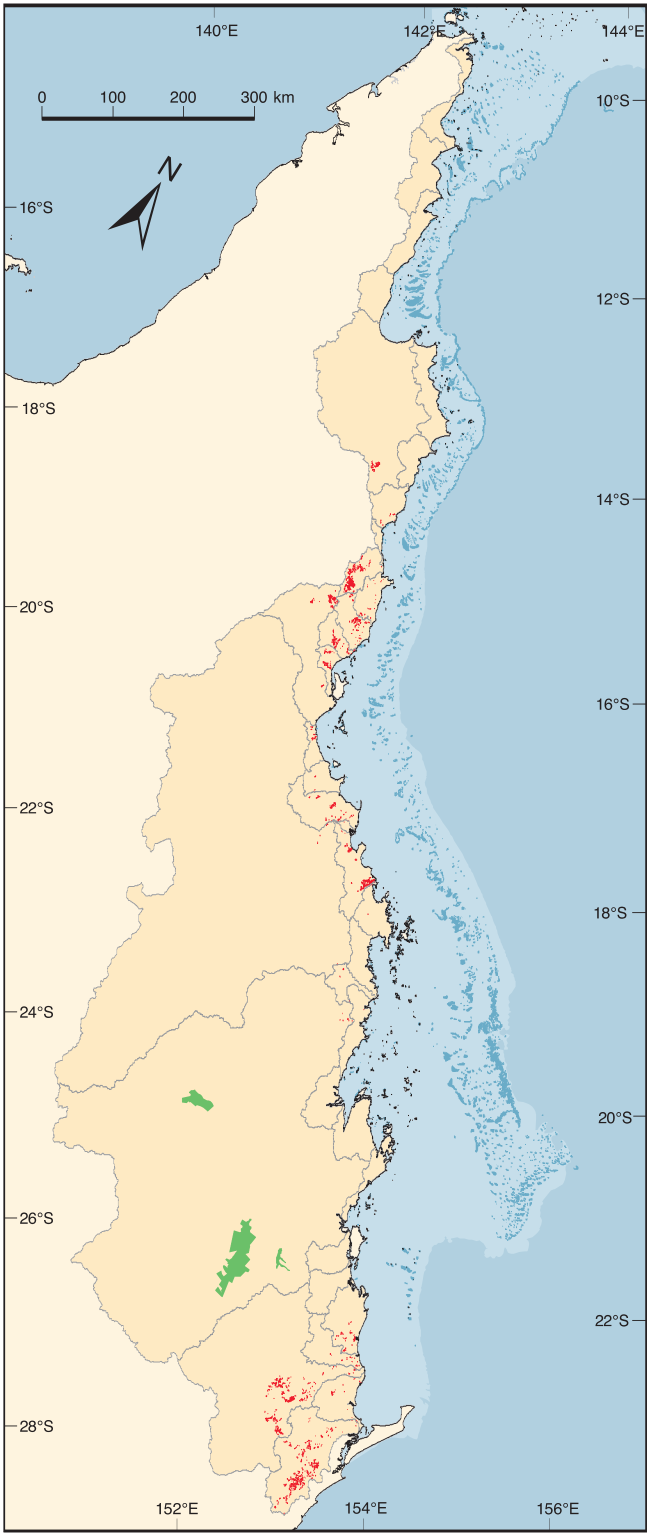
Pasture converted to banana cultivation in the upper Tully flood plain
Photo: M. Furnas, AIMS

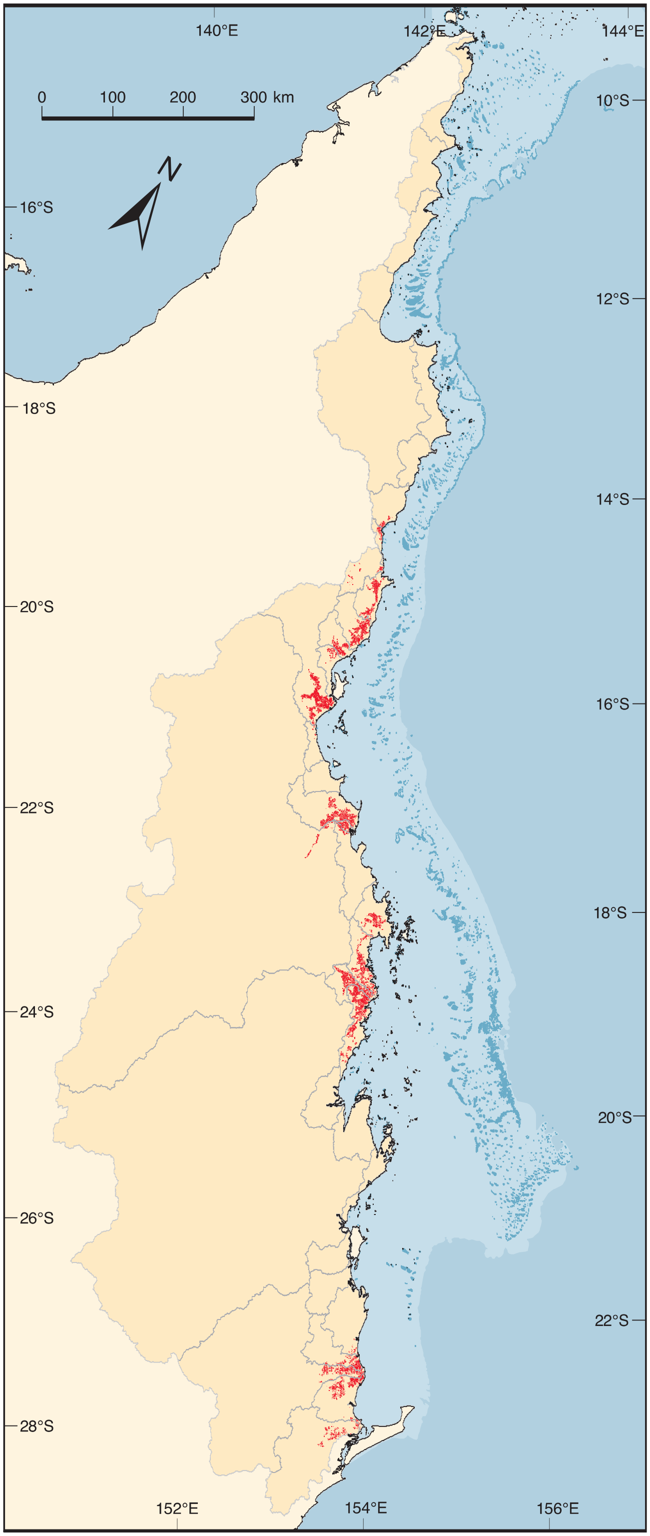
Aquaculture

At the present time, prawn aquaculture farms with an aggregate pond area close to 5 km^2 are licensed to operate along the Queensland coast. A significant increase in this area is projected over the next decade. The effluent produced during prawn harvesting and pond water management is currently pumped into coastal waters and waterways [520], either directly or through settling ponds. The volume of effluent varies with the size and operational procedures of the prawn farm over the course of the year. Nitrogen and phosphorus outputs from prawn farms with once-through circulation designs are on the order of 1 kg N ha^{-1} day^{-1} and 0.1 kg P ha^{-1} day^{-1}, respectively [382]. These outputs place an upper limit of 200 tonnes of nitrogen and 20 tonnes of

The extent and distribution of land used for horticulture, small crops and cotton cultivation within the GBRCA. The apparent area of horticulture and small crops is exaggerated on the map by the boundaries drawn around individual areas to allow visualisation. The cotton cropping regions identify areas where cotton is grown, not the actual area of cotton crops.
Data source: GBRMPA

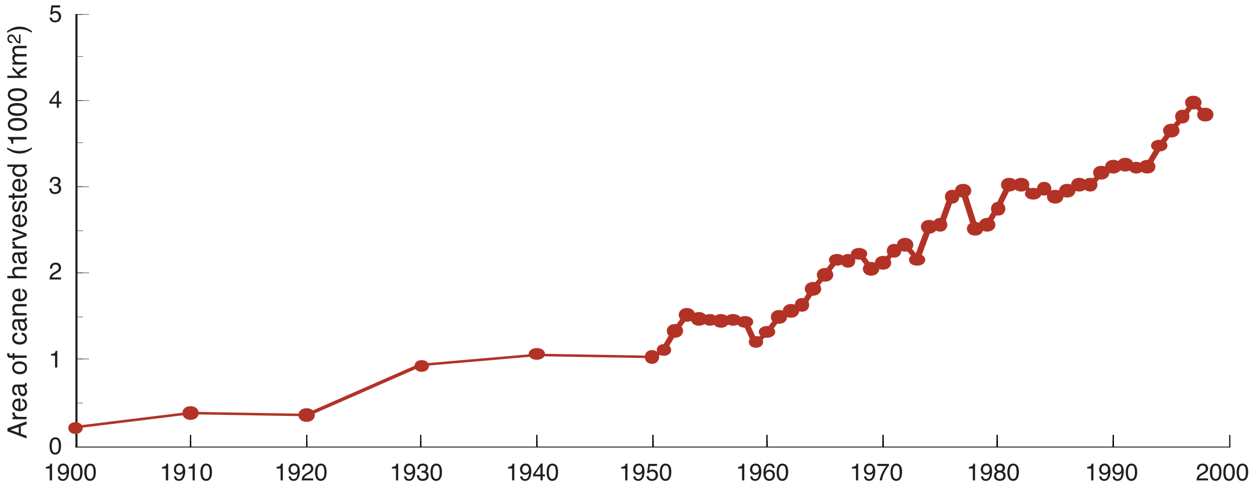
Grains, small cropping and horticulture
Cotton (general area only)
GBR catchment



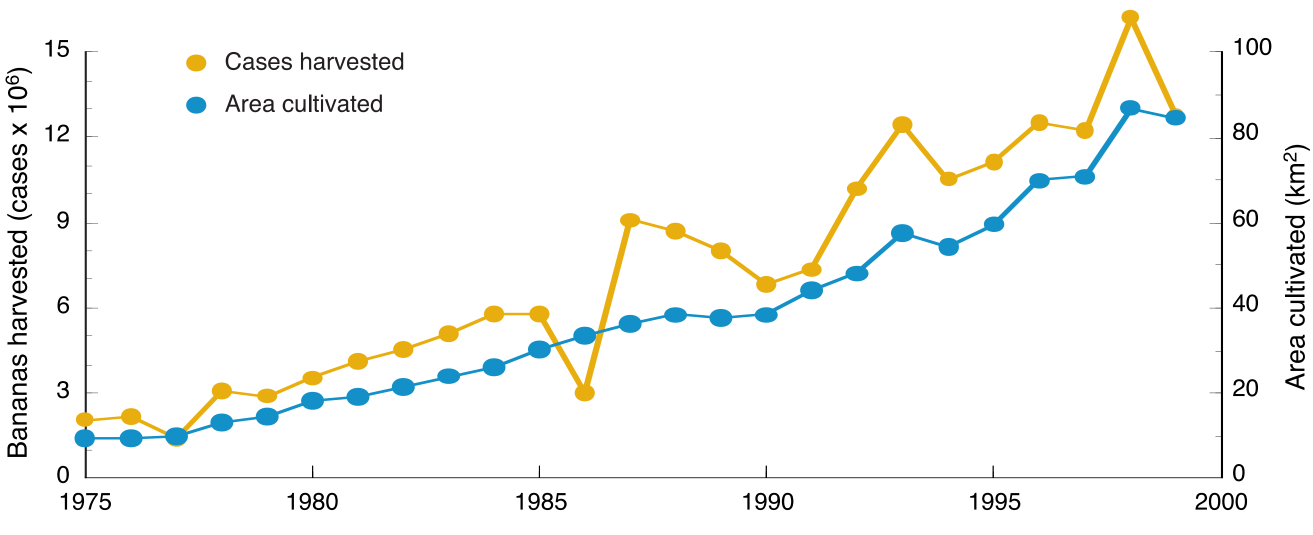


The extent and distribution of land used for sugarcane cultivation within the GBRCA. Sugar cultivation areas are based upon 1994 mapping. The apparent area of sugar crops is exaggerated on the map by the boundaries drawn around individual areas to allow visualisation.
Data source: GBRMPA

Sugarcane cultivation
GBR catchment



The area of sugarcane harvested in the GBRCA since 1900.
Data source: Queensland Canegrowers



Changes in the area used for banana cultivation and recent banana harvests in the Tully and South Johnstone River catchments.
Data source: Queensland Horticulture Institute

phosphorus discharged annually into coastal waters with pond effluent each year.

Prawn aquaculture farm
Photo: J. Jones, GBRMPA

Chapter 4

Hydrology of rivers in the Great Barrier Reef Catchment

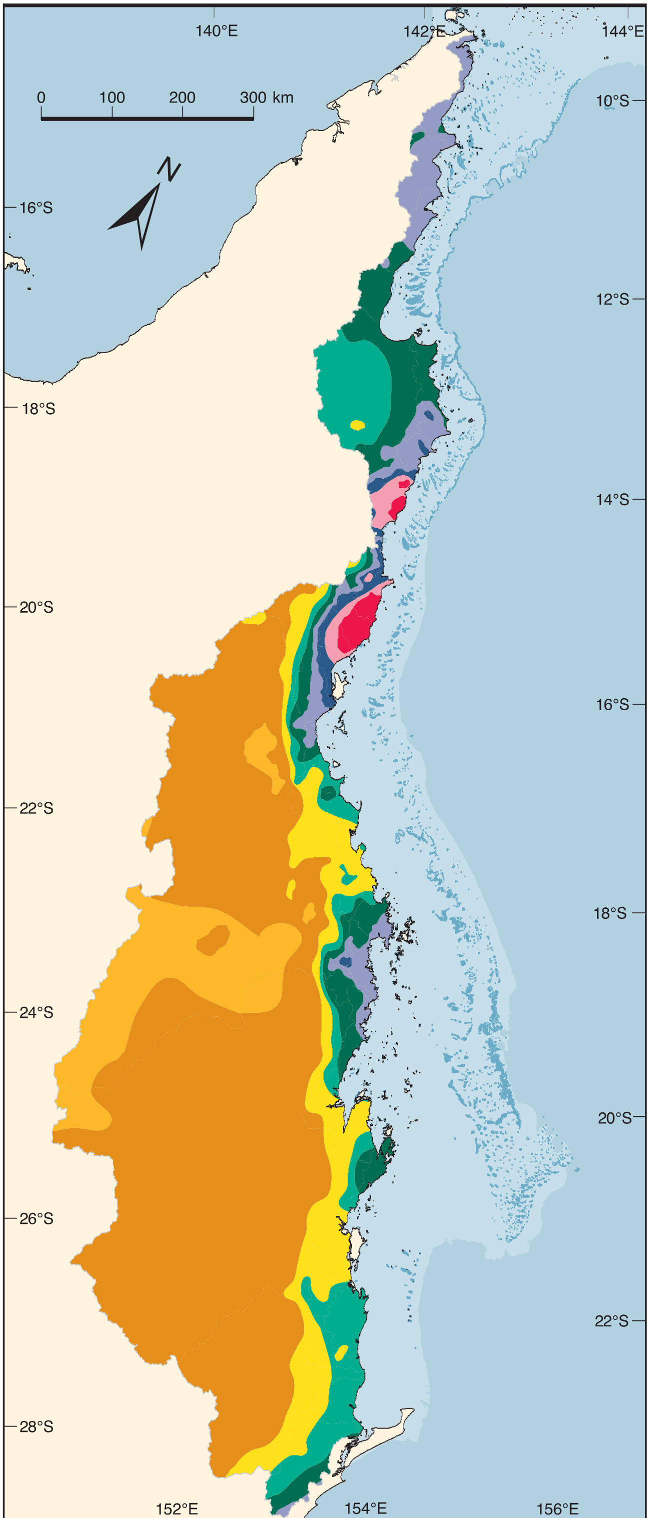
The movement of sediment and nutrients from the land to the Great Barrier Reef lagoon is governed by the volume, intensity and distribution of rainfall on catchments and the subsequent downstream flow of water through streams and rivers. Discharge from tropical Australian rivers is amongst the most variable in the world [134, 547]. This variability, which is characteristic of both wet and dry catchments, is a consequence of climatic and geographic factors, including:

- the spatial distribution of mean annual rainfall (latitude, topography);
- seasonal variations in rainfall (monsoonal climate);
- inter-annual fluctuations in rainfall associated with global climate variability (e.g. ENSO);
- year-to-year differences in the number and intensity of tropical cyclones;
- the unpredictable movement of tropical cyclones;
- short-term variability in the intensity of rainfall during individual storm events; and
- absorption and losses of water within catchments

Each of these factors contributes to soil erosion and sediment movement at both local and catchment scales.

'The Suttor was reported by Charley to be joined by so many gullies and small creeks running into it from the high lands, which would render travelling along its banks extremely difficult, that I passed to the east side of Mount McConnel, and reached by that route the junction of the Suttor with the newly discovered river, which I called the Burdekin, in acknowledgement of the liberal assistance which I received from Mrs. Burdekin of Sidney, in the outfit of my expedition. The course of this river is to the east by south; and I thought that it would most probably enter the sea in the neighbourhood of Cape Upstart. Flood marks from fifteen to eighteen feet above the banks, showed that an immense body of water occasionally sweeps down its wide channel.'

Leichardt, L. 1847 Journal of an Overland Expedition in Australia from Moreton Bay to Port Essington, T & W Boone, London.



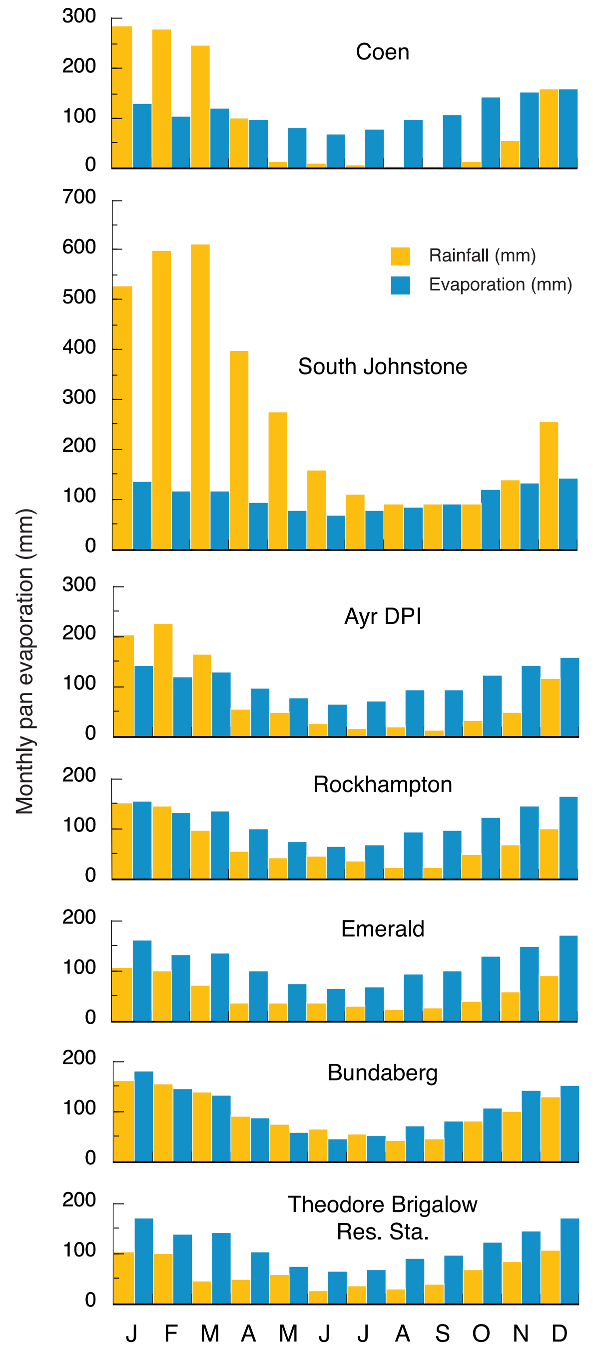
The average distribution of annual rainfall within the GBRCA between 1969 and 1999.
Data source: BOM

3,201 – 6,000 mm
2,401 – 3,200 mm
2,001 – 2,400 mm
1,601 – 2,000 mm
1,201 – 1,600 mm
1,001 – 1,200 mm
801 – 1,000 mm
601 – 800 mm
0 – 600 mm

Rainfall and evaporation

The regional distribution of average annual rainfall in the GBR catchment and its seasonal variability affect the volume of runoff and the amount of materials carried in that runoff [189]. North and central Queensland have a tropical or subtropical monsoonal climate, depending on latitude, with distinct wet and dry seasons [286, 287]. Regardless of location, most (60-80%) of the annual rainfall occurs during the summer wet season (November-April). Within the wet season, rainfall occurs most predictably between December and March. The duration and intensity of individual wet seasons are influenced by regional and global-scale climate processes such as the Asian monsoon, the waxing and waning of the El Niño/Southern Oscillation (ENSO) [287] and larger, but still poorly defined climatic phenomena such as the Pacific Decadal Oscillation (PDO) [46]. Gradual, but significant changes in the intensity, though not quantity of rainfall in eastern Australia have occurred over the last 50 years [349, 353, 591]. During the wet season, significant or intense rainfall is often associated with tropical cyclones, post-cyclonic rain depressions or southward excursions of the monsoonal trough [56, 161].

Rainfall is not evenly distributed throughout the GBR catchment (Table 15). The highest average rainfall occurs in the coastal mountain ranges and on the adjacent coastal plains between Daintree (16°S) and Ingham (18°S). The coastal concentration of high rainfall is caused by the orographic uplift of warm humid air from the Coral Sea as it crosses the coastal mountains and Great Escarpment. Mt Bellenden Ker, near Babinda (17°S), receives a mean annual rainfall exceeding 6,000 mm, with the highest annual total exceeding 12,000 mm [189, 517]. Over one eight-day period, 3,847 mm of rain was recorded at this site [189]. Average annual rainfall on the coastal plain between Tully and Babinda consistently exceeds 3,000 mm. Smaller pockets of high rainfall (annual means > 1,500 mm) occur in the Iron Range/McIlwraith Range region of Cape York



Mean monthly rainfall and potential evaporation at representative coastal and inland locations within the GBRCA. Data source: BOM

Table 15. Average annual rainfall and pan evaporation at representative sites in or immediately adjacent to the GBRCA. Bolded sites indicate locations where annual rainfall exceeds evaporation. Data source: BOM

Site	Coastal/ Inland	Annual Rainfall mm	Years Averaged	Annual Evaporation mm	Years Averaged
Thursday Island	C	1746	1950-1993		
Cape York PO	C	1744	1887-1993		
Lockhart River Airport	C	2087	1956-1996		
Coen	I	1163	1887-1990	2021	1973-1999
Cooktown	C	**1540**	1942-1996	**1506**	1987-1999
Laura	I	936	1887-1990		
Palmerville	I	1038	1889-2000	2211	1970-1999
Pt. Douglas	C	1992	1884-1996		
Cairns	C	2007	1941-1996	2057	1965-1999
Herberton	I	1140	1886-1990		
Babinda	C	**4217**	1912-1999		
Innisfail	C	**3636**	1887-1990		
South Johnstone	C	**3332**	1920-2000	**1486**	1965-1999
Tully	C	**4136**	1925-2000	**1200**	
Koombooloomba Dam	C	**2741**	1960-2000	**1033**	1965-1997
Ingham Composite	C	**2109**	1968-2000	**1305**	1997-1999
Townsville	C	1109	1940-1996	2396	1969-1999
Ayr DPI Research Station	C	954	1951-2000	1797	1967-1999
Bowen	C	1010	1870-1987	2034	1965-1966
Charters Towers	I	657	1882-1990		
Proserpine	C	1792	1876-1990		
Collinsville	I	719	1939-2000	1635	1967-1999
Mackay	C	1606	1959-2000		
Rockhampton	C	819	1939-2000	1871	1951-1999
Clermont	I	670	1870-2000	1773	1980-1999
Monto	I	733	1930-1993	1459	1969-1993
Yepoon	C	1344	1891-1996		
Emerald	I	639	1883-1990	1936	1968-1999
Alpha	I	565	1887-1990		
Gladstone	C	1020	1872-1958	1573	1967-1992
Brigalow Research Station	I	731	1965-2000	1914	1968-1999
Bundaberg	C	1142	1883-1990	1572	1998-1999
Tambo	I	529	1877-2000	1948	1969-1999
Theodore	I	732	1924-2000	952	1965-1966

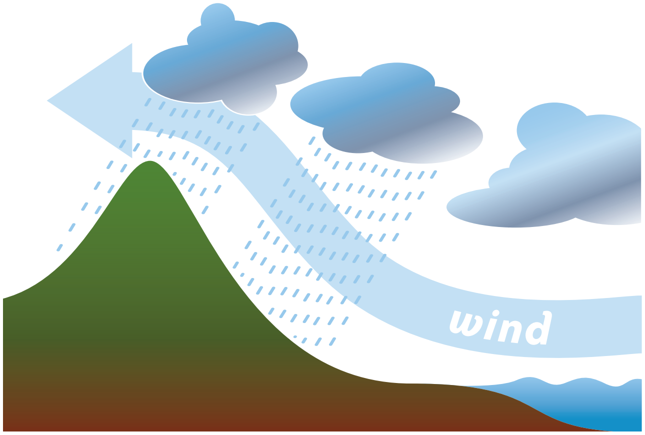
Peninsula (12°S and 13°S) and the Eungella Ranges west of Mackay (21°S). Most of the coastline between Cape York and Ingham receives over 1,200 mm of rain per year. South of Mackay, high rainfall is restricted to small areas south of Shoalwater Bay and the ranges along the southern margin of the Mary River catchment.

Annual rainfall decreases rapidly westward of the crest of the coastal mountain range. Along the western margins of the Fitzroy and Burdekin River drainage basins, mean annual rainfall is approximately 500-600 mm.

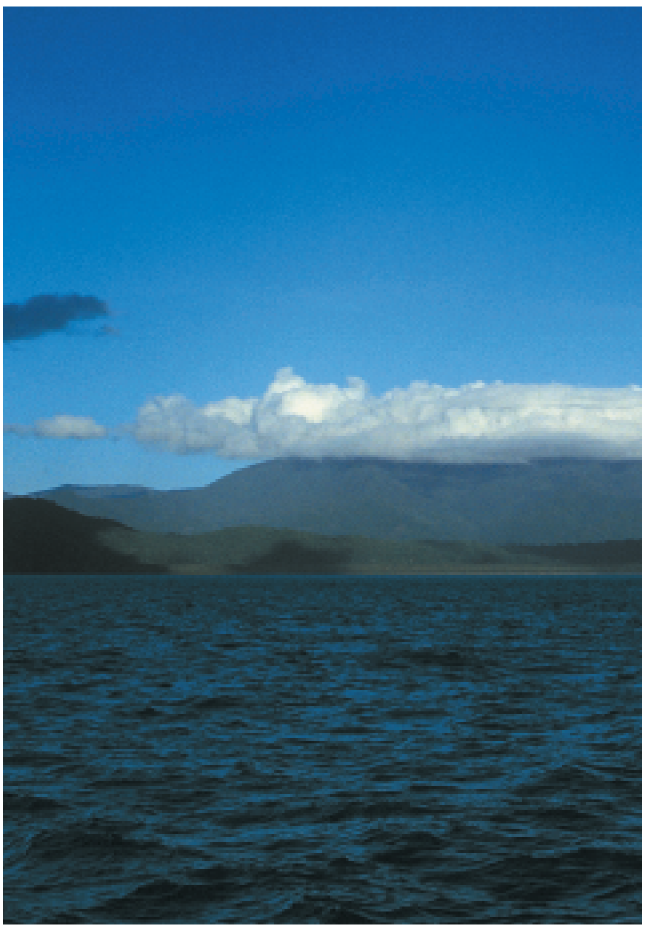
Average rainfall within catchments of river-gauging stations ranges from 3,717 mm per year (Russell River) to 488 mm (Elliott River sub-catchment of the Burnett River). Gauged catchments on six rivers (Daintree, Mulgrave, Russell, Johnstone, Murray and Tully; total area = 4,717 km^2 or 1.1% of the GBR catchment) average over 2,000 mm of annual rainfall and 31 gauged catchments (total area = 93,620 km^2 or 22% of the GBR catchment) receive over 1,000 mm. In contrast, two gauged sub-catchments (Belyando and Elliott Rivers; total area = 74,653 km^2 or 18% of the GBR catchment) average less than 600 mm of rain per year and seven gauged catchments (total area = 137,415 km^2; 32% of the GBR catchment) receive less than 700 mm.

Area-weighted estimates of average annual rainfall within the larger drainage basins range from 3,016 mm (Mulgrave-Russell Rivers) to 727 mm (Burdekin River). Six basins (Daintree, Mossman, Mulgrave-Russell, Johnstone, Tully, and Murray: total area = 9,756 km^2 or 2% of the GBR catchment) have average annual rainfalls exceeding 2,000 mm. An additional 19 basins (total area = 93,621 km^2 or 22% of the GBR catchment) receive an average annual rainfall in excess of 1,000 mm. By comparison, six basins with an area of 314,467 km^2 (74% of the total GBR catchment) receive less than 800 mm of rain per year. Based on the average rainfall distribution, total annual

Cloud forest on Mt. Bartle Frere
Photo: M. Furnas, AIMS



The "orographic effect" producing coastal rainfall as warm humid air flows up and over coastal mountains.



Orographic clouds over the coastal mountains near Babinda Photo: M. Furnas, AIMS

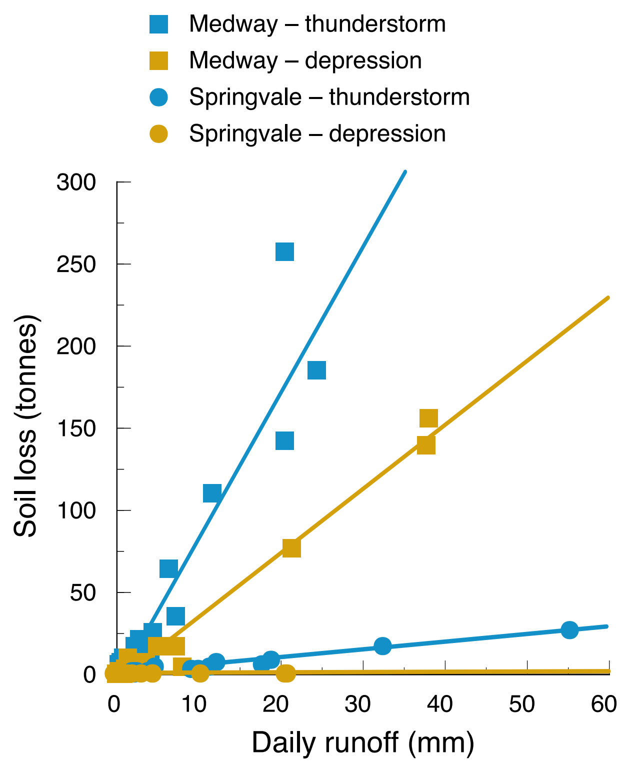
rainfall into the GBR catchment is estimated to be 380 km^3 (380 billion m^3). Drainage basins on Cape York Peninsula (10% of the GBR catchment) receive approximately 14% of the total rainfall (54 km^3). Wet-tropical catchments (3% of the GBR catchment) receive 33 km^3 (9% of the total rainfall). Just under 293 km^2 of rain (77%) falls on the dry catchments bordering the central and southern GBR (Burdekin River to Mary River).

Evaporative losses of water from soils and vegetation in the GBR catchment are as large as rainfall inputs. Annual rainfall significantly exceeds potential evaporation losses from soils and vegetation only at coastal sites in the wet-tropical zone bordering the central GBR. Evaporation is routinely measured at weather stations as water loss from open pans (pan evaporation). Actual evaporative water loss from soils and plants in natural and modified landscapes (evapotranspiration) is further influenced by a range of physical and biological factors such as soil type and vegetation cover. As a general rule, maximum evaporation rates from vegetated landscapes (potential evapotranspiration) are approximately 60-70% of the pan evaporation rate [84].

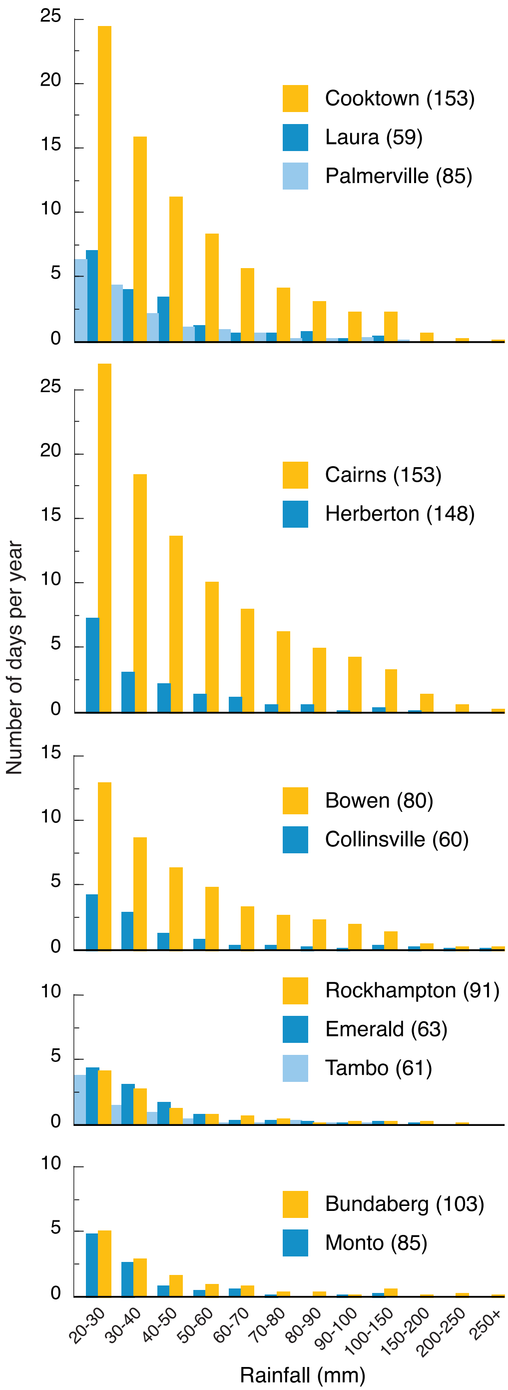
Monthly rainfall only consistently exceeds potential evapotranspiration on a consistent basis in the wet tropics (e.g. South Johnstone). On Cape York Peninsula, summer monsoonal rainfall usually equals or exceeds concurrent evapotranspiration, but from March onward, potential evapotranspiration is greater. Potential evapotranspiration rates exceed average monthly precipitation for much of the year at most locations south of Ingham. Along the southwestern margin of the GBR catchment, monthly potential evapotranspiration exceeds the average rainfall by 2- to 4-fold. Most small streams stop flowing for extended periods. The large and generally consistent disparity between rainfall and potential evapotranspiration means that surface soils in GBR catchments, particularly at inland locations and away from permanent streams, are characterised by extended periods of water deficit. Surplus water for runoff and groundwater recharge is usually only present in the summer when rainfall during intense storms temporarily exceeds local evaporative losses and soil infiltration rates.

The nature of vegetation within catchments significantly influences the amount of water available for runoff. Forested catchments, regardless of soil type, typically lose more moisture through evapotranspiration and direct evaporation than catchments dominated by bare ground or grass [592]. Total evapotranspiration rates increase with the amount of rainfall, but the proportion of rainfall lost annually through evapotranspiration increases with the degree of aridity. In dry areas, water loss through deep-rooted trees and shrubs is an important process preventing the salinisation of surface soils [563].

The frequency of intense rainfall has a large influence on landscape erosion rates [589, 590]. Erosive surface flows develop when rainfall exceeds the infiltration capacity of the soil. Soil loss rates are influenced by the total amount of rainfall, intensity of short-term rainfall during individual storms [160], catchment topography (surface slope), soil type and ground cover (vegetation and litter) [90]. Over short periods, local water runoff and soil loss rates in both wet-tropical and arid catchments are more directly related to the intensity of rainfall than the quantity [55, 90]. Peak runoff flows have the greatest energy with which to erode soils and move sediment out of catchments. Even the most permeable rainforest soils [55] can only absorb a certain amount within a short time period. Once surface soils are water saturated and local water inputs exceed the infiltration rate, excess water remains at the surface and runs off. Rain falling in many small, isolated storms or falling at low rates on a continuous basis is more likely to be absorbed into the soil and retained within catchments than the same amount of rain falling in intense bursts of a few minutes or hours.



Measured soil losses from two small sub-catchments of the Nogoa River (western Fitzroy River basin) in relation to daily rainfall under different rainfall regimes.
Replotted from Ciesiolka, 1987



The average annual occurrence of significant rainfall events (daily rainfall > 20 mm) at selected coastal and inland sites at similar latitudes in the GBRCA. Values in parentheses are the average number of yearly raindays at the sites.
Data source: BOM

The regional distribution and frequency of intense rainstorms within the GBR catchment parallels the distribution of average annual rainfall. Coastal locations receive rain on more days each year (80-153 for the coastal sites in Table 15) than inland sites at similar latitudes (59-85 for the inland sites in Table 15). Coastal areas also receive heavy rainfall (arbitrarily taken as greater than 100 mm per day) more frequently than inland sites. Maximum daily rainfalls recorded at representative low altitude coastal sites range between 252 and 627 mm (median = 404 mm). In contrast, maximum daily rainfalls recorded at representative inland sites range between 120 and 419 mm (median = 174 mm). Only one of the representative inland sites shown in Table 15 (Brigalow Research Station) has received over 100 mm of daily rain more than four times in a 10-year period. In contrast, daily falls exceeding 100 mm are recorded, on average, one to four times each year at coastal sites north of Rockhampton (23.5°S) with falls exceeding 250 mm recorded every 2 to 16 years. Although intense rainfall events are infrequent at any particular location in the drier inland sections of the GBR catchment, the Burdekin and Fitzroy River catchments are sufficiently large that there are usually one to several such events within them each year that can generate substantial local runoff and erosion. To the south of Rockhampton, large daily rainfalls are infrequent, with 100 mm daily falls only occurring every 2 to 12 years.

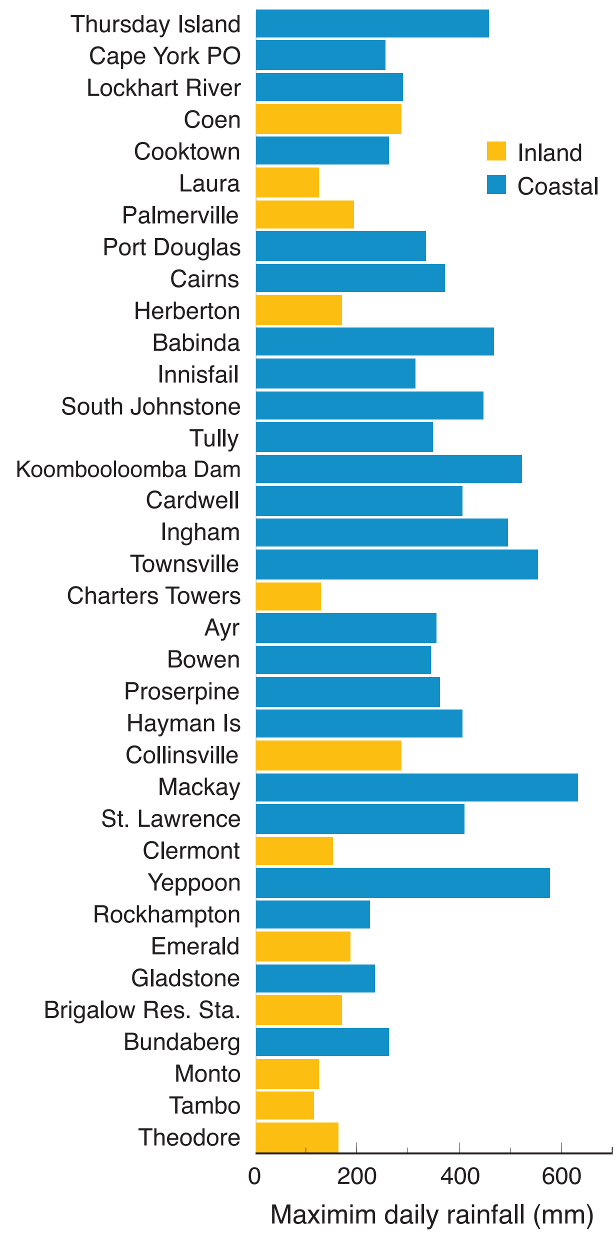
This pattern of seasonally variable and episodically intense rainfall influences freshwater runoff from the GBR catchment in a number of ways. Throughout the dry areas of the GBR catchment, volumes and intensities of rainfall likely to cause significant erosion and major floods occur infrequently. Small falls in dry catchments will be largely absorbed by dry local soils, with minimal loss from the catchment. Overall, less than 10% of the rain falling into the large dry Burdekin, Fitzroy and Burnett River basins ultimately leaves the basins as river runoff. In contrast, more than half of the rainfall on eight of the smaller coastal catchments leaves as runoff. Most of the runoff from both wet and dry catchments is generated by a few large rainstorms.

Low-pressure weather systems remaining after cyclones cross the coast and tropical thunderstorms associated with the summer monsoonal trough are the principal sources of intense or widespread rainfall in inland areas. The influence of summer rainfall from the monsoon trough declines from north to south. Whether due to cyclones or summer monsoonal activity, large storms that produce major inland floods occur less than once per decade. In the southern half of the GBR catchment, drought is normal. Most of the floods that transport sediment and nutrients into the GBR, though not the largest, are generated in coastal catchments and sub-catchments east of the Great Escarpment.

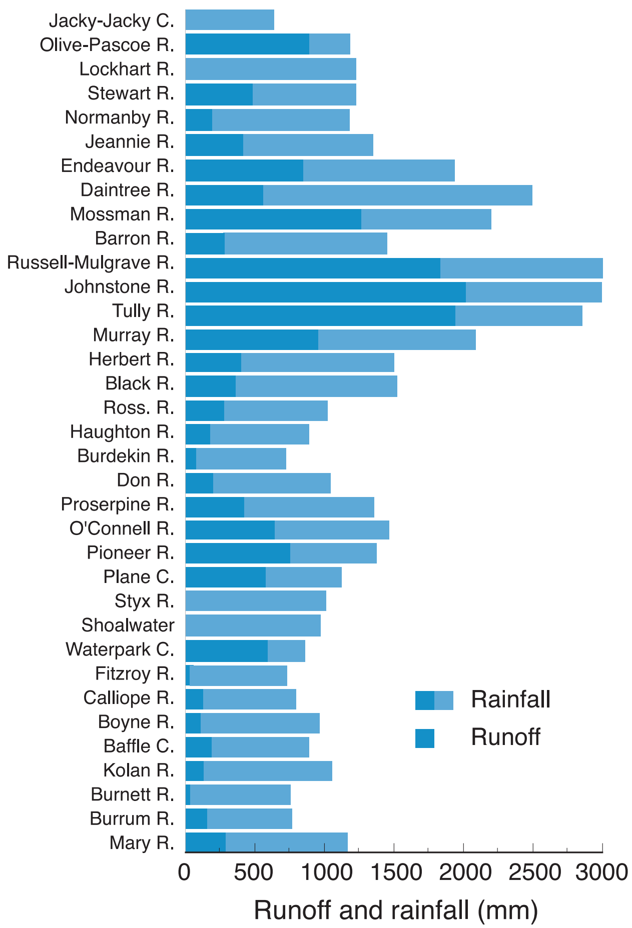
Hydrological factors affecting runoff

Freshwater discharge from rivers follows seasonal, interannual and decadal fluctuations of rainfall. Runoff from both wet and dry catchments is highly variable. Plots of daily and annual discharge from the Burdekin River over time scales ranging from years to centuries illustrate this variability. Pronounced variability is readily apparent at each time scale.

During most years, discharge largely occurs in the wet season (November – April) as discrete events separated by periods of low flow. Hydrographs of individual flood events are typically characterised by an initial peak in water level, followed by a rapid, then slower decline to baseflow levels. In dry basins such as the Burdekin River, little if any discharge occurs during the winter dry season (June-October), largely because there is little rainfall and groundwater inflow to the river. Intermittent rainfalls through the year and groundwater inputs sustain some year-round flow in

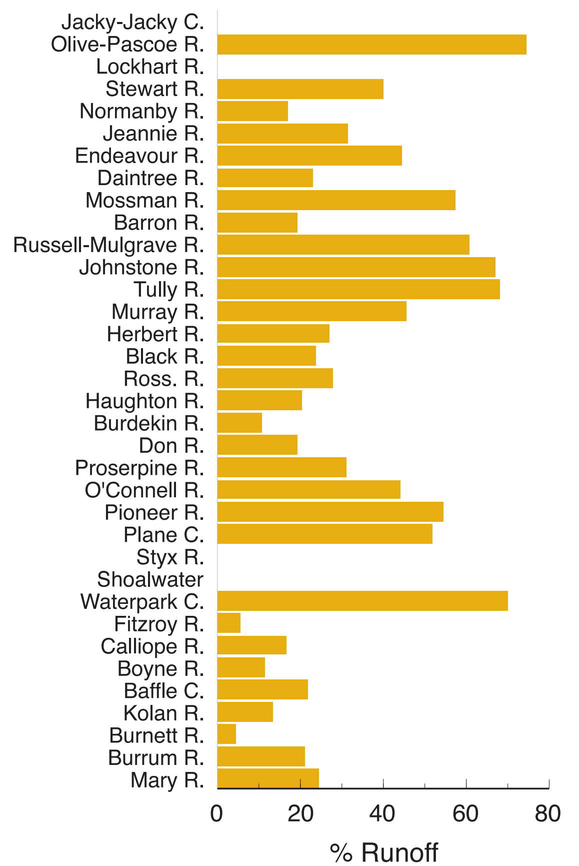


Maximum daily rainfalls recorded at selected coastal and inland sites in the GBRCA between 1975 and 2000. Data source: BOM



Average area-specific annual rainfall (1969-1999) onto and runoff from (1968-94) drainage basins of the GBRCA. Data source: BOM, QNR&M

wet tropics rivers. In both wet and dry catchment rivers, the number, timing and size of flow events vary considerably between years. This can result in significant inter-annual variability in total runoff. The recorded maximum and minimum annual discharges recorded in the Burdekin River vary over a 100-fold range. In contrast, the maximum and minimum annual discharges from the wet-tropical Tully River differ less than 5-fold. Over time spans of decades, annual discharges from the Burdekin River go through distinct “wet” and “dry” phases. The 1930s, 1960s and 1980s were “dry” decades while the 1950s and 1970s were relatively “wet”. Two extreme discharge years (1974, 1991) have occurred during the 72-year period of gauging.



The proportion of average annual rainfall on gauged GBRCA drainage basins that leave as runoff (1968-94 average runoff). Gaps indicate basins without gauged discharge. Data source: BOM, QNR&M

Total discharge for any year, however, is often not well correlated with water height during flood events.

A third time scale of variability in discharge is apparent in the 350-year record of annual discharge from the Burdekin River which has been reconstructed from banding patterns in massive corals (*Porites* spp.) collected at nearshore reefs in the Palm Islands (18° 30'S) [223]. The banding pattern in massive corals from coastal reefs can track the volume of discharge from nearby rivers much like tree rings provide a record of climate and tree growth. Reductions in coastal salinity during floods cause temporary changes in the skeletal extension rates of the corals. This leads to changes in the normal seasonal variation of density and structure in the calcium carbonate skeleton of the coral [33]. When these corals are cut into thin sections and illuminated with ultraviolet light, zones of lower skeletal density formed during periods of low salinity can be seen as luminescent bands which can be dated much like tree rings.

Based on coral banding patterns, short runs of wetter and drier years are distributed within longer periods of high and low average runoff lasting several decades. The coral banding record suggests that at least six major runoff events occurred in the 100-year period between 1650 and 1750. This wet epoch was followed by two intervals of lower than average runoff separated by a 25-year period of high runoff in the late 19th century. This high-runoff period coincides with the initial phase of pastoral expansion and mining development in the Burdekin River catchment. Over the last 200 years, however, drought or low runoff, has been the most common state.

Event-based fluctuations in runoff

Tropical cyclones and cyclone-spawned rain depressions can cause intense and widespread rainfall on large areas within the GBR catchment. On average, two or three cyclones influence the GBRWHA each year [406]. Virtually all parts of the GBR catchment can be affected by cyclones.

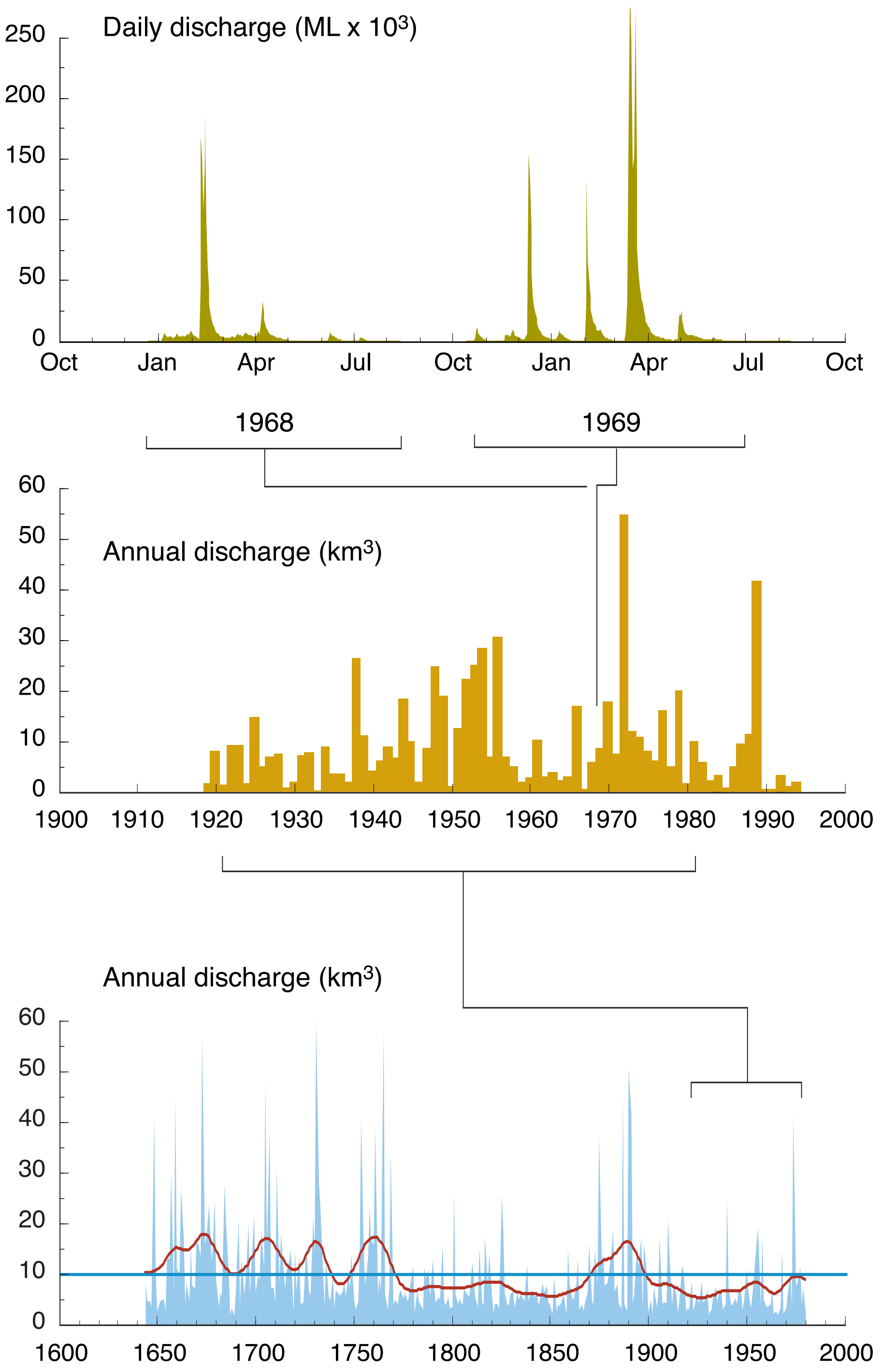
Luminescent lines in the skeleton of a massive coral (Porites sp.) revealed by UV illumination of a cut thin section. Brighter and darker bands correspond to periods of greater or lesser freshwater runoff.
Photo: J. Lough, AIMS

Variability in freshwater discharge from the Burdekin River over different time scales.

Top: Daily discharge over the 1967-68 and 1968-69 water years (1 Oct – 30 Sept).

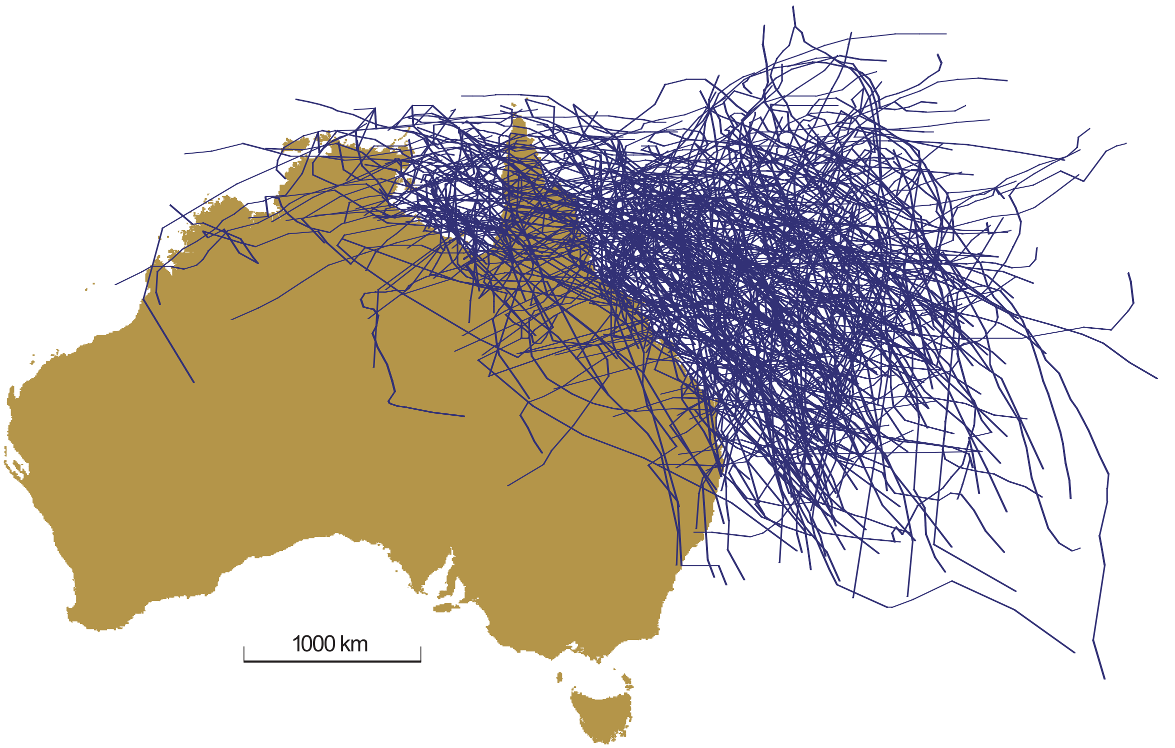
Middle: Gauged annual discharge at Home Hill between 1921 and 1996.

Bottom: Annual discharge between 1640 and 1980 inferred from fluorescent banding records in massive corals. The dark horizontal line is the average annual discharge for the period between 1921 and 1996. The red line is a 30-year running average of the inferred annual discharge. Coral-derived estimates of runoff were supplied by P. Isdale and J. Lough (AIMS). Discharge data source: QNR&M

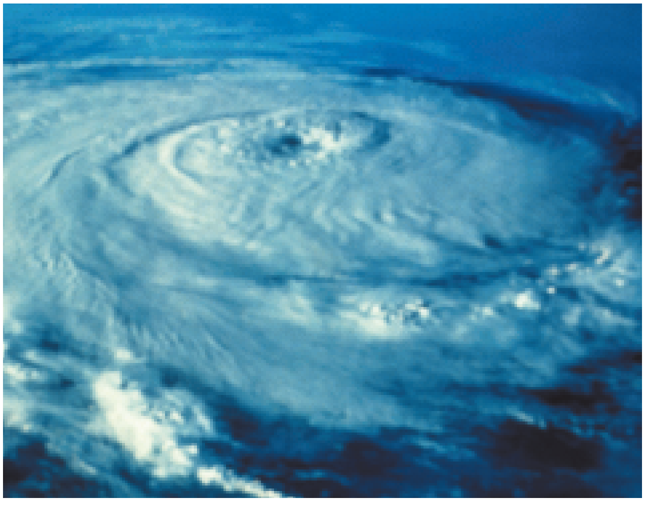


Cyclones form in the Coral Sea, Arafura Sea and Gulf of Carpentaria between December and April when surface water temperatures exceed 26°C, but usually 28°C. Individual storm tracks are erratic. Most Coral Sea cyclones move to the south and east, eventually dying at sea, but a significant number move westward toward the Australian continent. Cyclones formed in the Gulf of Carpentaria episodically bring significant rainfall to northern or inland regions of the GBR catchment, chiefly the upper Herbert, Burdekin and Fitzroy River catchments. Significant rainfall may occur in coastal catchments even when a cyclone does not cross the coast (e.g. Cyclone Joy, before it made landfall in January 1991). Once they move inland, cyclones lose their warm-water energy source and quickly degenerate into rain depressions. These low-pressure weather systems can deliver massive volumes of rainfall to large areas, or just a few catchments. The volume of rainfall depends on the amount of moisture associated with a particular storm system, its size and where it makes landfall.

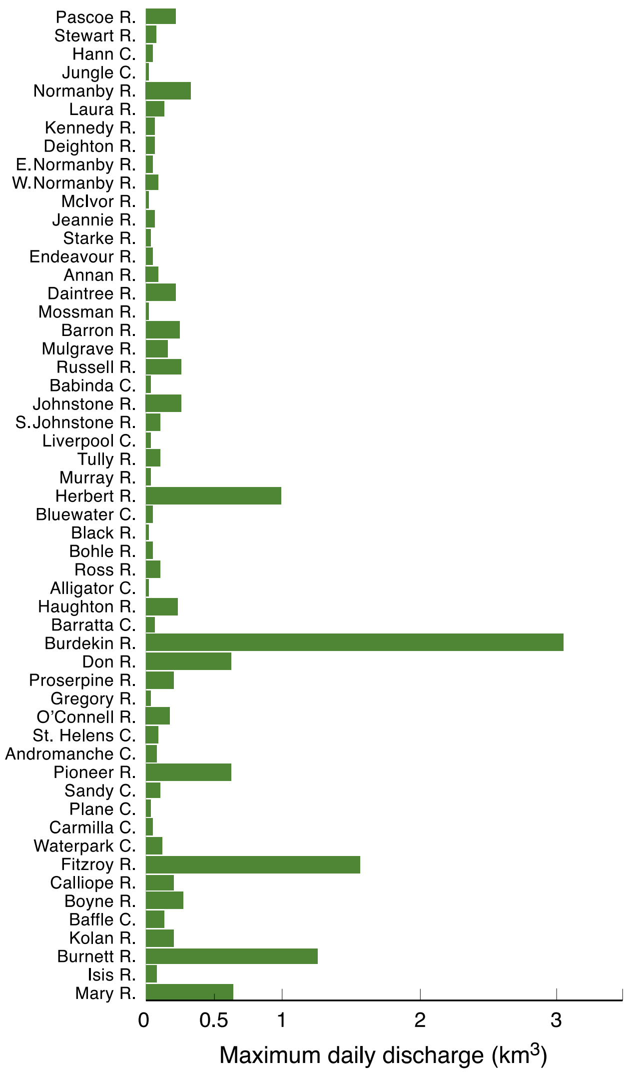
Within a wet season, peaks in river discharge almost always follow discrete storms. Floods account for a large, if not the predominant portion of total annual discharge from most catchments. Maximum daily discharges from individual catchments span a wide range. For larger catchments such as the Burdekin, Fitzroy, Herbert and Burnett Rivers, daily discharges exceeding 1 km^3 (10^6 ML) have been recorded. The number of floods from a particular river in any year varies with the nature of the wet season, latitude and topography of catchment. In monsoonal catchments of Cape York Peninsula or the dry catchments bordering the southern GBR, most runoff occurs in a single wet-season flood. The size and duration of these floods varies greatly from year to year. In drier river catchments bordering the central and southern GBR (e.g. Don River), no flow may occur in drought years. In contrast, the smaller catchments of the wet tropics (e.g. Tully River)



Tracks of cyclones influencing northeastern Australia between 1969 and 1997.
Map provided by M. Puotinen, JCU



Tropical cyclone photographed from a space shuttle
Photo: NASA



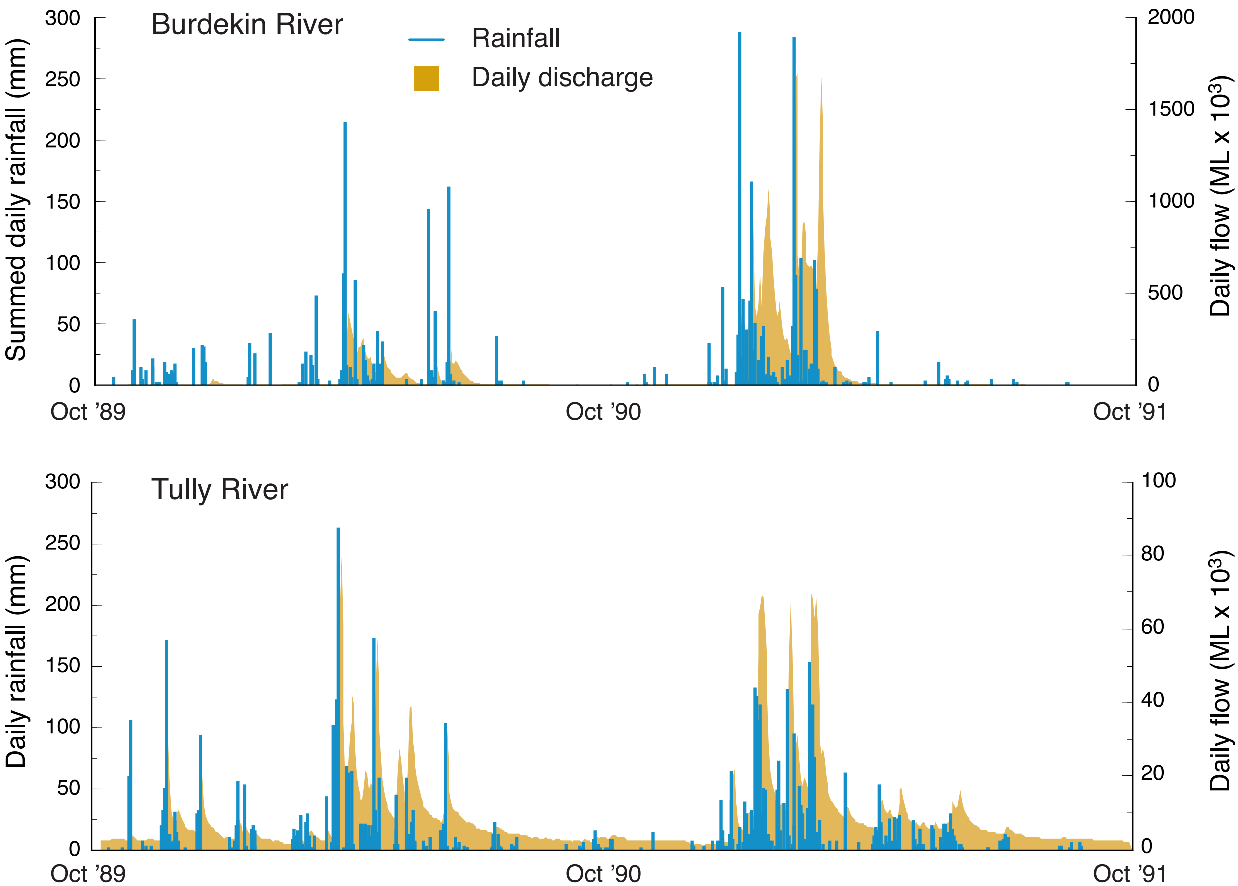
Maximum recorded daily discharges from gauged rivers and streams flowing into the GBRWHA.
Data source: QNR&M

are characterised by regular rainfall and usually have several flood events of varying size within a wet season.

The time interval between rainfall into and discharge from a catchment depends on the size of the catchment, the quantity of rainfall, and in larger catchments, where the rainfall occurred. For small drainage basins such as the Tully River, the interval between rainfall and flood

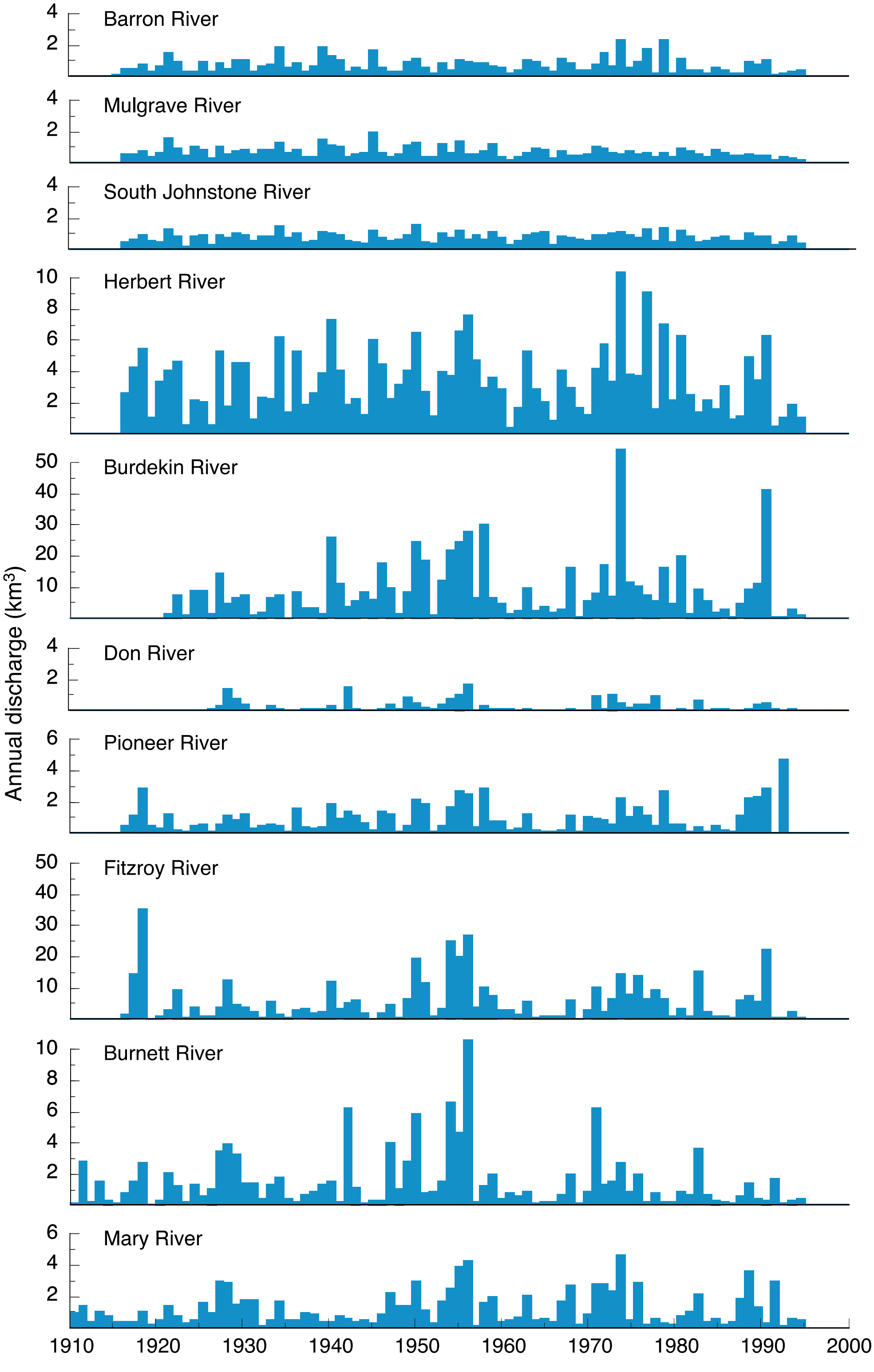
Burdekin River in flood
Photo: M. Furnas, AIMS

Burdekin riverbed during the dry season
Photo: M. Furnas, AIMS



Daily rainfall and discharge from the Burdekin River and Tully River during the 1989-91 water years. Daily rainfall in the Burdekin basin is taken as the summed daily rainfall measured at Charters Towers and Collinsville.
Data source: BOM, QNR&M

peaks is very short, sometimes on the order of hours, as large storms can inundate most, if not all of the basin and the distance between the headwaters and river mouth is short (< 100 km). As a consequence, floods in small catchments are brief, usually lasting only a few days after the rain stops. The large aggregate discharge from the small rivers of the wet tropics is due to the occurrence of multiple floods within a wet season. For the large dry catchments such as the Burdekin, the link between rain and significant river flow is most noticeable for the floods following tropical cyclones. Because of the size of these catchments, large floods may be generated by heavy rainfall within a single sub-catchment. Floodwaters from these storms can take days to weeks to work their way down from the headwaters to the mouth. Alternatively, large



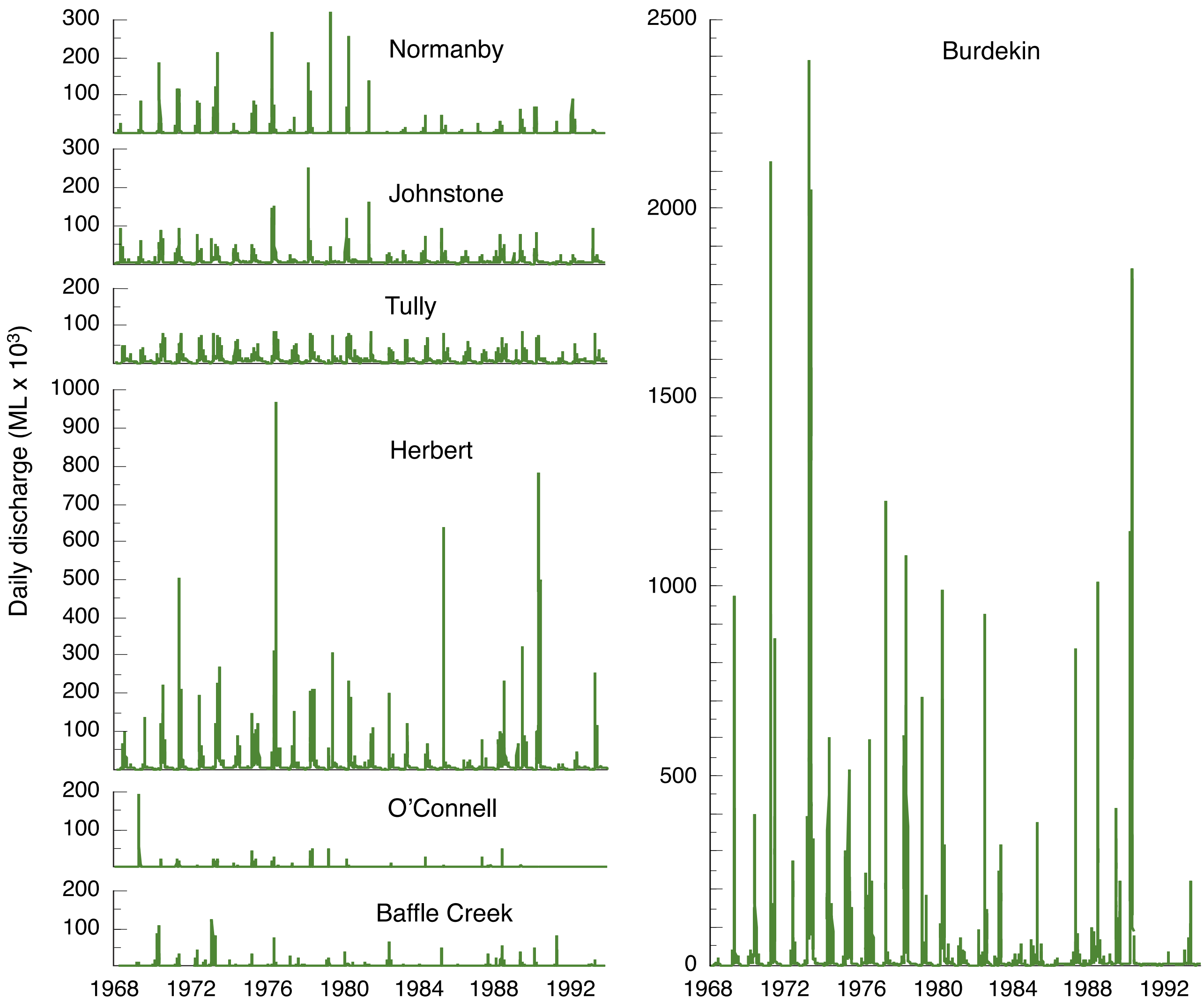
Inter-annual variability in discharge from long-record rivers flowing into the central and southern GBRWHA. Note scale changes. Data source: QNR&M

amounts of coastal rainfall at the bottom of the larger catchments may cause short-lived floods and inundation of the floodplain, with relatively little rainfall in the dry upper portion of the catchment.

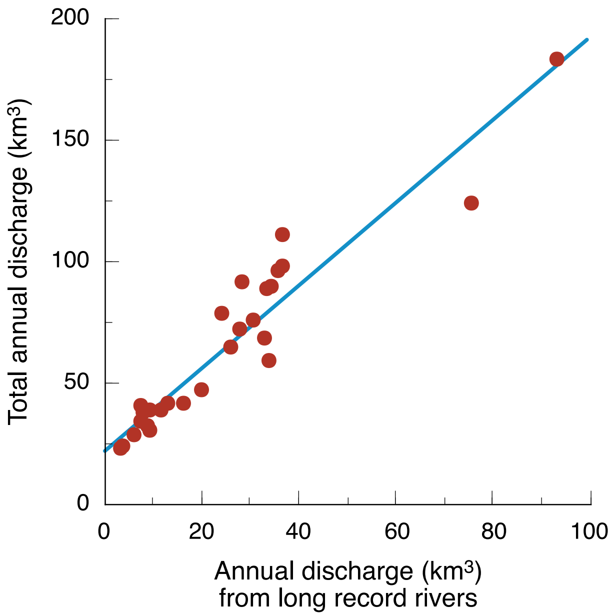
Latitudinal, inter-annual and decadal variations in runoff

Over periods of decades, variability in terrestrial runoff follows fluctuations in rainfall associated with global (ENSO), seasonal (monsoonal) and regional (cyclones) climate processes. This variability is evident in the multi-decade records of discharge from ten north and central Queensland rivers (Mary, Burnett, Fitzroy, Pioneer, Don, Burdekin, Herbert, South Johnstone, Mulgrave, Barron). The three northern rivers in this group (Barron, Mulgrave and South Johnstone) are characterised by relatively low (typically < 2 km^3 per year), but consistent annual discharges. While year-to-year variations in runoff from the northern catchments are clearly evident, there is relatively little variation in runoff over time scales of decades. In contrast, discharge records from the dry-catchment rivers of the central and southern GBR catchment (Burdekin to Mary Rivers) are characterised by both year-to-year and decadal variability. The observed pattern of discharge from the dry catchment rivers reflects drought conditions throughout southern Queensland which are influenced by global climate (chiefly ENSO) processes and the unpredictable behaviour of infrequent tropical cyclones.

The gauged catchments of the ten "long-record" rivers have an aggregate area of 315,860 km^2 or 75% of the total GBR catchment. For the 1968-94 period when discharge from rivers and streams throughout the GBR catchment was most comprehensively gauged, total discharge from the gauged mainland drainage basins was strongly correlated with the aggregate gauged discharge from the ten long-record rivers. Over this 26-year period, measured discharge from these rivers averaged 59% of the total



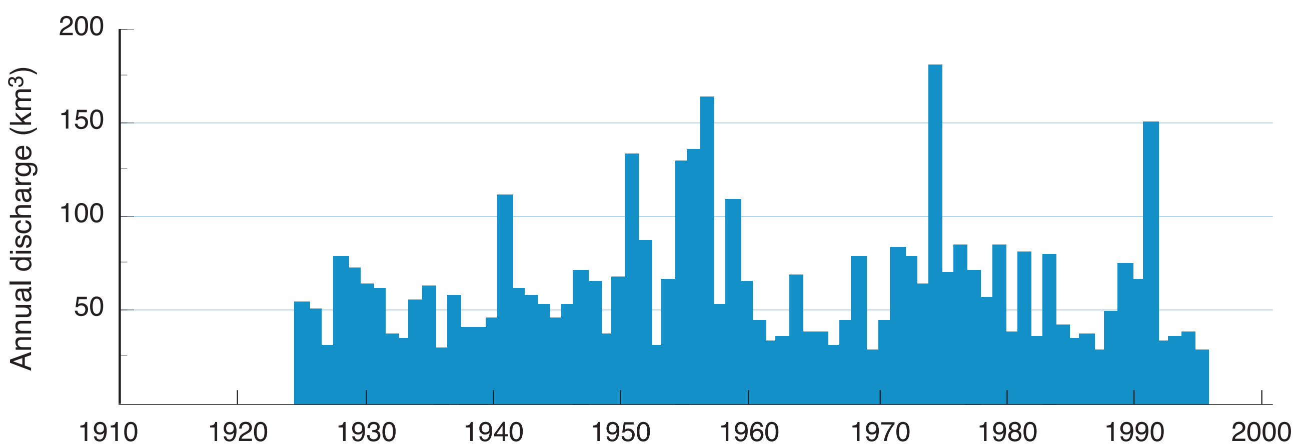
Daily and year-to-year variations in discharge from selected wet and dry catchment rivers flowing into the GBRWHA. Data source: QNR&M



The relationship between total freshwater runoff from gauged drainage basins and aggregate freshwater runoff from the ten long-record rivers (Barron, Mulgrave, South Johnstone, Herbert, Burdekin, Don, Pioneer, Fitzroy, Burnett, Mary) between 1968 and 1994.
Data source: QNR&M

estimated runoff from all drainage basins. Because of the strength of this correlation, the aggregate discharge from the long-record rivers can be used to estimate total freshwater discharge to the GBR since the mid-1920s.

Based on extrapolations from the aggregate discharges from the long-record rivers, total annual freshwater runoff from the GBR catchment between 1924 and 1996 is estimated to have ranged between 27 km^3 (1987) and 180 km^3 (1974) with an average of 62 km^3. Total estimated runoff exceeded 100 km^3 in eight years and 150 km^3 in two (1956, 1974). In addition to the pronounced year-to-year variations in runoff, longer periods of relatively wet and dry conditions are also evident. Despite the link between global climate processes such as ENSO and weather in northeastern Australia, there is no clear correlation between the occurrence of individual ENSO events and annual river discharge. This is largely because of confounding interactions between the number, volume and intensity of rainfall events, particularly those associated with tropical cyclones [354]. Over longer time periods, global-scale climate processes such as ENSO, similar fluctuations in the Indian Ocean and the Pacific Decadal



Estimated total freshwater runoff to the GBRWHA between 1922 and 1995 extrapolated from gauged freshwater runoff in the ten long-record rivers.
Data source: QNR&M

Oscillation (PDO) likely have a profound impact on the amount of rainfall and its distributions in northern Australia.

Estimating annual runoff from catchments and drainage basins

The Queensland Department of Natural Resources and Mines (QNR&M) is responsible for monitoring stream flow throughout Queensland. Water levels are continually monitored in one or more important rivers or streams within 31 of the 35 mainland drainage basins adjacent to the Great Barrier Reef. The water level data are recorded at the gauge site, but increasingly are also transmitted to a central computer for real-time presentation, analysis and storage. This water level data is used to predict and monitor the downstream progression of floods within river systems.

Water heights (metres of water above an arbitrary reference level) are converted to estimates of instantaneous river flow (cubic metres per second – cumecs) by use of a rating table or rating function (rating curve) for the measurement station. The rating function is derived by measuring the cross-sectional area of the stream and cross-sectionally averaged water flow rates over the range of water heights encountered at that gauging site. The rating table or function is used in conjunction with water height measurements to calculate instantaneous flow past the gauging station. At gauging sites without hard boundaries such as natural rock banks or concrete walls (e.g. dam spillways), it is necessary to re-measure stream cross sections and recalculate rating functions from time to time to take account of bank and streambed changes. To calculate daily discharge (usually in megalitres – ML), average discharge rates within contiguous discrete intervals over a 24-hour period are summed. Daily discharges can be summed to produce an estimate of monthly or annual discharge at the gauging site. Because of the strong link between seasonal rainfall and discharge

River gauging station, Euramo
Photo: M. Furnas, AIMS

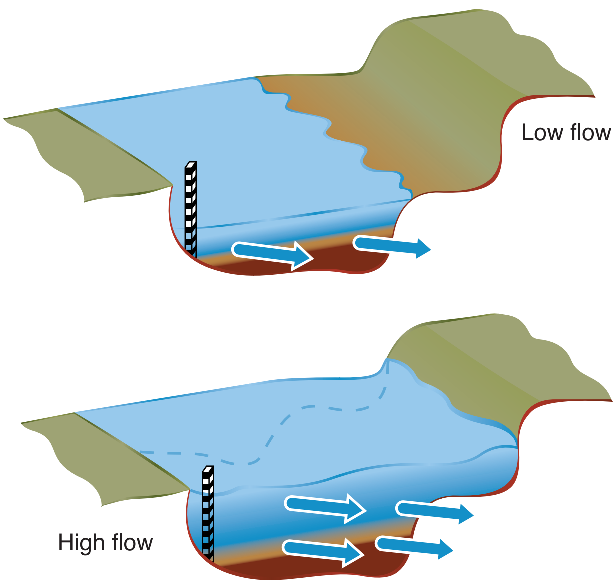


Illustration of the relationship between water height and discharge.

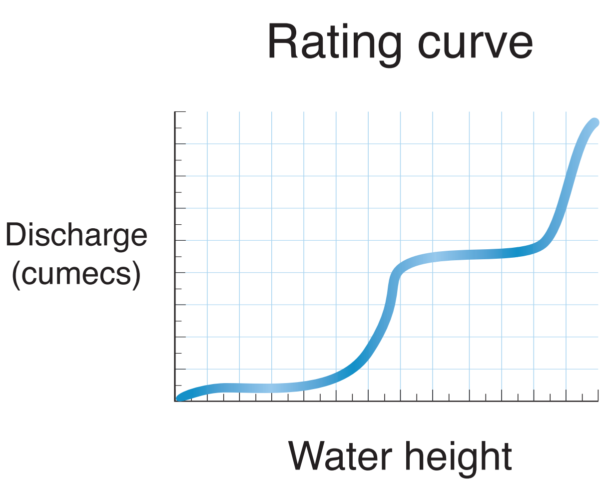


Illustration of a rating curve.

in all drainage basins, annual discharge is most usefully presented using water or hydrological years (in this book - 1 October to 30 September). This time interval encompasses each annual wet season as a single entity.

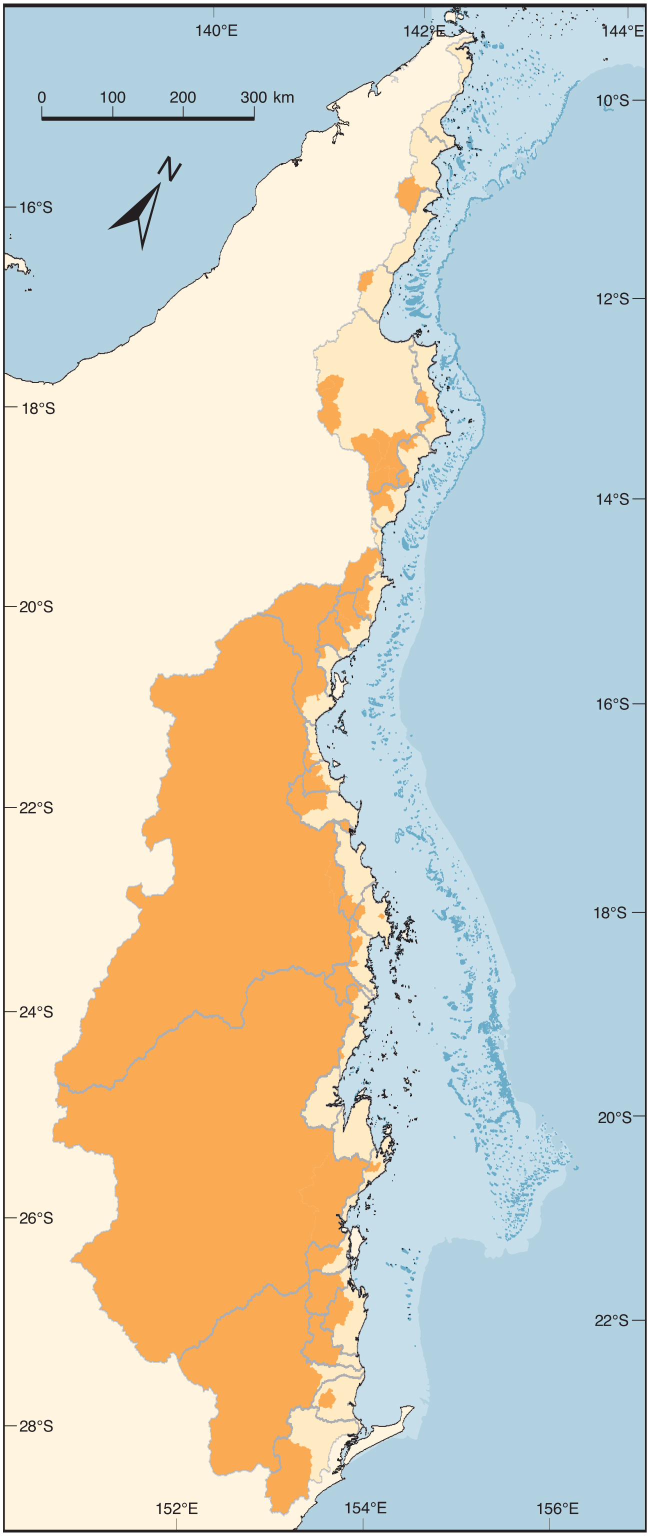
Estimates of total annual discharge from the QNR&M drainage basins have been calculated by extrapolating the average annual discharge per unit area from the gauged (sub-)catchments (mm runoff per m^2) in each drainage basin to the total area of the basin. This extrapolation assumes that the quantity of runoff reaching the GBR from each km^2 of the ungauged portions of a drainage basin is similar to that coming from the gauged portion of the basin. Runoff from 345,264 km^2 (82%) of the GBR catchment is captured by the QNR&M river gauging network. For individual drainage basins, the area covered by gauging ranges from nil (Jacky-Jacky Creek) to 99+% (Burdekin River). In smaller drainage basins, the largest river or stream is only gauged at one location. Bigger rivers, however, are gauged at several locations to track the size and progression of floods. For the purpose of estimating runoff to the GBR, the gauging record from the most downstream site or the aggregate discharge from unconnected sub-catchments in one basin is used. In the case of the four mainland drainage basins without gauged streams (Jacky Jacky Creek, Lockhart River, Styx River, Shoalwater), runoff has been estimated from the area-weighted average rainfall for those basins and the runoff-rainfall ratios from adjacent drainage basins of similar character. The proportion of total rainfall on individual drainage basins which leaves as runoff ranges from 5% (Burnett River) to > 60% (Olive-Pascoe River, wet-tropical rivers, Waterpark Creek).

Gauged annual discharges of freshwater to the GBR between 1968 and 1994 range from 11 to 125 km^3 with an average close to 40 km^3 (Table 16). Gauged runoff from the wet-tropical rivers of the central GBR (Daintree River to Tully River) averaged 13 km^3 per year, 34% of the total gauged discharge. By comparison, gauged discharge from the Burdekin and Fitzroy Rivers averaged only 16.1 km^3 per year (40% of total measured runoff). Maximum gauged discharges in a year from four rivers (Normanby, Herbert, Burdekin and Fitzroy) exceeded 10 km^3. The largest amount of runoff was measured during the 1973-74 wet season when significant floods were recorded in most central and southern GBR river systems. During this wet season, discharges of 54 and 35 km^3 were recorded from the Burdekin and Fitzroy Rivers, respectively. The second largest discharge event occurred during the 1990-91 wet season when cyclone Joy caused major flooding in central and southern GBR river systems (total annual discharge to the GBR = 93.5 km^3). There was relatively little runoff (<30 km^3) during the 1968-69, 1987-88 and 1991-94 wet seasons, largely due to the very low discharges from the Burdekin and Fitzroy Rivers.

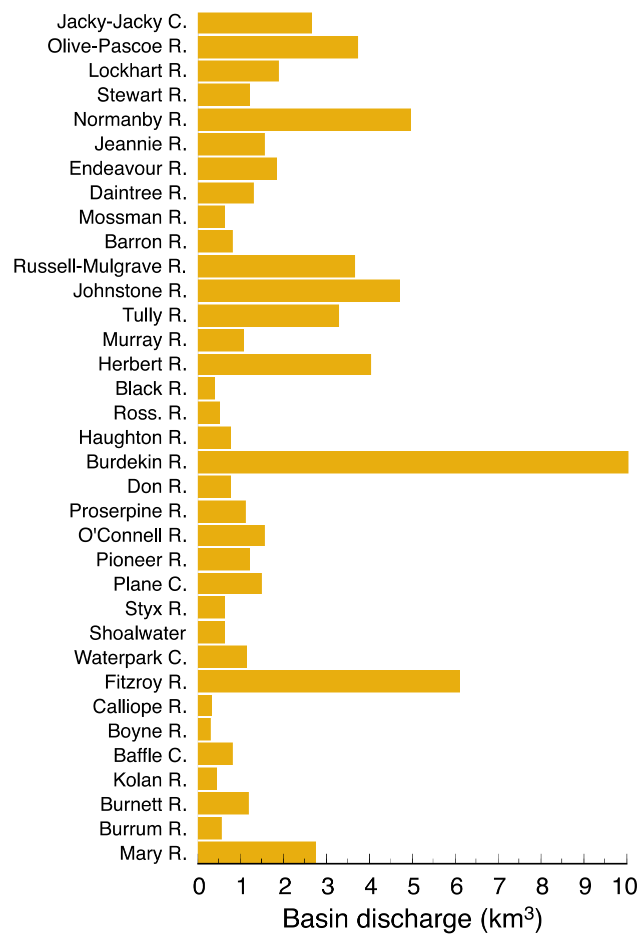
Taking ungauged areas of each drainage basin into account, average annual discharges from mainland drainage basins for the 1968-94 period are estimated to range from 0.3 km^3 (Boyne River) to 10.3 km^3 (Burdekin River). Eight drainage basins (Olive-Pascoe, Normanby, Russell-Mulgrave, Johnstone, Tully, Herbert, Burdekin and Fitzroy Rivers) have average annual discharges in excess of 3 km^3. Maximum annual discharges range from 1.1 km^3 (Calliope River) to 54.5 km^3 (Burdekin River). Four basins had no discharge in at least one year (Black, Don, Pioneer, Boyne Rivers). In contrast, minimum annual discharges from three wet-tropical drainage basins bordering the central GBR (Russell-Mulgrave, Johnstone, Tully) exceeded 1 km^3.

For the 27-year period between 1968 and 1994, the average annual freshwater discharge from all basins to the GBR is estimated to be 71 km^3. The highest estimated discharge was in 1973-74 (186.5 km^3) and the lowest (22.4 km^3) in 1987-88. Total annual discharge exceeded

Burdekin River flood staff at Macrossan, near Charters Towers
Photo: M. Furnas, AIMS



Land area within the GBRCA covered by the QNR&M river gauging network.
Data source: QNR&M



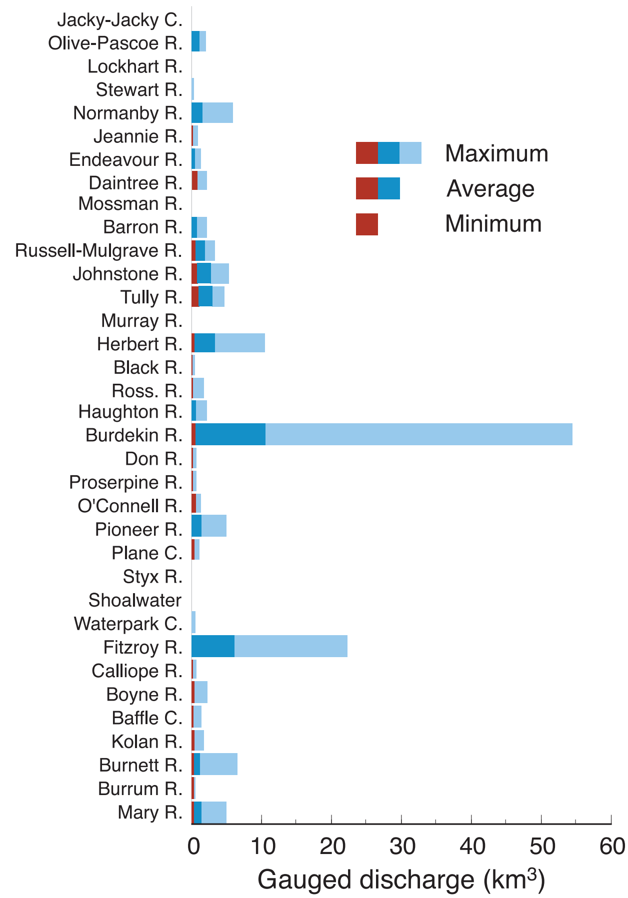
Estimated average annual freshwater discharge from mainland drainage basins of the GBRCA.
Data source: QNR&M

100 km³ in three years (1973-74, 1978-79, 1990-91) and was less than 30 km^3 in three other years (1967-68, 1987-88, 1991-92).

Over the 1968-1994 period, the largest volume of runoff (annual average = 16.4 km^3) comes from the two largest catchments (Burdekin and Fitzroy Rivers) while the highest annual discharges by area (> 1,000 mm runoff m^{-2}) comes from the smaller wet-tropical catchments of the central GBR (Mossman, Russell-Mulgrave, Johnstone, Tully).

The monsoonal catchments of Cape York Peninsula (10-15°S), with a total area of 41,000 km^2, have an aggregate annual discharge of 16 km^3, or 23% of the GBR catchment total. The small wet-tropical drainage basins of the central GBR (15-18°S) which make up only 3.5% of the total GBR catchment have an aggregate annual discharge of 17 km^3 or 24% of total runoff. In contrast, the 366,690 km^2 of dry drainage basins bordering the central and southern GBR (87% of the GBR catchment) discharge an average of 38 km^3 of runoff each year (53% of total runoff).

How does the volume of runoff compare with volumes of fresh and salt water in the GBR system as a whole? Average annual freshwater runoff (71 km^3) is approximately 1% of the volume of seawater in the GBR lagoon (approx. 7,600 km^3) and 16-41% of the estimated volume of rainwater falling onto the GBR shelf (170-440 km^3) [144]. The 71 km^3 of runoff is equivalent to a layer of freshwater 32 cm thick spread over the area of the GBR shelf. By contrast, the freshwater in rain falling directly onto the shelf would produce a freshwater layer between 75 and 200 cm thick. Shelf water salinities are maintained within a relatively narrow range (34-36‰) by constant mixing between the shelf and adjacent oceanic waters of the Coral Sea. Overall, terrestrial runoff is a minor, though important component of the total water budget for the GBR lagoon system. Of greater relevance to the ecosystems within the GBR, the 71 km^3 of freshwater runoff equals 24% of the



Minimum, average and maximum annual freshwater runoff to the GBRWHA from gauged drainage basins (1968-94). Data source: QNR&M

Table 16. Total measured discharge from gauged QNR&M drainage basins and estimated total discharge from gauged drainage basins between 1968 and 1994.

Water Year Beginning	Gauged Discharge km^3	Total Estimated Discharge km^3
1968	46.0	69.2
1969	12.8	23.3
1970	23.5	41.8
1971	59.3	97.5
1972	54.5	90.6
1973	44.6	79.7
1974	124.7	186.5
1975	44.3	73.0
1976	57.5	99.5
1977	53.7	93.6
1978	29.6	46.6
1979	65.5	114.5
1980	20.5	38.8
1981	55.3	91.2
1982	19.6	37.7
1983	42.3	58.6
1984	22.2	38.6
1985	20.5	41.0
1986	19.4	32.3
1987	11.4	22.4
1988	25.4	40.8
1989	47.3	77.0
1990	39.8	64.8
1991	93.5	124.8
1992	13.1	28.1
1993	18.0	34.5
1994	18.4	30.0
Average	40.1	65.8

water volume (295 km^3) inshore of the 20 m isobath and 72% of the volume (97 km^3) within the 10 m isobath. These coastal waters are the first part of the GBR affected by terrestrial runoff.

As will be shown, the quantity of freshwater discharged from individual catchments is a central factor in calculating sediment and nutrient exports to the GBR.

Chapter 5

Vegetation communities, landscape processes and agricultural practices affecting runoff of sediment and nutrients

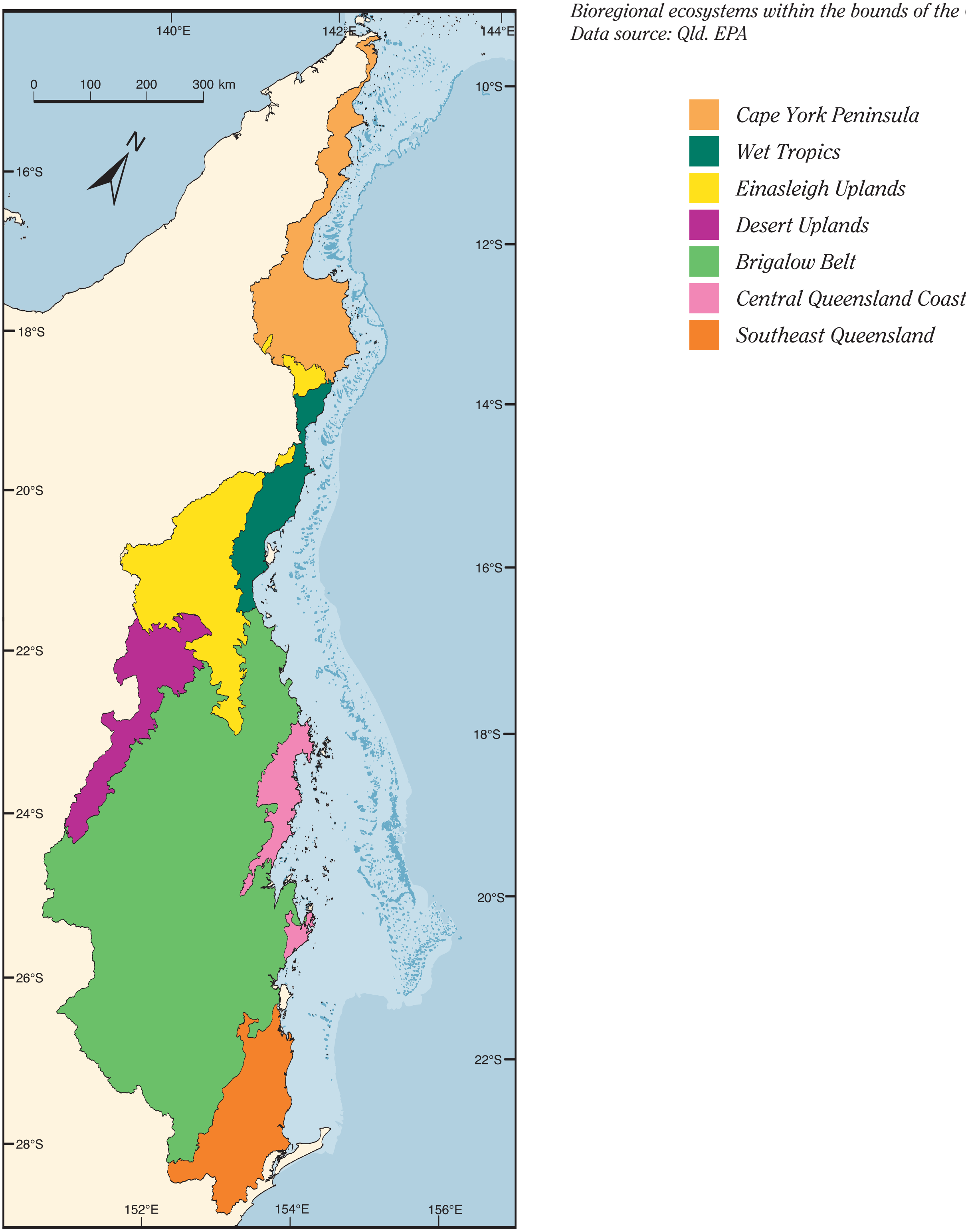
Bioregional ecosystems

Queensland has a great diversity of natural vegetation communities. Statewide, these communities have been aggregated into thirteen broadscale bioregional ecosystems on the basis of landform, climate and the dominant natural vegetation communities [454]. All or part of seven bioregional ecosystems occur within the boundaries of the Great Barrier Reef catchment (Table 17). Each bioregional ecosystem, in turn, contains a mosaic of distinct vegetation assemblages growing in response to the local topography, soils, rainfall and water availability. Two of the seven bioregional ecosystems, (Wet Tropics, Central Queensland Coast) lie fully within the bounds of the GBR catchment.

Cape York Peninsula

Bordering the far northern GBR, the portion of the Cape York Peninsula bioregional ecosystem in the GBR catchment is largely covered by *Eucalyptus*–dominated woodlands and open forests [351]. To the north of Cape Weymouth (12° 30'S), patches of heathland growing on sandy soils and sand dunes extend along the coastal zone. Rainforest and rainforest-related plant communities occur in areas of

Rainforest, Paluma, north Queensland
Photo: M. Furnas, AIMS



Bioregional ecosystems within the bounds of the GBRCA.
Data source: Qld. EPA

Table 17. Areas of bioregional ecosystems within the boundaries of the GBRCA. Data source: Qld. EPA.

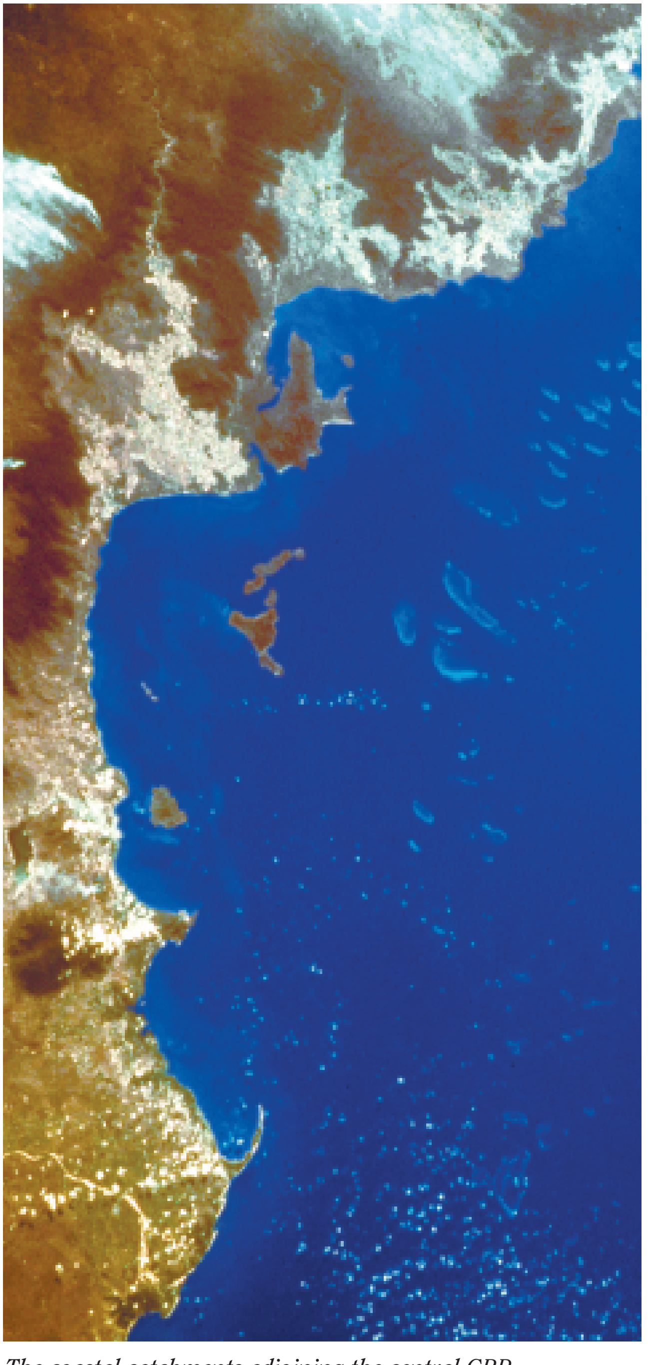
Bioregional Ecosystem	Area in the GBRCA km^2	Relative Area %
Cape York Peninsula	39,110	9.2
Wet Tropics	18,528	4.4
Einasleigh Uplands	53,098	12.5
Desert Uplands	27,281	6.4
Central Queensland Coast	14,045	3.3
Brigalow Belt	237,062	55.9
Southeast Queensland	35,158	8.3

higher rainfall around the Iron Range and McIllwraith Range, and as gallery forests along watercourses [271]. Mangroves and shrubland communities dominate in low-lying coastal areas. The Normanby River drainage basin contains extensive areas of permanent and seasonally flooded wetlands. Apart from the Normanby River basin, the drainage basins of eastern Cape York Peninsula are relatively small and the rivers with them, short.

Wet Tropics

The Wet Tropics bioregional ecosystem encompasses the coastal plain and mountain ranges between Cooktown (16°S) and Townsville (19°S). Various types of rainforest dominate high rainfall areas within the bioregion. The structure of these rainforest communities varies with soil type, altitude and average rainfall. Drier coastal and inland sections of the wet-tropical bioregion are covered by eucalypt and *Melaleuca* forests.

Prior to European settlement, tropical rainforest covered approximately 13,000 km^2 throughout north Queensland. At present, approximately 10,000 km^2 (77%) remains, mostly on the coastal mountains and steeper upland terrains [570, 571]. A significant proportion of the rainforest at low elevations has been cleared for agriculture, particularly for the cultivation of sugarcane. Most of the remaining tropical rainforest between Townsville and Cooktown is now conserved within the Wet Tropics World Heritage Area,



The coastal catchments adjoining the central GBR photographed from the Space Shuttle. Light areas over land are clouds, land cleared for agriculture and smoke plumes from bush fires (top). Vegetation colours were distorted in image processing
Photo: NASA

Hand-clearing scrub in the Mulgrave Shire
Photo: JCU North Queensland Photographic collection

although large proportions of some specific rainforest types have been cleared [454, 553, 554, 570, 571].

Brigalow Belt

The Brigalow Belt, an extensive inland zone once largely covered by *Acacia* and eucalypt woodlands, is the largest bioregional ecosystem of the GBR catchment [588].

Extending from northern New South Wales to the coast near Townsville (19°S), the Brigalow Belt encompasses much of the Burdekin and Fitzroy River drainage basins, and inland sections of the Burnett River drainage basin. Within this bioregion, stands of *Acacia*–dominated woodland (Brigalow) were once distributed within an extensive open woodland dominated by eucalypts. Stands of vine thicket with rainforest affinities grow along the eastern margin of the Brigalow Belt [233]. Brigalow woodlands are characterised by a number of *Acacia* species or close relatives [233]. They often grow on clay soils [180] which are found through the Fitzroy River basin. *Acacia* trees are legumes, and can fix atmospheric nitrogen to assist their growth in the poor inland soils. The eucalypt woodlands of the Brigalow Belt generally grow on higher ground and non-clay soils. Within Brigalow stands, the understory contains small trees, shrubs, or in more open woodlands, various types of grasses, which makes it an attractive habitat for cattle grazing [5]. Prior to European settlement, burning of the Brigalow by Indigenous peoples is thought to have reduced the prevalence of woody shrubs, favouring open woodlands with an understory of grasses [356].

A great deal of effort and resources have been directed into to tree clearing and agricultural development within the Brigalow Belt [279, 356]. Early land clearing, largely carried out by hand, proceeded slowly. Cleared land often needed repeated re-clearing due to the suckering habit of Brigalow species. Extensive stands of the exotic prickly pear cactus (*Opuntia* sp.) developed throughout the Brigalow Belt during the early part of the 20th century, until killed by the *Cactoblastus* moth. Woody weeds remain a problem in many areas. Mechanised land clearing campaigns launched with government support in the 1960s have led to the modern distribution of remnant vegetation in the region. Satellite image analysis [34, 171] and vegetation mapping (Qld. EPA, 2001) indicates that most of the native Brigalow community has been cleared or thinned, largely for pasture development. At present, less than 1% of the original Brigalow woodland remains undisturbed [453]. The highest tree clearing rates in the GBR catchment still occur within the Brigalow Belt bioregion [410, 411, 412].

Land clearing
Photo: QDPI

Desert Uplands vegetation
Photo: P. O'Reagain, QDPI

Einasleigh and Desert Uplands

Portions of the Einasleigh Uplands and Desert Uplands bioregional ecosystems lie along the western boundary of the GBR catchment [335, 336]. The upper catchments of the Herbert and Barron Rivers and the northern sub-catchment of the Burdekin River form part of the Einasleigh Uplands bioregion. All three catchments contain significant outcrops of basalt and associated basalt-derived soils [221]. Eucalypt woodlands and forests of various types are the dominate vegetation communities. Cattle grazing is the major land use.

The southwestern margin of the Burdekin River catchment falls within the Desert Uplands bioregional ecosystem. This bioregion is characterised by highly weathered soils of low fertility [284, 285]. Plant communities within the Desert Uplands are mostly open *Eucalyptus* and *Acacia* woodlands, or shrublands with a tussock grass understory. Most of the land is used for cattle grazing.

Central Queensland Coast

Moist uplands and the adjoining coastal plain along the central Queensland coast form the major part of the Central Queensland Coast bioregional ecosystem [586]. This bioregion is bounded to the west by the Brigalow Belt, which extends to the coast through two dry, low relief corridors: Townsville-Proserpine and Sarina-Gladstone. A disconnected section of the Central Queensland Coastal bioregion occurs in the hills surrounding Cape Townshend (21°S), extending south along the coast near Yeppoon. There are tropical rainforest communities in the coastal mountains west of Mackay. Vegetation communities in the Central Queensland Coastal bioregion contain a mixture of species from the Wet Tropics, Southeastern Queensland and Brigalow Belt bioregions. Soils in coastal regions are primarily of alluvial origin, derived from the granitic ranges of the Great Escarpment.

Southeast Queensland

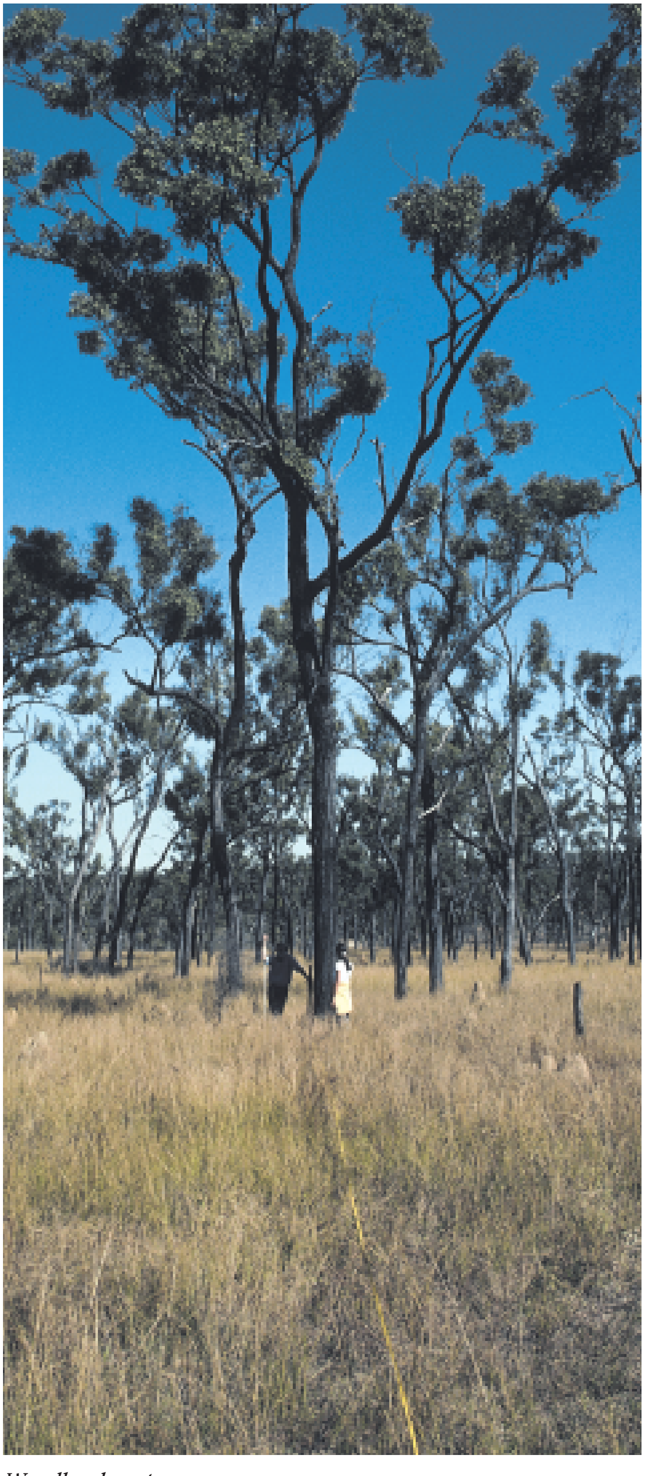
The southern portion of the GBR catchment falls within the Southeast Queensland bioregional ecosystem [587]. Prior to 1850, the Southeast Queensland region contained extensive stands of sub-tropical rainforest, moist eucalypt forest, woodlands and dry open forests. Rainforest and moist forests are now primarily restricted to higher elevations, while eucalypt, *Corymbia* and *Melaleuca* woodlands predominate at lower elevations. The portion of this bioregion within the GBR catchment contains a range of soils on a diversity of bedrock types. While blocks of native vegetation remain, extensive areas of forest have been logged and woodlands in most of the bioregion have been cleared for grazing and agriculture.

Wetlands in the GBR catchment

There are permanent and seasonal wetlands in all parts of the GBR catchment [50, 51]. They are an integral part of natural river systems. Seasonal wetlands typically fill during the summer wet season (November-April) as a result of rainfall or flooding and dry out during the winter dry season (May-October).

Identified freshwater wetlands in the GBR catchment [51] have an area close to 7,500 km^2, approximately 1.8% of the total catchment (Table 18). The catalogued area of wetland is conservative because surveys may not include billabongs, farm dams, construction works and other small sources of water. Approximately half of the area of the identified freshwater wetland is on Cape York Peninsula, largely on the Normanby River floodplain.

Permanent and seasonal freshwater wetlands make up approximately 11.5% of the area of the drainage basins on Cape York Peninsula which flow into the GBR, 3.2% of the area of drainage basins in the wet tropics, but less than 1% of dry-tropical basin area. An additional 4,800 km^2 of mixed freshwater-estuarine wetlands (ca. 1.2% of the GBR



Woodland pasture
Photo: P. O'Reagain, QDPI

Seasonal wetland (wet season)
Photo: M. Furnas, AIMS

Seasonal wetland (dry season)
Photo: M. Furnas, AIMS

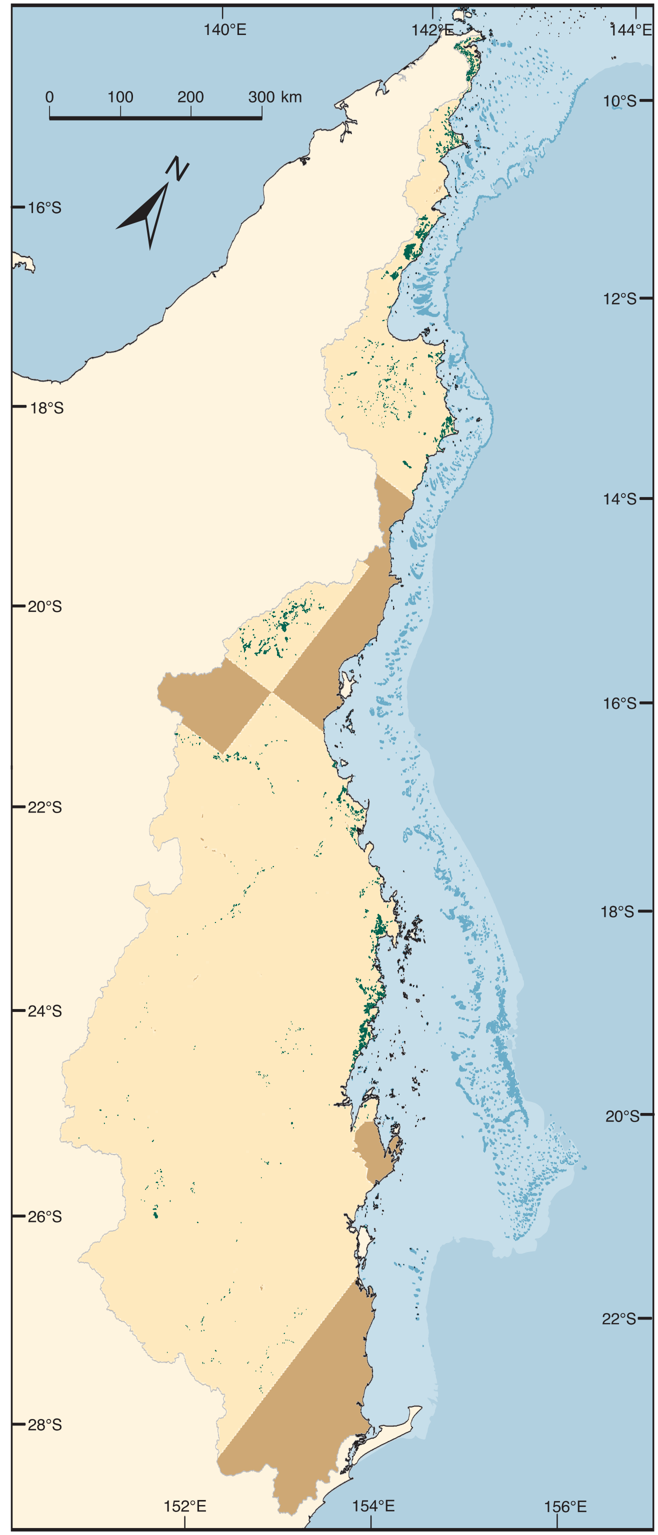
catchment) are distributed along the coast. These coastal wetlands are largely formed on soils derived from marine sediments and receive their freshwater input from rainfall and small coastal streams. There are approximately 6,000 km^2 of marine wetlands, largely mangroves, in estuaries.

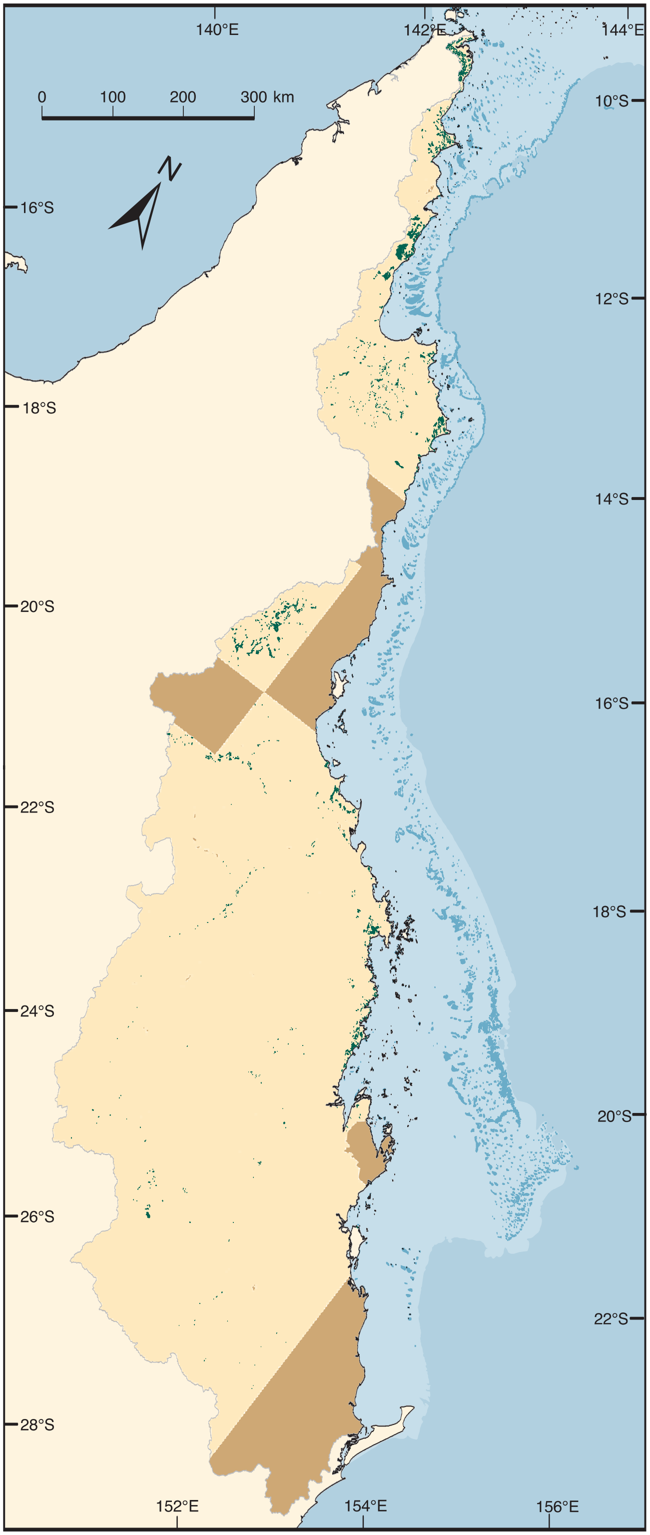
Freshwater wetlands are characterised by standing or slowly-flowing water. They develop where low, flat topography or depressions favour the retention of surface water. The local inflow of water or rainfall only needs to temporarily exceed evaporative and drainage losses to fill the wetland. On floodplains, the inundation and persistence of seasonal wetlands largely depends on the volume of river water entering the floodplain system. Eroded soil and organic matter washed into wetlands settle out of suspension under the low-energy conditions. As a result, wetlands are zones of soil and nutrient accumulation. The floodplains of rivers in the GBR catchment have largely been built by sediment accumulation in marine and freshwater wetlands. Recurring, though not always continuous, inputs of soil, organic matter and dissolved nutrients make wetlands highly productive, particularly when flooded. Nutrients not incorporated into wetland soils and biomass, or converted to gaseous forms (respiration, denitrification, methane production), are exported further downstream.

Over the last 150 years (Table 19), land clearing and agricultural development in GBR catchments have changed both the area and status of wetlands. Wetlands on Cape York Peninsula remain relatively undisturbed, apart from damage caused by cattle and feral pigs. In contrast, the area of wetlands and seasonally inundated floodplain vegetation in catchments between the Daintree and Fitzroy Rivers (Qld Herbarium, 2000) has decreased by approximately 5,000 km^2 (52%) since European settlement in Queensland [226, 443, 444, 445]. The largest relative changes have been in freshwater *Melaleuca* swamps and inundated lowland rainforests of the wet

The inferred extent of pre-1850 wetland vegetation communities in mapped areas of the GBRCA based upon distributions of remnant vegetation and catchment characteristics. The area of of wetland communities is exaggerated by the boundaries drawn around small vegetation patches to make them visible. Maps of inferred pre-1850 wetland vegetation in the wet tropics have not as yet been published.
Data source: Qld. EPA, 1999

Wetland Vegetation
GBR Catchment
GBR Catchment (unmapped)





The extent of remnant wetland vegetation communities (ca. 1997) in mapped areas of the GBRCA. The area of of wetland communities is exaggerated by the boundaries drawn around small vegetation patches to make them visible. Maps of current wetland vegetation communities in the wet tropics have not as yet been published.
Data source: Qld. EPA, 1999

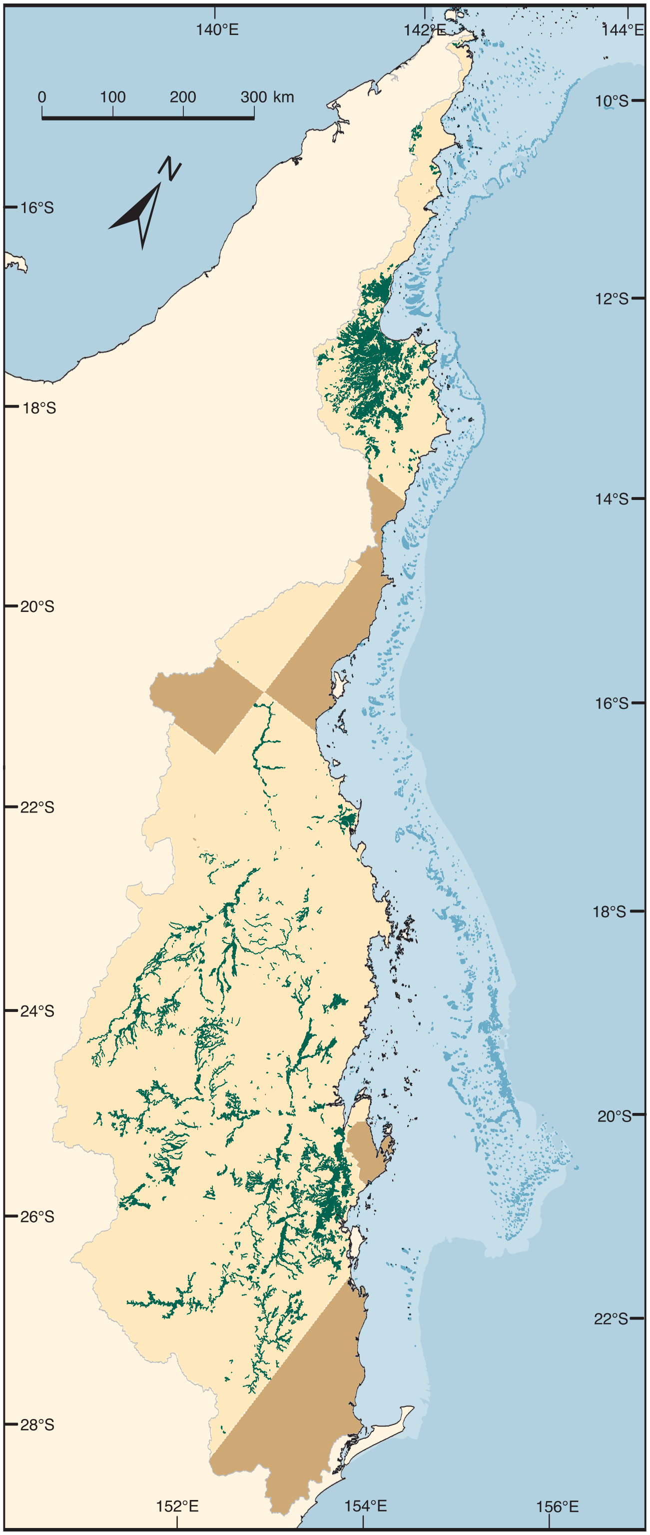
Wetland Vegetation
GBR Catchment
GBR Catchment (unmapped)

tropics which have been extensively cleared and drained for pasture development and sugarcane cultivation [226]. Again, the extent of change is probably underestimated because small wetland areas on river floodplains or along smaller tributary watercourses may not have been recognised or mapped before clearing and waterway modification. Water now flowing through managed watercourses or artificial drainage networks once flowed through seasonally inundated swampy meadows [393] or lowland swampy forests. Most of the pre-1850 swampy meadow habitat on floodplains has disappeared. Low-lying lands cleared for agriculture may re-flood seasonally if land contours and drainage patterns are not greatly changed. These flooded agricultural lands will act to some degree as seasonal wetlands although the normal wetland vegetation communities are not present.

Urban wetland, Townsville
Photo: M. Furnas, AIMS

The extent to which wetlands in the GBR catchment currently influence the magnitude of freshwater, sediment and nutrient runoff is not well resolved. Gauging records are relatively short (75 years) relative to inferred long-term variations in river flow [223] and rainfall [353, 591]. Some wetland systems, particularly mixed freshwater-saline wetlands along the coastline and low-lying coastal *Melaleuca* forests are only affected by small volumes of runoff derived from local catchments. In contrast, the extensive floodplains of the larger river systems (e.g. Normanby, Herbert, Burdekin, Fitzroy) indicate that substantial amounts of sediment and associated nutrients are deposited during major floods. During these major flood events, freshwater inputs (often vastly) exceed the water storage capacity of wetlands. In the central and southern GBR, much of this floodplain vegetation has now been cleared. When floods do not exceed river or tributary bank heights, the water and sediment remain within the channel network. River channels have now been engineered and agricultural drainage networks developed so that floodplains only become inundated

Cromarty wetlands, north Queensland
Photo: M. Furnas, AIMS



The extent of pre-1850 floodplain vegetation communities (ca. 1997) in mapped areas of the GBRCA. The area of of floodplain communities is exaggerated by the boundaries drawn around small vegetation patches to make them visible. Maps of inferred pre-1850 floodplain vegetation communities in the wet tropics have not as yet been published.
Data source: Qld. EPA, 1999

Floodplain Vegetation
GBR Catchment
GBR Catchment (unmapped)

under extreme flood conditions. Flood waters on floodplains are largely carried away from the main river channel and are ultimately discharged from smaller creeks and secondary channels. When flood waters do not overtop the river bank, nutrients and entrained fine sediments pass more quickly through the river system, bypassing former wetland areas on the floodplain.

Riparian vegetation

Vegetation growing along streambanks (riparian vegetation) significantly influences the movement of eroded soil and associated nutrients into watercourses [239]. A number of distinctive plant assemblages are found within the riparian zone of streams and rivers in the GBR catchment. Riparian plant communities are typically more developed than plant communities further from streams, particularly in drier areas because there is usually surface or subsurface water near stream and river channels. Current riparian communities and their inferred distribution prior to 1850 have been mapped along major streams and rivers through much of the GBR catchment (Qld. EPA, 2000) (Table 20).

The composition of riparian vegetation communities varies with the local topography, rainfall, stream flow characteristics and streambank soils. Permanent surface or sub-surface water supports distinctive rainforest-affiliated gallery forests and vine thickets along watercourses in some dry areas [236]. Where riparian soils remain inundated for significant periods of time, wetlands may develop. In rainforests and wet sclerophyll forests, the forest vegetation often grows directly to the water edge without a clearly defined riparian zone. *Eucalyptus*, *Casuarina* and *Melaleuca* spp. are dominant riparian tree species in dry catchments. Exotic shrubs and grasses (e.g. Para grass – *Urochloa mutica*) often dominate riparian plant communities bordering small streams and drains in agricultural areas where native trees and shrubs have

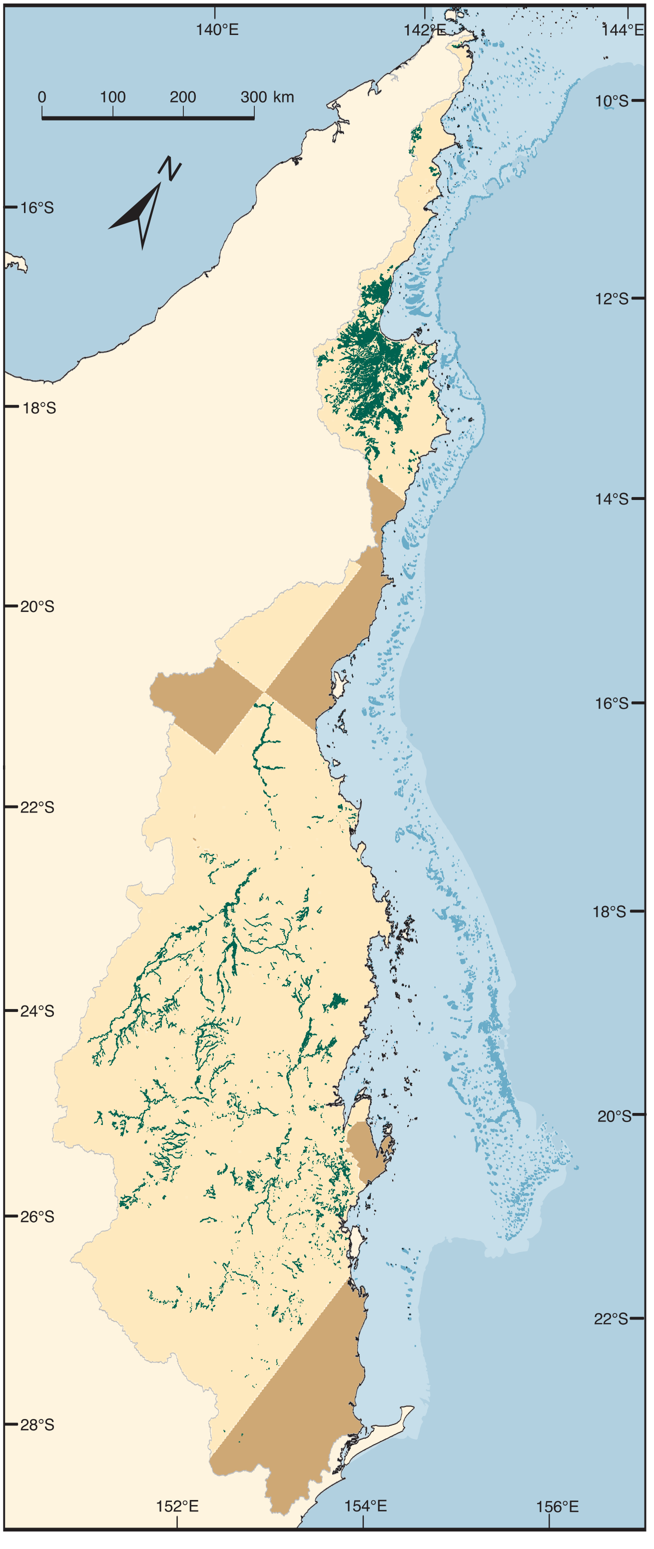
Flooding on the Herbert River floodplain
Photo: GBRMPA

Table 18. Areas of significant wetlands in drainage basins of the GBR catchment.
Data source: Blackman, 2000

Basin Name	Basin Area km^2	Bioregional Ecosystem(s)	Wetland Type km^2 Freshwater	Mixed	Marine
Jacky-Jacky C.	2,963	Cape York Pen.	172	176	423
Olive-Pascoe R.	4,179				
Lockhart R.	2,883	Cape York Pen.		391	201
Stewart R.	2,743	Cape York Pen.		448	
Normanby R.	24,408	Cape York Pen./Einasleigh Upld.	4,304	55	878
Jeannie R.	3,637	Cape York Pen.	440		
Endeavour R.	2,104				
Daintree R.	2,192	Wet Tropics	<0.1		61
Mossman R.	466				
Barron R.	2,136				
Mulgrave-Russell R.	1,983	Wet Tropics	36	24	64
Johnstone R.	2,325	Wet Tropics	13	83	21
Tully and Murray R.	2,790	Wet Tropics	394	223	
Herbert R.	9,843	Wet Tropics	11	445	360
Black R.	1,057				
Ross R.	1,707	Brigalow Belt N.	28		
Burdekin-Haughton R.	130,126	Brigalow Belt N./Einasleigh Upld.	1,074	643	55
Don R.	3,695	Brigalow Belt N.		111	
Proserpine R.	2,535	Central Queensland Coast		169	
O'Connell R.	2,387				
Pioneer R.	1,570	Central Queensland Coast	8		263
Plane C.	2,539				
Styx R.	3,012				
Shoalwater	3,605	Central Qld Coast/Brigalow Belt N.	10	671	3,492
Waterpark C.	1,835				
Fitzroy R.	142,537	Brigalow Belt S.	963	1,013	
Calliope R.	2,236	Brigalow Belt S.			95
Boyne R.	2,590				
Baffle C.	3,996				
Kolan R.	2,901				
Burnett R.	33,248				
Burrum R.	3,358				
Mary R.	9,440	South East Qld.	0	151	0
Total			**7,453**	**4,602**	**5,913**

Table 19. Estimated pre-1850 and current areas of remnant mangrove, riparian, wetland and floodplain vegetation in mapped sections of GBR catchment drainage basins. Areal estimates of vegetation types for Cape York Peninsula, Barron River, Herbert River and dry tropics basins were derived from vegetation mapping by the Queensland Herbarium (Qld. EPA, 2000). Wetland areas for Russell-Mulgrave, Johnston, Tully and Murray River basins were taken from Russell, 1992; Tait, 1995. Pre-1850 wetland vegetation cover on Cape York Peninsula is presumed to equal current cover areas as there has been little if any clearing in these catchments. – = no data given.

		Pre-1850 Areas				Remnant Areas			
Basin Name	Basin Area	Mangroves	Riparian	Wetlands	Floodplain	Mangroves	Riparian	Wetlands	Floodplain
							km^2		
Jacky Jacky C.	2,963	15.6	253.7	54.1	185.4	15.6	253.7	54.1	185.4
Olive-Pascoe R.	4,179	126.1	50.8	272.2	35.8	126.1	50.8	272.2	35.8
Lockhart R.	2,883	15.2	131.8	418.7	321.0	15.2	131.8	418.7	321.0
Stewart R.	2,743	702.8	80.7	186.9	58.3	702.8	80.7	186.9	58.3
Normanby R.	24,408	5229.8	327.7	762.5	131.6	5229.8	327.7	762.5	131.6
Jeannie R.	3,637	244.0	175.8	164.9	129.5	244.0	175.8	164.9	129.5
Endeavour R.	2,104	48.7	27.6	113.5	17.1	48.7	27.6	113.5	17.1
Daintree R.	2,192					–	2.2	28.4	2.7
Mossman R.	466								–
Barron R.	2,136	–	16.9	0.7	9.9	–	15.6	0.2	7.6
Mulgrave-Russell R.	1,983	7.8	17.6	28.4	45.3	7.9	3.1	13.0	21.3
Johnstone R.	2,325	24.1	–	60.4	–	30.8	–	21.0	–
Tully-Murray R.	2,790	16.1	151.7	114.1	102.2	16.1	59.0	35.6	20.8
Herbert R.	9,843	–	154.8	62.5	2.8	–	142.8	51.6	1.8
Black R.	1,057	–	–	–	–	–	–	–	–
Ross R.	1,707	27.8	0.3	19.5	–	27.7	0.3	19.0	–
Haughton R.	4,044	360.3	64.1	94.7	210.4	352.4	51.7	59.0	42.0
Burdekin R.	130,126	4.6	2853.3	234.2	2812.3	2.8	2671.1	214.5	1860.4
Don R.	3,695	202.1	135.3	32.4	20.4	195.3	94.1	11.6	1.7
Proserpine R.	2,535	126.4	25.2	147.6	–	123.9	18.3	33.9	–
O'connell R.	2,387	131.0	40.9	47.9	–	125.4	10.4	8.8	–
Pioneer R.	1,570	11.3	53.5	41.6	73.3	6.9	19.0	2.3	64.7
Plane C.	2,539	202.1	53.1	319.0		190.3	28.4	74.6	
Styx R.	3,012	330.7	55.0	0.6	101.9	322.8	53.8	0.1	6.3
Shoalwater	3,605	229.4	0.4	5.5	41.6	226.3	0.4	5.5	26.0
Waterpark C.	1,835	–	–	–	–	–	–	–	–
Fitzroy R.	142,537	–	1117.8	59.1	4867.2	–	1352.1	47.1	1877.7
Calliope R.	2,236								
Boyne R.	2,590								
Baffle C.	3,996								
Kolan R.	2,901								
Burnett R.	33,248								
Burrum R.	3,358								
Mary R.	9,440								
Total	**423,070**	**1,673**	**4,740**	**1,268**	**8,287**	**8,011**	**5,570**	**2,599**	**4,812**



The extent of remnant floodplain vegetation communities (ca. 1997) in mapped areas of the GBRCA. The area of of floodplain communities is exaggerated by the boundaries drawn around small vegetation patches to make them visible. Maps of current floodplain vegetation communities in the wet tropics have not as yet been published.
Data source: Qld. EPA, 1999

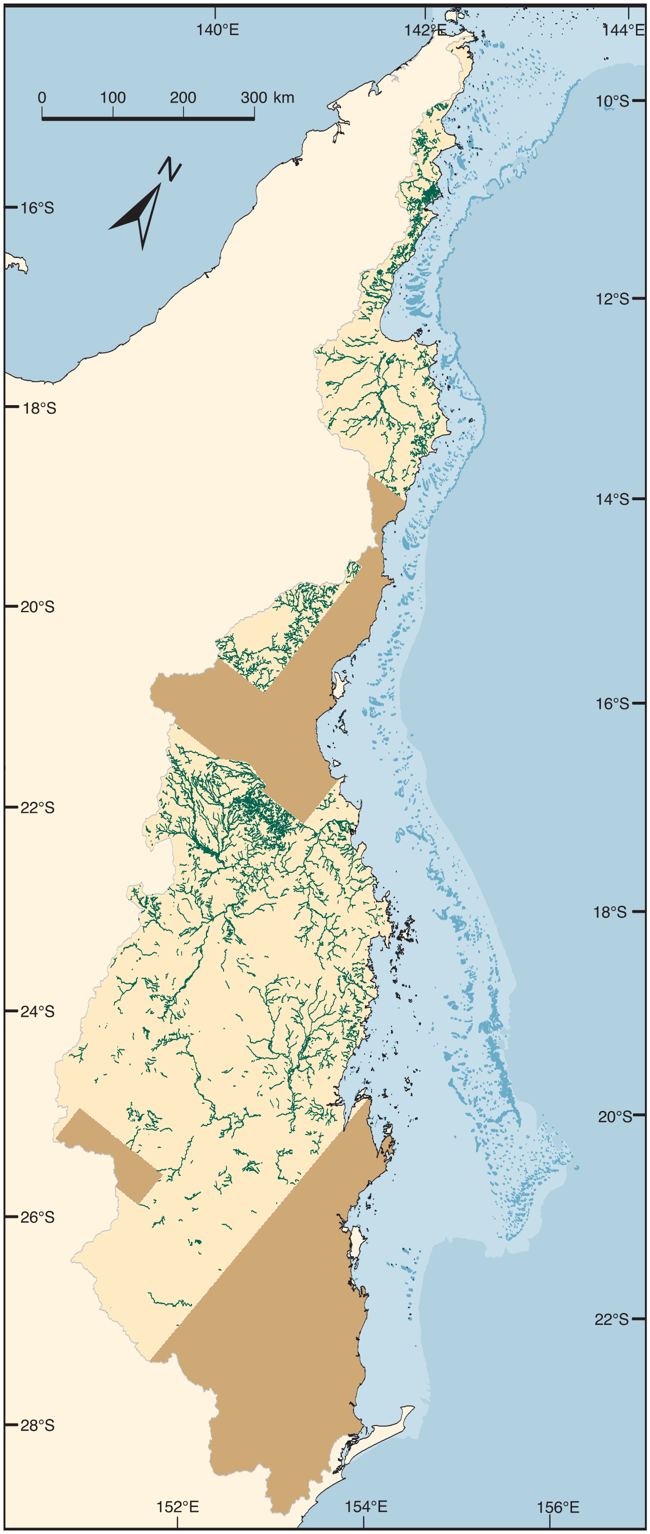
Floodplain Vegetation

GBR Catchment

GBR Catchment (unmapped)

Table 20. Relative condition of riparian vegetation in catchments bordering the GBRWHA. Data from summaries in the State of the Rivers Reports, QNR&M.

Catchment	Year	Subcatchment	Very Good	Good	Moderate % mapped	Poor	Very Poor
Tully & Murray Rivers	1998	Lower Tully Tributaries	20	6	5	7	62
		Jarra Creek	40	6	0	44	10
		Banyan Creek	23	7	11	0	59
		Hull River & Coastal Tribs.	43	16	27	0	14
		Upper Tully & Nitchaga Creeks	69	14	17	0	0
		Davidson & Echo Creeks	0	0	6	0	94
		Murray River	28	7	21	24	20
		Dallachy Creek	40	20	40	0	0
		Meunga & Kennedy Creeks	26	7	10	45	12
		Coastal Creeks	20	44	26	10	0
		Overall	28	10	18	16	28
Herbert River	1996	Marine	0	0	22	44	34
		Lower Herbert River	11	38	0	34	17
		Trebonne Creek	0	0	2	26	72
		Coastal Streams	3	2	5	12	78
		South Upland Streams	38	62	0	0	0
		North Upland Streams	5	6	21	21	47
		Upper Herbert River	0	11	26	38	25
		Dry Catchment Streams	21	9	20	16	34
		Wet Catchment Streams	0	1	3	9	87
		Overall	7	6	11	18	58
Burnett River	1999	Central Burnett	11	17	23	22	27
		North Burnett	23	21	15	10	31
		Kolan	43	9	12	15	21
		Lower Burnett	22	16	7	10	45
		Burrum	44	16	22	11	7
		Lower Barambah	12	6	8	19	55
		Upper Barambah	7	7	19	24	43
		Boyne	39	2	15	23	21
		Overall	23	13	17	17	29
Mary River	1997	Northern Creeks	36	7	15	18	24
		Tinana Creek	24	10	14	33	19
		Southwest Creeks	17	4	8	24	47
		Upper Mary	14	8	28	26	24
		Central Creeks	0	3	0	13	84
		Mary River	0	0	44	32	24
		Northwest Creeks	2	5	18	19	58
		Overall	13	7	17	23	40

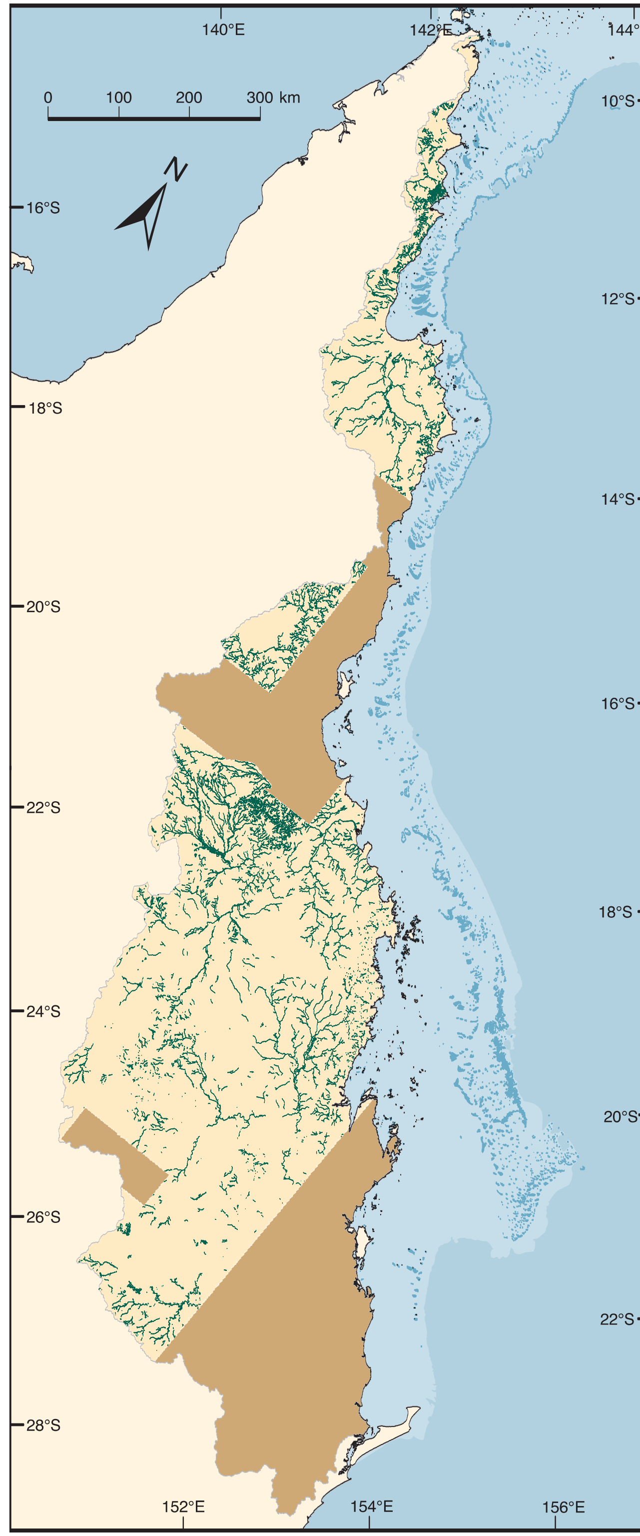


The inferred extent of pre-1850 riparian vegetation communities in mapped areas of the GBRCA based upon distributions of remnant vegetation and catchment characteristics. The area of riparian communities is exaggerated by the boundaries drawn around small vegetation patches to make them visible. Maps of inferred pre-1850 riparian vegetation in the wet tropics have not as yet been published.
Data source: Qld. EPA, 1999

Riparian Vegetation
GBR Catchment
GBR Catchment (unmapped)

The extent of remnant riparian vegetation communities (ca. 1997) in mapped areas of the GBRCA. The area of riparian communities is exaggerated by the boundaries drawn around small vegetation patches to make them visible. Maps of current riparian vegetation communities in the wet tropics have not as yet been published.
Data source: Qld. EPA, 1999

Riparian Vegetation
GBR Catchment
GBR Catchment (unmapped)



Riparian vegetation on lowland stream
Photo: GBRMPA

Flooded cane farm drain with grass-covered riparian vegetation
Photo: C. Roth, CSIRO

been cleared from the riparian zone, exposing the banks and water to full sunlight [73].

Human activities have altered riparian vegetation to some degree in a large proportion of the GBR catchment, either directly through clearing, or more extensively, through trampling and grazing by cattle [136, 225, 240, 430, 431, 518, 519]. Grazing or browsing cattle remove vegetation in the riparian zone, reducing its natural trapping efficiency. As cattle move, their hooves disturb sediments in the stream channel and break up bank soils, making these sediments and soils more susceptible to erosion. In dry areas, especially during droughts, cattle congregate near watercourses for water, shade and food, concentrating damage in the riparian zone. Where animals have access to watercourses for long periods, paths worn down steep streambanks are initiation sites for gully development [367].

Riparian vegetation reduces soil loss from catchments by physically stabilising stream banks and trapping eroded soils carried by overland water flow. The efficiency with which riparian vegetation traps sediment is governed by the slope of the land adjacent to the watercourse, the width of the riparian zone and the near-ground vegetation density. Experimental trials in the wet tropics show that grass strips of sufficient width can trap up to 80% of eroded soil entering the riparian zone [293, 320]. Stream and gully banks with vegetation cover, even grass, are many times more resistant to erosion than bare banks [2,3]. However riparian vegetation does not permanently protect banks from erosion. All streambanks are subject to some erosion that can eventually undercut and wash away local plant communities. Because of the ready availability of water, streambank plant communities usually regenerate quickly after disturbances.

The effectiveness of riparian or other vegetation in reducing soil losses varies within catchments. At the top

Lowland farm drain with poorly developed riparian vegetation
Photo: C. Roth, CSIRO

of catchments, most erosion occurs on hillslopes and in gully networks. Soil eroded from gullies largely comes from the sides of gullies rather than from gully extension [52, 387, 544]. Re-vegetation of upland streams and gullies will cover banks and slow water flow, trapping eroded soil before it reaches larger streams [200]. Clearing, burning or grazing of vegetation along gully and stream banks exposes the bank to the erosive power of floodwaters.

Riparian vegetation in GBR catchments has been cleared for a variety of reasons. Flat floodplain soils adjacent to watercourses are preferred sites for grazing cattle and growing crops. Floodplain soils often have elevated

Cattle in streambed
Photo: JCU Historical Photographic Collection

concentrations of biologically accessible nutrients such as phosphorus [5]. There is a strong economic incentive to maximise the area of easily cropped land on floodplains by clearing and cultivating to the water's edge. However, clearing of riparian vegetation accelerates landscape soil loss by removing natural sediment traps and shortening the distance between readily eroded paddock soils and the river system.

The status of riparian vegetation within the GBR catchment is still only partly resolved (Tables 19-22). There have been detailed surveys of riparian vegetation in several catchments. The results show that a significant proportion of the riparian vegetation along both large and small watercourses has been thinned or reduced in width. The degree of disturbance is often greater along smaller streams and waterways that comprise most of the stream frontage in catchments [317]. Most eroded soil initially enters river systems through these small, seasonally flowing streams. The enormous number of small streams in all catchments makes management practices such as fencing streams to exclude cattle, very difficult and expensive.

Table 21. Riparian buffer widths for large creeks and rivers in the Central Highlands of Queensland. For streams of this size, “good” buffer widths exceed 400m, “medium” width = 220-400 m and “poor” width is less than 220 m.
Data from McCosker and Cox, 1997.

Shire	Stream distance Assessed (km)	Good Width %	Medium Width %	Poor Width %
Bauhinia	711	62	12	26
Belyando	1051	74	13	13
Broadsound	595	66	20	14
Duaringa	431	60	26	13
Emerald	344	61	32	7
Jericho	757	71	16	13
Peak Downs	235	86	10	4
Total	**4124**	**69**	**17**	**14**

Table 22. Riparian buffer widths for small creeks in the Central Highlands of Queensland. For streams of this size, "good" buffer widths exceed 220 m, "medium" width = 110-220 m and "poor" width is less than 110 m.
Data from McCosker and Cox, 1997.

Shire	Stream distance Assessed (km)	Good Width %	Medium Width %	Poor Width %
Bauhinia	2134	67	13	20
Belyando	1479	85	6	9
Broadsound	1223	66	14	20
Duaringa	1428	56	15	29
Emerald	1185	74	9	17
Jericho	923	78	9	13
Peak Downs	888	89	7	4
Total	**9260**	**72**	**11**	**17**

The sediment trapping efficiency of riparian vegetation communities is best maintained by preserving vegetation corridors of adequate width along watercourses, fencing watercourses to exclude cattle, and providing water and shade away from streams to give cattle alternatives to using the riparian zone.

Vegetation communities and land clearing

Modern increases of sediment and nutrient runoff into the GBR are mostly due to increased soil erosion throughout the GBR catchment and losses of agricultural fertilisers applied to cultivated land.

Gully erosion, Burdekin River catchment
Photo: C. Roth, CSIRO

The inferred broad-scale distribution of natural (pre-1788) vegetation community structural types in the GBRCA. Data source: AUSLIG, 1997

- Forest (T4, M3, M4)
- Medium woodland (M1, M2)
- Low woodland (L1, L2, L3, L4)
- Grasslands, sugarcane, pasture (F4, G3, G4)
- Heathlands (Z3)

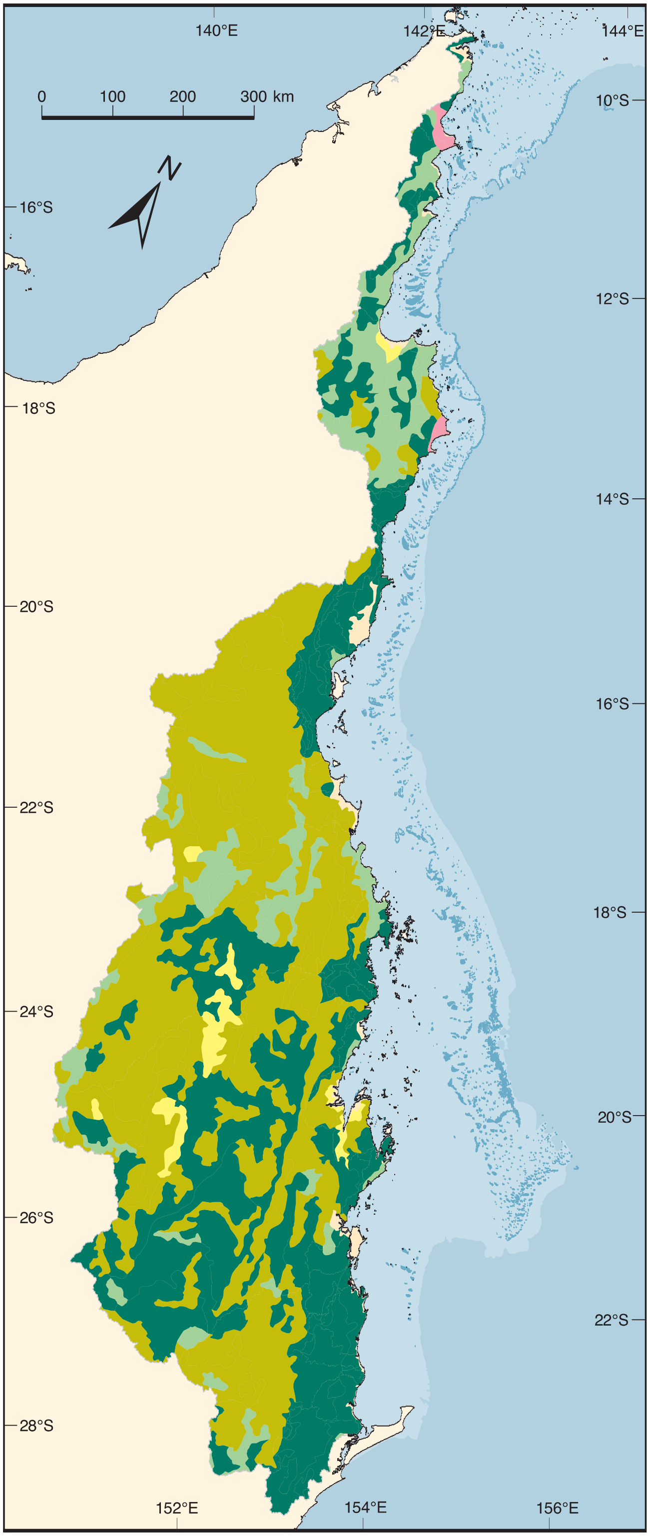


Table 23. Distribution of major vegetation cover types in in GBR catchment basins prior to European settlement (ca. 1788) as estimated by AUSLIG, 1997. Structural types are based on the density and height of the dominant type of overstory vegetation in a contiguous area. Unclas - unclassified, DSP - dense sown pasture, TG - Tussock grassland CTG-CS - closed tussock grassland/closed shrubland, LOW - low open woodland, LW - low woodland, LOF - low open forest, LCF - low closed forest, OW - open woodland, W - woodland, OF - open forest, CF - closed forest, TCF - tall closed forest, H - heathland.

Basin Name	Basin Area km^2	Unclas	DSP	TG	CTG-CS	LOW	LW	LOF	LCF km^2	OW	W	OF	CF	TCF	H
Jacky Jacky C.	2,963	172						697				676	396		795
Olive-Pascoe R.	4,179	116					1,299	361			12	1,835	349		206
Lockhart R.	2,883	138					1,024	500			3	6	1,211		
Stewart R.	2,743	26					1,354	78				991	294		
Normanby R.	24,408	126			608	1,619	7,162	5,058			2,316	7,255	84		
Jeannie R.	3,637	183					657	735			1,028	513			521
Endeavour R.	2,104	9					163	140			836	667	252		38
Daintree R.	2,192	13					41					296	1,843		
Mossman R.	466	10									4	111	340		
Barron R.	2,136	4				26	0				1,202	154	757		
Mulgrave-Russell R.	1,983	44										128	1,421	389	
Johnstone R.	2,325	3											1,413	908	
Tully R.	1,683							45				112	1,526		
Murray R.	1,107	20						205				206	675		
Herbert R.	9,843	28									4,712	3,447	1,656		
Black R.	1,057	17				19				370		429	221		
Ross R.	1,707	85				108				1,167		202			
Haughton R.	4,044	75				545				2,317	553	82			
Burdekin R.	130,126			2,381		9,365	2,873	3,567	808	51,154	43,359	15,835	780		
Don R.	3,695	70				1,233				1,865	527				
Proserpine R.	2,535	99				195	927			49	570		695		
O'Connell R.	2,387	76					47				566	1,175	523		
Pioneer R.	1,570										86	1,058	426		
Plane C.	2,539	54					284				301	1,621	89		
Styx R.	3,012	49			295						2,090	418			
Shoalwater	3,605	173			867						1,311	1,191			
Waterpark C.	1,835	145					313				60	1,317			
Fitzroy R.	142,537	85		4,455	57		622		4,027	1,631	63,951	67,169	258		
Calliope R.	2,236	21							184			1,998			
Boyne R.	2,590	22										2,263	305		
Baffle C.	3,996	227										3,500	270		
Kolan R.	2,901	49										2,761	90		
Burnett R.	33,248	26							2,554		21,678	8,733	258		
Burrum R.	3,358	146										2,672	539		
Mary R.	9,440	28					64				174	8,124	1,050		
Total	423,070	2,340	0	6,835	1,826	13,105	16,831	11,386	7,573	58,555	145,338	136,947	17,724	1,297	1,561
% GBRCA		0.55	0	1.6	0.4	3.1	4	2.7	1.8	13.8	34.3	32.4	4.2	0.3	0.4

Soil erosion, which begins the movement of soil and nutrients from catchments, is a continuous, but entirely natural part of landscape change and evolution. Catchments and the soils within them are produced by natural weathering, erosion, sediment transport and sediment re-deposition over thousands to millions of years. These processes have moved sediment and nutrients downward through catchments into the GBR for the entirety of its existence. The rate of soil erosion and nutrient loss depends on the erodability and composition of soils, the amount and distribution of rainfall and the energy provided by flowing water to move sediment downstream in rivers. The distribution of soils, rainfall and the distribution of rainfall volumes are natural and are unlikely to be influenced by human activities. There is clear evidence, however, that human land use has changed soil erosion rates at the landscape level. Cropped or grazed land, particularly where the vegetation is removed and the soil is physically disturbed, have soil loss rates far in excess of rates in landscapes covered by native vegetation and carefully managed pastures [348, 399].

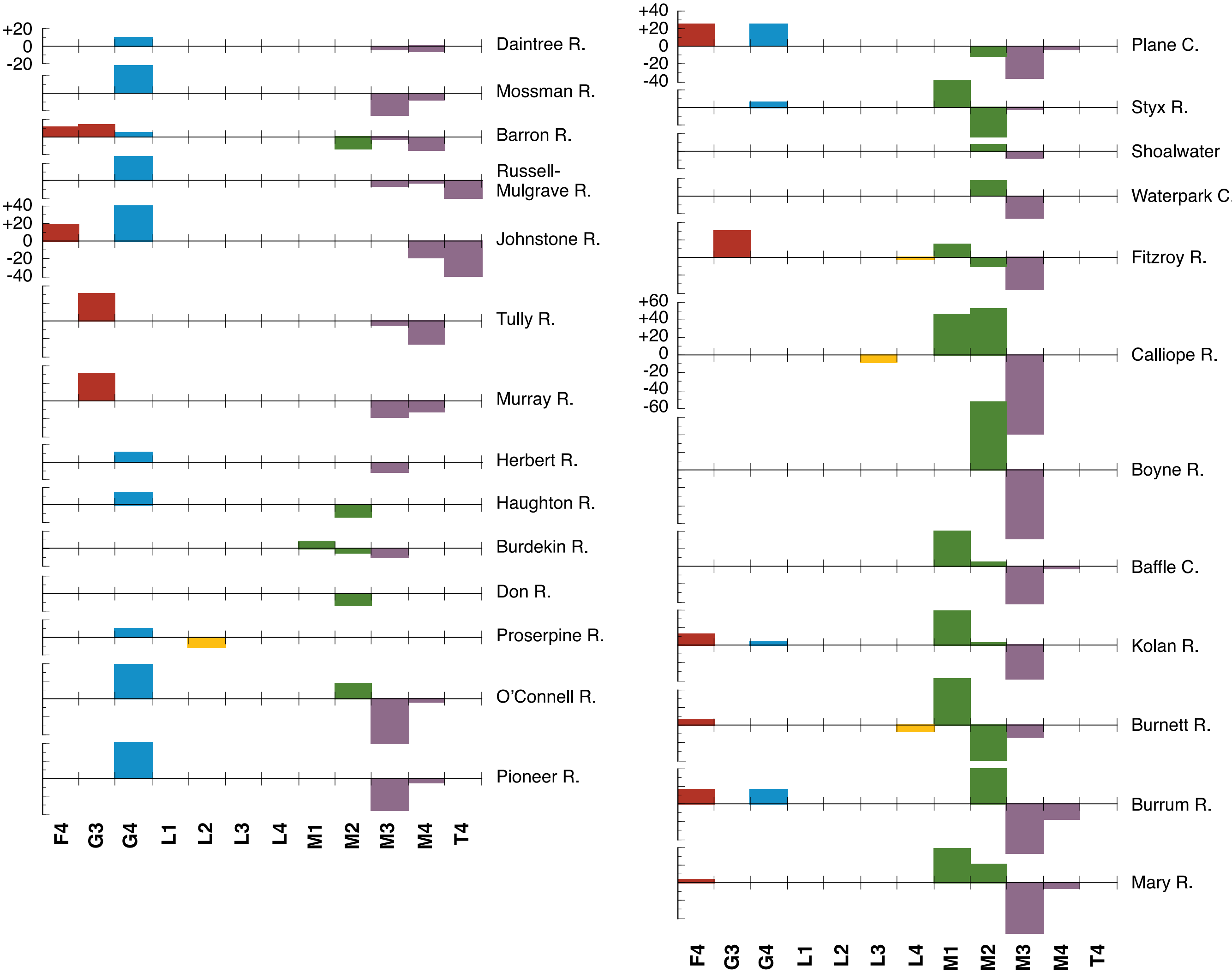
There have been several attempts to map the composition and extent of modern vegetation communities in the GBR catchment, and from them, to estimate the composition and distribution of natural (pre-1850) vegetation. An examination of the various mapping efforts provides an overview of human effects on the GBR catchment.

Prior to the beginning of European settlement in the mid 1800s, much of the GBR catchment was covered by a mix of forest and woodland vegetation (Table 23). Ground cover varied in response to climate, seasonal changes in rainfall, and burning from natural causes and by Indigenous peoples. The dominant vegetation communities of the GBR catchment have been characterised and mapped using structural characteristics (e.g. woodland, forest, grassland) and dominant overstory species (Table 24). The distributions

Cattle in well-grassed open woodland
Photo: QDPI

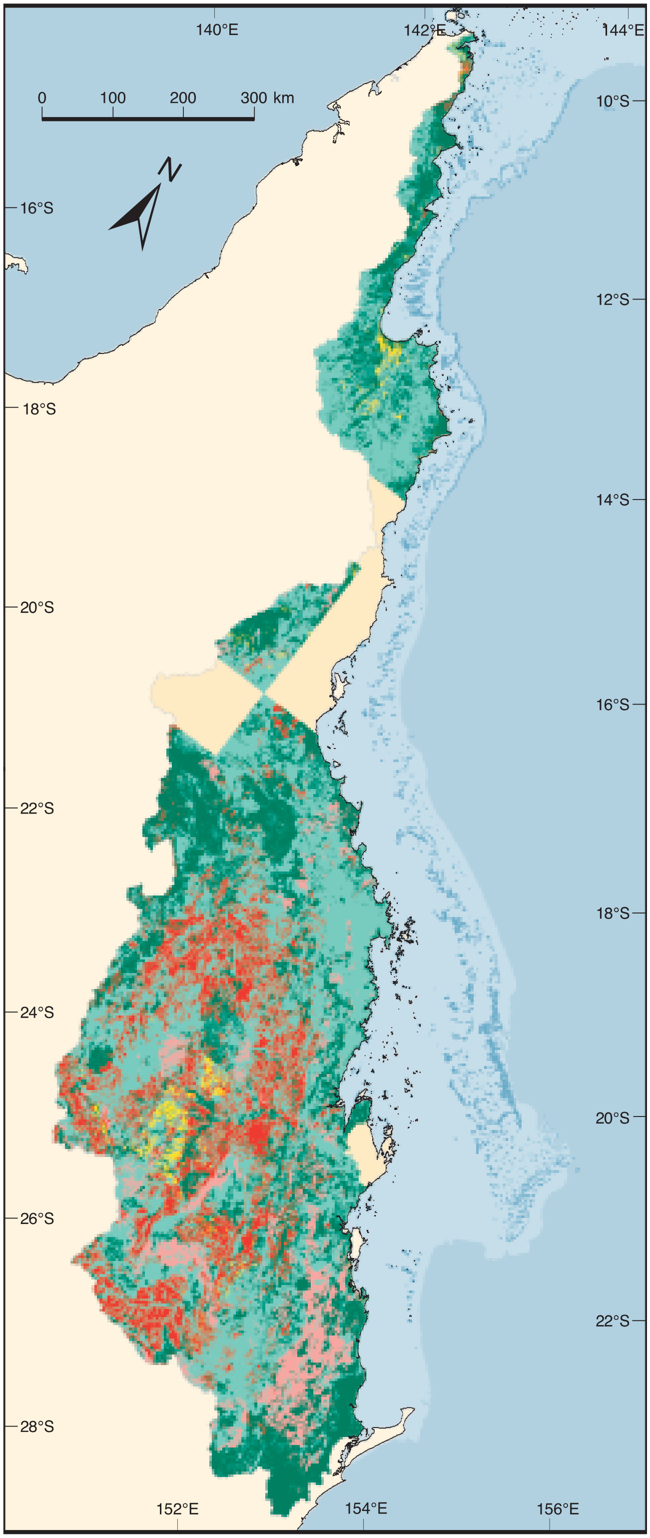
Table 24. Distribution of major vegetation cover types in in GBR catchment basins at the present time (ca. 1988) as estimated by AUSLIG, 1997. Structural types are based on the density and height of the dominant type of overstory vegetation in a contiguous area. Uncl - unclassified, DSP - dense sown pasture, TG - Tussock grassland CTG-CS - closed tussock grassland/closed shrubland, LOW - low open woodland, LW - low woodland, LOF - low open forest, LCF - low closed forest, OW - open woodland, W - woodland, OF - open

Basin Name	Area km^2	Unclas	DSP	TG	CTG-CS	LOW	LW	LOF	LCF km^2	OW	W	OF	CF	TCF	H
Jacky Jacky C.	2,963	172						697				676	395		795
Olive-Pascoe R.	4,179	116					1,299	361			12	1,835	349		206
Lockhart R.	2,883	138					1,024	500			3	6	1,212		
Stewart R.	2,743	27					1,354	77				991	294		
Normanby R.	24,408	127			608	1,619	7,162	5,058			2,316	7,255	84		
Jeannie R.	3,637	182					657	736			1,028	513			521
Endeavour R.	2,104	9					163	140			836	667	252		38
Daintree R.	2,192	13			214		41					296	1,712		
Mossman R.	466	11			143						4	111	308		
Barron R.	2,136	4	239	294	99	19					907	98	440		
Mulgrave-Russell R.	111	1,983	45	15	538							1,386			
Johnstone R.	2,325	4	424		908								990		
Tully R.	1,683	0		522				45				27	1,089		
Murray R.	1,107	20		332				206				2	547		
Herbert R.	9,843	28	119		1,100						4,712	2,347	1,538		
Black R.	1,057	17				20				370		428	221		
Ross R.	1,707	86				108				1,168		202			
Haughton R.	4,044	74			553	545				2,317		82			
Burdekin R.	130,126	0		9,306	250	9,365	2,965	3,461	808	62,466	37,335	3,386	780		
Don R.	3,695	70			30	1,233				1,865	497				
Proserpine R.	2,535	100			248	195	669			49	609		664		
O'Connell R.	2,387	77			899		3				964		445		
Pioneer R.	1,570	0			642						82	502	344		
Plane C.	2,539	54	623		631		284				33	725			
Styx R.	3,012	49			484					878	1,089	352			
Shoalwater	3,605	174			867					2	1,566	935			
Waterpark C.	1,835	146					313				354	900			
Fitzroy R.	142,537	85	1,994	46,945	2,597		622		418	22,389	50,693	16,089	130		
Calliope R.	2,236	22								1,002	1,156	24			
Boyne R.	2,590	22								7	1,965	265	330		
Baffle C.	3,996	228	17							1,489	189	1,912	161		
Kolan R.	2,901	49	360		111					1,084	73	1,144	79		
Burnett R.	33,248	26	2,159	514	275				89	17,394	8,660	4,131			
Burrum R.	3,358	147	526		539						1,269	877			
Mary R.	9,440	28	370				63			3,642	2,126	2,737	474		
Total	423,070	2,348	6,845	57,913	11,733	13,104	16,620	11,281	1,315	116,121	118,476	49,322	14,225	0	1,561
% GBR Catchment		0.6	1.6	13.7	2.8	3.1	3.9	2.7	0.3	27.4	28.0	11.7	3.4	0	0.4



Estimated changes (as % basin area) in the structure of dominant overstory vegetation in GBRCA drainage basins between 1788 (native vegetation) and 1988 (current vegetation). Basins without recorded changes are not shown. See maps on pages 127 and 123. Data source: AUSLIG, 1997

F4	-	*Dense sown pasture*
G3	–	*Tussock grassland or sedgeland*
G4	–	*Closed tussock grassland or closed sedgeland (includes sugarcane)*
L1	–	*Low open woodland*
L2	–	*Low woodland*
L3	–	*Low open forest*
L4	–	*Low closed forest*
M1	–	*Open woodland*
M2	–	*Woodland*
M3	–	*Open forest*
M4	–	*Closed forest*
T4	–	*Tall closed forest*

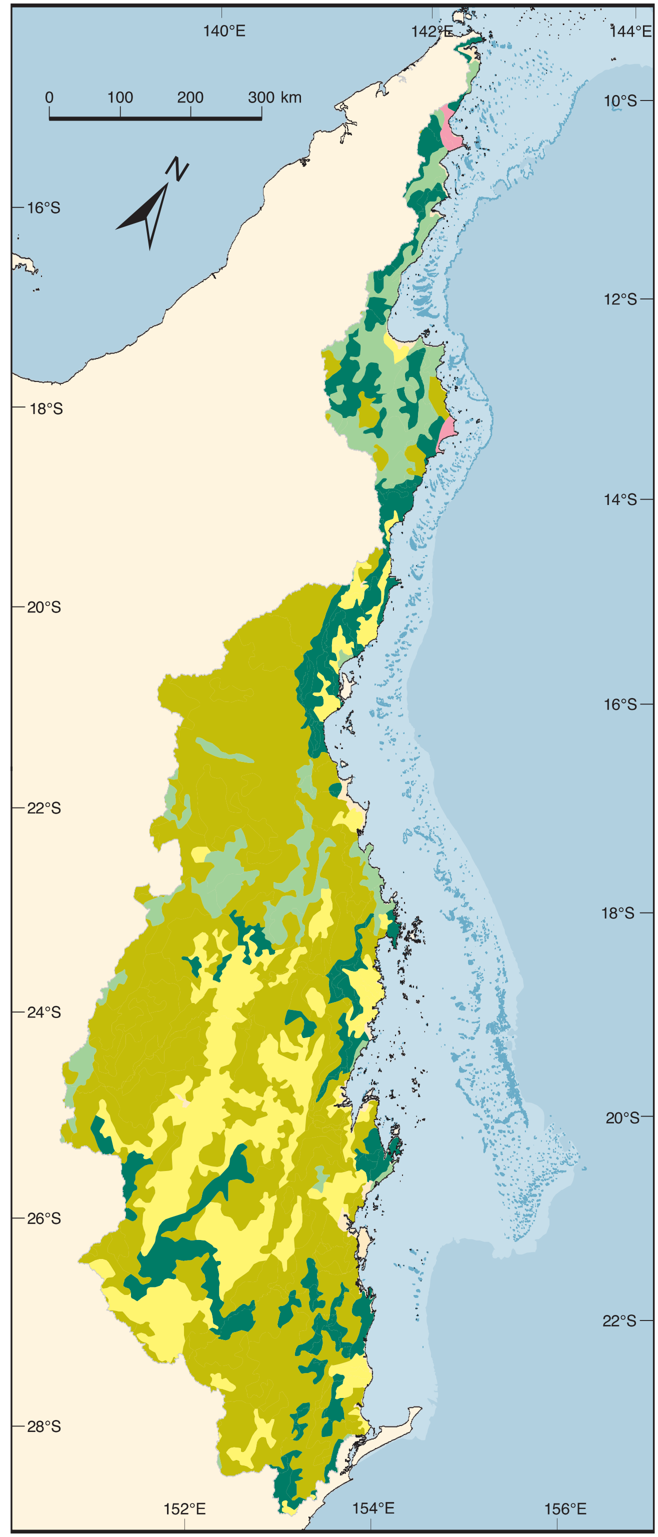


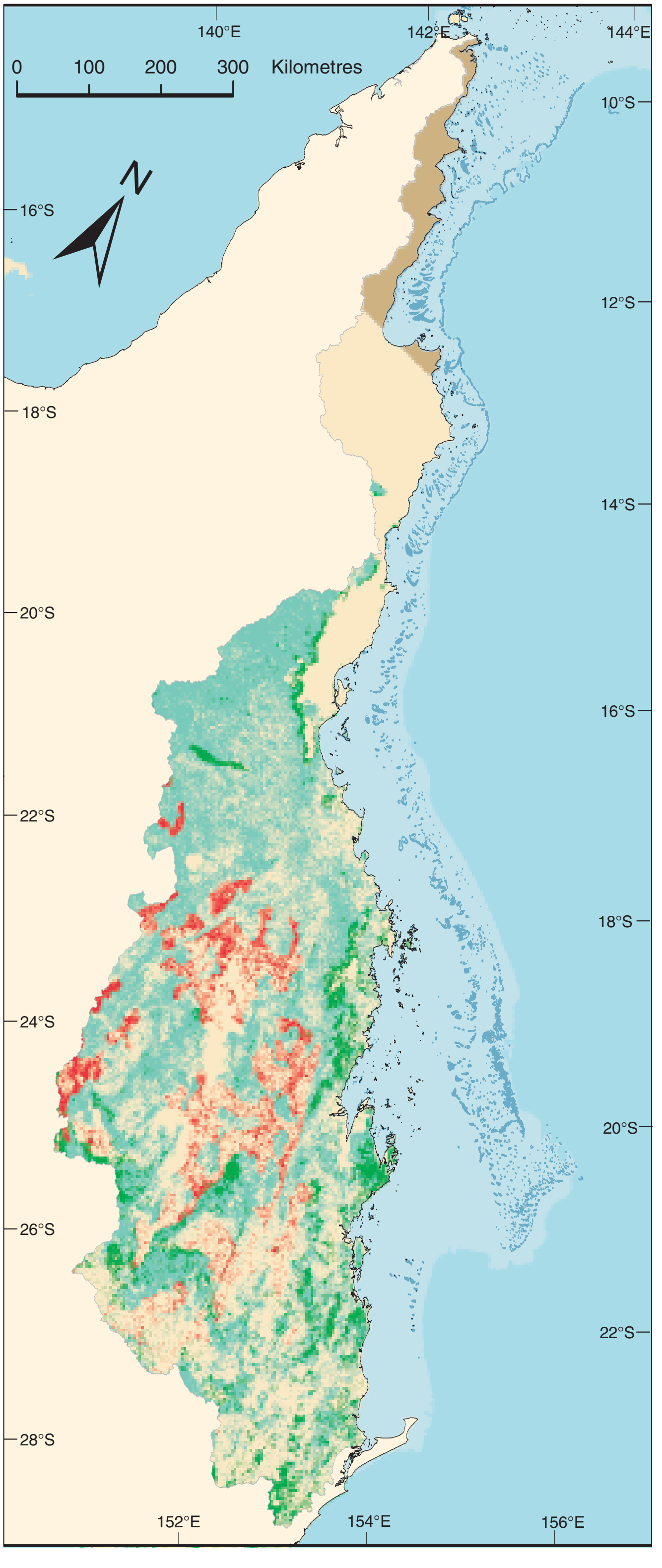
The inferred (pre-1850) distribution of major vegetation communities in the GBRCA based on distributions of remnant vegetation and catchment characteristics. Community classifications are based on ground-based vegetation mapping, satellite imagery and aerial photography. Blank areas indicate sections of the GBRCA where vegetation classifications have not been released at this time.
Data source: Qld. EPA, 2001

Eucalypt dominated
Acacia dominated
Corymbia dominated
Grassland
Other
GBR catchment, unclassified

The modern (ca. 1988) broad-scale distribution of major vegetation structural types in the GBRCA.
Data source: AUSLIG, 1997

- Forest (T4, M3, M4)
- Medium woodland (M1, M2)
- Low woodland (L1, L2, L3, L4)
- Grasslands, sugarcane, pasture (F4, G3, G4)
- Heathlands (Z3)



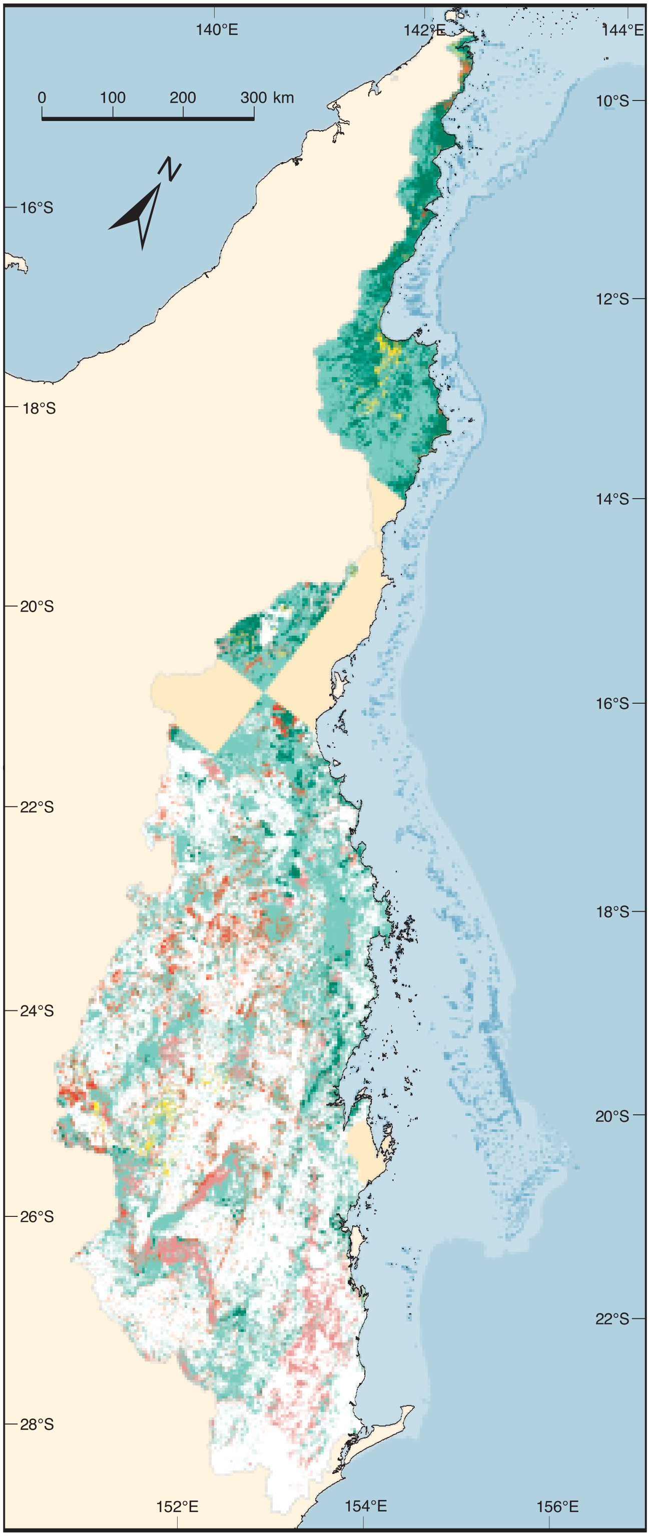


The present (ca. 1995) distribution of eucalypt, Acacia-dominated forest and woodland communities in the GBRCA derived from interpretation of satellite imagery (LANDSAT MSS) of remnant vegetation. Vegetation communities in the wet tropics and on Cape York Peninsula (14°S – 17°S) were not classified. Unclassified areas south of 17°S and outside of the wet tropics can be regarded as cleared or altered.
Data source: BRS, 1999

Eucalypt
Acacia
Other
Cleared
Unmapped or unclassified

The present distribution (ca. 1997) of major remnant vegetation communities in the GBRCA. Community classifications are based upon ground-based vegetation mapping, satellite imagery and aerial photography. Unclassified areas indicate sections of the GBRCA where vegetation classifications have not been released. Data source: Qld. EPA, 2001

- *Eucalypt dominated*
- *Acacia dominated*
- *Corymbia dominated*
- *Grassland*
- *Other*
- *Cleared*
- *GBR catchment, unclassified*



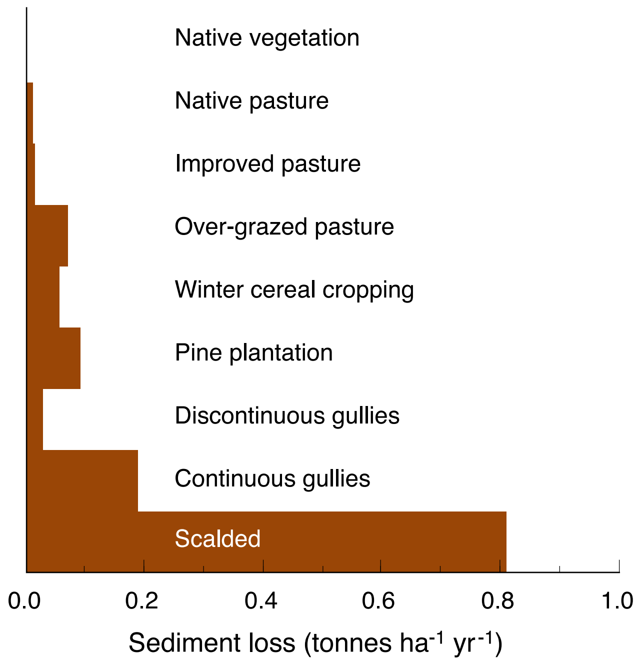
of dominant plant communities are based on analysis of aerial and satellite imagery validated by ground surveys of remnant vegetation (AUSLIG, 1997; Qld. EPA, 2000, [5,34]). Although different approaches have been used, the various mapped distributions of pre-1850, uncleared vegetation communities in drier regions of the catchment are generally similar. At present, maps of the more diverse and complicated vegetation communities in the wet tropics have not been published, though in limited areas, remnant vegetation has been mapped in detail [490, 554].

Eucalyptus, Corymbia and *Acacia* woodlands form the dominant overstory vegetation communities of the GBR catchment, particularly in inland and drier coastal areas. Prior to 1850, it is estimated that forests (174,000 km^2) and woodlands (234,000 km^2) of varying tree height and density covered 96% of the GBR catchment. During the last 150 years, the areas covered by forests and woodlands have changed to 76,000 km^2 and 264,000 km^2, respectively, or 80% of the GBR catchment. The total area of forest and woodland has decreased because of land clearing or vegetation thinning for cropping and grazing. The greatest losses have taken place in the *Acacia*-dominated Brigalow communities of the Fitzroy and Burdekin River basins. There have been declines in the area of forests (M4, T4) and closed woodlands (M3) in virtually all of the mainland drainage basins with parallel increases in the extent of open- and low- woodland communities (M1, M2). The net change includes a 57,500 km^2 increase in open woodlands, presumably due to tree thinning. Increases in the area of grasslands include developed pastures (F4, G3) and land planted with sugarcane (G4).

Broad-scale estimates of land cover, land use and major remnant vegetation distributions are now largely derived through analysis of satellite imagery (Qld. EPA, 2001, [34, 171]). The spatial resolution of modern satellite imagery is on the order of metres, making it possible to identify crops, accurately measure the areas of complete tree clearance, and map small remnant vegetation patches. There are limits to satellite image interpretation because of the difficulty of discriminating vegetation thinning and changes in understory vegetation (woody shrubs, grasses). The latter problem can be minimised by using imagery collected late in the dry season when green grass cover is minimal or, at least, most different from overstory vegetation. During extreme drought conditions, the extent of tree cover may also be underestimated. Satellite-based estimates of vegetation cover need to be carefully validated against ground surveys and aerial-photo based mapping of clearing, vegetation cover and vegetation type.

Pre-1850 vegetation communities in the GBR catchment were not entirely pristine. In all but the wettest parts, the natural vegetation was subject to episodic fires started by lightning, and over the last 40-60,000 years, by Indigenous peoples [153, 235, 242, 355, 356, 407, 472]. The frequency of burning prior to 1850 is still not well resolved, but it was extensive and probably varied with drought conditions and the quantity of burnable vegetation and litter. For practical purposes, the vegetation communities produced by natural fires and aboriginal burning can be considered the natural state of land cover in the GBR catchment prior to modern agricultural clearing. Over the 8-10,000 years during which the modern GBR formed, sediment and nutrient loads in regional river systems have been governed by this level of land disturbance.

There are very few net erosion rates measured in undisturbed or relatively undisturbed landscapes in the GBR catchment. Estimated annual erosion rates in grazed habitats range from virtually nil [58] to ca. 1,800 tonnes per km^2 in gully systems of the upper Burdekin River catchment [548]. Some landscapes in the GBR catchment are naturally erosive due to topography, soil type and rainfall [389]. There is evidence that gully erosion has taken place in parts of the



Soil loss from small catchments on the Southern Highland, NSW in relation to vegetation cover and land use. Data replotted from Neil and Fogarty, 1991.

Burdekin River catchment for hundreds, if not thousands of years [89]. The earliest European explorers in the region reported that the Burdekin River became turbid during flood events [274], indicating active erosion. Post-settlement land clearing triggered an increase in gully erosion in southeastern Australia [122, 393, 396, 550]. A similar increase in gullying within the GBR catchment is also likely, although the degree is probably different.

Most measurements of erosion from undisturbed land have been made to compare with soil loss rates from experimental cropping or grazing plots. There are considerable differences between soil loss rates from plots (< 1 km^2) or small-catchments (< 100 km^2) and the net export of sediment from whole river catchments due to short-range soil movements within sub-catchments and sediment storage in catchments. Broad-scale estimates of sediment delivery to the GBR based on relationships between land use and soil loss produce reasonable estimates when they assume that net sediment export from catchments is only 10% of the landscape soil erosion rate (delivery ratio = 0.1) [339, 418]. A detailed mathematical model of sediment export from the Burdekin River catchment based on hillslope erosion, sediment transport hydrology and a delivery ratio of 0.1 estimates net sediment export at 2.4 million tonnes per year which is similar to measured values (Chapter 8) [389]. In limited areas, such as steep cleared hillsides in the wet tropics, sediment delivery ratios exceeding 0.8 have been measured (80% of eroded soil reaches the stream network) [548]. Annual soil loss rates as high as 2,000 tonnes per ha have been recorded from banana paddocks on steep hillsides [548].

Land clearing in the GBR catchment

Modern human land use in drier inland sections of GBR drainage basins usually begins with livestock grazing in native woodland, followed by tree and vegetation thinning or removal to produce pastures or paddocks. Vegetation clearing initiates physical, geochemical and biological

The first estimate of land clearing in the GBRCA (ca. 1988) prepared by analysis of satellite imagery.
Data source: Graetz et al., 1995

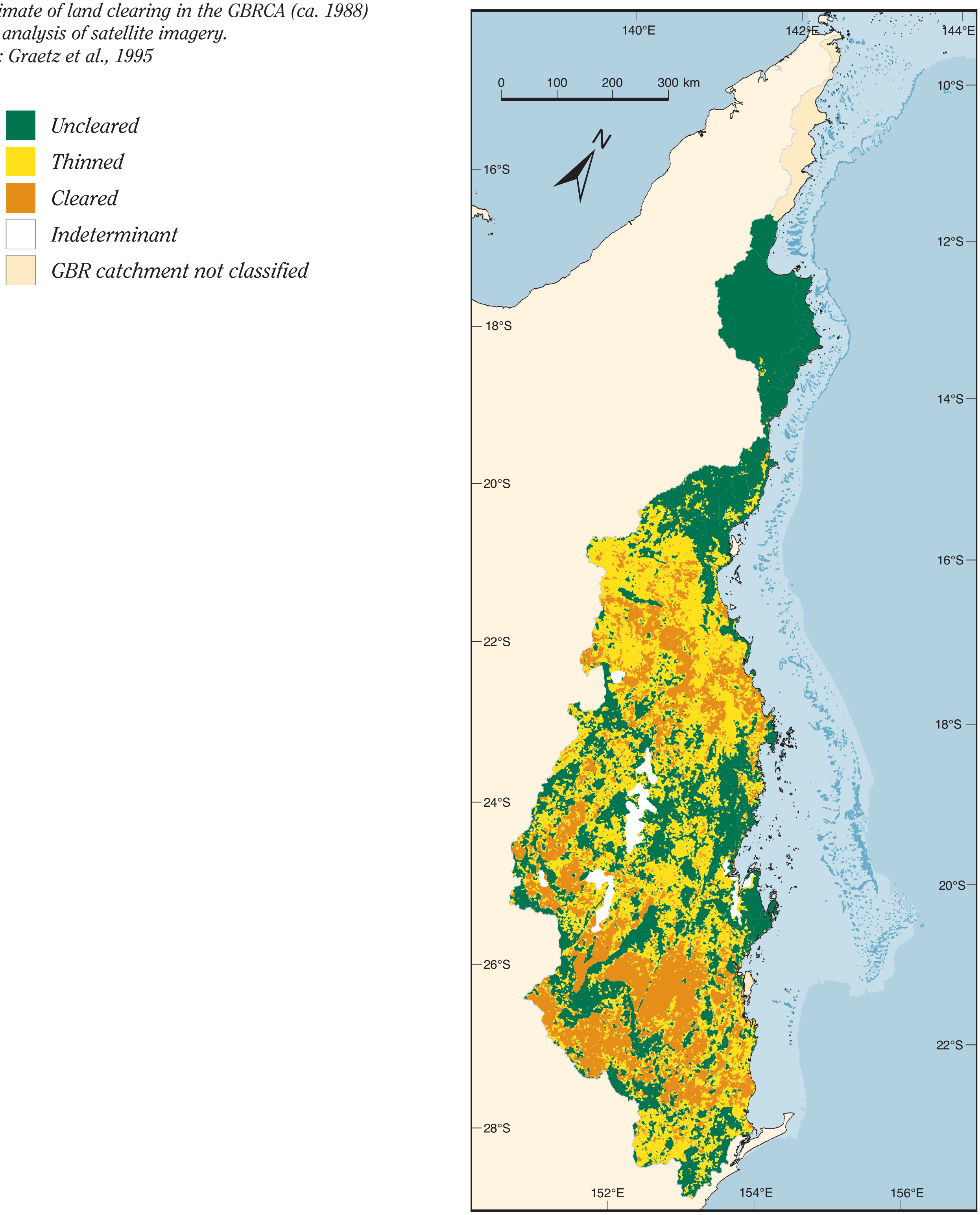


Table 25. Estimates of land clearing in the GBRCA (ca. 1988) derived from analysis of satellite imagery. Data source: Graetz *et al.,* 1995.

Basin Name	Basin Area km²	Cleared	Thinned	Uncleared km²	Indeterminate	Unclassified
Jacky Jacky C.	2,963	404		1,255	826	477
Olive-Pascoe R.	4,179	851	2,790	111	137	291
Lockhart R.	2,883		619	1,965		298
Stewart R.	2,743			2,694		49
Normanby R.	24,408	7	133	24,263		5
Jeannie R.	3,637		1	3,531		105
Endeavour R.	2,104			2,046		58
Daintree R.	2,192	11		2,114		67
Mossman R.	466	5	14	423		24
Barron R.	2,136	9	88	2,034		4
Mulgrave-Russell R.	1,983	46	231	1,637		70
Johnstone R.	2,325	2	404	1,875		44
Tully R.	1,683	14	242	1,401		26
Murray R.	1,107		166	906		35
Herbert R.	9,843	77	1,357	8,368		41
Black R.	1,057	55	446	539		17
Ross R.	1,707	336	893	442		36
Haughton R.	4,044	414	2,707	878		45
Burdekin R.	130,126	30,405	64,485	32,780	2,458	0
Don R.	3,695	1,794	1,601	259		40
Proserpine R.	2,535	646	868	904		117
O'Connell R.	2,387	350	864	1,083		90
Pioneer R.	1,570	90	376	1,094		10
Plane C.	2,539	278	544	1,593		124
Styx R.	3,012	133	1,090	1,432	336	21
Shoalwater	3,605	34	477	2,192	844	59
Waterpark C.	1,835	39	96	1,579		121
Fitzroy R.	142,537	42,704	43,238	51,771	4,616	208
Calliope R.	2,236	1,070	794	367		5
Boyne R.	2,590	669	1,290	589		42
Baffle C.	3,996	1,062	2,122	692		120
Kolan R.	2,901	1,250	1,238	410		4
Burnett R.	33,248	11,193	12,558	9,493		5
Burrum R.	3,358	785	1,562	939		73
Mary R.	9,440	356	3,389	5,691		3
Total	**423,070**	**95,088**	**146,684**	**169,350**	**9,216**	**2,732**
% of GBRCA		**22.5**	**34.7**	**40.0**	**2.2**	**0.6**

Newly cleared paddock
Photo: C. Roth, CSIRO

processes that directly influence the magnitude of sediment and nutrient runoff. The clearing process may involve tree cutting, knocking down standing vegetation, poisoning with herbicides, burning living and dead vegetation and deliberate overgrazing. In individual paddocks, the degree of clearing may vary from selective thinning of trees and undergrowth to the complete removal of all natural vegetation.

Because of the size of the GBR catchment, the extent of land clearing has largely been estimated by analysis of satellite imagery. The first large-scale landcover map based on satellite imagery was produced in the late 1980s [171]. Based on this analysis, 95,000 km^2 of land in the GBR catchment was classified as cleared (22%) and 147,000 km^2 as thinned (35%) (Table 25). Approximately 40% of the

Table 26. Summary statistics for tree clearing (1991-1999) in GBRCA drainage basins. Cleared areas for pre-1991 were derived from Barson et al. (2000). Post-1991 cleared areas were obtained from results of the Statewide Landcover And Trees Study (SLATS: QNR&M; 1999a, 1999b, 2000).

		Area Cleared				% Cleared			
Basin Name	Area km^2	pre-1991	1991-95	1995-97 km^2	1997-99	pre-1991	1991-95	1995-97	1997-99
Jacky-Jacky C.	2,963	0	0	0	0				
Olive-Pascoe R.	4,179	57	0	0	0	1.4			
Lockhart R.	2,883	130	0	< 0.1	0	4.5		< 0.01	
Stewart R.	2,743	81	0	0	0	2.9			
Normanby R.	24,408	1,155	10.9	0.8	0.7	4.7	0.04	< 0.01	< 0.01
Jeannie R.	3,637	99	0	1.9	2.0	2.7		0.05	0.06
Endeavour R.	2,104	165	0.3	5.0	5.0	7.8	0.01	0.24	0.24
Daintree R.	2,192	564	0.3	0.3	0.4	25.7	0.01	0.02	0.02
Mossman R.	466	54	0.1	0.2	0.1	11.6	0.01	0.05	0.02
Barron R.	2,136	783	2.1	7.7	3.7	27.0	0.07	0.27	0.13
Mulgrave-Russell R.	1,983	612	0.9	0.4	0.4	30.9	0.05	0.02	0.02
Johnstone R.	2,325	1,212	1.7	1.6	0.4	52.1	0.07	0.07	0.02
Tully R.	1,683	576	0.9	1.5	0.6	34.2	0.06	0.09	0.03
Murray R.	1,107	463	7.8	4.2	3.0	41.9	0.70	0.38	0.27
Herbert R.	9,843	1,971	22.9	11.7	8.4	20.0	0.23	0.12	0.08
Black R.	1,057	181	1.4	3.6	3.9	17.2	0.13	0.34	0.36
Ross R.	1,707	245	1.0	2.6	5.9	14.3	0.06	0.15	0.34
Haughton R.	4,044	1,130	6.3	12.0	12.5	27.9	0.16	0.30	0.31
Burdekin R.	130,126	40,179	576.8	524.6	486.0	30.9	0.44	0.40	0.37
Don R.	3,695	2,184	3.6	2.8	1.9	59.1	0.10	0.08	0.05
Proserpine R.	2,535	992	4.2	14.0	2.9	39.1	0.16	0.55	0.11
O'Connell R.	2,387	1,175	2.7	4.2	4.2	49.2	0.11	0.17	0.17
Pioneer R.	1,570	1,021	0.5	5.1	0.9	65.0	0.03	0.32	0.06
Plane C.	2,539	514	7.9	20.4	13.5	20.2	0.31	0.80	0.53
Styx R.	3,012	630	3.9	6.4	6.4	20.9	0.13	0.21	0.21
Shoalwater	3,605	599	1.3	1.8	1.7	16.6	0.03	0.05	0.05
Waterpark C.	1,835	14	2.4	3.3	3.8	0.8	0.13	0.18	0.20
Fitzroy R.	142,537	51,057	607.9	686.8	746.1	35.8	0.43	0.48	0.52
Calliope R.	2,236	91	1.3	1.3	4.1	4.1	0.06	0.06	0.18
Boyne R.	2,590	1	1.1	0.5	2.1	<0.01	0.04	0.02	0.08
Baffle C.	3,996	0	3.8	11.1	18.3		0.10	0.28	0.46
Kolan R.	2,901	0	1.6	3.8	5.7		0.05	0.13	0.20
Burnett R.	33,248	7,972	23.3	49.0	62.5	24.0	0.07	0.15	0.19
Burrum R.	3,358	310	2.7	17.1	13.8	9.2	0.08	0.51	0.41
Mary R.	9,440	1,509	11.7	32.0	37.9	16.0	0.12	0.34	0.40
Total	**423,070**	**117,726**	**1,313**	**1,438**	**1,459**	**27.9**	**0.31**	**0.34**	**0.34**

Table 27. Current major types of land use and land cover in the GBR catchment (ca. 1999) defined by satellite imagery. Data source: BRS, 2001

Basin Name	Basin Area km^2	Cropping/ Dairying	Improved Pasture	Native Grazing	Sparse Grazing	Total Grazing km^2	Native Forest	Rainforest	Lake/ Rock	Unused/ Unclass.
Jacky Jacky C.	2,963			1,048	881	1,930	17			1,017
Olive-Pascoe R.	4,179	57		1,689	1,018	2,707	1,273			142
Lockhart R.	2,883	130		1,880	476	2,356	57			340
Stewart R.	2,743	4	77	1,222	880	2,179	391			170
Normanby R.	24,408	243	912	6,261	12,369	19,542	3,713	50		861
Jeannie R.	3,637	99		332	665	996	1,576			966
Endeavour R.	2,104	149	15	828	253	1,097	577	189		92
Daintree R.	2,192	564		597	13	610	170	813	11	25
Mossman R.	466	54		153	14	167	51	184		10
Barron R.	2,136	498	79	979	10	1,068	220	309	30	13
Mulgrave-Russell R.	1,983	612		381	303	684	35	510	84	58
Johnstone R.	2,325	1,212		431	29	460	21	565	22	46
Tully R.	1,683	576		675	335	1,010	9	66		22
Murray R.	1,107	463		289	257	546			15	82
Herbert R.	9,843	1,552	419	3,108	3,337	6,864	1,283			143
Black R.	1,057	129	53	411	446	910	18			0
Ross R.	1,707	88	157	990	222	1,369	137			114
Haughton R.	4,044	472	657	1,987	74	2,719	394			459
Burdekin R.	130,126	6,401	33,778	30,912	43,330	108,020	13,159		898	1,648
Don R.	3,695	189	1,996	1,034	247	3,276	8			222
Proserpine	2,535	825	167	1,308	81	1,557	8			146
O'Connell	2,387	1,060	115	1,013		1,128	18			181
Pioneer R.	1,570	987	34	539		573	8			2
Plane C.	2,539	444	70	1,476	10	1,556	333			205
Styx R.	3,012	11	619	1,618	610	2,846	7			148
Shoalwater	3,605	25	575	1,987	197	2,759	663			158
Waterpark C.	1,835		14	551	258	822	380		5	628
Fitzroy R.	142,537	2,352	48,705	53,430	18,383	120,518	6,457			13,210
Calliope	2,236	91		2,001	12	2,013				132
Boyne R.	2,590	0	1	2,476	1	2,479				111
Baffle C.	3,996			3,000	15	3,015	596			384
Kolan R.	2,901			2,437	39	2,476	371			55
Burnett R.	33,248	1,890	6,082	18,931	1,344	26,357	4,897			103
Burrum R.	3,358	129	181	1,906	300	2,387	687			156
Mary R.	9,440	806	703	4,580	826	6,109	2,509			15
Total	423,070	22,111	95,409	152,961	87,236	335,105	40,042	2,685	1,065	22,063
% GBR Catchment		5.2	22.6	36.0	20.6	79.2	9.5	0.6	0.3	5.2

Table 28. Estimates of remnant vegetation remaining in catchments of the GBRCA in 1997 and 1999 and annual clearing rates. Discrepancies between basin area and classified area are likely due to pixel size and rounding errors in adding areas of many small vegetation patches.
Data source: Qld. EPA, 2001

Basin Name	Basin Area km^2	Classified Area km^2	Remnant Veg. Cover (1997) km^2	% Catchment Cleared	Remnant Veg. Cover (1999) km^2	% Catchment Cleared	Annual Clearing Rate (%)
Jacky Jacky C.	2,963	2,935	2,903	1.1	2,903	1.1	0.00
Olive-Pascoe R.	4,179	4,218	4,209	0.2	4,209	0.2	0.00
Lockhart R.	2,883	2,867	2,846	0.7	2,846	0.7	0.00
Stewart R.	2,743	2,701	2,675	1.0	2,675	1.0	0.00
Normanby R.	24,408	24,353	24,053	1.2	24,053	1.2	0.00
Jeannie R.	3,637	3,899	3,834	1.7	3,834	1.7	0.00
Endeavour R.	2,104	2,064	1,997	3.2	1,997	3.2	0.00
Daintree R.	2,192	1,914	1,785	6.7	1,785	6.7	0.01
Mossman R.	466	537	437	18.5	437	18.5	0.00
Barron R.	2,136	1,579	1,002	36.5	1,000	36.7	0.07
Russell-Mulgrave R.	1,983	1,992	1,458	26.8	1,457	26.9	0.02
Johnstone R.	2,325	2,321	1,257	45.8	1,256	45.9	0.03
Tully R.	1,683	1,640	1,216	25.9	1,215	26.0	0.04
Murray R.	1,107	1,200	808	32.7	803	33.1	0.22
Herbert R.	9,843	9,844	8,408	14.6	8,392	14.8	0.08
Black R.	1,057	1,053	882	16.2	874	17.0	0.41
Ross R.	1,707	1,347	1,011	25.0	993	26.3	0.68
Haughton R.	4,044	4,347	3,095	28.8	3,057	29.7	0.44
Burdekin R.	130,126	120,320	92,997	22.7	91,954	23.6	0.43
Don R.	3,695	3,565	2,764	22.5	2,750	22.9	0.20
Proserpine R.	2,535	2,552	1,667	34.7	1,661	34.9	0.12
O'Connell R.	2,387	2,362	1,240	47.5	1,232	47.9	0.18
Pioneer R.	1,570	1,584	1,017	35.8	1,011	36.2	0.19
Plane C.	2,539	2,540	1,234	51.4	1,206	52.5	0.56
Styx R.	3,012	3,022	1,766	41.6	1,728	42.8	0.64
Shoalwater	3,605	3,702	2,886	22.0	2,882	22.1	0.05
Waterpark C.	1,835	1,770	1,475	16.7	1,464	17.3	0.31
Fitzroy R.	142,537	142,682	61,758	56.7	60,233	57.8	0.53
Calliope R.	2,236	2,213	763	65.5	759	65.7	0.10
Boyne R.	2,590	2,485	1,258	49.4	1,257	49.4	0.01
Baffle C.	3,996	4,113	2,590	37.0	2,562	37.7	0.34
Kolan R.	2,901	2,925	1,321	54.8	1,314	55.1	0.13
Burnett R.	33,248	33,465	13,026	61.1	12,924	61.4	0.15
Burrum R.	3,358	3,369	2,086	38.1	2,063	38.8	0.35
Mary R.	9,440	9,473	4,043	57.3	4,017	57.6	0.13
Total	**423,070**	**412,951**	**257,769**	**37.6**	**254,800**	**38.3**	**0.36**

Table 29. Four estimates of the extent of tree and vegetation clearing in the GBRCA.

	Time	Extent	Cleared	Thinned km²	Total
Changes in distributions of major vegetation communities (1788-1988). Australian Survey and Land Information Group (AUSLIG, 1997). Clearing estimate based on increase in area of grassland and dense sown pasture. Thinning estimate based on increase in area of open woodland.	Late-1980's	Whole GBRCA	68,100	57,600	125,700
CSIRO - Land cover disturbance on the Australian continent. Graetz et al., 1995. Areas based on interpretation of satellite imagery.	Late-1980's	Whole GBRCA	95,100	146,700	241,800
Queensland Natural Resources & Mines and Bureau of Resource Sciences. Barson et al., 2000, Qld. Dept. of Natural Resources 1999a,b. Areas based on interpretation of satellite imagery.	Mid-1990's	Whole GBRCA	117,700	152,800	270,500
Queensland Herbarium - Cape York Peninsula and dry regions adjoining the central GBR Qld. EPA, 2001. Areas based on interpretation of aerial photos, ground-based vegetation surveys and interpretation of satellite imagery.	Late-1990's	Part GBRCA*	158,400		

(* = 413,000 km^2)

mapped area within the GBR catchment (169,000 km^2) was classified as uncleared. The Brigalow and eucalypt woodland communities of the Burdekin (95,000 km^2) and Fitzroy River basins (86,000 km^2) had the greatest extent of clearing. Estimated proportions of cleared land exceeded 30% in the Burdekin, Don, Fitzroy, Calliope and Burnett River drainage basins. The lowest levels of clearing were recorded on Cape York Peninsula, in the mountain ranges between Townsville and Port Douglas, the mountain areas west of Mackay and the Shoalwater Bay military reserve. This initial classification produced the largest estimate of cleared and thinned land in the GBR catchment. The imagery for this effort was collected during the 1980s when drought conditions were widespread throughout much of the GBR catchment. The relatively higher estimates of cleared land may therefore reflect alterations in the optical properties of tree and vegetation cover associated with drought conditions.

Gully erosion
Picture: QDPI

Fire in woodland
Photo: P. O'Reagain, QDPI

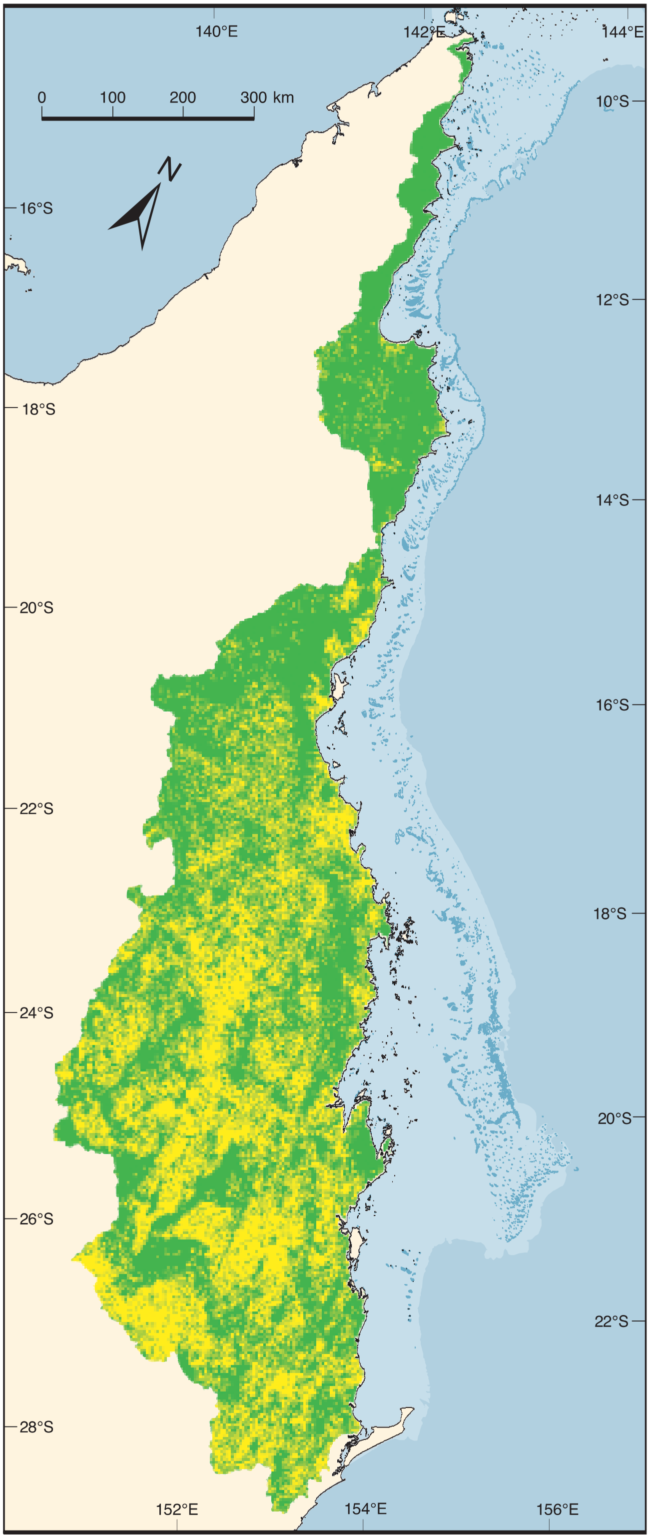
A more detailed estimate of vegetation cover, land use and clearing was initiated by the State (QNR&M) and Commonwealth (BRS) Governments in the early 1990s [34]. Ongoing estimates of the rate of tree clearing in the GBR catchment have been made through the Statewide Landcover And Trees Study (SLATS) [410, 411, 412] of the Queensland Department of Natural Resources and Mines. SLATS documents ongoing changes in woody vegetation (tree) cover throughout Queensland. The SLATS procedures ensure that changes in tree cover are measured in a consistent way (Table 26).

Based on the 1991 BRS tree-cover and land use classification, there were 118,000 km^2 of cleared woodland (28% of the GBRCA) in mapped sections of the GBR catchment. Native woody vegetation, including thinned woodlands, covered 305,000 km^2 (61% of the GBR catchment). By 1995, native woody vegetation cover decreased to 247,000 km^2 (60%) while the area of cleared land increased to 156,000 km^2 (39%). Between 1995 and 1999, the area of cleared land increased to 161,000 km^2 (Table 27). Using the BRS/SLATS data, the extent of tree clearing exceeded 50% of basin area in four drainage basins (Johnstone, Don, O'Connell, Pioneer) and 30% in ten. Over the 1991-1999 period, clearing activity reduced tree cover by ca. 0.3% in each of the two to four year reporting intervals. In 1999, cropping lands and improved pastures accounted for 28% of the GBR catchment (Table 27, BRS, 2001). The highest clearing rates on both an absolute and relative basis were in the remnant Brigalow and eucalypt woodland communities of the Burdekin and Fitzroy River basins.

The most recent assessment of tree clearing in the GBR catchment has been made by the Queensland Herbarium (Qld. EPA, 2001) (Table 28). This estimate is derived from aerial and satellite imagery, validated by extensive ground-based vegetation mapping (Qld. EPA, 1999). The total cleared area is estimated to be 158,000 km^2 (40% of the GBR catchment). The extent of clearing within individual drainage basins ranges from 0.2% (Olive-Pascoe Rivers) to 65.7% (Calliope River). Again, the largest cleared areas are in the Burdekin River (38,200 km^2), Fitzroy River (82,300 km^2) and Burnett River (20,300 km^2) basins. By the Queensland Herbarium criteria, the extent of tree clearing exceeds 30% of basin area in sixteen drainage basins and 40% in ten. As in the other classifications, the vegetation communities most affected by clearing have been the Brigalow woodlands of the Fitzroy and Burdekin River basins.

The estimates of clearing and vegetation change, can be compared, but with caution, because different criteria are used in each study. Overall however, the magnitude of the reduction in tree cover is of similar order (Table 29).

Because of the large natural seasonal and drought-related fluctuations of grass cover in dry-tropical savannas and woodlands, satellite-based estimates of vegetation clearing have focused on trees and woody vegetation. Climate (drought), fire and cattle grazing influence grass cover in catchments and have major effects on landscape-scale erosion and runoff rates. It is important to remember that clearing of trees and tall woody vegetation does not remove the underlying grasses. Pasture grass enhancement is one of the principal reasons for vegetation clearing. Pastures which are developed from cleared woodlands can have effective ground cover if they have a high level of grass cover. On the other hand, fire or overgrazing of woodland pastures under dry conditions can remove virtually all of the grass and litter cover from the soil surface without substantially changing the tree canopy. In considering satellite-based estimates of tree clearing and their implications for estimates of soil and nutrient runoff, it is important to remember that it is the type as well as the amount of the groundcover which is changed. Tree cover affects erosion and runoff rates, but grasses, understory shrubbery and litter have a greater effect.



The extent of land clearing (ca. 1995) in the GBRCA inferred from interpretation of satellite imagery (LANDSAT MSS). Data source: BRS, 1999

Cleared

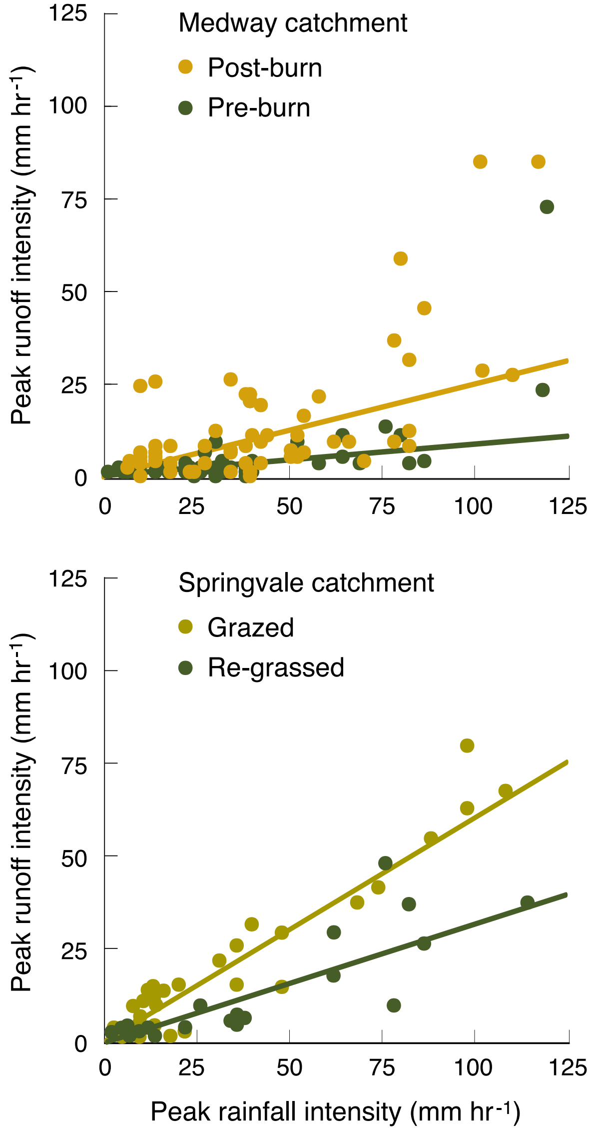
Uncleared

Effects of land clearing

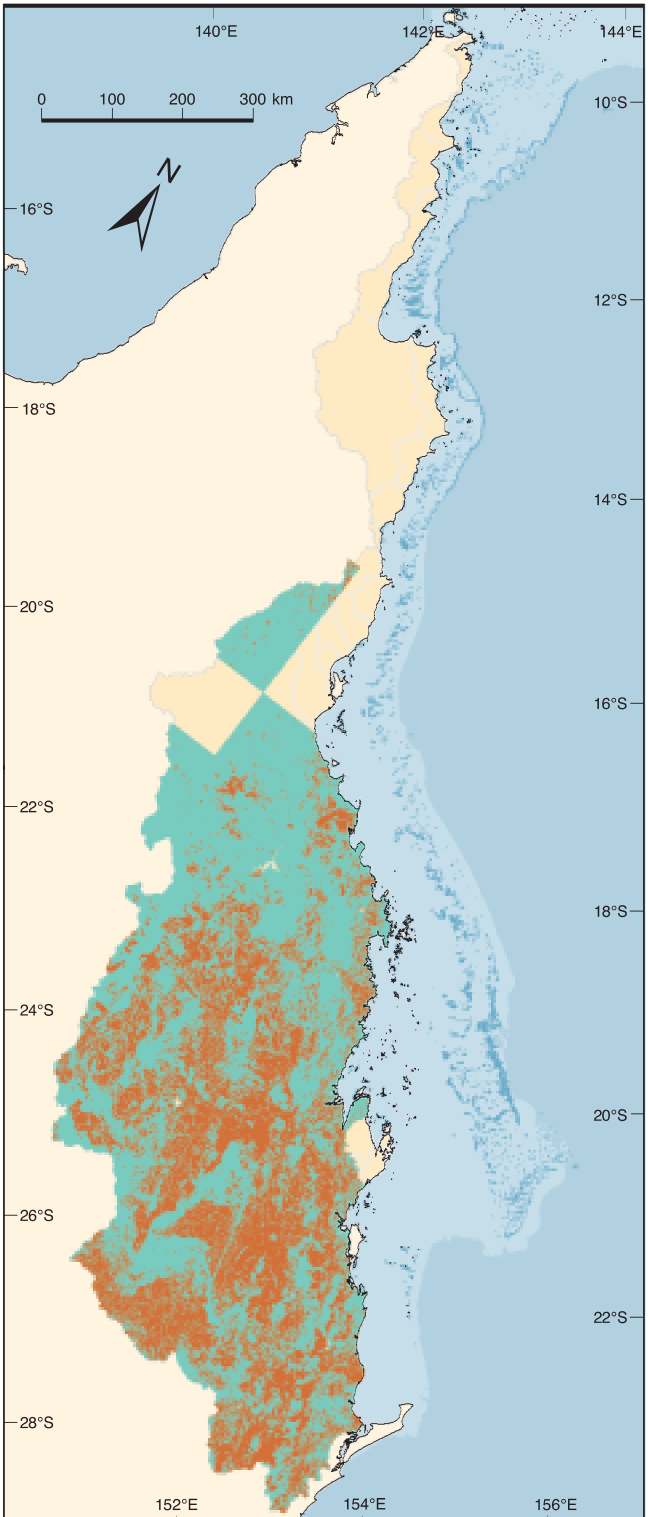
Removal of vegetation greatly changes sediment and nutrient runoff. Vegetation protects the soil surface from the direct impact of raindrops, increases surface roughness to slow overland water flow, promotes water infiltration and affects soil chemical and structural properties.

Rain falling on bare ground dislodges soil particles which are carried away by surface flows [181]. The erosive power of rainfall depends on rainfall intensity, the susceptibility of the soil surface to erosion, ground cover and slope. Even thin layers of standing water or leaf litter greatly reduce the erosive power of raindrops. In the absence of surface water flows, soil particles dislodged by raindrops may only be transported a short distance before being re-deposited. As rain intensity increases, however, soil particles will be moved greater distances downslope by dislodgement, transport and redeposition.

Several things happen when rain is intercepted by vegetation, depending on the nature of the rainfall, canopy type (trees, shrubs or grass), its density and height. Canopy interception, particularly when the canopy is formed of shrubs or grasses, greatly reduces the erosive energy of rainfall. Large drops intercepted by vegetation or litter are broken into smaller droplets which dissipates their kinetic energy. If the vegetation canopy is tall, however, drops may reform and regain much of their original kinetic energy. Some of the rainwater intercepted by the vegetation canopy is diverted to ground level down plant shoots, stems and trunks (stemflow) where it can infiltrate around the base of plants. The conversion from direct rainfall to indirect rainfall and stemflow depends on the thickness of the vegetation cover, regardless of its height. In pastures and woodlands, grass tussocks, both alive and dead, are particularly efficient conduits for infiltration of water into the soil [173, 174, 340].



Relationships between peak rainfall intensity (maximum 7.5-min rainfall) during storm events and peak runoff from two small sub-catchments of the Nogoa River (western Fitzroy River basin) with different degrees of vegetation cover. Top) Runoff rates before and after catchment vegetation was burned. Bottom) Runoff rates from a heavily grazed catchment before and after stock were excluded. Plotted lines are based on rainfall intensities less than 100 mm per hour. Replotted from Ciesiolka, 1987.



The extent of tree clearing (ca. 2000) in mapped areas of the GBRCA. Blank areas indicate sections of the GBRCA where vegetation classifications have not been released at this time. Data source: Qld. EPA, 2001

Cleared

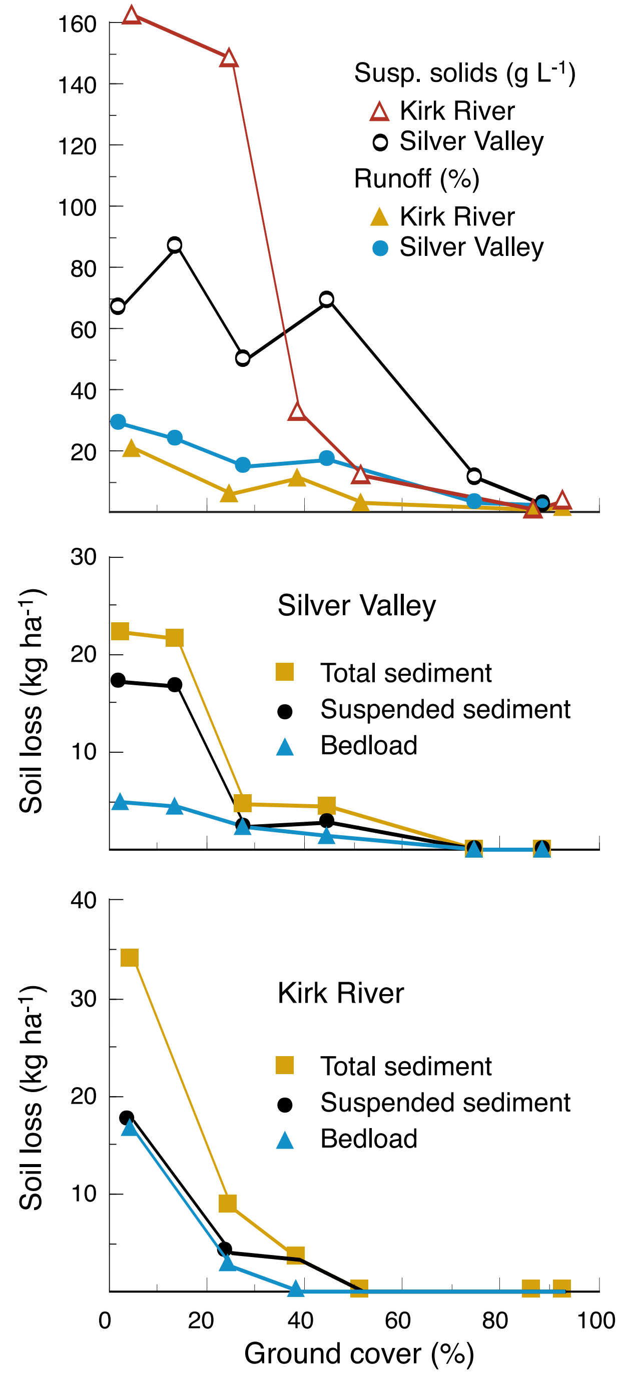
Uncleared

GBR catchment, unmapped

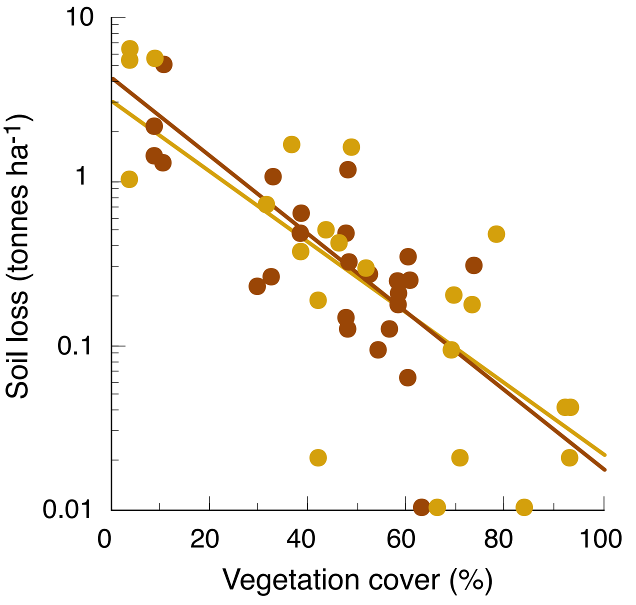
Tree clearing may not increase runoff if grass cover remains high. In most of the GBR catchment, grass production is largely determined by water availability. The grass is consumed by termites, fire or cattle. In semi-arid woodland pastures with low levels of groundcover, rainfall intensity (mm per hr) has a greater effect on runoff and soil loss than the amount of rainfall [90]. In woodlands with a high level of ground cover, the total amount of rainfall in a rainstorm becomes increasingly more important in determining the degree of runoff [272].

The effects of vegetation clearing on runoff volume, soil loss and soil properties have been demonstrated in experiments carried out in Brigalow woodlands of the Fitzroy River basin [272]. After baseline measurements of runoff and soil loss in three adjacent catchments, two were cleared. One was used for dryland grain cropping and one sown with pasture grasses. Runoff frequency, runoff volume (mm of water from a rain storm) and peak runoff rates (mm water per hour) increased in the two cleared catchments. Annual runoff volumes from the cleared catchments increased by 3 to 6% compared to the uncleared catchment. In this relatively flat country, annual soil losses from the uncleared, cropped and pasture catchments averaged 10, 170 and 30 tonnes per km^2 (100, 1,700 and 300 kg ha^{-1} yr^{-1}). Apart from what was removed in harvested crops, there was no clear decline in soil nutrients from the cleared catchments over a 5-year period.

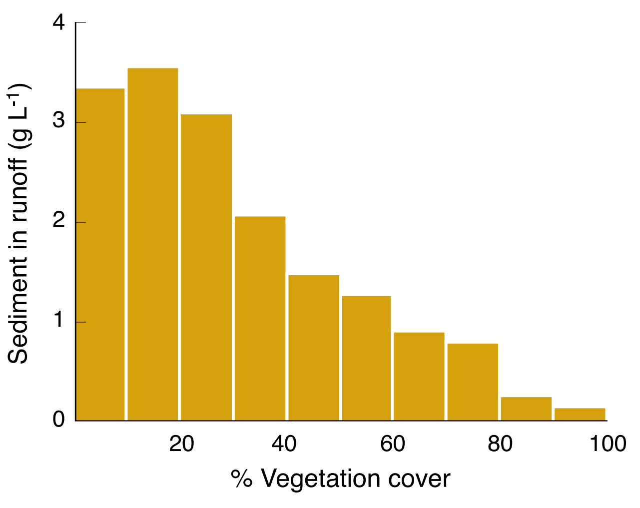
The small-scale roughness of a landscape strongly influences soil and nutrient retention. Coarse soil particles (e.g. sand) and plant litter eroded by surface water flows may only move a short distance before being trapped by vegetation and small undulations in ground level. Because of local redeposition, there may be little net loss of coarser sediments from disturbed hillslopes [395]. This pattern of local erosion and trapping of soil has been defined as an "erosion cell" [375]. Within erosion cells, topographically



The proportion of rainfall lost as runoff, suspended sediment concentrations and soil loss rates from experimental plots at two woodland pasture sites (Burdekin River basin) in relation to the degree of vegetative ground cover.
Replotted from Pressland et al., 1991.



Relationships between annual soil loss from and hillslope vegetation cover in two small sub-catchments of the Nogoa River (Fitzroy River basin) between 1981 and 1984. Note logarithmic scale.
Data replotted from Ciesiolka, 1987



Suspended sediment concentrations in runoff from grassed plots at Cardigan Station (Burdekin River basin) in relation to the degree of ground cover.
Replotted from McIvor et al., 1995

higher areas, however slight, are eroded, producing sediment which is transported downslope to collection sites. The deposited material builds up and is eventually re-eroded. Fine clay-sized particles, on the other hand, can move substantial distances, both within or out of catchments after suspension in runoff.

Vegetation cover has a strong effect on the movement of sediment. Many field observations and experiments show that runoff volume and soil loss are inversely related to the degree of ground cover, particularly of grasses [90, 173, 319, 381, 455, 456, 471]. Low vegetation cover may be the results of low water availability, soil infertility, surface erosion, vegetation clearing, cultivation, grazing or fire. Water runoff, soil erosion and nutrient losses from hillslopes, pastures and catchments remain relatively modest when cover levels of low vegetation (not plant basal stem area) exceed 40% of the ground surface area. Soil loss rates increase rapidly when vegetation cover declines below this value. Patches of bare soil with a hard surface crust (scalds) produce the highest water runoff rates, although not always soil losses. The slaked and compacted surface soil in scalded patches strongly resists water infiltration [340]. This water remains on the surface, where it is channelled into adjoining drainage networks. There are fewer burrowing soil animals in scalded patches due to the harder surface and lower availability of food. The hard surface inhibits the regrowth of new vegetation, slowing the recovery of scalded patches.

Effective ground cover is not solely provided by living plants. Ground cover provided by dead plant material (litter) also reduces water runoff and soil loss by protecting the soil surface from direct rainfall and adding to local surface roughness [90]. Litter is made up of dead grass and leaves, twigs and branches from overstory trees and woody shrubs. Leaf litter directly covers the ground surface while larger pieces trap soil carried by surface water flows. Plant litter is a major food resource for soil animals, especially termites, which make water-absorbing burrows and carry organic matter downward into the soil. The quantity of litter at a site depends on local levels of plant production, grazing pressure, the abundance and activity of soil animals and the recent fire history of the site. Fires consume both living plants and aboveground plant litter, laying the soil surface bare to rainfall.

Effects of grazing

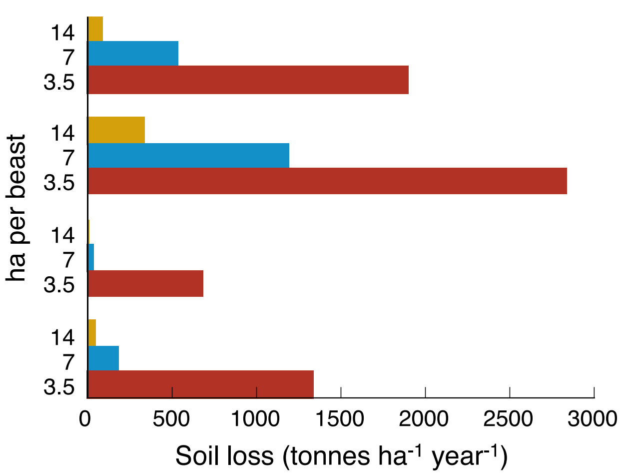
Throughout the drier regions of the GBR catchment, fire and cattle grazing are the principal agents which remove the groundcover produced by grasses and other low shrubs. The regrowth and retention of grass cover varies with grazing pressure [456], soil nutrient status [83], and particularly, the availability of soil water [563]. Because annual potential evapotranspiration exceeds annual rainfall in the drier southern and inland sections of the GBR catchment, most of the growth of shallow-rooted grasses occurs during and immediately after the summer wet season. During the dry season and droughts, low soil-moisture levels limit re-growth of grazed or burnt grasses and shrubs. As a result, reduced ground cover may persist until drought-breaking rains bring sufficient water. When rain comes, it falls on bare soil susceptible to rapid erosion.

Grazing by cattle can significantly affect soil erosion and nutrient loss. The hooves of cattle disturb and loosen the soil surface [368], increasing its susceptability to erosion. The largest effect of grazing, however, is the removal of vegetation and ground cover. In dry conditions, even small numbers of cattle can strip sparse grass cover from paddocks and keep them bare. Water runoff and soil losses from experimental paddocks increase with the density of grazing animals [173, 449]. Soils in heavily grazed paddocks are characterised by lower porosity, lower organic content and reduced populations of soil animals. Vegetation removal, particularly of grasses, deprives termites of their primary food resource. Burrows created by termites and other soil insects are a major conduit for water infiltration into soils [174, 205].

Ungrazed woodland pasture
Photo: M. Furnas, AIMS

Heavily grazed pasture
Photo: QDPI

Termite mounds, Normanby River
Photo: M. Furnas, AIMS



Effect of stock density (grazing pressure) on soil loss from four experimental plots in woodland pastures near Charters Towers (Burdekin River basin).
Replotted from Scanlan and McIvor, 1995

Effects of fire

Fire has been an important part of the ecology of semi-arid landscapes in northern Australia. The distribution and composition of plant communities in drier parts of the Great Barrier Reef catchment reflect the fire history of the region. Fire temporarily removes the tops of most grasses, low growing shrubs and the underlying plant litter, exposing soils to dessication and erosion by rainfall, particularly intense, drought-breaking rains [90, 395]. Dominant trees, shrubs and grasses of the dry savannas and woodlands have well-developed evolutionary adaptations to fire [242, 407, 472]. Many native plants rely on fire or fire-related disturbance of established plant communities to propagate and grow, or to maintain their presence in vegetation communities [487].

The frequency and extent of fires reflect the availability of ignition sources (lightning, humans) and the quantity of burnable vegetation (fuel). Ecosystems with infrequent fires and large amounts of dry fuel eventually produce large, hot fires that kill larger plants and bake surface soils [213]. Frequent or out-of-season fires with more limited or less combustible fuel resources produce small, cooler fires that leave more vegetation intact for rapid regrowth.

Fire accelerates the mineralisation of nutrient (N,P)-containing organic matter, both above-ground and in surface soils, to inorganic forms (NH_4^+, NO_3^-, PO_4^{3-}) that are readily assimilated by plants; the "ash bed" effect [473, 545]. If there is sufficient soil water, local re-growth of grasses and other small plants is stimulated after fire. The new growth attracts grazers, both native and domestic. Rotational burning of dry vegetation was carried out by Indigenous hunters to attract or concentrate game [59]. Burning to control exotic weeds, woody weeds and stimulate new growth in pastures is part of grazing land management in many parts of the GBR catchment. However, too-frequent or inappropriate burning

Scalded paddock
Picture: C. Roth, CSIRO

ultimately reduces the amount of vegetation available to retard surface runoff of soil and nutrients during early wet-season rains, and increases the quantity of nutrients accessible to leaching.

Modern land use in the drier portions of the GBR catchment – clearing of natural woodland vegetation and grazing at levels chronically exceeding the carrying capacity of the pasture vegetation community, have reduced the natural vegetation cover in much of the interior of the GBR catchment. These changes have accelerated landscape erosion [392]. The extent of vegetation clearing is therefore

Grass fire
Photo: P. O'Reagain, QDPI

a major factor influencing exports of soil and associated nutrients in runoff.

Sugarcane cultivation in the GBR catchment

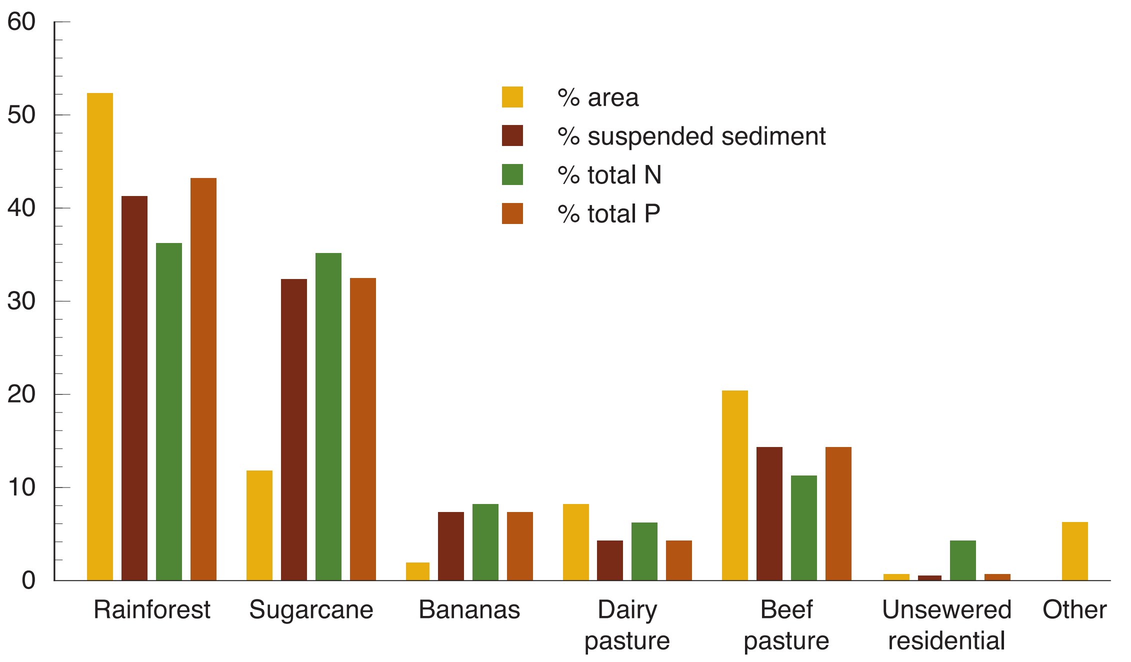
Sugarcane is the most valuable crop grown in the GBR catchment. First planted near Brisbane during the 1840s, sugarcane was one of the first crops grown in Queensland. Commercial cultivation of sugarcane in the GBR catchment began in 1863, and with government incentives, plantations were established along the coast as far north as Daintree (Queensland Yearbook, 1901). The early development of the sugar industry was concentrated on coastal floodplains, particularly those with high natural rainfall (e.g. Burnett, Pioneer, Herbert, Johnstone Rivers). The fledgling industry was plagued by disease and labour troubles, but by 1900, cane was harvested from approximately 200 km^2 (20,000 ha) of land. The early plantations have since been replaced by an industry based on family-owned farms. Over the last century, the area of sugarcane harvested in the GBR catchment has increased 20-fold to ca. 4,400 km^2, approximately 1% of the total catchment area. The modern industry is based on mechanisation of virtually all aspects of cultivation and harvesting.

Most of the sugarcane produced in the GBR catchment is still grown on the coastal plain. A relatively small amount is grown on the Atherton Tablelands, west of Cairns and Innisfail. The Herbert River drainage basin contains the largest harvested area of caneland, followed closely by the Haughton River and Plane Creek drainage basins. The Plane Creek basin has the highest proportion of area (over 22%) planted with sugarcane. As the sugar industry developed on the wet-tropical floodplains of north Queensland, a significant proportion of the lowland rainforest and wetlands were cleared [226, 554]. Recent caneland expansions have largely been in drier coastal regions such as the Burdekin Delta where irrigation is necessary. Irrigation water is largely drawn from local aquifers or dams.

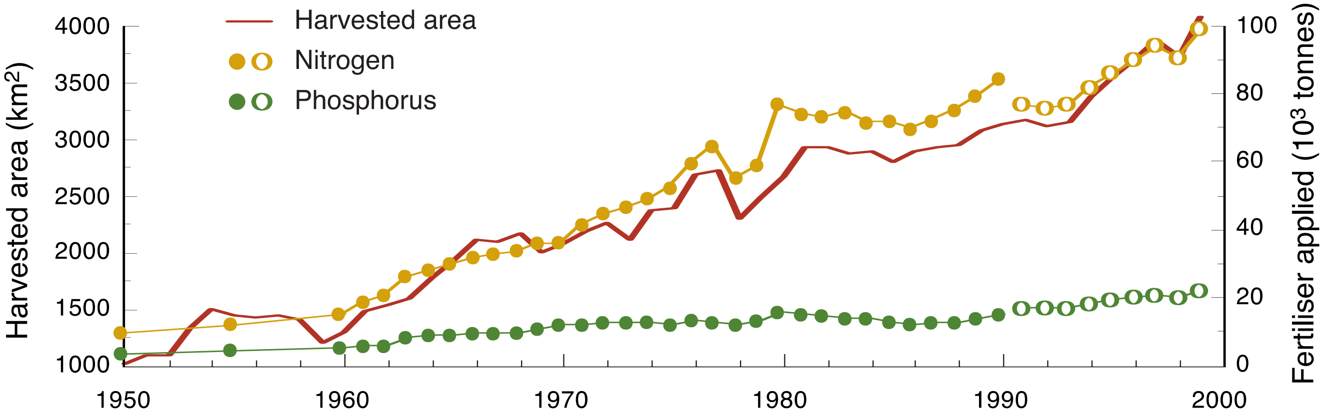
Land used for sugarcane and banana cultivation produces a disproportionate fraction of soil and nutrient losses from the GBR catchment [217,414]. In the Johnston River basin, land used for sugarcane production (12% of catchment area) produces 30-35% of the soil and nutrient exports. Banana farms, comprising only 2% of the catchment in the mid 1980s, contributed approximately 8% of total sediment and nutrient losses. The area of bananas cultivated in the Johnstone River drainage basin has continued to expand [330]. Native rainforest, covering 52% of the Johnston River catchment, is the source for 36% of sediment and 42% of nutrient exports [217]. Pastures (30% of basin area) are estimated to contribute less than 20% of the sediment and nutrient load.

At present, there is no extensively-documented, spatially weighted estimate for total soil losses from canelands in the GBR catchment. This is not surprising given the diversity of topographies, soil types and rainfall regimes in which sugarcane is grown. The most recent estimate, based on the available data, puts sediment inputs to the GBR from canelands at 1.25 million tonnes per year [414]. Soil loss rates can range up to 500 tonnes ha^{-1} $year^{-1}$ when inappropriate cultivation methods are used in high rainfall areas [398]. In contrast, soil loss rates are probably very low on flat, low-rainfall floodplains such as the Burdekin delta. In the 1970s, soil loss rates between 40 and 200 tonnes ha^{-1} $year^{-1}$ were measured in cane paddocks near Mackay [448]. In variable terrains of the wet tropics, annual soil losses from conventionally cultivated plots (annual tillage, trash burned) varied 10-fold (50-500 tonnes ha^{-1}) between sites, soil types and years (rainfall) with an overall average close to 150 tonnes ha^{-1} $year^{-1}$ [398]. When trash blanketing and no-tillage cultivation methods are used, soil loss rates are much lower (5-15 tonnes ha^{-1}). This indicates that resistance to soil dislodgement through soil surface protection and preservation of soil structure is particularly important in high rainfall regions. The relatively small amount of soil eroded from no-tillage plots is largely from the smallest size fractions (silt, clay) which contain the highest particle-associated nutrient concentrations [398]. Green cane harvesting with trash blanketing and no-tillage cultivation is now used by a large and still growing proportion of the sugarcane industry, particularly in wetter areas of the GBR catchment.

Canelands receive most of the fertiliser applied in the GBR catchment. Nitrogen and phosphorus applications have risen steadily since the early 1960s [404], largely because of the increasing area of sugarcane planted, and to a lesser extent, the increasing cultivation of other crops (cotton, bananas, vegetables) which require high fertiliser inputs. Recommended nitrogen (N) and phosphorus (P) application rates for sugarcane are 120-250 and 15-25 kg ha^{-1}, respectively [251]. In 1990, the most recent year for which comprehensive statistics have been published, total

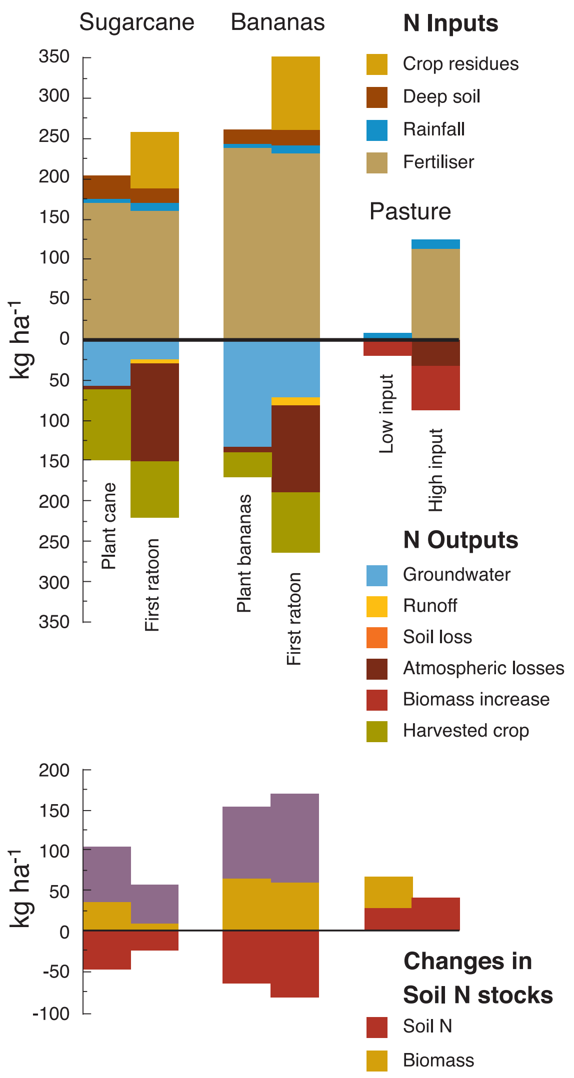


Relative contributions of major land cover types or land uses to exports of suspended sediment, total nitrogen and total phosphorus from the Johnstone River over 1991-95. Data replotted from Hunter and Walton, 1997



Fertiliser nitrogen and phosphorus applied to cropped land in the GBRCA since 1950 and the area of sugarcane harvested. Closed symbols show fertiliser inputs to the GBR catchment estimated by Pulsford (1996). Open symbols indicate estimated fertiliser nitrogen and phosphorus inputs after 1990 based upon the average fertiliser applications to the GBR catchment between 1980 and 1990 normalised to the harvested area of sugarcane and the post-1990 areas of harvested sugarcane. Data sources: Queensland Canegrowers, Pulsford, 1996

fertiliser nitrogen and phosphorus applications in the GBR catchment were close to 80,000 and 13,000 tonnes, respectively [404]. Since that time, the harvested area of caneland has increased by 800 km^2, bringing the total harvested area close to 4,400 km^2. Most of this recent expansion has taken place in the Herbert, Burdekin, Tully-Murray, Haughton, Proserpine, O'Connell River and Plane Creek drainage basins. If total fertiliser nitrogen and usage is proportional to the quantity applied to sugarcane, nitrogen and phosphorus application rates in the GBR catchment between 1980-1990 would average 27.25 tonnes N km^{-2} and 5.65 tonnes P km^{-2} of harvested caneland (272.5 kg N and 56.5 kg P ha^{-1}). If overall N and P usage has continued at this rate relative to the area of sugarcane now harvested (a conservative assumption given the increasing area of other fertilised crops), current fertiliser inputs of nitrogen and phosphorus to the GBR catchment are on the order of 100,000 tonnes of N and 20,000 tonnes of P per year.



Inputs and outputs of nitrogen (top) and changes of soil nitrogen stocks (bottom) in paddocks used for growing sugarcane, bananas and pasture grass in the wet-tropical Johnstone River catchment. Negative bars in stocks histograms represent storage in soils.
Data replotted from Moody et al., 1996

Several things can happen to the nitrogen and phosphorus applied to paddocks or pastures, depending on the crop, topography, soil type, rainfall, soil moisture, fertiliser type and cultivation practices. The most detailed study of nutrient behaviour in soils under sugarcane, banana and pasture crops within GBR catchment was carried out in the Johnstone River catchment [334, 400, 424]. The experimental area was characterised by high rainfall (>2,000 mm per year), sloping topography and highly permeable krasnozem soils.

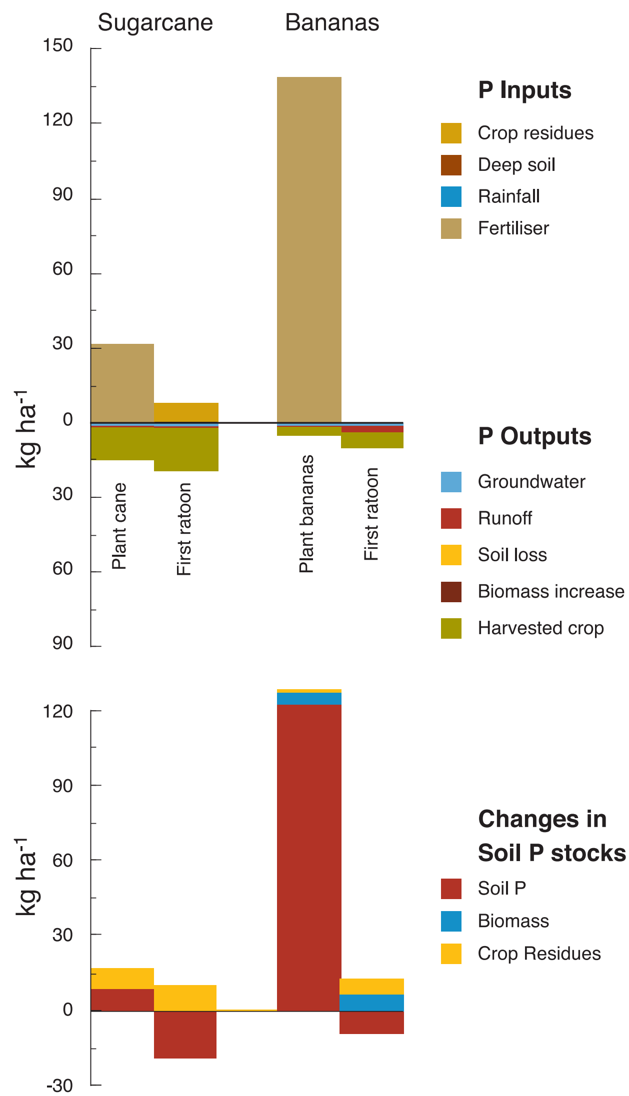
In the cropping plots, nitrogen inputs and losses were largely balanced. Fertiliser was the principal nitrogen source in fertilised sugarcane and banana paddocks, although decaying crop residues recycled significant amounts of plant-accessible nitrogen. Smaller inputs of nitrogen came from rainfall and deep soil layers. Approximately half of the added N was removed in the harvested crop. Relatively large amounts of soluble nitrate-N were lost from soils underlying both sugarcane and banana crops to groundwater through downward infiltration of water. Regional rainforest soils have similar high water infiltration rates [54, 160]. Significant amounts of nitrogen were also lost to the atmosphere through volatilisation and denitrification by soil bacteria. Relatively little nitrogen was lost from the experimental plots by soil erosion or surface runoff. The extent of erosion depends on the cultivation practices used [398, 403]. Over the two-year course of the experiment, there was a net increase in total soil nitrogen as decreases in inorganic nitrogen stocks were offset by increases of organic nitrogen in plant biomass and crop residues.

The two pasture systems tested (high and low nutrient inputs) were characterised by net declines in available soil nitrogen. Significant losses of nitrogen through volatilisation or denitrification were restricted to the high-input pasture. The low-input pasture system was characterised by a net loss of plant biomass through grazing. In contrast, there was a large increase in grass biomass in the high-input pasture, accounting for nearly half of the added nitrogen in fertiliser.

In the case of phosphorus [334, 400, 424], one-off applications on plant cane and bananas in the first year of the experiment increased stocks of insoluble mineral phosphorus as the added phosphate (PO_4^{3-}) became bound to the iron-rich krasnozem soil [332]. This was particularly clear in the banana paddock. Only a small proportion of this bound phosphorus was recovered in the harvested crop, or converted to soluble soil phosphorus and organic residues. There were small increases in the phosphorus associated with decaying crop residues in both the sugarcane and banana paddocks. Because most of the phosphorus remained strongly bound to soil particles, little was lost through infiltration to groundwater. As with nitrogen, little phosphorus was lost from the experimental plots by surface runoff and soil erosion.

The strong tendency for phosphorus to bind to soils greatly influences its fate in GBR catchments. A large portion of the phosphorus applied over the last fifty years to sugarcane paddocks in the GBR catchment remains in surface soils [416]. In a number of sugarcane growing areas, surface soils are now phosphorus-enriched to a degree that further additions are unlikely to significantly increase crop yields [416]. Losses of phosphorus from these catchments will be directly related to soil loss rates.

In another study carried out over two years on the Herbert River floodplain [53], approximately half (43%) of the fertiliser nitrogen added to sugarcane paddocks (170 kg N ha^{-1} $year^{-1}$) was removed in harvested cane. Over the same period 37% of the applied nitrogen was lost through surface runoff and gaseous losses (volatilisation, denitrification), 5% through subsurface percolation into field drains and 15% (25 kg N ha^{-1} $year^{-1}$) by infiltration into the groundwater.



Inputs and outputs of phosphorus (top) and changes of soil phosphorus stocks (bottom) in paddocks used for growing sugarcane and bananas in the wet-tropical Johnstone River catchment. Negative bars in stocks histograms represent storage in soils.
Data replotted from Moody et al., 1996

Harvested canefield with trash blanket
Photo: C. Roth, CSIRO

Newly planted cane paddock
Photo: M. Furnas, AIMS

The widespread use of green cane harvesting - trash blanketing (GCTB) and no-tillage cultivation methods have significantly effected runoff of sediment and nutrients from canelands [398]. Prior to the adoption of GCTB cultivation, canefields were regularly ploughed and tilled. Fields were burnt before harvesting, leaving disturbed bare soil exposed to early summer rains. Under a GCTB cultivation regime, the sugarcane leaves are mechanically stripped from the green stalks at harvest and left on the ground. The trash layer protects the soil from direct rainfall, and as the residue is broken down and worked into the soil, the organic matter releases nutrients and builds soil structure. The organic matter in the trash also provides food for burrowing soil animals that facilitate water infiltration. At present, almost all (> 90%) of the sugarcane grown in the wet tropics is harvested using GCTB methods (Queensland Yearbook, 1999). A significant and growing proportion of the sugarcane harvested from southern districts is also harvested green.

Other crops

A variety of grain (e.g. sorghum, maize), fibre (e.g. cotton), vegetable (e.g. tomatoes, potatoes), tropical fruit (e.g. pineapples, mangos, bananas) and horticulture crops (cut flowers) are currently grown in the GBR catchment. Most of the vegetables and fruit are grown on the coastal plain, while grains and cotton are grown inland using irrigation or dryland cropping methods. Although the total area used for horticultural crops is small (160 km^2 in 1997) [418], these crops are typically fertilised at rates similar to or greater than sugarcane [251]. For example, the area of banana cultivation in the GBR catchment has increased dramatically, since 1975, chiefly in the Tully and Johnstone River drainage basins (Chapter 1). Because of the higher economic returns currently available from bananas, sugarcane paddocks and pastures are being converted to banana cropping. At present, recommended fertiliser applications [251] for banana crops in the wet tropics are 485 kg N ha^{-1} $year^{-1}$

and 20-50 kg P ha^{-1} $year^{-1}$. In the Tully River catchment, approximately half of the total nitrogen fertiliser input is now applied to bananas [330]. Banana paddocks on sloping ground are susceptible to high soil and nutrient loss rates because the soil between rows is kept relatively clear and much of the fertiliser is applied on the soil surface. In the Johnstone River catchment, banana crops occupying 2% of the catchment area were the source of approximately 8% of the sediment, nitrogen and phosphorus exported from the catchment [217].

Urban land use and sewage discharge

Land in urban areas (less than 150 km^2) covers only a small fraction of the total GBR catchment. Nutrient inputs from urban areas largely come as sewage discharge from treatment plants [66]. Small but unquantified amounts of sewage-derived nutrients from urban and semi-rural areas also enter the GBR through groundwater and coastal streamwaters contaminated by septic tank waste. Other urban sources of nutrients and pollutants include industrial wastes and stormwater runoff containing oils, lawn fertilisers and animal waste. At present, there is no centralised inventory of nitrogen and phosphorus exports from licensed sewage plants along the GBR. Only a small number of sewage plants discharge directly into the GBR lagoon or streams flowing into the GBRWHA. Some municipalities discharge their plant effluent onto land, managed wetlands (Ingham) or land fills (Gladstone). The nutrients in this treated effluent may eventually reach the GBR in floodwaters or groundwater, but the quantity is not known and is probably small.

The volume of sewage processed by treatment plants is largely proportional to the population served. Approximately 500 L of water is treated daily for each person [66]. As a general guide, each resident in an urban area annually produces 5 kg of nitrogen and 1.5 kg of phosphorus in treated sewage effluent [66]. To estimate an upper limit to the quantity of nutrients potentially discharged into the

Sugarcane harvesting
Photo: C. Roth, CSIRO

Bananas
Photo: M. Furnas, AIMS

GBR in sewage effluent, the approximate annual per capita export of nitrogen (5 kg) and phosphorus (1.5 kg) from treatment plants can be multiplied by the population of major coastal urban centres (ca. 450,000). This yields a maximum export of nitrogen close to 2,250 tonnes per year and a maximum phosphorus export of 675 tonnes per year. These inputs are small relative to natural and agricultural nutrient inputs from the land (Chapter 8), but may be locally significant in coastal embayments or estuaries.

Chapter 6

Suspended sediments in rivers of the Great Barrier Reef catchment

'April 8 Thunder-storms had probably fallen higher up its course, causing a fresh; for its waters, hitherto clear, had become turbid. (pg. 207, along the Burdekin River)'

Leichardt, L. 1847 Journal of an Overland Expedition in Australia from Moreton Bay to Port Essington, T & W Boone, London.

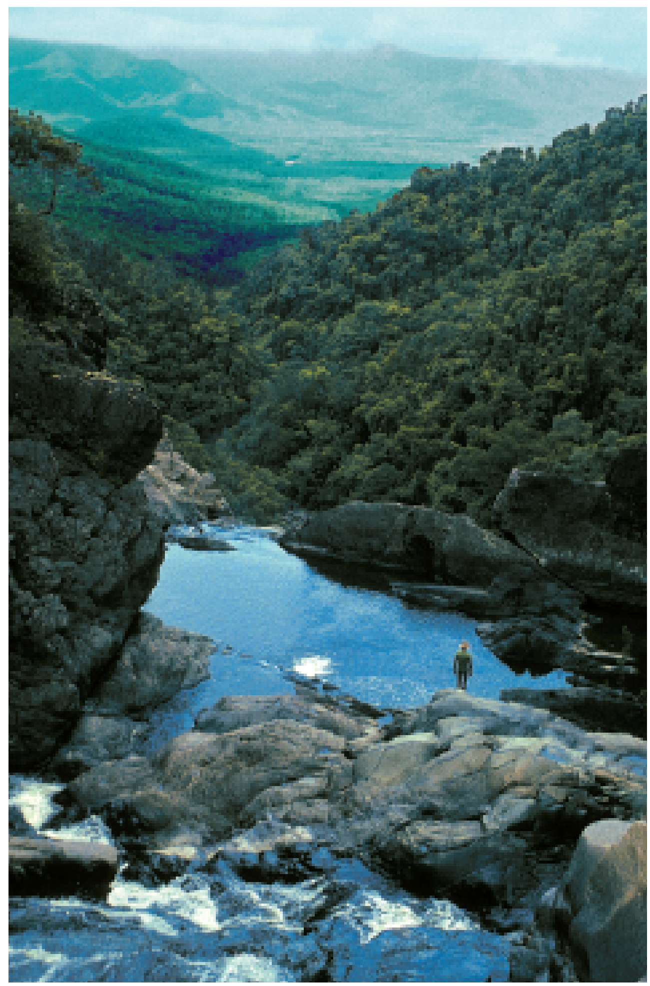
The amount of sediment carried by rivers and exported from catchments is governed by catchment size, topography, the nature of catchment soils, the volume of water discharged and the energy of flow in the catchment. Not surprisingly, sediment exports increase with catchment size [547]. Larger catchments typically export more sediment (tonnes per year) because they usually discharge more water, have a larger erodible land surface and a larger network of river- and streambanks susceptible to erosion. In contrast, small catchments typically export more sediment from a given area (tonnes per km^2) because they are steeper for their size and have less capacity to store eroded soils in the river system [325].

The energy to erode surface soils and transport sediment in rivers comes from the velocity and turbulence of flowing water. The sediment transport capacity (energy) of flowing water increases with the volume flowing in a channel or across a width of land, the slope (steepness) of the land or channel and the roughness of the ground surface or channel sides [392]. Clearly, water flowing down a steep hillside or through a narrow gully has more energy to erode and

Cattle Creek, Herbert River floodplain
Photo: M. Furnas, AIMS

transport sediment than water moving slowly across a flat landscape such as a floodplain.

Once eroded soil reaches the stream and river network, its downstream movement depends on the volume and rate of flow in the stream channel, the turbulent energy of the stream and the suspension properties of the sediment particles. Where the amount of sediment in a stream or inputs of new sediment exceed the transport capacity of the stream due to a slowing of flow or a decrease in stream turbulence, less sediment can be transported,



Mountain creek, Paluma Range, north Queensland
Photo: M. Furnas, AIMS

Particle size ranges in river sediments.

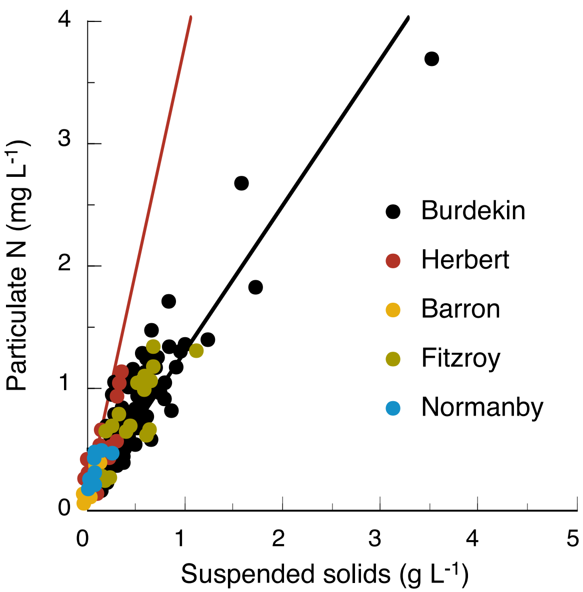
Boulders			>256 mm
Cobbles	256	-	64 mm
Pebbles	64	-	4 mm
Granules	4	-	2 mm
Sand	2	-	0.063 mm
Silt	0.063	-	0.004 mm
Clay	0.004	-	0.00012 mm

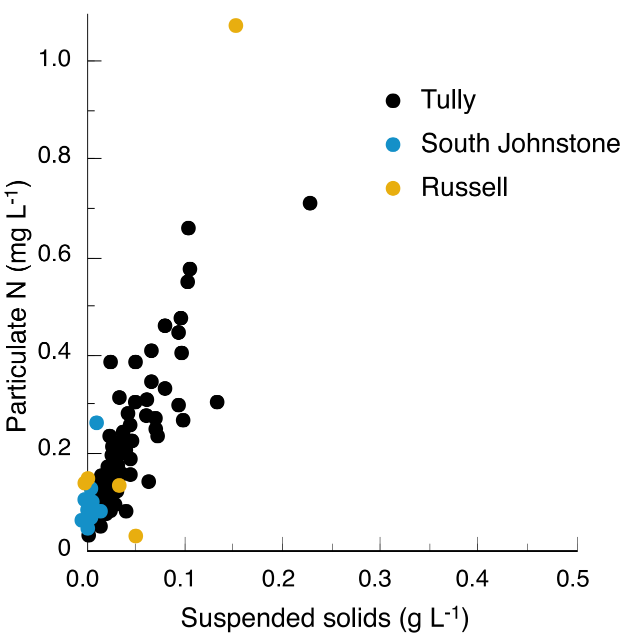
Burdekin River in the dry at Macrossan, near Charters Towers
Photo: M. Furnas, AIMS

leading to sediment deposition and accumulation. Floodplains form when floodwaters leave the river channel, spread out and slow, dropping their sediment load. Alternatively, where the volume of water in a flooding river or stream exceeds the transport capacity of the channel (including any adjacent floodplain), the floodwaters will widen or deepen the channel by bank and bed erosion. As a result, the width of river channels in the GBR catchment are largely determined by discharge volumes in very large, but infrequent flood events [8, 132, 376].

Approximate sinking velocities of sediment particles at 20°C

Fine sand	250-125 µm	1000	m per day
Very fine sand	125-63 µm	300	"
Silt	31 µm	75	"
Silt	16 µm	20	"
Silt	8 µm	5	"
Silt	4 µm	1	"
Clay	2 µm	300	mm per day
Clay	1 µm	75	"
Clay	.5 µm	20	"
Clay	.25 µm	5	"
Clay	0.12 µm	1	"





Relationships between particulate nitrogen and suspended sediment concentrations in dry (top) and wet (bottom) catchment rivers flowing into the GBR. Lines in the upper plot show linear regressions fit to the data from dry (black) and wet (red) catchment rivers.

Different things happen to coarse and fine sediments within catchments and river systems. In non-clay soils, coarser particles (sand, gravel) often make up most of the soil mass. These coarse particles dominate riverbed sediments in the monsoonal rivers of north Queensland. Larger particles require progressively higher energy conditions to be dislodged and moved. Coarse sand and gravel are predominantly moved along the riverbed by floods. The largest components of riverbed deposits (cobbles and boulders) only move under extreme flood conditions [7, 132].

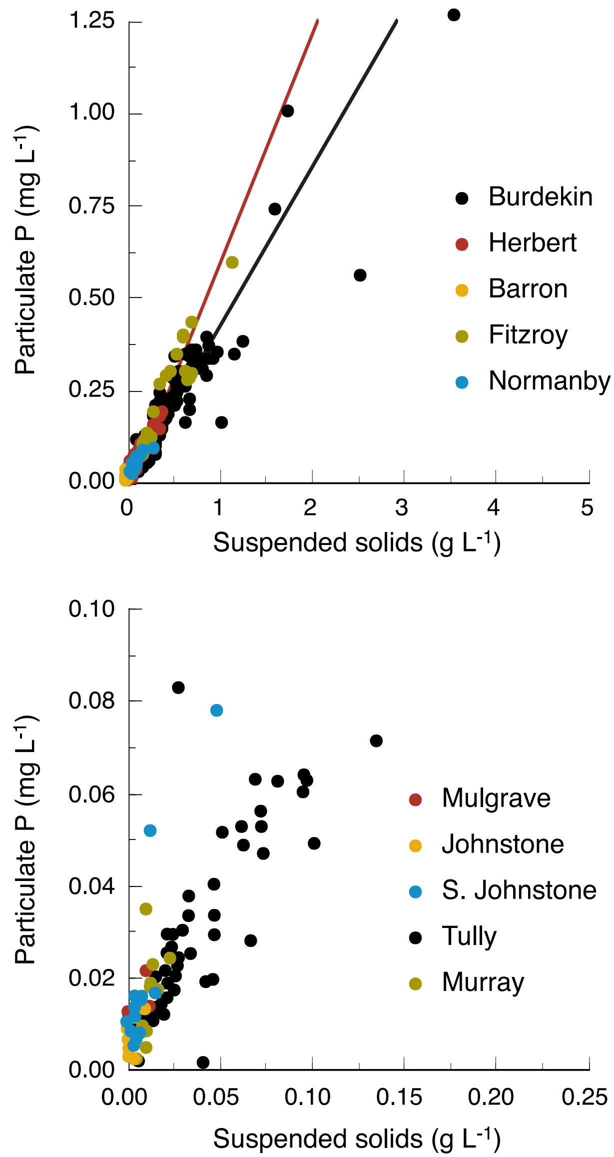
In contrast, dispersed clay particles (< 2 µm) have very slow sinking rates (cm per day). Sinking rates of the very smallest particles (colloids <0.1 µm) are negligible. Once dispersed, clay and colloid particles can be kept in suspension by very low levels of turbulence [128] and are transported over long distances in streams with little sedimentation loss. Fine silts and clays only accumulate in dams and weirs, still backwaters or shallow wetlands on floodplains where flow rates are low and water residence times are long relative to particle sinking velocities. Once clay- and silt-sized particles reach the stream network, most will be rapidly transported out of the catchment into the GBR.

While the water transport capacities of streams and rivers are largely determined by the size of large, rare flood events, most sediment is moved by more numerous small to medium-sized floods [376]. During small flows or wet seasons with lower than average discharge, eroded soils and sediment accumulate on alluvial fans in gullies, in agricultural drainage networks and in river channels [78, 90, 91, 392]. This sediment is re-eroded and moved downstream by major flood events, transforming the riverbed [7, 19]. Coarse sand may only move a few centimetres or metres down a hillside in a year. Sandbars in a riverbed may only move a kilometre downstream.

Due to modern accelerated erosion rates on agricultural and grazing lands, coarse sediments have been accumulating in river channels, forming extensive riverbed deposits (sand slugs) which are only slowly moving downstream [352]. The coarser sediments which form sand slugs will remain in the river system for hundreds to thousands of years [133, 135]. Even in small catchments, most of the coarse sediment in upland soils eroded during the last 150 years has not reached the coast [135, 387]. Dams and weirs trap these coarse sediments and prevent their downstream movement. However, there is no evidence that impoundments in the GBR catchment have materially reduced sediment export from catchments. Modern (post-1900) exports of sand and coarser sediments from rivers of the GBR catchments are largely derived from the huge amounts of sediment stored in downstream river reaches, most of which are below impoundments.

Most of the nutrients exported from catchments in particulate form are bound to the fine sediments (<2 µm) which come from the silts and clay in soils. While larger (sand, silt) particles often make up most of the mass in soils, the organic matter and nutrients are primarily associated with very fine silts and clays. The clay contents of surface soils in the GBR catchment span a wide range (Table 10). Some soils in the krasnozem, black earth, prairie soil and grey clay Australian Great Soil groups have clay contents exceeding 70%.

Sediment transport in all rivers of the GBR catchment is dominated by silt and clay. Until recently, relatively few measurements have been made of suspended and bedload sediment transport in rivers of the GBR catchment [40, 207]. Suspended sediment, largely silt and clay, accounts for 80-90% of the sediment load currently transported by the Burdekin River [40]. Similarly, suspended clay particles comprise over 95 % of the sediment load discharged by the Fitzroy River [207]. These high percentages are not surprising given the extensive distribution of clay soils



Relationships between particulate phosphorus and suspended sediment concentrations measured in dry (top) and wet (bottom) catchment rivers flowing into the GBR. Lines in the top graph show linear regressions fit to the data from dry (black) and wet (red) catchment rivers.

Table 30. Summary statistics for suspended sediment concentrations measured in dry and wet catchment rivers of the GBRCA.

Dry Catchment Rivers		Cape York	Normanby	Ross	Haughton mg L^{-1}	Burdekin	Fitzroy
Wet Season	Average	10	108	22	110	394	505
	Median	8	89	14	96	279	526
	Maximum	27	300	69	200	3,559	1,145
	Minimum	3	50	3	41	74	174
Dry Season	Average	4		12		141	
	Median	3		5		143	
	Maximum	9		24		190	
	Minimum	1		5		73	

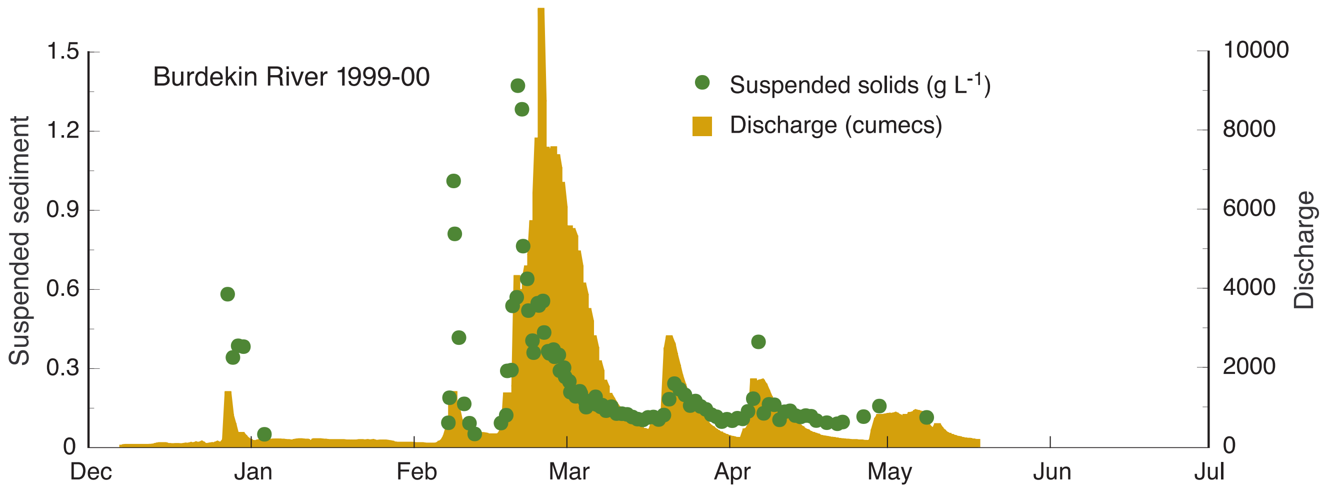
Wet Catchment Rivers		Barron	Mulgrave-Russell	Johnstone	Tully mg L^{-1}	Murray	Herbert
Wet Season	Average	43	305	7	32	13	93
	Median	23	4	6	23	12	66
	Maximum	151	7,638	49	230	24	788
	Minimum	2	1	1	2	6	1
Dry Season	Average	9	2	4	21	7	19
	Median	10	2	3	7	7	5
	Maximum	17	4	8	99	8	266
	Minimum	3	0	1	2	4	1

throughout the Fitzroy, and to a lesser extent, the Burdekin River basins (Chapter 3).

Particulate nitrogen and phosphorus loads in GBR rivers follow suspended sediment concentrations. GBR catchment soils, whether fertilised or not, naturally contain substantial stocks of nitrogen and phosphorus (Chapter 3). As a result, concentrations of particulate nitrogen (PN) and phosphorus (PP) in river waters are closely correlated with the concentration of suspended sediment. The average nitrogen and phosphorus content of particulate matter in rivers draining wet and dry catchments parallel the composition of catchment soils. Particulate matter collected in three wet-catchment rivers (Russell, South Johnstone, Tully) has an average nitrogen content (0.37% of dry weight), three times that of particulate matter of rivers from dry or largely dry catchments (0.12% of dry weight). Similarly, the average phosphorus content of suspended particulate from wet-catchment rivers (0.06% of dry weight) is 40% higher than suspended matter from dry catchment rivers (0.043% of dry weight). The nitrogen content of suspended matter from the Burdekin and Fitzroy rivers is close to the average soil nitrogen content in these catchments. This indicates that the extensive grazing lands of these catchments are the predominant source of the particulate nitrogen. In contrast, the nitrogen content of suspended matter collected in wet-catchment rivers is 2.7 times that of the average nitrogen content of soils in those catchments. The average phosphorus content of suspended matter in both wet- and dry-catchment rivers is close to the average phosphorus content of soils in those types of catchment (0.059% and 0.037% of dry weight, respectively).

The similarity between the phosphorus content of catchment soils and riverine suspended matter further indicates that most of the phosphorus bound to eroded soil stays bound to the fine sediment in rivers [61, 373]. In contrast, the higher nitrogen content of suspended particulate matter from wet-tropical rivers suggests that the particulate nitrogen in river waters either comes from nitrogen-enriched soils in the catchment, or that small particles of nitrogen-enriched organic matter are preferentially washed out of eroding soils.

Regardless of catchment type, the good correlation between particulate nutrient (N,P) and suspended sediment concentrations means that useful estimates of particulate nitrogen and phosphorus exports from rivers can be derived from estimates of fine sediment exports from catchments.



Suspended sediment concentrations in the Burdekin River over the 1999-2000 wet at Ayr. Water samples were manually collected at near-daily intervals from the highway bridge.

Turbidity logger in the Burdekin River
Photo: M. Furnas, AIMS

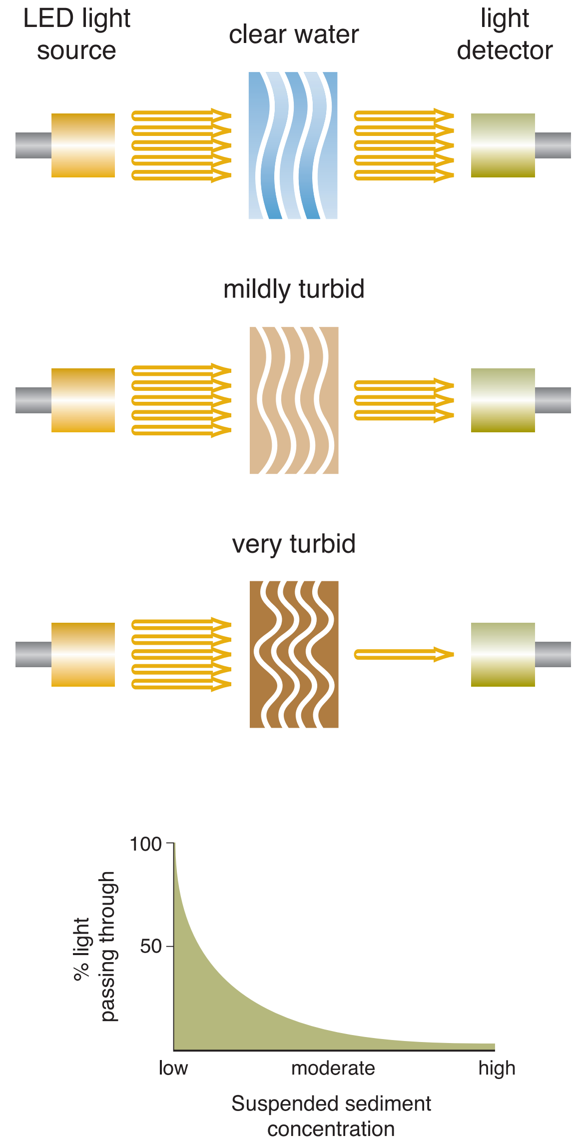
Suspended sediment concentrations in north Queensland rivers

Until recently, estimates of fine sediment loads in rivers of the GBR catchment were based on a relatively small number of samples collected from a few rivers [40, 207, 216, 326, 346]. These data clearly showed that mean suspended sediment loads differed between rivers. Over the last 10 years, this information base has been expanded by extensive sampling in a number of rivers draining into the central and northern GBR (Table 30). The summary statistics do not show the often large and rapid changes in suspended loads that occur during floods. Even in major rivers where discharge changes relatively slowly, daily sampling is often needed to resolve the large fluctuations in sediment loads.Sampling of suspended sediments and nutrient loads during major flood events is hampered by the remote location of many rivers and difficulty in reaching sampling sites [326]. Often, specialised instruments are needed to sustain the high sampling rates necessary for periods of days to weeks under flood conditions.

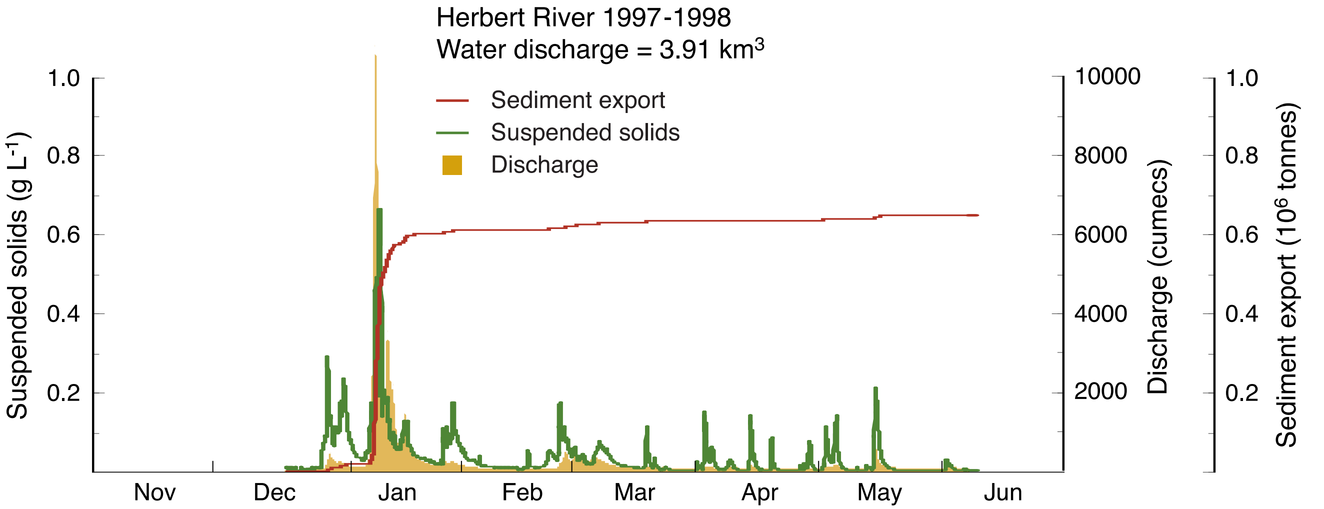
Where the composition and size distribution of suspended particles is relatively stable with time and discharge rate, the turbidity of river waters can be used as a measure of the suspended sediment load [163]. Light passing through the river water is scattered or blocked by suspended particles and absorbed by dissolved coloured organic compounds. Most of the light attenuation is due to clay-sized particles (<0.01 to 2 µm) which are the most numerous particles in natural waters and make up most of the suspended sediment load.

Turbidity is readily measured by optical instruments, although care is needed in their calibration to resolve effects of particle size [74, 224]. The smallest clay and colloidal particles block light most efficiently while larger (silt-sized) particles contribute disproportionately to suspended sediment mass. Turbidity sensors are therefore most sensitive to the concentration of the very fine suspended particles which also carry most of the particulate nutrients in river waters. When coupled to an electronic data recorder and provided that their optical surfaces are kept clean, turbidity sensors can be deployed in rivers for extended periods. The instruments can remain in place during large and small flood events. Time series of turbidity data show that suspended sediment loads and therefore, particulate nutrient concentration change rapidly in response to seasonal discharge fluctuations in north Queensland rivers.

Ranges of suspended sediment concentrations in wet- and dry-catchment rivers differ substantially. The turbidity record shown from the Herbert River is representative of the relationship between flow and suspended sediment concentrations in rivers that drain wet-tropical catchments. Suspended sediment concentrations increase rapidly as water levels rise, peak briefly at or slightly before the peak in discharge, then decline rapidly to low baseflow levels. An integration (running sum) of the amount of fine sediment carried by the Herbert River past the measurement site is characterised by abrupt increases during the season's flood events. During the wet season, the bulk of the annual water discharge and sediment export from the Herbert catchment may occur in a few days of high river flow. In wet seasons where the bulk of the annual discharge occurs during a single major flood (e.g. after a cyclone) most of the



Measuring suspended sediment loads by monitoring the turbidity of river waters. Top: Turbidity sensors measure the amount of light passing through river water. Particles and coloured materials in the water absorb or scatter the light beam. With increasing turbidity, less light reaches the detector. Bottom: Illustration of the relationship between the % light passing through water over a fixed distance and the suspended sediment concentration.

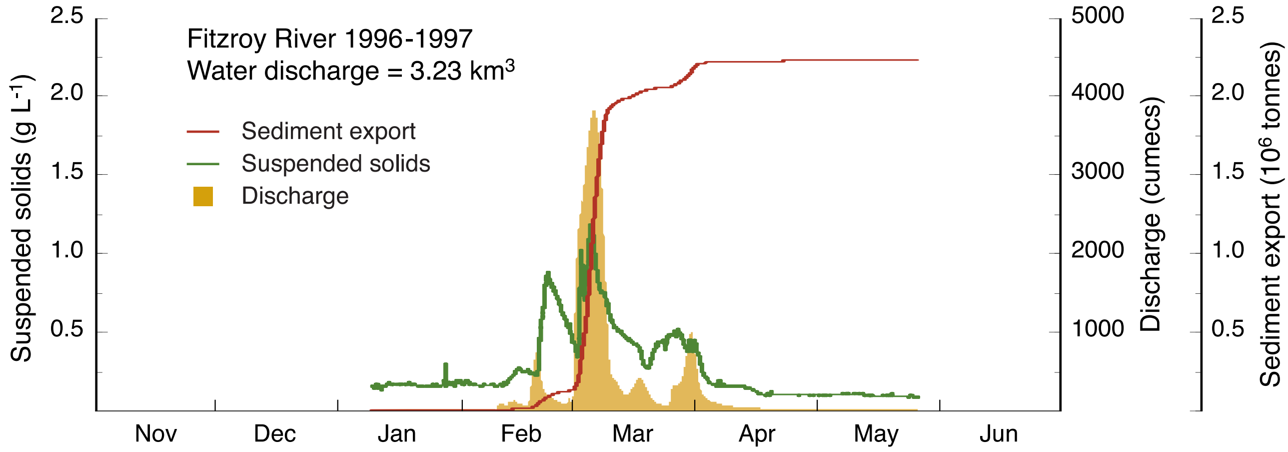


Suspended sediment concentrations (green line) in the Herbert River at Ingham in relation to instantaneous discharge (brown shaded area) during the 1997-8 wet season. Suspended sediment concentrations were measured with a submerged turbidity sensor at 30-minute intervals. The red line shows the cumulative suspended sediment transport past the measurement site.

Gairlock Bridge submerged by flood, Herbert River
Photo: M. Furnas, AIMS

annual sediment and nutrient export from the catchment will also occur in this short period (ca. 1 week). To accurately estimate annual export of water, sediment and nutrients from catchments of the monsoonal tropics, sampling efforts must be focused on these brief high-discharge events.

Although the concentrations of suspended sediment increase during floods, they are not closely correlated with river height. Suspended sediment loads at a particular water level or discharge rate are usually higher when the river is rising as newly eroded soils are washed into the river. Early summer floods carry higher concentrations of suspended sediment for a particular level of discharge than late wet-season floods. Maximum suspended sediment concentrations recorded during floods in the Herbert River are close to 0.8 g L^{-1} (800,000 tonnes per km^3 of discharge). Even higher suspended sediment concentrations



Suspended sediment concentrations (green line) in the Fitzroy River at Rockhampton in relation to river discharge (brown shaded area) over the 1996-97 wet season. Suspended sediment concentrations were measured with a submerged turbidity sensor at 30-minute intervals. The red line shows the cumulative suspended sediment transport past the measurement site.

(> 1 gm L^{-1}) have been recorded in spot samples collected from the lower Russell River. In contrast, maximum suspended sediment concentrations in the Tully River during large flood events only approach 0.25 g L^{-1}. In wet-tropical rivers, high suspended sediment concentrations (> 0.1 g L^{-1}) only last for a few days during major floods, although significant discharge may persist for several weeks. During summer low-flow periods, suspended sediment concentrations in wet-catchment rivers are usually less than 0.05 g L^{-1} (50,000 tonnes per km^3 of discharge). Only a small proportion of the annual sediment load is exported during the dry season (normally June-October) due to low in-stream suspended sediment concentrations and low water discharge rates.

The large dry catchment rivers (Fitzroy and Burdekin) of the central and southern GBR carry higher suspended sediment loads than the rivers of the wet tropics. Because of the lower levels of vegetation cover in these dry catchments as a consequence of lower rainfall, clearing and grazing, and the widespread distribution of clay soils in parts of these drainage basins, the Burdekin and Fitzroy Rivers are highly turbid when actively flowing. At the peak of large flood events, maximum suspended sediment concentrations in the Burdekin River can range


Turbid flood waters in the Burdekin River
Photo: M. Furnas, AIMS

between 1 and 3 g L^{-1} (1 to 3 million tonnes of sediment per km^3 of discharge). Peak suspended sediment concentrations in the lower Fitzroy River during small summer flows can reach 1.5 g L^{-1}. Maximum suspended sediment concentrations in the Fitzroy River are probably much higher, but no significant floods have been sampled. As in the wet-tropical rivers, these high concentrations only last for a few days. During low-flow conditions, suspended sediment conditions in the Burdekin River are generally between 0.05 and 0.20 g L^{-1}.

In any wet season, rivers in the wet tropics typically have several flows or floods while dry-catchment rivers of the central and southern GBR catchment usually only have one, or rarely two, significant flow events. Because the Burdekin and Fitzroy River catchments are so large, significant floods may develop within just one sub-catchment. These large sub-catchments have their own soil, vegetation, topography and erosion characteristics [351,352] which produces runoff with different levels of turbidity and suspended sediment loads. Flood conditions in the large rivers may persist for weeks as the rainwaters work their way out of the catchment. As in the wet-tropical rivers, suspended sediment concentrations peak rapidly on the rising edge of the flood, reaching maximum values at or just prior to the flood peak. Concentrations then decline exponentially over several weeks.

Chapter 7

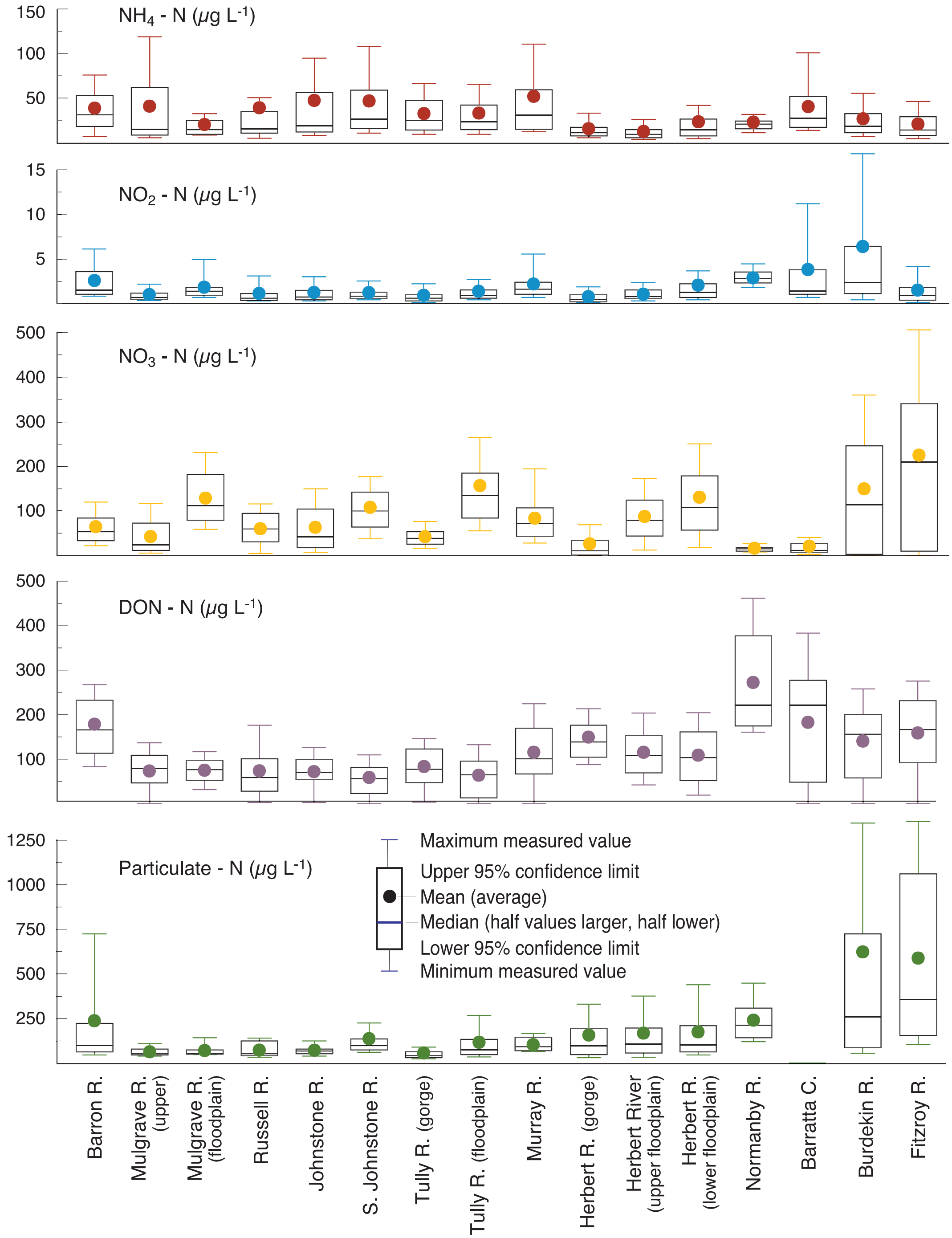
Nutrients

in rivers of the Great Barrier Reef catchment

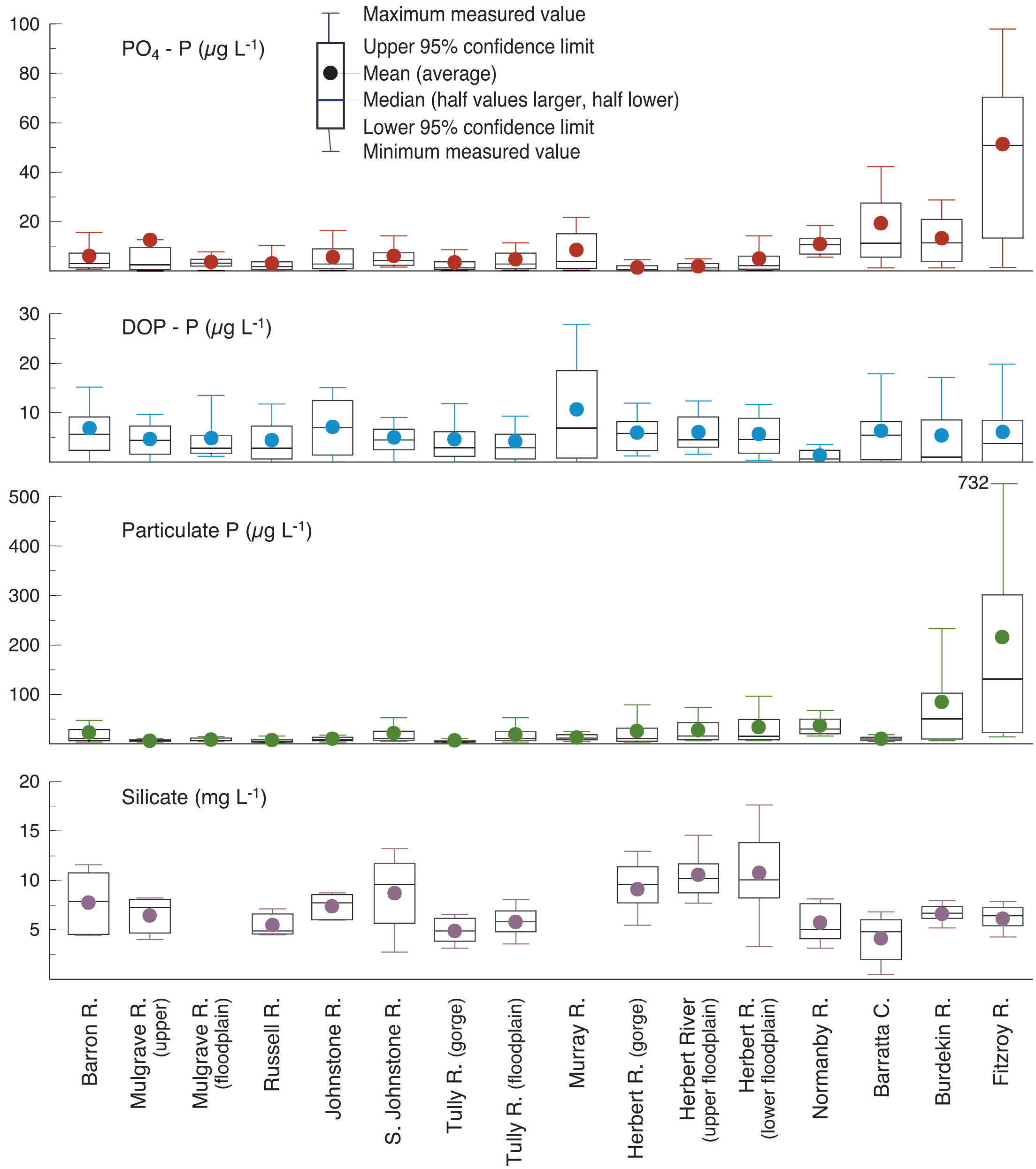
Plants, animals and microbes require a number of chemical elements to live and grow (Table 31). Most are only needed in tiny amounts (micronutrients). While concentrations of micronutrient elements are typically very low in natural soils and waters (in the parts-per-million to parts-per-billion range), they can usually sustain natural levels of ecosystem productivity. In contrast, biologically available stocks of the major structural nutrient elements, nitrogen (N) and phosphorus (P) in soils, rivers and marine waters are often insufficient to support significant increases in biomass or productivity. Carbon, the principal structural element in all living matter, is usually very abundant in tropical ecosystems because of naturally high primary production rates as a result of high ambient light levels and warm temperatures. A variety of evidence indicates that nitrogen[142, 147, 458, 462], and to a lesser extent, phosphorus availability [459] often limit planktonic and benthic algal biomass in the Great Barrier Reef. In the absence of recycling, concentrations of nitrogen in readily available forms (NH_4^+, NO_3^-) in GBR waters are usually at levels (ca. <5 µg N L^{-1}) that would be exhausted within hours by algal and bacterial demand. The level of primary production by

Table 31. Nutrient elements required by living cells.

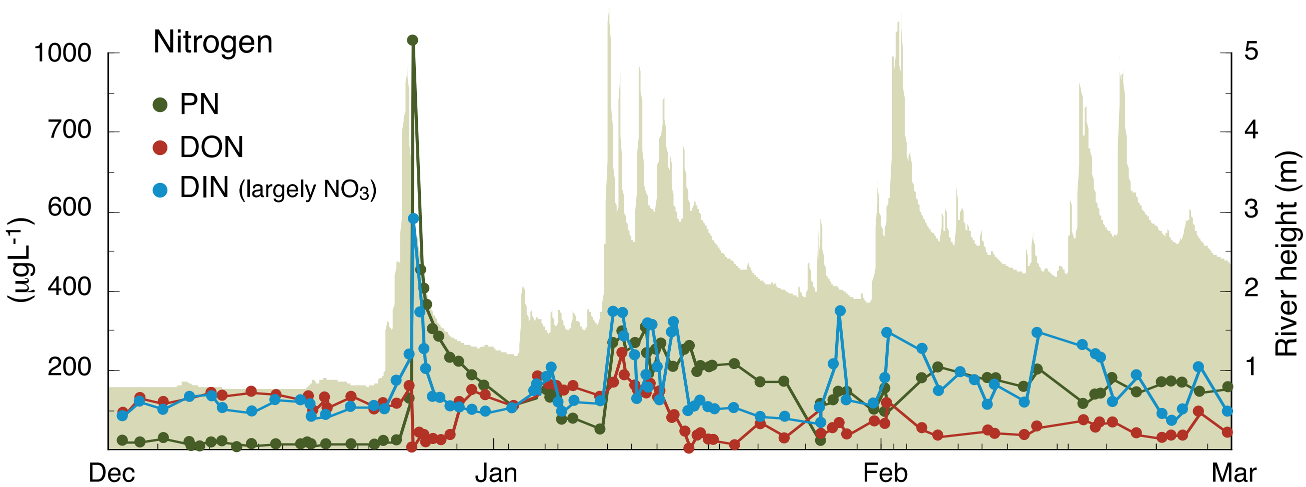
Element	Symbol	Required For
Nitrogen	N	proteins, nucleic acids, energy metabolism
Phosphorus	P	nucleic acids, cellular membranes, energy metabolism
Silicon	Si	cell walls (diatoms)
Iron	Fe	energy metabolism enzyme function nitrogen fixation
Copper	Cu	energy metabolism enzyme function
Nickel	Ni	enzyme function
Molybdenum	Mo	nitrogen fixation
Zinc	Zn	enzyme function
Cobalt	Co	enzyme function
Elements with a nutritional role which are abundant in seawater		
Sodium	Na	
Sulfur	S	
Potassium	K	
Calcium	Ca	
Magnesium	Mg	
Boron	B	

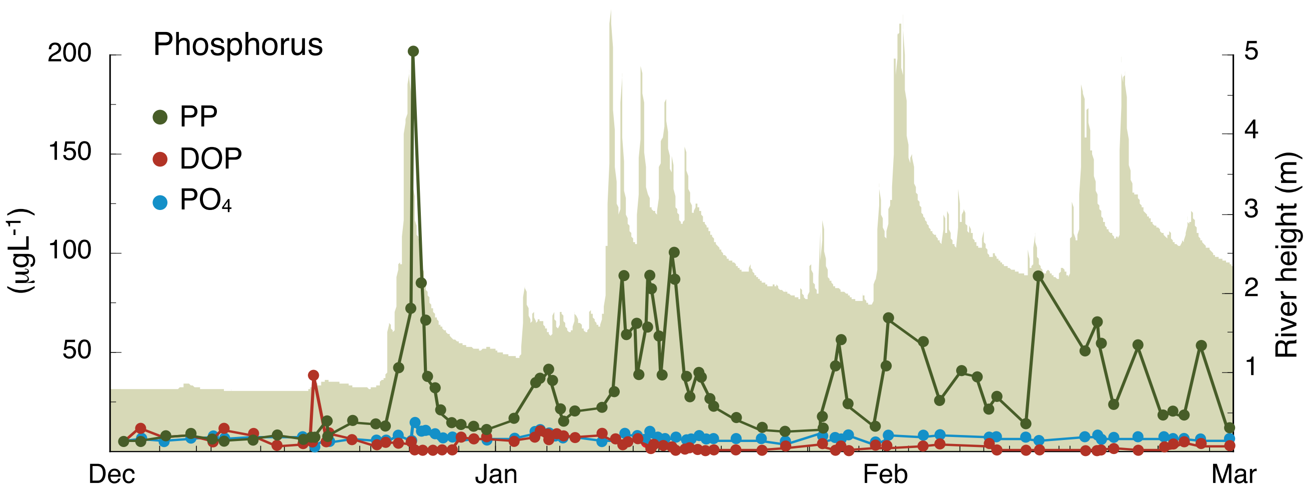


A summary of fixed nitrogen concentrations measured by AIMS in rivers of the GBR catchment (1987-2000).

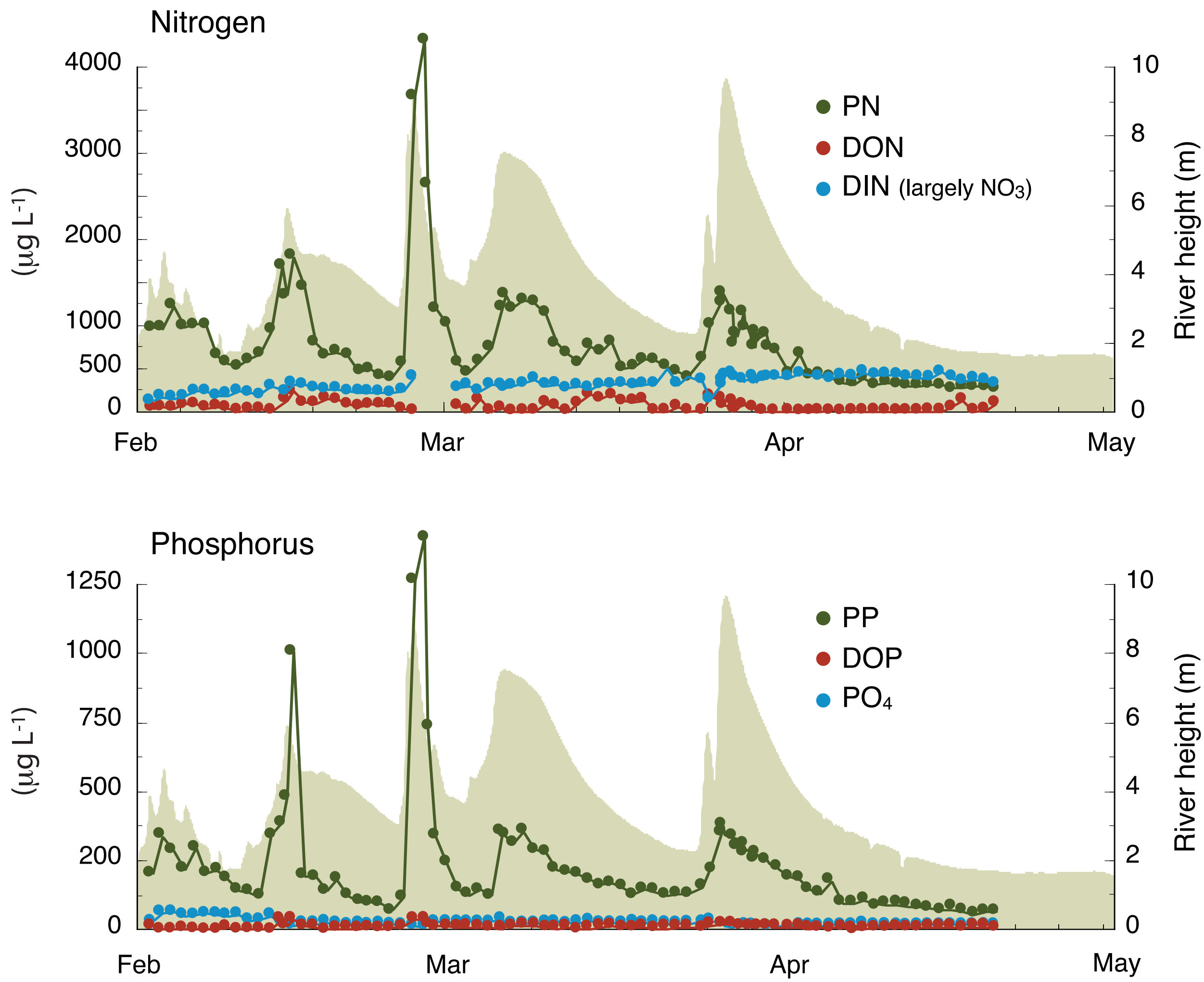


A summary of phosphorus and silicate concentrations measured by AIMS in rivers of the GBR catchment (1987-2000).

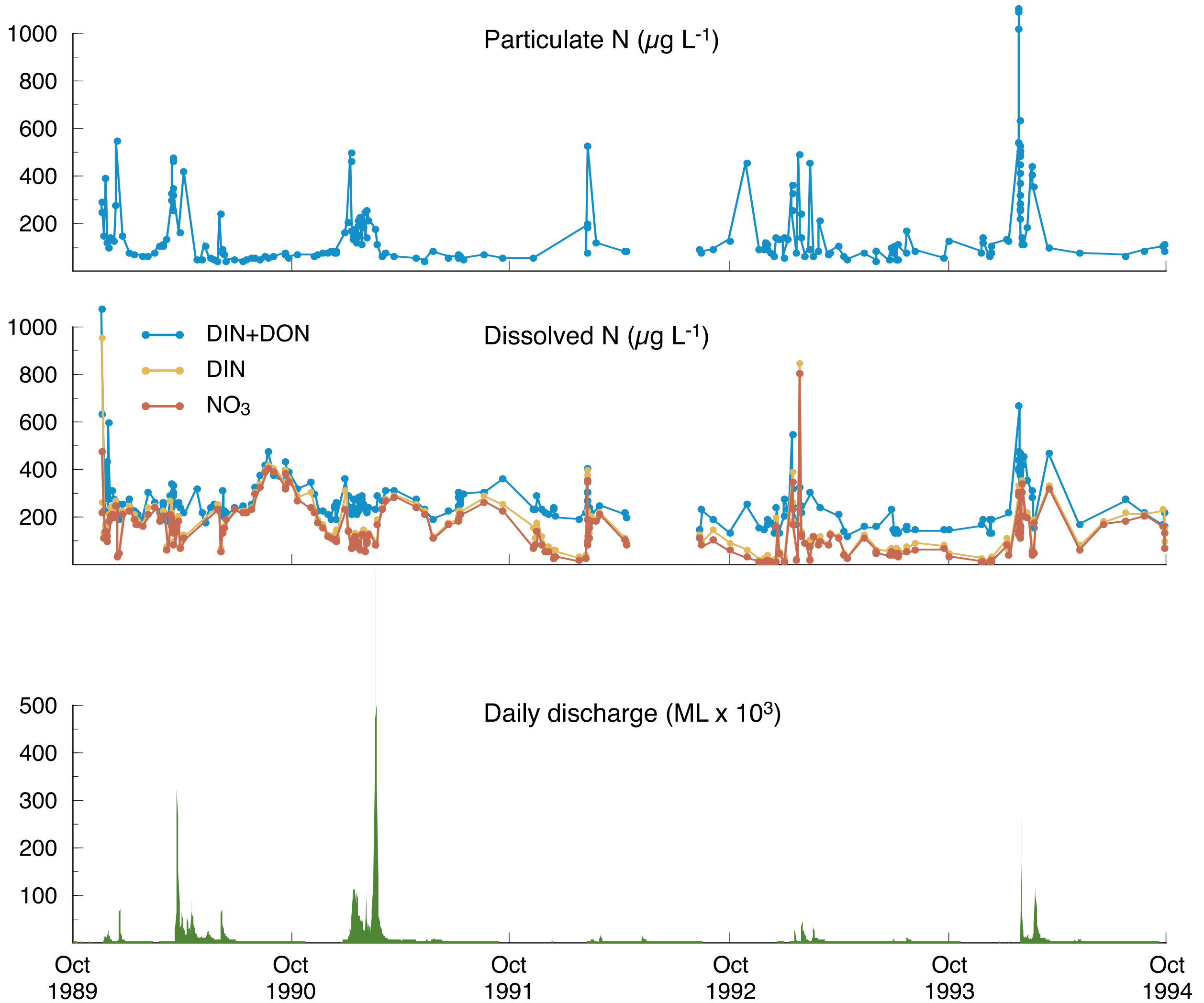




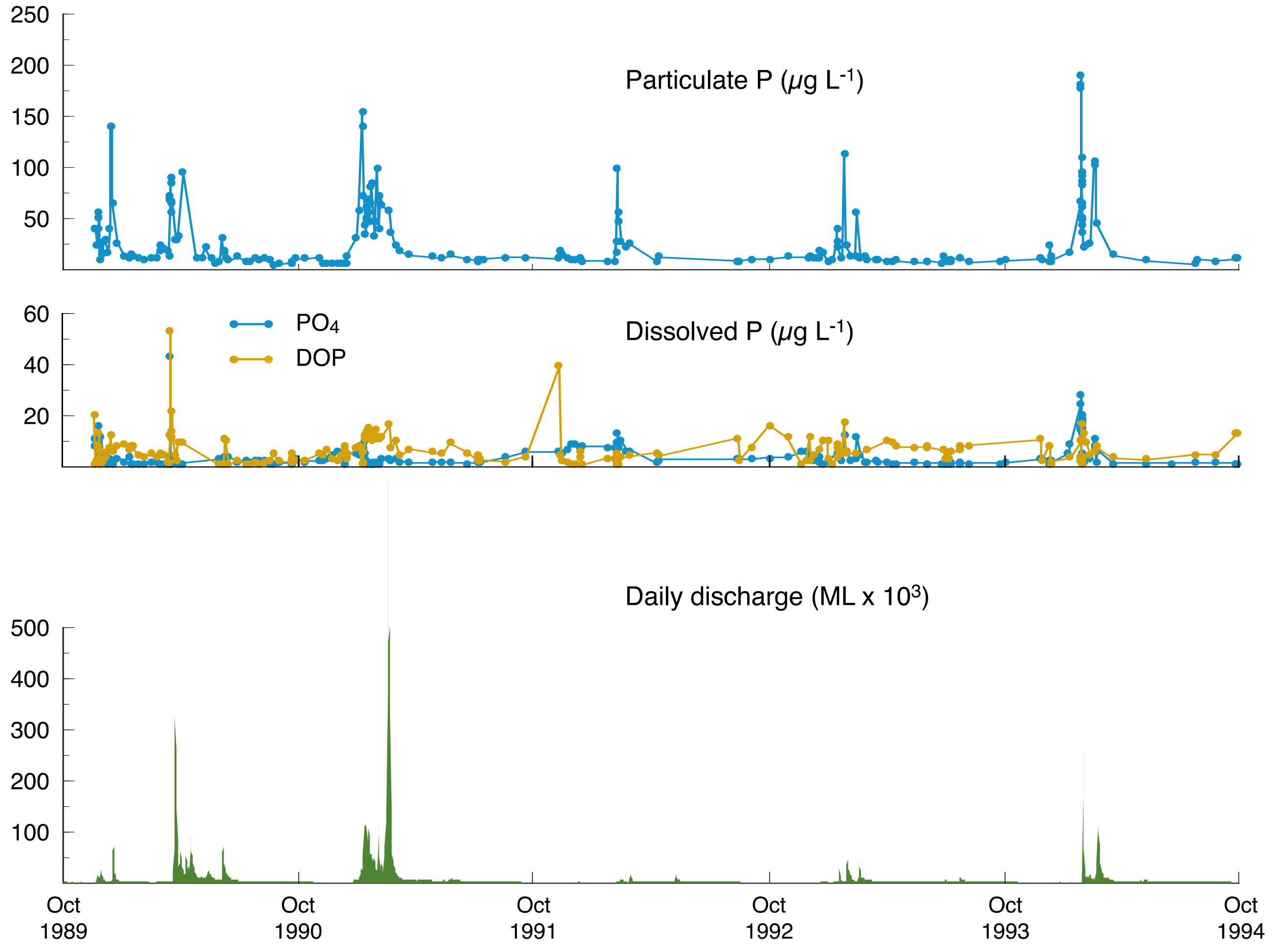
Daily changes in nutrient concentrations in the South Johnstone River (South Johnston) relative to concurrent river flow (shaded background) over the 1990-91 wet season. Discharge data source: QNR&M



Short-term (daily) changes in nutrient concentrations in the Burdekin River relative to concurrent river flow (shaded background) over the 1996-97 wet season.
Discharge data source: QNR&M



Particulate nitrogen (top) and dissolved fixed nitrogen (middle) concentrations measured in the lower Herbert River (Ingham) between 1 Oct 1989 and 1 Oct 1994 in relation to daily discharge.
Discharge data source: QNR&M



Particulate phosphorus (top) and dissolved phosphorus (middle) concentrations measured in the lower Herbert River (Ingham) between 1 Oct 1989 and 1 Oct. 1994.
Discharge data source: QNR&M

planktonic and benthic algae, in turn, governs the biomass and productivity of animals in the ecosystem [295]. On land, nitrogen or phosphorus limitation constrains the productivity of forest and pasture ecosystems. Nitrogen and phosphorus are usually the primary constituents of fertilisers added to increase or sustain productivity in agricultural systems [404, 417].

Rivers transport nutrients in several forms: as free dissolved ions (e.g. NH_4^+, NO_3^-, PO_4^{3-}; as part of dissolved organic compounds (urea, amino acids); or in suspended particulate matter. Particulate matter collected from rivers includes living organisms such as algae or bacteria, non-living (detrital) organic matter and inorganic nutrients or nutrient-containing organic matter bound to suspended sediment particles. Nutrient concentrations in river waters depend on biological and chemical processes in catchment soils, runoff and erosion which transport water, soil and nutrients to the rivers, and water flows which move dissolved and particulate materials.

Seasonal variations in river nutrient concentrations

Average nutrient concentrations vary between rivers. There are also clear upstream-downstream differences in mean concentrations and relative abundances of different nutrient forms. However differences between the average nutrient characteristics of rivers are usually smaller than variations in concentrations over time in individual rivers. The relative abundance of particulate forms of nutrients can vary dramatically and quickly. These fluctuations occur in response to rainfall and the resulting changes in river flow. Nutrient concentrations usually vary most during the summer wet season when river flows also vary the most. The relative importance of in-stream biological processes varies inversely with river flow and the time water spends in any section of the river [73, 432].

Bananas in the upper Tully River valley
Photo: M. Furnas, AIMS

Nitrate (NO_3^-) is the most abundant form of dissolved inorganic nitrogen (DIN) in both wet- and dry-catchment rivers. Concentrations of nitrite (NO_2^-) and ammonium (NH_4^+) in river waters are typically low and relatively constant throughout the year. Small amounts of nitrate occur naturally in rainwater [146]. The nitrate in river waters largely comes from bacterial oxidation of ammonium in oxygenated catchment soils, surface waters and groundwaters. Agricultural fertilisers are an additional source of nitrate in catchments with significant cropping activity. The fertiliser-derived nitrate can either be a constituent of the fertiliser [417] or be produced by soil bacteria from other fertiliser constituents (e.g. ammonia, urea).

In most rivers (e.g. South Johnstone, Tully, Burdekin, Fitzroy Rivers), nitrate concentrations are generally highest during wet season flood events. In some, however (e.g. Herbert River), the highest nitrate concentrations occur at the end of the dry season when high nitrate groundwater inputs make a larger relative contribution to water in the river. These differences reflect the nature of catchment water and nutrient sources. When nitrate concentrations are highest in the wet season, it is usually during the first flow or flood event of the season (the first flush), when large amounts of water wash across and through catchment soils. Groundwater is an important source of nitrate in the wet tropics rivers (e.g. Herbert and Tully River catchments) where there is usually some rain throughout the year. In these wet catchments, highly permeable soils may lose significant nitrogen to ground water and the river system [54, 160, 401].

In contrast to other wet tropics rivers, nitrate concentrations in the Herbert River decline during large flood events due to dilution of the catchment sources. Although nitrate concentrations fall during floods, the total amount of nitrate exported from the catchment increases due to the larger volume of water discharged.

Nitrate concentrations exhibit only small changes during floods in the two largest dry-catchment rivers (Burdekin, Fitzroy). Nitrate inputs to the river in surface runoff are diluted by the large volumes of water in floods. Groundwater inputs to these dry rivers are unknown, but are small in relation to surface water inputs. Only small portions of these large catchments receive agricultural fertilisers. The nitrate exported is largely produced by natural microbial processes operating in catchment soils and waterways.

There is little variation in dissolved organic nitrogen (DON) concentrations relative to river flow in both wet and dry catchment rivers. DON concentrations in rivers draining wet-tropical catchments (Tully, South Johnstone) are typically less than 200 µg-N L^{-1}. In the two large dry-catchment rivers (Burdekin, Fitzroy), DON concentrations can reach 400 µg-N L^{-1}. There is little evidence of DON dilution during flood events, suggesting a surface source. DON is the principle (up to 80%) form of nitrogen exported from pristine river catchments which are far-removed from clearing pressure and atmospheric sources of nitrate from fossil fuel combustion [374, 528]. The relative contribution of nitrate and DON to river nitrogen levels and exports may therefore indicate the degree of human disturbance.

Dissolved phosphorus (PO_4^{3-} and DOP) concentrations in wet- and dry- catchment rivers respond differently to floods and seasonal changes in flow. In wet or predominantly wet-catchment rivers (e.g. Tully, South Johnstone, Herbert Rivers), phosphate and dissolved organic phosphorus levels are generally less than 20 µg-P L^{-1}, regardless of season and discharge rate, and increase only slightly, if at all, during flood events. Their relative constancy indicates that chemical solubility processes operating in river waters and on suspended soil particles largely determine dissolved phosphorus concentrations [61, 137, 139, 373]. In contrast, dissolved phosphorus concentrations in the large dry-catchment rivers (Burdekin and Fitzroy Rivers) exhibit pronounced increases during wet season flood events, with peak concentrations in excess of 100 µg P L^{-1}.

Not surprisingly, concentrations of particulate nitrogen (PN) and phosphorus (PP) increase with river flow in both wet- and dry-catchment rivers, reflecting higher suspended sediment loads during flood events. While particulate nitrogen and phosphorus concentrations are correlated with suspended sediment load (Chapter 6), they are not well correlated with discharge, due to rapid changes in suspended load in both large and small flood events. Under most conditions, the highest particulate nitrogen and phosphorus concentrations are found in the turbid dry-catchment rivers (Burdekin, Fitzroy) and are lowest in the relatively clearer wet-tropical rivers (Tully, South Johnstone).

Recent changes in river nutrient levels

During the last 100 years, the extent of human land use has changed significantly in catchments bordering the central and southern GBR (Chapter 5). The degree of change has increased dramatically since the 1960s due to widespread land clearing, the introduction of drought-hardy cattle and increasing use of chemical fertilisers.

The best evidence for human-related changes in nutrient export from catchments comes from a 13-year record of nutrient concentrations in the lower Tully River. Because of the high variability in both nitrogen and phosphorus concentrations over seasonal periods and during floods, the detection of catchment trends in short (less than 5-year) data records is unlikely, regardless of the number of samples collected.

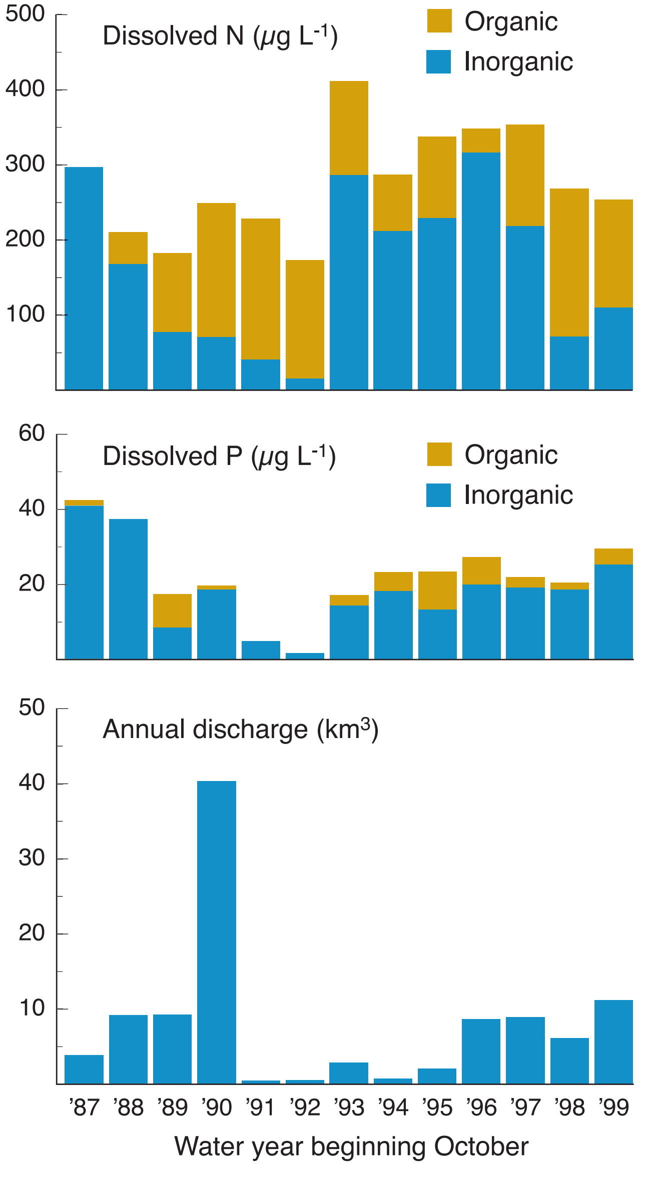
There are two patterns of change in nutrient levels in the long-term Tully River nutrient record. Prior to 1993, baseflow (low-water) nitrate concentrations were relatively constant, with minimum values below 50 µg N L^{-1}. From 1993, however, baseflow nitrate concentrations progressively increased reaching minimum levels close to 125 µg N L^{-1} in May 2000 [330], a 2.5-fold increase (14% p.a.). Over the same period, baseflow particulate nitrogen concentrations also increased from ca. 25 to 75 µg N L^{-1} (15% p.a.). Phosphate (PO_4^{3-}) concentrations went through a number of changes in the late 1980s, then from 1993 onward, baseflow phosphate concentrations also increased 2.5-fold (14% p.a.). No increases in baseflow concentrations of particulate phosphorus, DON or DOP were observed. The post-1993 period is also characterised by increased variability of particulate nitrogen and phosphorus concentrations. This greater variability reflects more frequent erosion events which carry soil and other particulate matter into the river.

The rise in baseflow nutrient levels and increased erosion rate coincide with a change in agricultural land use in the Tully and Murray River drainage basins. Beginning in the late 1980s, grazing lands in the upper Tully floodplain, where pastures remain grass-covered throughout the year, have been converted to more intensive cultivation of bananas, and to a lesser extent, sugarcane. Between 1987 and 1999, land area planted with sugarcane in the Tully and Murray

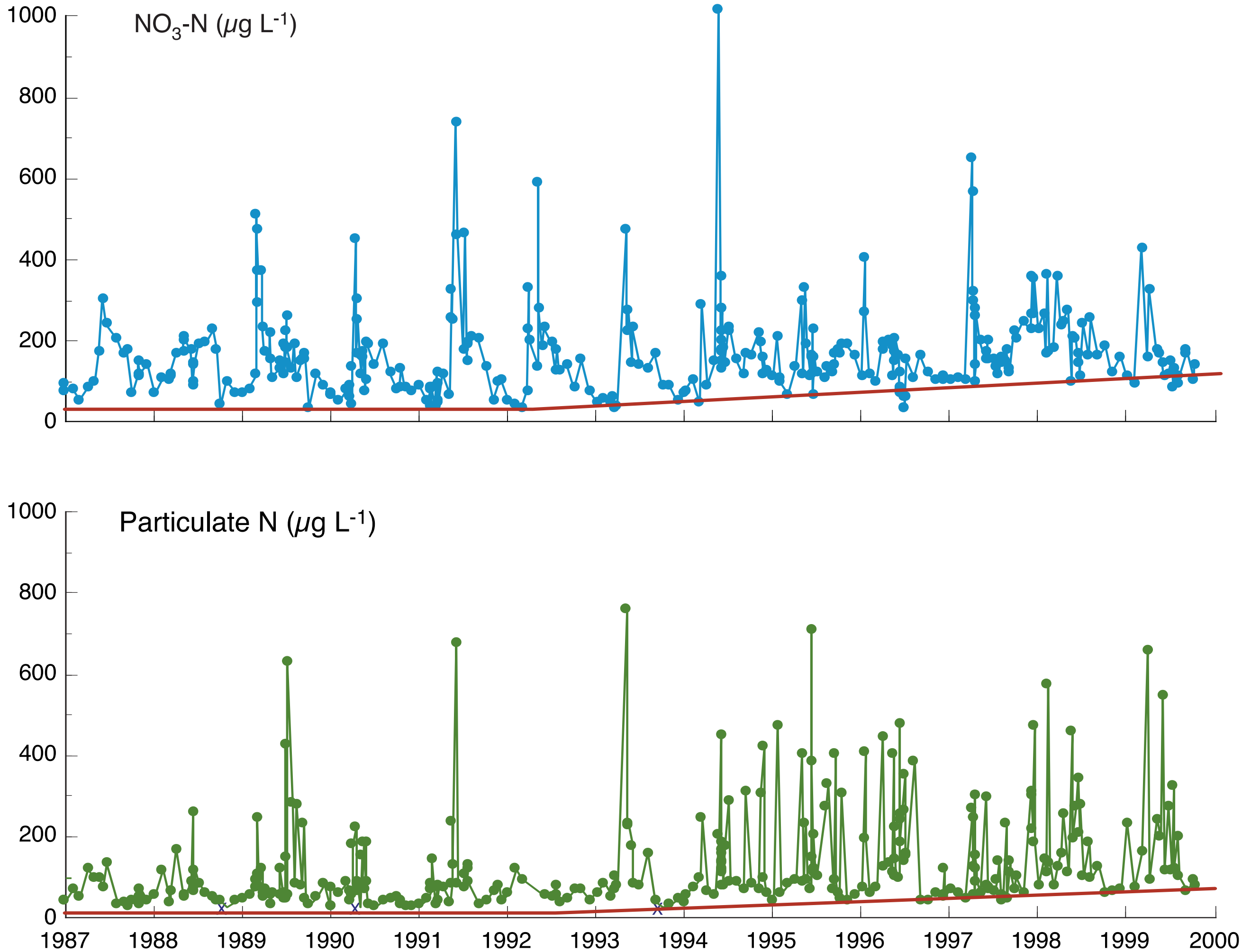
River basins has doubled from 125 to 247 km^2 [330]. The area planted with bananas increased from 17.3 to 30.4 km^2. The most intensive fertiliser applications are made on the banana crop which receives ca. 480 kg of N per ha, compared with ca. 120 kg per ha on sugar. Applications of fertiliser nitrogen to sugarcane in the Tully and Murray River drainage basins doubled from 1,500 to 3,000 tonnes while nitrogen applied to bananas increased from less than 500 tonnes to 1,500 tonnes [330].

There was a different relationship between discharge and nutrient levels in the Burdekin River during the same 13-year period (1987-2000). The Burdekin River has little or no baseflow during the dry season. Groundwater inputs, if any, are small. There was no trend in the average concentration of total dissolved nitrogen, (ca. 300 µg N L^{-1}) over this period. There were, however, distinct year-to-year fluctuations in nitrate and DON levels. The lowest nitrate concentrations were recorded during the 1991-1992 and 1992-1993 drought years. This is most likely due to low rainfall and reduced flushing of nutrients from catchment soils. Nitrate and DON concentrations in river waters varied inversely over the 13-year period, although on a year-to-year basis, there was no correlation between discharge and the relative nitrate/DON balance. Between 1988 and 1993 Burdekin River waters were characterised by relatively lower nitrate concentrations (generally less than 150 µg - N L^{-1}) and relatively higher DON (greater than 150 µg -N L^{-1}). The balance was reversed between 1993 and 1998, with relatively low DON and high nitrate. This reversal probably reflects a change in catchment conditions during wetter years of the late 1990s.

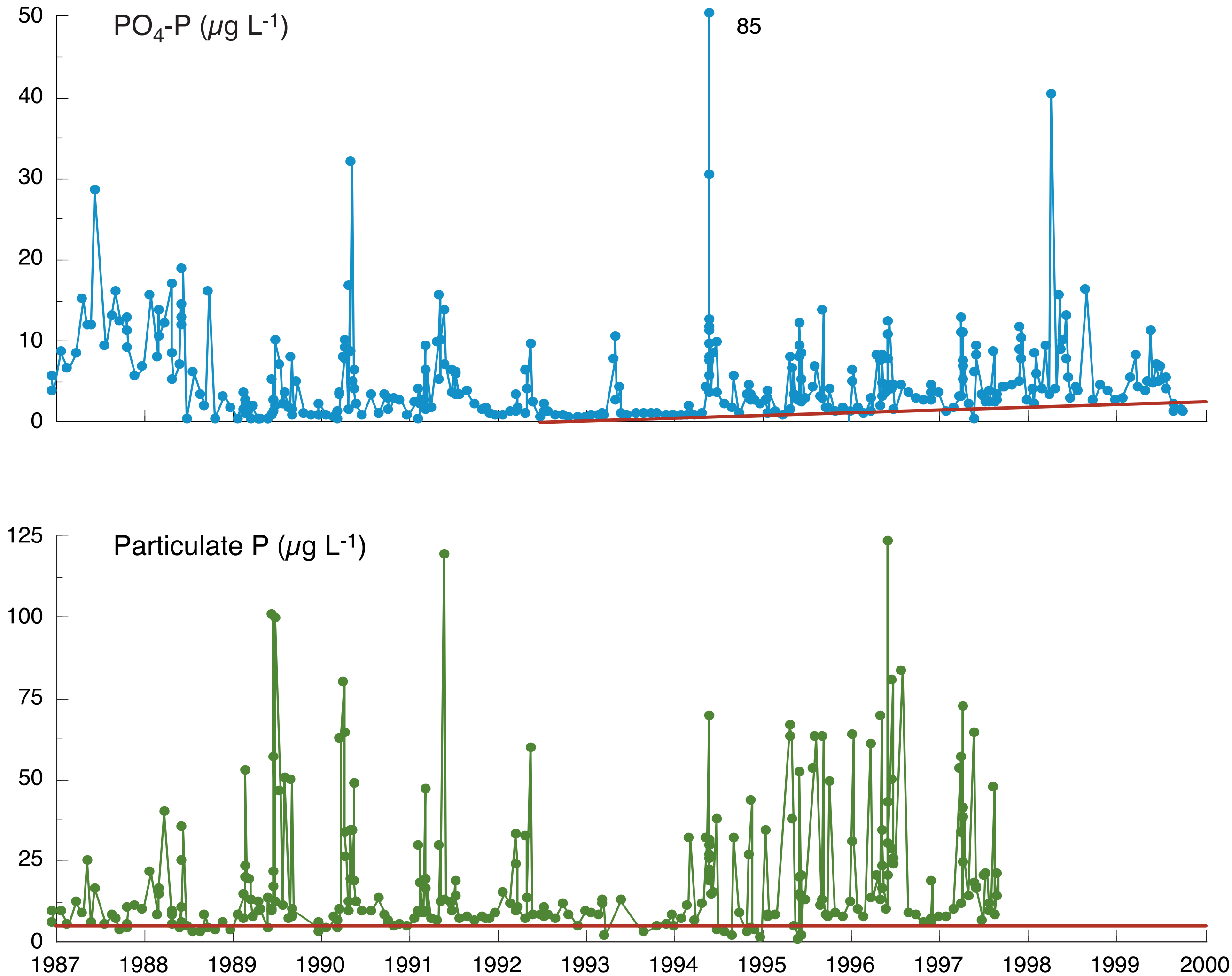
In contrast to nitrogen, average dissolved phosphorus concentrations in the Burdekin River varied considerably over the 13-year period. These variations were largely due to long-term fluctuations in phosphate (PO_4^{3-}) concentrations. Between 1987 and 1991, phosphate and total dissolved phosphorus concentrations declined from 40-60 µg P L^{-1}



Year-to-year variations in volume-averaged dissolved nitrogen and phosphorus concentrations in the Burdekin River.



Temporal changes in nitrate (top) and particulate nitrogen (bottom) concentrations in the lower Tully River (Euramo) between 1 July 1987 and 1 July 2000. The red lines, placed by eye, indicate trends in concentrations under baseflow conditions. Replotted from Mitchell et al., 2001



Temporal changes in phosphate (top) and particulate phosphorus (bottom) concentrations in the lower Tully River between 1 July 1987 and 1 July 2000. The red lines, placed by eye, indicate trends in concentration under baseflow conditions. Replotted from Mitchell et al., 2001 to less than 10 µg P L^{-1}. There were very low dissolved phosphorus levels during the low-discharge 1991-92 and 1992-93 wet seasons. Since then, mean phosphate and total dissolved phosphorus concentrations in Burdekin River waters have increased to approximately 40 µg P L^{-1}. It is unclear whether changes in soluble phosphorus, (largely PO_4^{3-}) concentrations are caused by rainfall and landscape processes which move soil and soluble phosphorus into the river, or in-stream factors that affect phosphorus solubility and biological activity.

Upstream-downstream changes in nutrients reflect catchment land use

A variety of factors influence nutrient concentrations in river waters as they flow downstream. Upstream-downstream (longitudinal) concentration changes reflect progressive inflows and losses of nutrients from the river system, additional water inputs from the catchment and in-stream chemical and biological processes which affect nutrient concentrations and speciation. In particular, agricultural activities which involve soil disturbance or fertiliser use might be expected to increase nutrient inputs to rivers through soil erosion, surface runoff and groundwater inputs.

Most sampling of nutrients in rivers of the GBR catchment has been carried out at lower catchment sites. In two rivers (Tully, Herbert), however, additional water samples were also collected at one or more upper catchment sites. These longitudinal data sets provide useful insights into the influence of agricultural land use on nutrient loads in regional rivers and to what nutrient levels might have been prior to modern land clearing.

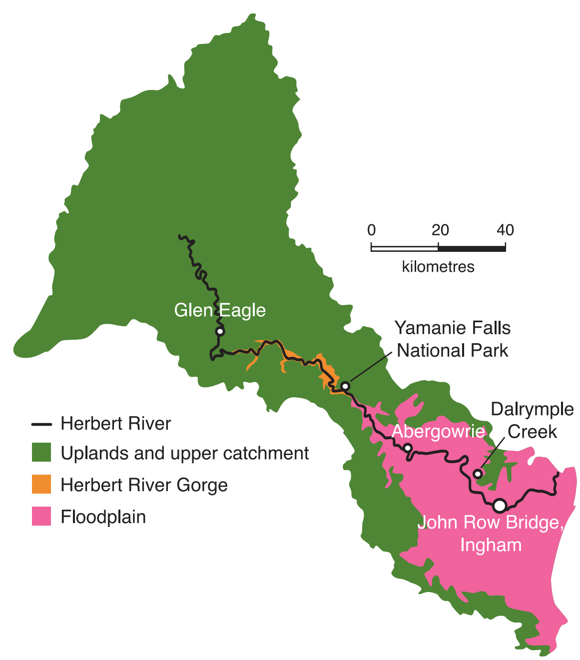
Herbert River

Dissolved and particulate nutrients were sampled over a five-year period (1989-94) at three sites along the lower Herbert River. The lowest sampling site was located near Ingham (John Row Bridge). This site is downstream of all but two of the Herbert River's major tributary streams

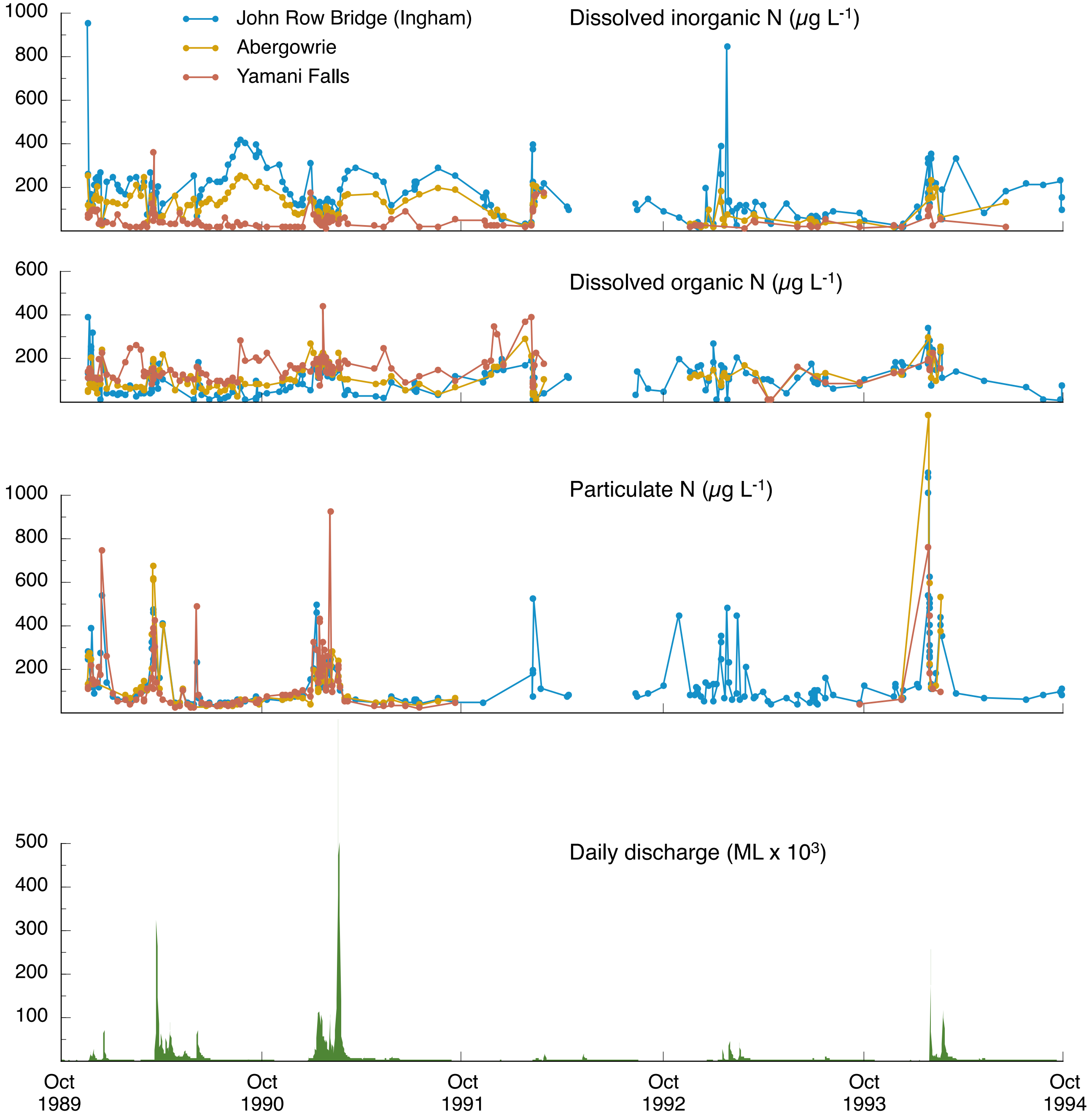
(Ripple Creek, Seymour River), but is upstream of the Ingham sewage treatment plant and regional sugar mills. Water was sampled concurrently at Yamani Falls National Park which is just upstream of the Herbert River floodplain, and at Abergowrie, approximately half-way between the John Row Bridge and Yamani Falls. The upper and lower sampling sites are 60 km apart.

Nearly half of the Herbert River floodplain and associated lowlands have been cleared of their pre-European vegetation cover: rainforest, wet and dry sclerophyll forest and coastal *Melaleuca* swamps or woodlands. This cleared land is now primarily used for sugarcane cultivation (ca. 400 km^2) and grazing [227]. In 1990, fertilisers applied on the floodplain contained 9,260 tonnes of nitrogen and 1,300 tonnes of phosphorus [404]. Most of the recent expansion of sugar cultivation in the Herbert River drainage basin has been in sub-catchments outside the main Herbert River catchment, so current fertiliser applications are likely to be of similar magnitude. The fertiliser nutrients have a variety of fates: immobilisation in surface soils (phosphorus), losses in surface runoff; volatilisation (nitrogen only); removal in harvested crop material; denitrification (nitrogen only) and percolation through soils into the groundwater (nitrogen only). Water and nutrient budgets for a floodplain sub-catchment indicate that approximately 15% of the nitrogen fertiliser moves through the soil into underlying groundwater [53]. Above the Herbert River Gorge, the upper catchment (ca. 7,500 km^2) is mostly covered by sclerophyll forest (wet and dry) and savanna woodlands. The woodlands are used for cattle grazing. There are several outcrops of basaltic rock and derived soils in the upper catchment of the Herbert River. These basaltic soils have a relatively high natural phosphorus content [156, 221].

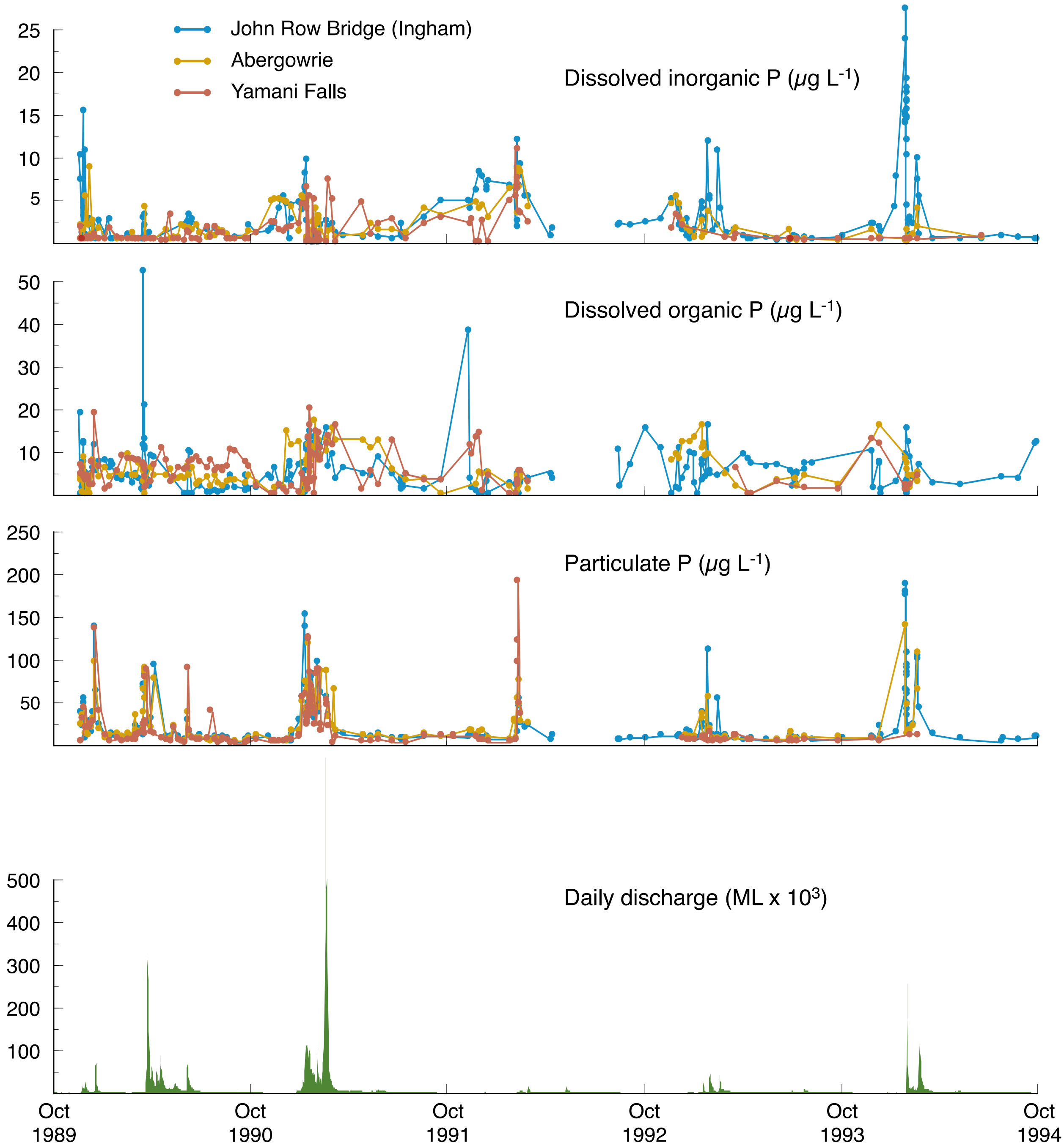
Based on flows measured above the Herbert River Gorge (Glen Eagle) and on the lower floodplain (Ingham), an average of 70% of the water discharged from the Herbert



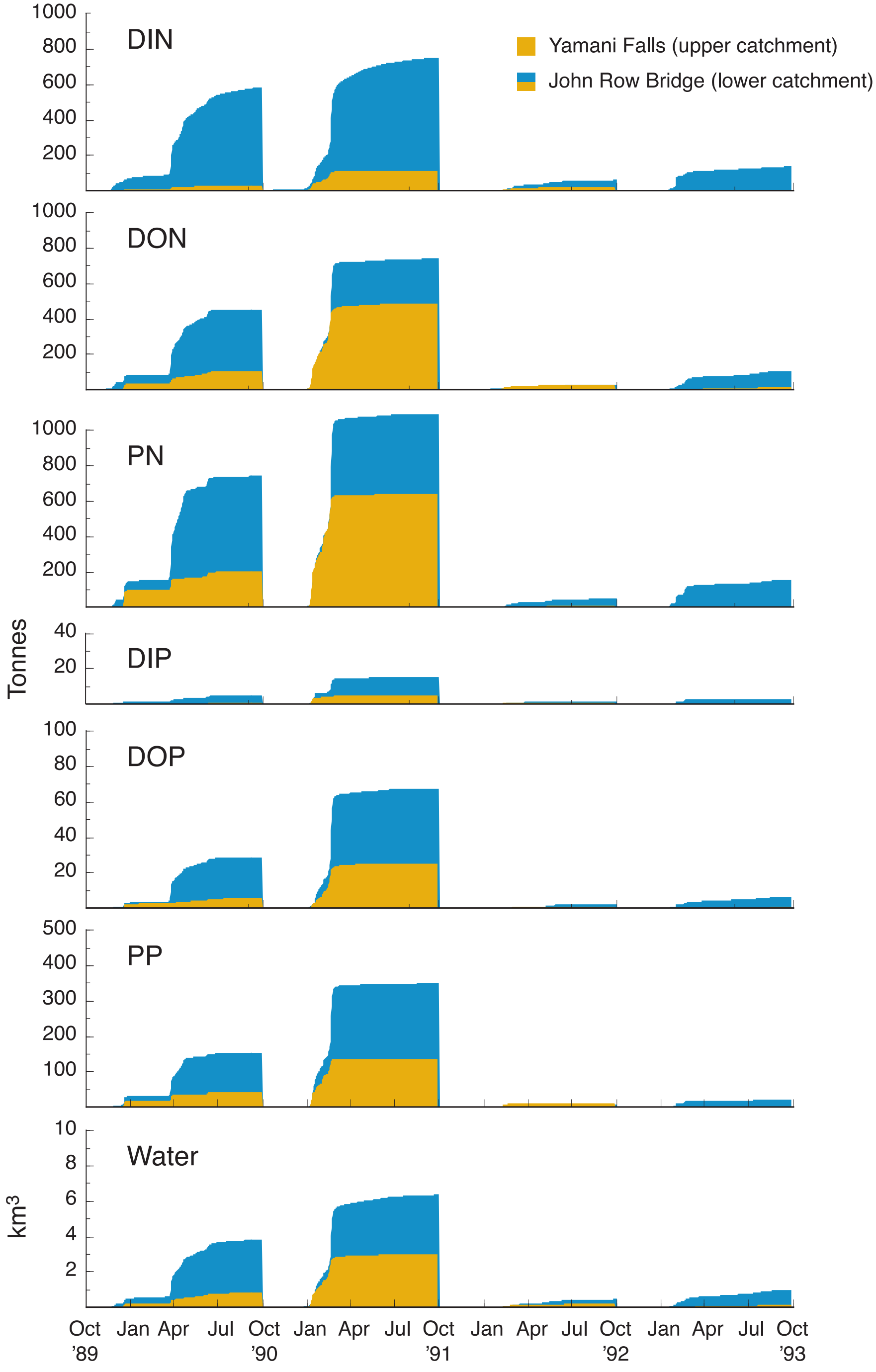
Longitudinal water sampling sites in the Herbert River catchment. Discharge was measured at Glen Eagle (upper catchment) and Ingham (total catchment).



Longitudinal changes in concentrations of dissolved and particulate nitrogen in the Herbert River (between 1 Oct 1989 and 1 Oct 1994). Samples were collected at sites in the Herbert River gorge (Yamani Falls), the upper floodplain (Abergowrie) and at the lower end of the coastal floodplain (Ingham). Discharge data source: QNR&M



Longitudinal changes in concentrations of dissolved and particulate phosphorus in the Herbert River (between 1 Oct 1989 and 1 Oct 1994). Samples were collected at sites in the Herbert River gorge (Yamani Falls), the upper floodplain (Abergowrie) and at the lower end of the coastal floodplain (Ingham). Discharge data source: QNR&M



Cumulative annual nutrient exports and water discharge estimated for a site immediately above the Herbert River gorge (Glen Eagle) and at the lower end of the coastal floodplain (Ingham) between 1 Oct 1989 and 1 Oct 1993. Exports at Glen Eagle were estimated by integrating the gauged flow at that site with nutrient concentrations measured concurrently at a sampling site in the Herbert River Gorge (Yamani Falls National Park).
Discharge data source: QNR&M

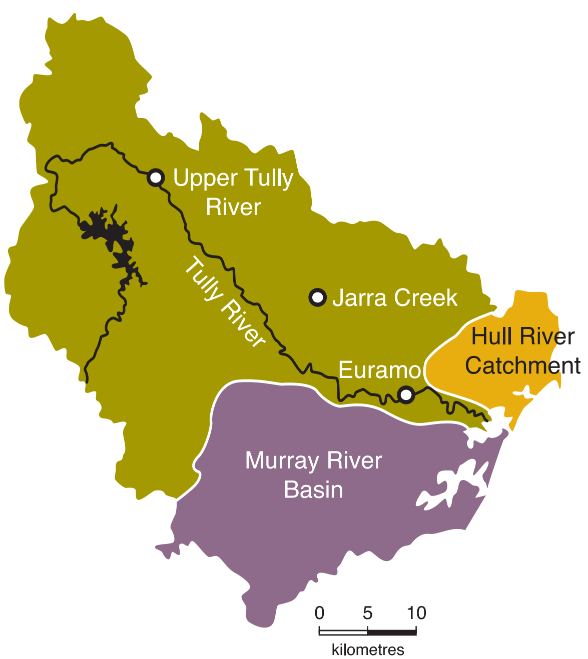
River comes from rainfall onto the floodplain, mountain slopes bordering the floodplain or the Herbert River Gorge. This proportion varies from 10 to 77% of the annual discharge, depending on the distribution of rainfall in the catchment. The proportion of total runoff from the floodplain is probably larger because a significant area of the floodplain drains away from the main river channel into peripheral creeks.

For five years (1989-94), there was no consistent difference between concentrations of ammonium (NH_4^+), nitrite (NO_2^-), particulate nitrogen (PN) and phosphorus species (PO_4^{3-}, DOP, PP) measured contemporaneously at the upper and lower ends of the floodplain. The absence of longitudinal trends indicates that their concentrations in river source waters are likely to be similar throughout the catchment, or that chemical processes stabilise concentrations in river and soil waters. In contrast, concentrations of dissolved organic nitrogen (DON) were consistently higher above the floodplain. The downstream decrease indicates dilution with low-DON water on the floodplain, or bacterial mineralisation of DON in the lower reaches of the river.

Most noticeably, concentrations of nitrate (NO_3^-) were almost always higher at Ingham than concentrations measured upstream. The difference was greatest during low-flow periods when a larger proportion of the water in the river comes from groundwater sources in the gorge and on the floodplain. Nitrate concentrations at the two sites were the same during floods when additional runoff from recent rainfall dominated flows. Nitrate concentrations at Abergowrie, the upper floodplain site, were usually intermediate between those in the gorge and at the lower end of the floodplain. Overall, close to 90% of the nitrate exported annually by the Herbert River comes from sources on the floodplain. The net increase in nitrate discharge (ca. 1,000 tonnes of nitrate-N p.a.) is similar to the estimated loss of fertiliser nitrogen to groundwaters (15% of 9,000 tonnes of fertiliser N) [53, 404].

Tully River

Nitrate is also the principle form of dissolved inorganic nitrogen in the Tully River. Nitrate concentrations near the bottom of the Tully River floodplain (Euramo) are consistently higher than those measured contemporaneously at the upper end of the floodplain (Tully Upper) and in tributary streams with mostly pristine rainforest catchments (Jarra Creek). Nitrate concentrations at Euramo have pronounced "first-flush" peaks at the beginning of each wet season. First-flush peaks are not seen in the time series from the upper catchment sites, suggesting that this nitrate has a floodplain source. Particulate nitrogen (PN) concentrations are also consistently higher at the bottom of the floodplain, but the difference is less pronounced than for nitrate. Because particulate nitrogen concentrations are correlated with suspended sediment concentrations, this increase is indicative of higher suspended sediment loads toward the mouth of the river.



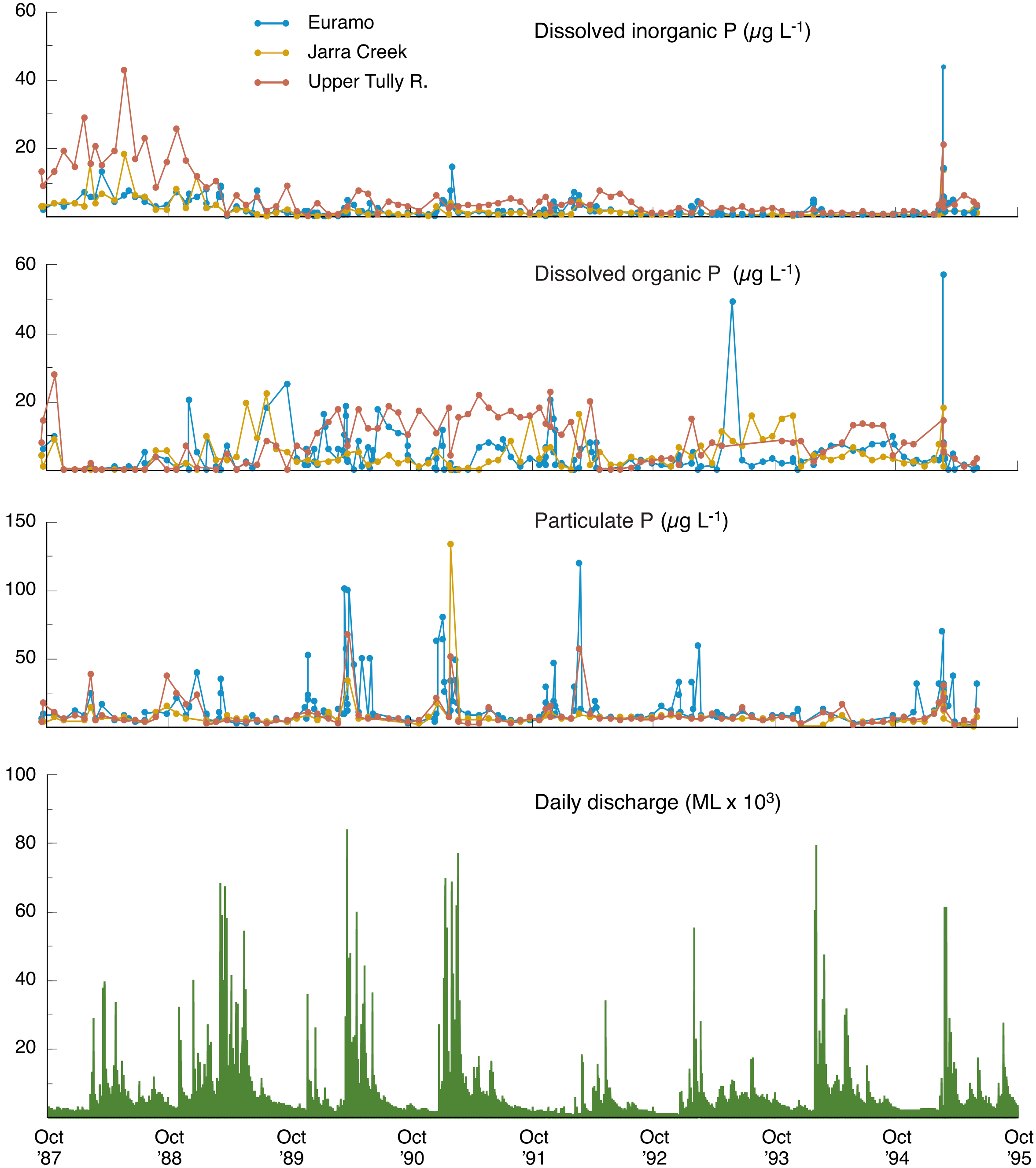
Longitudinal water sampling sites in the Tully River catchment. Discharge was measured at Euramo.

Longitudinal and temporal changes in phosphorus species in the Tully River differed from those of nitrogen. During the first few years of sampling in the late 1980s, phosphate concentrations at the upper floodplain site were consistently higher than observed in a little disturbed peripheral stream (Jarra Creek) or at the lower floodplain site. The reason for the higher phosphate concentrations is not known. After October 1989, phosphate concentrations at the upper floodplain site fell to levels similar to those at other sampling sites. Dissolved organic phosphorus and particulate phosphorus did not exhibit any clear or consistent longitudinal trend over the eight-year sampling period.

Longitudinal sampling of nutrients in the Herbert and Tully Rivers shows that most of the nitrate exported from these two river systems comes from a floodplain source. A similar downstream nitrate increase occurs in the Johnstone River where there is extensive cultivation of sugarcane and bananas in the lower catchment [217]. There is no obvious natural source for this additional nitrate. Agricultural fertilisers are almost certainly the source. The Johnstone, Tully and Herbert River drainage basins receive substantial nitrogen inputs in the form of agricultural fertilisers (ca. 7,600, 4,800 and 10,500 tonnes of nitrogen in 2000, respectively). Much of this fertiliser nitrogen is delivered in a readily soluble form [417], or in forms which can be converted to soluble forms by soil bacteria. Nitrate and particulate nitrogen concentrations in runoff from undisturbed woodland and rainforest catchments are similar to or lower than concentrations on the floodplain. The downstream declines in DON concentrations do not account for the increase in nitrate as a result of bacterial mineralisation. There are no large natural reserves of nitrogen in floodplain soils that could sustain long-term leaching or evidence of significant nitrogen fixation. If anything, wetlands on uncleared pre-1850 floodplains would have removed nitrogen through denitrification in anaerobic wetland soils.

The different flood-related patterns of nitrate variability in the Herbert and Tully Rivers show the relative importance of different sources. In the Herbert River, the tendency for nitrate concentrations to be elevated during low-flow conditions and diluted during floods suggests that inputs of high-nitrate groundwater [53] are responsible for the higher concentrations. Dilution occurs because the groundwater inputs through aquifers are relatively constant and not closely coupled to surface runoff. The flood-associated nitrate peaks in the Tully River are most likely due to leaching of nitrate from more permeable surface soils and perhaps, to a lesser extent, more rapid groundwater movements in the smaller Tully River catchment. The rise in baseflow nitrate concentrations in the Tully River clearly suggests increasing inputs through groundwater since the late 1980s.

Longitudinal changes in dissolved inorganic nitrogen (top), dissolved organic nitrogen (upper middle) and particulate nitrogen (lower middle) concentrations at upper (Tully Upper, Jarra Creek) and lower (Euramo) catchment sites in the Tully River basin between 1 Oct. 1987 and 1 Oct 1995. Discharge data source: QNR&M



Longitudinal changes in dissolved inorganic phosphorus (top), dissolved organic phosphorus (upper middle) and particulate phosphorus (lower middle) concentrations at upper (Tully Upper, Jarra Creek) and lower (Euramo) catchment sites in the Tully River basin between 1 Oct 1987 and 1 Oct 1995. Discharge data source: QNR&M

Despite parallel increases in the level of phosphorus fertiliser usage in cropping areas, no significant downstream changes in soluble phosphorus have been found. Regardless of discharge rates, dissolved phosphorus concentrations are most likely controlled by the strong tendancy for phosphorus to bind to soil particles [61, 333, 373]. Phosphorus largely remains in and on catchment soils, rather than washing out in surface runoff and groundwaters. Appreciable phosphorus exports only occur during floods when soil erosion rates increase greatly.

Chapter 8

Terrestrial sediment
and nutrient inputs to the Great Barrier Reef

How much sediment and nutrients reach the Great Barrier Reef in terrestrial runoff? While there now is considerable information about sediment and nutrient concentrations in rivers of the Great Barrier Reef catchment, it is the total load of materials reaching the GBR that ultimately affects the health of reef, benthic and pelagic communities in the GBR ecosystem.

Sediment and nutrient exports from rivers can be calculated from repetitive sampling of dissolved and suspended material concentrations in rivers and relating that to the concurrent water discharge rates. Because nutrient and sediment concentrations in north Queensland rivers often vary rapidly during flood events, daily, and sometimes more frequent sampling may be needed to accurately calculate export fluxes. During the low-flow conditions of the dry season, suspended sediment and nutrient concentrations generally do not change appreciably, and the volume of discharge is relatively small.

At any particular time, the amount of sediment or nutrients transported out of a river mouth or past a point (kg sec^{-1}) equals the concentration of these materials (kg m^{-3}) multiplied by the concurrent water discharge rate (m^3 sec^{-1}): export flux = concentration x discharge rate. Discharge is derived from river height and a rating curve (Chapter 4). The sediment or nutrient export rate over a longer interval (kg $time^{-1}$) is calculated as the average concentration within discrete contiguous time intervals (kg m^{-3}) multiplied by the volume of water discharged (m^3 per time) in those intervals. Calculated estimates of seasonal or annual nutrient and sediment export are the integration (running sum) of the export fluxes calculated over a series of consecutive discrete time intervals (e.g. daily).

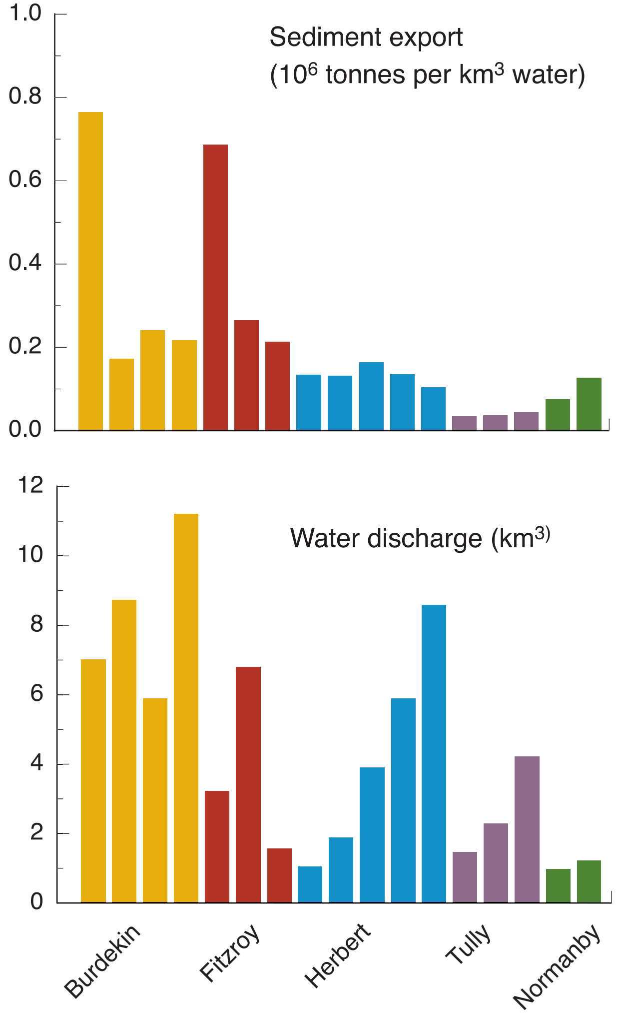
Water discharge is typically measured throughout the year and summarised on a daily basis (usually as megalitres per day). The most intensive time series of nutrient and suspended sediment concentration measurements have been made during the wet season (November – April) when flow is greatest and in-river concentrations are changing most rapidly. Detailed nutrient and sediment data sets for rivers have been collected over periods of two and thirteen wet seasons. These data sets include two wet-tropical rivers (South Johnstone and Tully), three dry catchment rivers (Normanby, Burdekin and Fitzroy) and one nominally mixed (wet/dry) catchment river (Herbert).

Most export of fine sediment from both wet and dry catchments takes place during floods when both discharge and suspended sediment concentrations peak (Chapter 6). Characteristics of sediment and particulate nutrient exports to the GBR lagoon differ between wet- and dry-catchment rivers due to the number and magnitude of flood events per wet season, the concentration ranges of suspended sediment during floods and the nitrogen and phosphorus content of the suspended sediment carried by the rivers.

On a tonnage basis, fine sediments make up most of the materials carried by GBR catchment rivers. Clay particles are the most important part of this suspended matter. Under energetic flood conditions, appreciable quantities of silt and fine sand are also carried in the suspended load. River channels of the GBR catchment do not have significant silt or clay deposits. Most fine soil particles that reach the main channels of river systems are quickly transported out of the catchment. Significant quantities of fine sediment are only stored in catchments when streams pass through wetlands or flood waters overtop their banks and inundate the adjacent floodplain. Compared with catchments of similar size in temperate regions, rivers in the GBR catchment have fewer large floods, particularly floods which overtop the banks [8]. Those that do are of shorter duration.

There are few direct measurements of coarse sediment (sand-gravel) transport as bedload in north Queensland rivers. In the Burdekin River, engineering models suggest that bedload sediment transport is about 10% of the suspended load [40]. Under low-flow conditions, silt and sand eroded from cultivated lands is temporarily stored in agricultural drains, the stream network and the estuary [19, 208]. This material is transported downstream and out of the estuary during floods, particularly those following cyclones. These coarse sediments do not contribute significantly to turbidity or nutrient fluxes. On reaching the river mouth, coarse sediments are rapidly deposited, forming the coastal delta [132]. Essentially all coarse sediment movement occurs during floods. Because of the great variability in the size of floods, individual measurements of bedload sediment transport are not reliable indicators of average bedload transport over longer periods.

The amount of sediment transported by a given amount of discharge (the volume-specific export coefficient – tonnes per km^3 or tonnes km^{-3}) varies between catchment types, and in some cases, between years depending on flow dynamics. The Burdekin and Fitzroy River catchments are the most variable. This reflects the size and geographical diversity of these large catchments. Individual sub-basins within the Burdekin and Fitzroy River drainage basins are large enough to have different average rainfalls, soil types, land cover characteristics and runoff-export dynamics. A large proportion of total catchment erosion and sediment export comes from smaller areas in the catchment with erodible, bare soils or well-developed gully networks [89, 389, 392, 399].



Volume-specific fine sediment exports and concurrent wet season water discharges from five rivers in the GBRCA. Discharge data source: QNR&M

Estimates of annual fine sediment export from the Burdekin River basin derived from turbidity measurements and water sampling range from 1.4 to 5.4 million tonnes. On a volume-specific basis, wet season sediment exports from the Burdekin River basin range from 0.2 to 0.8 x 10^6 tonnes km^{-3} (1996-97 and 1998-99 wet seasons, respectively). These estimates do not include exports during massive floods (e.g. 1946, 1974, 1991). Enormous amounts of sediment are transported during these large floods. During flood peaks the Burdekin River moved fine sediment at rates approaching 2 x 10^6 tonnes km^{-3} of discharge. It is estimated that 8.4 x 10^6 tonnes of sediment were transported past Ayr in one 24-hour period during the 1946 flood [40].

Between 1996 and 2000, estimated fine sediment exports from the Fitzroy River ranged between 0.3 and 2.2 x 10^6 tonnes per year. During this time when there were no significant floods, volume-specific fine sediment export coefficients varied between 0.2 and 0.7 x 10^6 tonnes km^{-3} of discharge, similar to estimates for the Burdekin River. When there is a very large flood in the Fitzroy River, annual sediment export and the quantity in any volume of runoff are likely to be much higher.

The lowest sediment export rates, both in absolute terms (0.05 - 0.19 x 10^6 tonnes per year) and on a volume-specific basis (0.035 - 0.045 x 10^6 tonnes km^{-3}) were measured in the Tully River. The low values reflect both the small size of the catchment and the high level of vegetation cover which reduces soil erosion. Volume-specific sediment exports from the mixed-wet/dry Herbert River catchment (0.105 - 0.165 x 10^6 tonnes km^{-3}) and largely dry, but little grazed Normanby River catchment on Cape York Peninsula (0.076 - 0.127 x 10^6 tonnes km^{-3}) are intermediate between the wholly wet and dry catchments. Over the years sampled, volume-specific sediment export coefficients for the Tully, Normanby and Herbert Rivers averaged 0.039, 0.102 and 0.135 x 10^6 tonnes km^{-3}, respectively.

There are few other volume-specific estimates of sediment export from northeast Queensland rivers. During the flood which followed Cyclone Sadie (February 1994) a sediment transport rate of 0.188 x 10^6 tonnes km^3 was measured in the lower Herbert River [326], 40% greater than the average sediment export rate for the entire wet season. This difference is not surprising, because suspended sediment concentrations are normally higher during floods (Chapter 6). Still higher sediment export loads (>0.5 x 10^6 tonnes km^{-3}) were measured in the South Johnstone River during the post-Sadie flood [216].

The ranges of volume-specific sediment export coefficients for the dry Burdekin and Fitzroy Rivers are greater than recorded for rivers of the wet tropics. This is due to the greater range of annual discharges, the greater diversity of sediment sources in the catchments and lower vegetation cover levels. In the absence of a clear relationships between discharge volume and sediment export, only an average volume-specific sediment export coefficient (0.366 x 10^6 tonnes km^3) can be calculated for the dry catchment rivers. This value is similar to the suspended sediment (washload) export flux of 0.306 x 10^6 tonnes per km^3 previously estimated for the Burdekin River from manual sampling [40]. As with the Tully River, the export coefficient derived from manual sampling is lower, probably because short-lived peaks in sediment load were not adequately sampled.

Terrestrial sediment inputs to the Great Barrier Reef

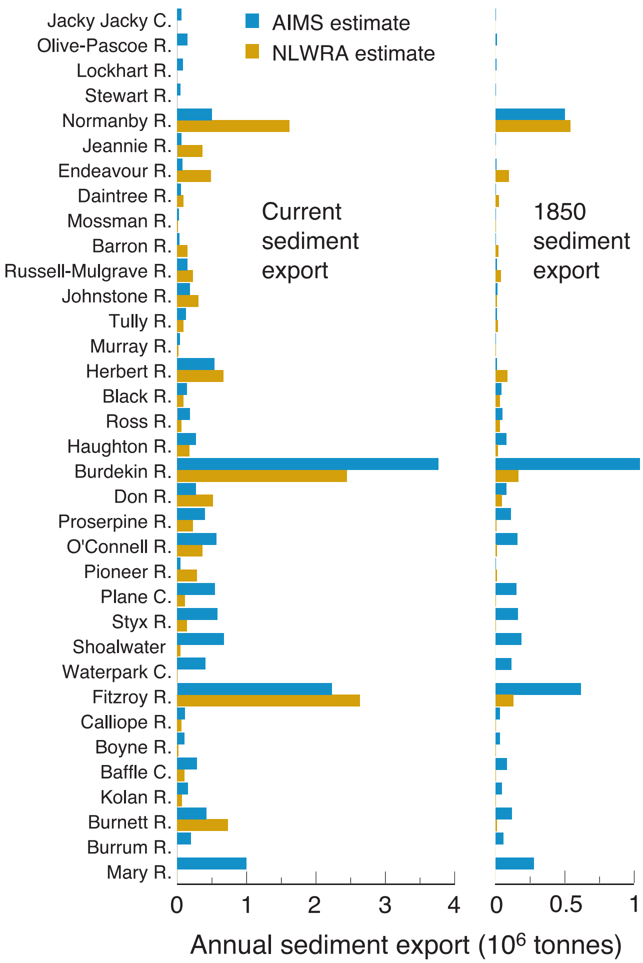
Annual inputs of terrestrial sediment to the Great Barrier Reef can be estimated by multiplying volume-specific sediment export coefficients appropriate for wet, mixed or dry drainage basins by the mean annual freshwater discharges from individual basins (Table 32). For this calculation, rivers draining wet-tropical drainage basins (including the Pioneer River) and drainage basins on Cape York (other than the Normanby River) are assumed to have volume-specific sediment export coefficients similar to the Tully River (0.039 x 10^6 tonnes km^{-3}). Dry drainage basins south of the Herbert River are taken to have sediment export coefficients similar to the Burdekin and Fitzroy Rivers (0.366 x 10^6 tonnes km^{-3}). Volume-specific export coefficients for the Normanby (0.102 x 10^6 tonnes per km^{-3}) and Herbert Rivers (0.135 x 10^6 tonnes per km^{-3}) are set at the mean of measured values for those rivers.

Using this approach, the average annual input of terrestrial sediment to the GBR is estimated to be 14.4 million tonnes (14.4 x 10^6 tonnes). The Burdekin and Fitzroy River drainage basins, which account for 23% of the freshwater discharge (16.4 km^3), deliver 42% of the total sediment input (6.0 x 10^6 tonnes). The remaining dry-tropical basins bordering the central and southern GBR contribute 22% of the runoff (17.2 km^3) and 44% of the sediment flux (6.3 x 10^6 tonnes). In contrast, wet-tropical drainage basins bordering the central GBR contribute 29% of the freshwater discharge (20.5 km^3), but only 8% of the sediment inputs (1.2 x 10^6 tonnes). Rivers on Cape York Peninsula account for 24% the of annual freshwater runoff (16.7 km^3) and 7% of the fine sediment delivery (1.0 x 10^6 tonnes).

Previous estimates of annual sediment inputs to the GBR range from 15 to 28 x 10^6 tonnes [41, 339, 350]. These estimates are based on mapping the volume of recent (<6,000 years

Table 32. Estimated average annual exports of nitrogen, phosphorus and sediment from wet (W) and dry (D) catchment basins into the GBRWHA.

Basin Name	Area km^2	Adjusted Runoff Volume km^3	Wet/ Dry	DIN Export	DON Export	PN Export	Total N Export tonnes	DIP Export	DOP Export	PP Export	Total P Export	Fine Sed Export 10^6 tonnes
Jacky-Jacky C.	2,963	1.56	W	268	124	228	620	7	9	50	66	0.06
Olive-Pascoe R.	4,179	3.71	W	634	295	539	1,469	16	22	118	156	0.14
Lockhart R.	2,883	1.94	W	332	154	282	769	8	11	62	81	0.08
Stewart R.	2,743	1.21	W	207	96	176	479	5	7	39	51	0.05
Normanby R.	24,408	4.95	W	846	394	720	1,960	21	29	158	208	0.50
Jeannie R.	3,637	1.54	W	263	122	224	610	6	9	49	65	0.06
Endeavour R.	2,104	1.82	W	311	145	265	721	8	11	58	76	0.07
Daintree R.	2,192	1.26	W	215	100	183	499	5	7	40	53	0.05
Mossman R.	466	0.59	W	101	47	86	234	2	3	19	25	0.02
Barron R.	2,136	0.81	W	139	64	118	321	3	5	26	34	0.03
Mulgrave-Russell R.	1,983	3.64	W	622	289	529	1,441	15	21	116	153	0.14
Johnstone R.	2,325	4.67	W	799	371	679	1,849	20	27	149	196	0.18
Tully R.	1,683	3.29	W	563	262	478	1,303	14	19	105	138	0.13
Murray R.	1,107	1.06	W	181	84	154	420	4	6	34	44	0.04
Herbert R.	9,843	4.01	W	686	319	583	1,588	17	23	128	168	0.54
Black R.	1,057	0.38	D	75	53	191	319	10	3	49	63	0.14
Ross R.	1,707	0.49	D	97	68	246	411	13	4	64	81	0.18
Haughton R.	4,044	0.74	D	146	103	372	621	19	7	96	122	0.27
Burdekin R.	130,126	10.29	D	2,027	1,430	5,176	8,633	265	92	1,338	1,695	3.77
Don R.	3,695	0.75	D	148	104	377	629	19	7	98	124	0.27
Proserpine R.	2,535	1.08	D	213	150	543	906	28	10	140	178	0.40
O'Connell R.	2,387	1.54	D	303	214	775	1,292	40	14	200	254	0.56
Pioneer R.	1,570	1.19	W	203	95	173	471	5	7	38	50	0.05
Plane C.	2,539	1.49	D	294	207	749	1,250	38	13	194	245	0.55
Styx R.	3,012	1.58	D	312	220	796	1,327	41	14	206	261	0.58
Shoalwater	3,605	1.83	D	360	254	919	1,533	47	16	238	301	0.67
Waterpark C.	1,835	1.11	D	219	154	558	931	29	10	144	183	0.41
Fitzroy R.	142,537	6.08	D	1,198	845	3,058	5,101	157	54	790	1,001	2.23
Calliope R.	2,236	0.30	D	59	42	151	252	8	3	39	49	0.11
Boyne R.	2,590	0.29	D	57	40	146	243	7	3	38	48	0.11
Baffle C.	3,996	0.78	D	154	108	392	654	20	7	101	128	0.29
Kolan R.	2,901	0.41	D	81	57	206	344	11	4	53	68	0.15
Burnett R.	33,248	1.15	D	227	160	578	965	30	10	150	189	0.42
Burrum R.	3,358	0.55	D	108	76	277	461	14	5	72	91	0.20
Mary R.	9,440	2.72	D	536	378	1,368	2,282	70	24	354	448	1.00
Total	423,070	70.8		12,982	7,627	22,298	42,907	1,022	517	5,551	7,090	14.4



A comparison between estimates of current and pre-1850 sediment exports from catchments adjoining the GBR obtained by AIMS and modelled estimates from the NLWRA calculated using the Sed Net model.
Data Source: NLWRA, 2002

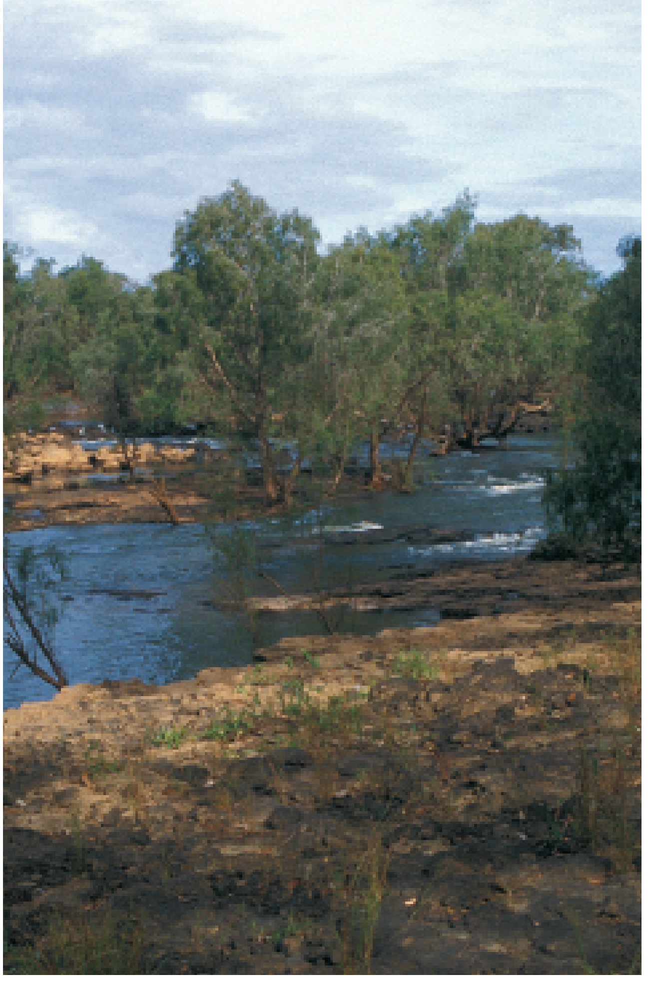
old) terrestrial sediments along the coast, extrapolations of sediment export from the Burdekin River, and calculations of net soil loss associated with various types of land use. These approaches must be interpreted with caution. Export estimates based on sediment accumulation need to identify the limits of relevant sediment deposits and average the input rate over the full 6,000 year period. Extrapolations of sediment input based on one river assume a constant discharge-export relationship for all rivers, an assumption which is clearly not correct. Estimates based on land use patterns are most sensitive to the value used for the delivery ratio, the fraction of eroded soil which ultimately reaches the river network in any one year.

The best alternative estimate of sediment inputs from drainage basins bordering the GBR comes from the Australian National Land and Water Resources Audit (NLWRA) [391,392]. These estimates are derived from mathematical modelling of soil erosion and sediment transport in river systems based on detailed topographic, vegetation, rainfall, soil type and land use mapping. The NLWRA modelling estimates an average annual sediment input to the GBR shelf of 12.1 million tonnes, similar to the 14.4 million tonnes calculated by extrapolation of derived export coefficients for wet- and dry-catchment rivers. The NLWRA modelling approach yields higher sediment fluxes from drainage basins on Cape York Peninsula, and to a lesser extent, wet-tropical catchments while the approach based on export coeffficients tends to estimate higher sediment fluxes from the drier basins bordering the southern GBR. Importantly, both approaches give similar estimates of sediment export from the better characterised Tully, Herbert, Fitzroy and Burdekin basins. There are obvious differences between the two approaches because of uncertainties in calibrating sediment erosion rates across the diversity of landscapes in the GBR catchment. Likewise, there are obviously limits to how closely a small number of averaged volume-specific sediment export coefficients can be applied to a diversity of drainage basins. The general agreement between the approaches at both the basin and whole-GBR scales is encouraging and indicates that the modern average sediment input to the GBR is most likely between 10 and 15 million tonnes (10-15 x 10^6 tonnes) per year.

Just as the volume of freshwater runoff varies from year to year, so too will sediment exports to the shelf. If the volume-specific sediment export coefficients are applied to the measured annual catchment runoff volumes between 1968 and 1994, calculated annual sediment exports from catchments vary nearly 20-fold between 3 x 10^6 tonnes (1987) and 59 x 10^6 tonnes (1974).

What were river sediment transport rates prior to 1850, before European settlement and modern clearing, farming and grazing activities began? At present, all drainage basins in the GBR catchment are used for some type of agricultural activity, largely cattle grazing. The large dry catchments which are the source of most of the freshwater runoff and sediment are characterised by widespread clearing and grazing. Only general estimates of pre-1850 sediment exports can be made. There is no information about annual sediment exports from large pristine catchments, wet or dry. We must look at smaller sets of data collected in appropriate sub-catchments, or to catchment modelling to estimate pre-1850 sediment exports from catchments.

The largely dry Normanby River basin on Cape York Peninsula provides the best example of what sediment exports from dry catchments might have been like prior to 1850. While cattle have been grazed throughout much of the catchment at one time or another and grazing continues in some upland sections, a significant proportion of the catchment has been destocked and is managed as a National Park (Lakefield National Park). Only small



Normanby River, Cape York
Photo: M. Furnas, AIMS

numbers of feral cattle remain in the National Park and adjoining state lands. There are significant numbers of feral pigs, however, in the wetlands of the lower floodplain [171]. Most of the Normanby River basin is covered by open eucalypt woodland with a seasonally sparse groundcover of grass. Well-developed riparian vegetation grows along rivers. Catchment vegetation is burnt on a rotating basis to mimic burning patterns previously used by local Indigenous peoples.

Two years of turbidity monitoring have been carried out in the Normanby River. Suspended sediment concentrations briefly reach 1 to 1.5 g L^{-1} during floods, but for most of the wet season, concentrations are less than 0.25 g L^{-1}. The sediment export coefficient is close to 100,000 tonnes km^{-3} of discharge. This value is probably similar to sediment export rates from dry catchments prior to 1850.

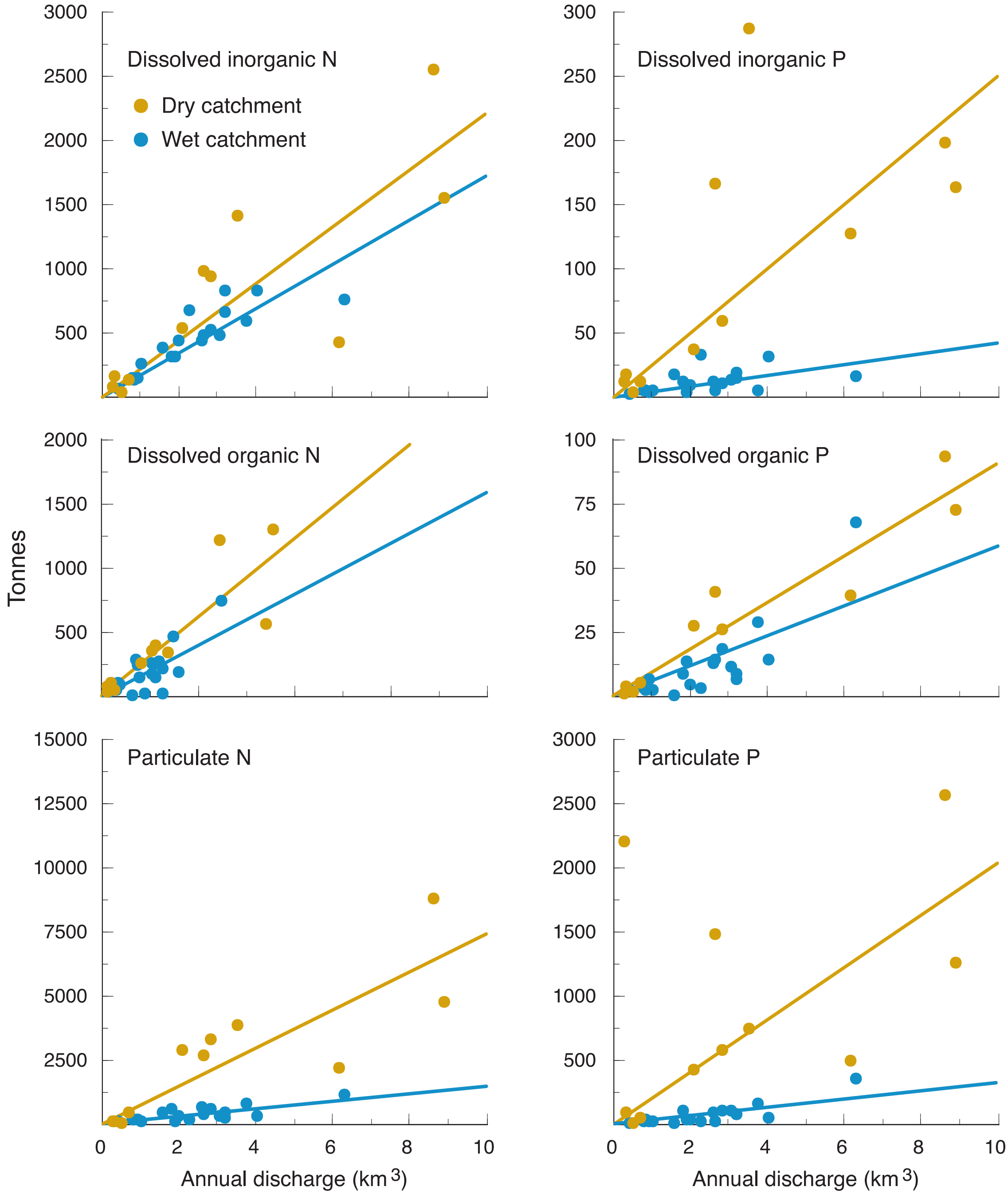
There are no comparable measures of sediment export from pristine or quasi-pristine wet-tropical catchments of similar size. The lowest volume-specific sediment export rate measured in the Tully River (28,000 tonnes km^{-3} of discharge) translates to an average catchment soil loss rate of 30 tonnes km^{-2} $year^{-1}$. This is considerably less than the soil loss rates (100-500 tonnes per km^{-2} $year^{-1}$) measured in small steep rainforest catchments [80]. Most of the sediment exported from the Tully River basin now comes from cleared agricultural land and eroded stream banks in the lower catchment. Before clearing, sediment losses from the heavily vegetated lowland forests and floodplains of the Tully River basin would have been very small. A volume-specific sediment export coefficient based on a lower range of soil loss rates (2,500 tonnes km^{-3} of discharge) is probably more appropriate for sediment export from floodplains of heavily vegetated wet-tropical catchments.

Using the above estimates of volume-specific sediment export from catchments, pre-1850 terrestrial sediment export to the GBR are estimated to average 4.4 million (4.4×10^6) tonnes per year, which is 28% of the current sediment export rate. Wet-tropical drainage basins would contribute approximately 1.3% of the pre-1850 sediment input to the GBR (0.05×10^6 tonnes per year), 13% (0.5×10^6 tonnes per year) would come from rivers on Cape York Peninsula (largely the Normanby River) and the remaining 85% (3.7×10^6 tonnes per year) would be exported from the dry drainage basins bordering the central and southern GBR. The relative contribution of wet and dry catchments to sediment export is reflected in the present distribution of recent terrigenous sediment on the GBR shelf, with most located in coastal waters south of Townsville (19°S).

Recent soil erosion and sediment export modelling by the NLWRA has yielded a lower estimate of pre-1850 sediment input to the GBR (1×10^6 tonnes year^{-1}). This modelling approach assumes full vegetation cover over the GBR catchment and the absence of significant gully erosion prior to 1850. The observed differences between estimates of sediment export based on landscape erosion rates and empirically calibrated discharge - export relationships for major catchment types are not surprising. Significantly, however, both approaches yield estimates of pre-1850 sediment inputs to the GBR below 5×10^6 tonnes year^{-1}. The differences reflect present uncertancies in estimates of catchment erosion rates and the small number of catchment discharge-export relationships.

Terrestrial nutrient inputs to the Great Barrier Reef

Plots of cumulative annual nitrogen and phosphorus exports from wet, mixed and dry drainage basins over several years show that nutrient exports from individual catchments are closely linked to wet season flood events and to total annual freshwater discharge. In all types of catchments, most of the annual freshwater, sediment, and nutrient export takes place during short intervals of days to weeks when floods peak. There is little nutrient export



Estimated annual exports of important forms of nitrogen and phosphorus from wet-catchment or wet-behaving (South Johnstone, Tully, Herbert Rivers) and dry-catchment (Burdekin, Fitzroy Rivers) rivers in relation to annual freshwater discharge. The slopes of the regression lines shown are given in Table 33.
Discharge data source: QNR&M

during low-flow conditions of the dry season, regardless of nutrient concentrations in river waters. Total annual nutrient exports to the GBR lagoon closely follow the total volume of water discharged. Large quantities of nutrients were exported from both wet and dry catchments during the 1990-91 and 1996-97 water years (Oct.-Sept.) because of the higher volumes of runoff in those years. Exports were very low during the 1991-92 and 1992-93 water years which were characterised by low rainfall and runoff through most of the GBR catchment.

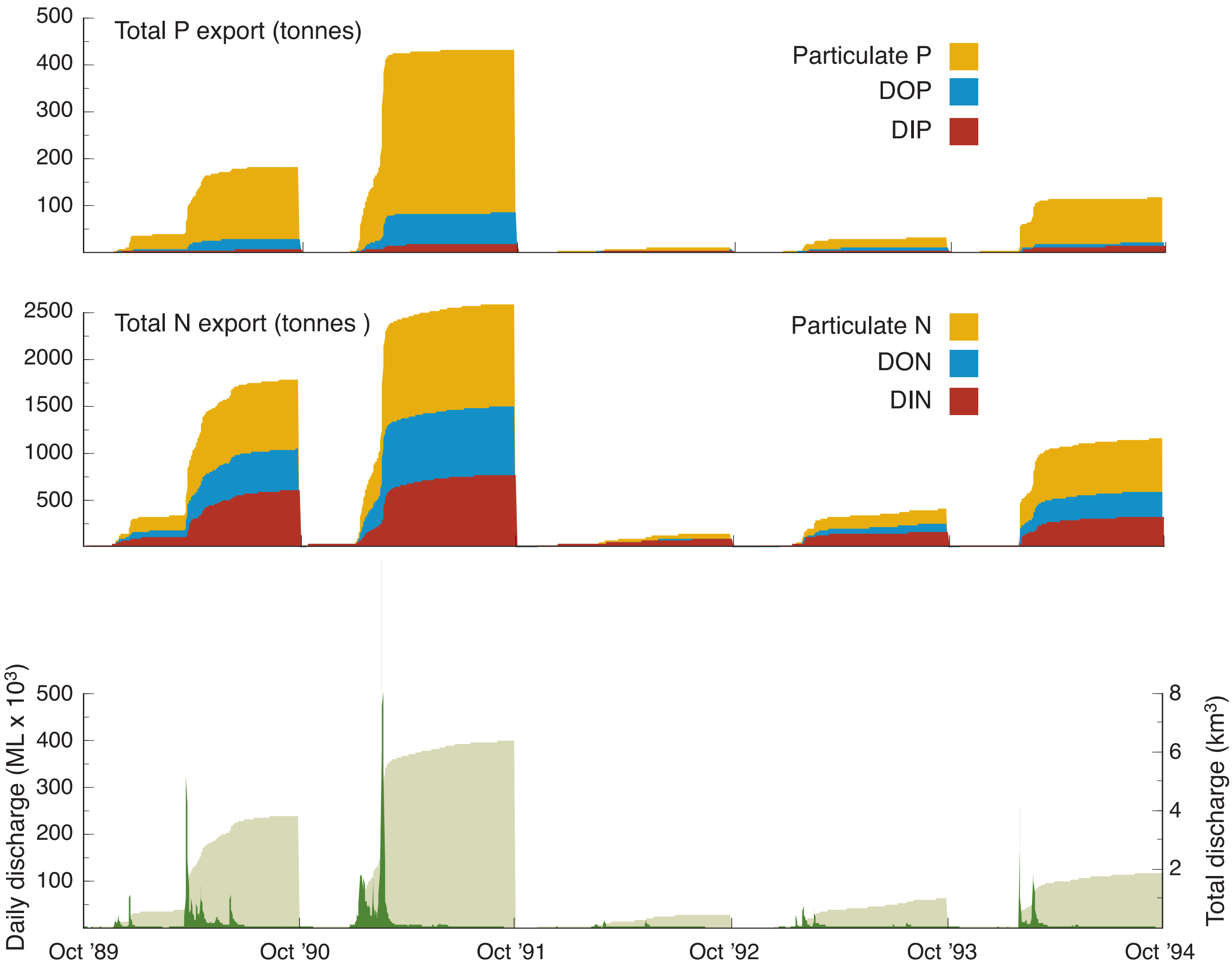
The relative abundance and export of individual nutrient species differs markedly between wet- and dry-catchment rivers. Most of the nitrogen exported from the wet-tropical South Johnstone, Tully and Herbert Rivers is in dissolved form, largely as nitrate (NO_3^-) and dissolved organic nitrogen (DON). These catchments have high levels of fertiliser application to sugarcane and banana crops. The proportion of dissolved nitrogen exported from dry catchments is lower. Despite this, the large dry tropics basins export greater quantities of nitrate to the GBR, because their discharge volumes are much greater. Very little nitrogen is exported from either wet or dry catchments as ammonium (NH_4^+) or nitrite (NO_2^-).

Particulate nitrogen (PN) dominates exports from the dry catchments. Over half of the nitrogen exported from the Burdekin and Fitzroy River basins is in particulate form. Both of these rivers have high suspended sediment loads and particulate nitrogen concentrations are correlated with suspended sediment concentrations. The lower relative export of particulate nitrogen from the wet-tropical catchments also reflects the lower suspended sediment concentrations in the rivers draining those catchments.

Particulate phosphorus (PP) is the principal form of phosphorus exported from both wet and dry catchments. This reflects the presence of phosphorus in natural soil minerals and tendency for phosphate ions (PO_4^{3-}) to

Table 33. Volume-specific export coefficients for wet and dry catchment rivers of the GBRCA.

Nutrient Species	Wet Tropics	Dry Tropics
	Export Coefficient (tonnes km^{-3})	
DIN	171	197
DON	80	139
PN	145	503
DIP	4.2	25.8
DOP	5.8	8.9
PP	32	130
Total N	**396**	**839**
Total P	**42**	**165**
N/P (by atoms)	**20.8**	**11.3**

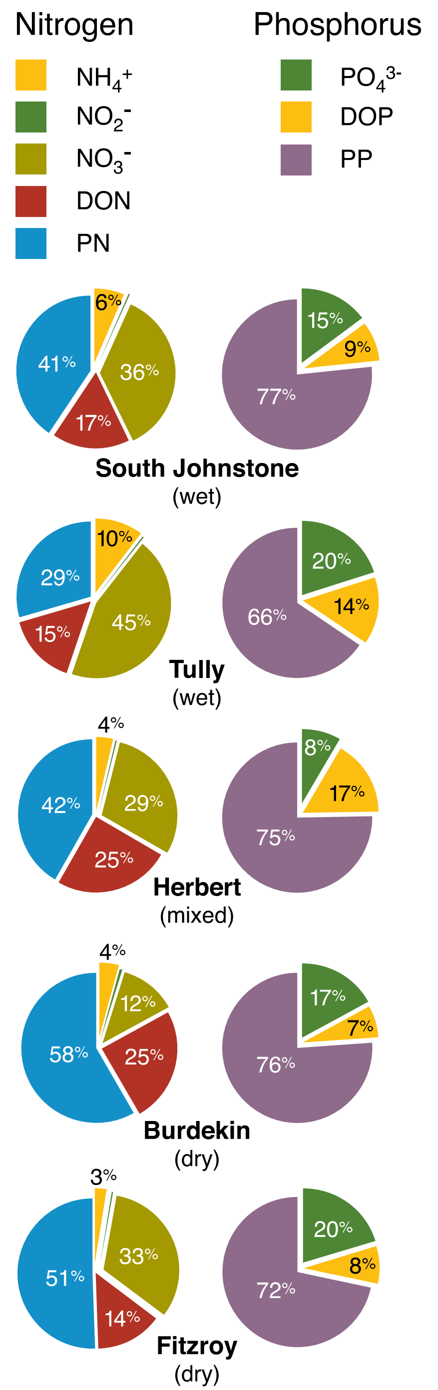


Cumulative annual exports of phosphorus (top) and nitrogen (middle) from the Herbert River between 1 Oct 1989 and 1 Oct 1994 in relation to daily and cumulative (shaded background) freshwater discharge (bottom).
Discharge data source: QNR&M

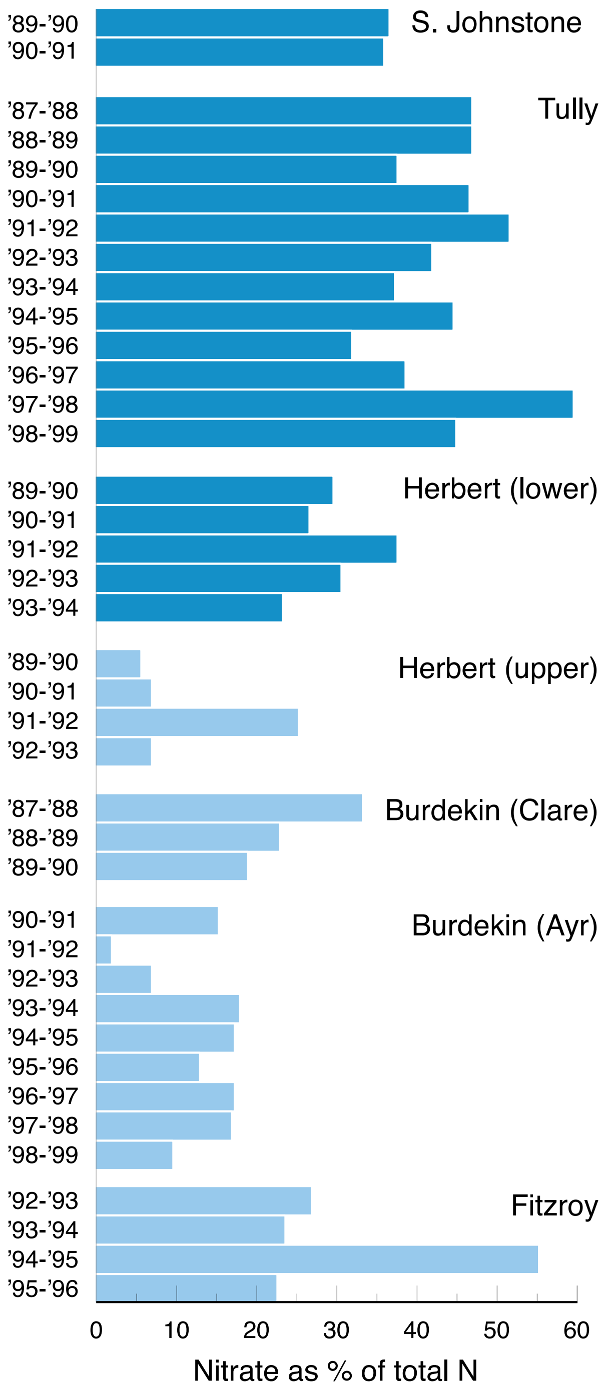
strongly bind to soil particles and fine sediments. As with particulate nitrogen, particulate phosphorus concentrations are strongly correlated with suspended sediment concentrations. Overall, particulate phosphorus accounts for 66 - 77% of the total phosphorus exported, with no clear difference between wet- and dry-catchment rivers. Dissolved inorganic phosphorus (PO_4^{3-}) contributes between 8-20% of the total P exported, again, with little difference between wet and dry catchments. Dissolved organic phosphorus (DOP) exports are similar.

For both wet and dry drainage basins, the quantity of nutrients transported by the principle rivers in those basins are correlated with the annual volume of freshwater runoff (Table 33). Exports of nitrogen and phosphorus from the wet-tropical catchments are better correlated with annual discharge than exports from the dry catchments. The weaker correlations for the relationships in the dry catchment rivers reflect the greater size and spatial diversity of the dry-catchments.

Discharge-export relationships differ between forms of nutrients. Volume-specific export coefficients for dissolved inorganic nitrogen (DIN, largely NO_3^-), dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) are only slightly higher in the dry-catchment rivers. In contrast, volume-specific exports of phosphate (DIP) from dry catchment rivers are six times higher than those for wet and mixed catchments. Volume-specific exports of particulate nitrogen (PN) and phosphorus (PP) from dry catchments are three to four times higher than from wet-catchments. Although most (ca. 70%) of its catchment is dry savanna woodland, the Herbert River has nutrient export characteristics more similar to those of the wet-tropical rivers. This reflects the hydrology of this mixed catchment where more than 66% of the water flowing at Ingham comes from the floodplain, the Herbert River gorge and mountains surrounding the floodplain. Water



Average contributions of important nitrogen (left) and phosphorus (right) species to annual runoff from five wet and dry catchment rivers.



Annual exports of nitrate (NO_3^-) as a percentage of total nitrogen exported from wet-tropical catchments receiving agricultural fertilisers (dark blue) and largely unfertilised dry catchments or sub-catchments (light blue).

discharged from the wet tropics rivers had more nitrogen relative to phosphorus (N/P = 21 by atoms) than the dry-catchment rivers (N/P = 11 by atoms). On an absolute basis, however, the Burdekin and Fitzroy River basins export twice the nitrogen (840 vs 400 tonnes N km^{-3}) and four times the phosphorus (165 vs 42 tonnes P km^{-3}) in a volume of water compared to the wet-catchment rivers.

By applying the volume-specific export coefficients derived for wet and dry drainage basins, current terrestrial nitrogen exports to the GBR lagoon are estimated to be 43,000 tonnes per year. Concurrent annual phosphorus exports from rivers are estimated to be 7,000 tonnes per year. Of the various forms of nitrogen, 30% of exports are in the form of dissolved inorganic nitrogen (DIN - chiefly NO_3^-), 18% as dissolved organic nitrogen (DON) and the remaining 52% as particulate nitrogen (PN). For phosphorus, 78% of estimated exports are in particulate form, 14% as dissolved inorganic phosphorus (PO_4^{3-}) and 7% as dissolved organic phosphorus (DOP).

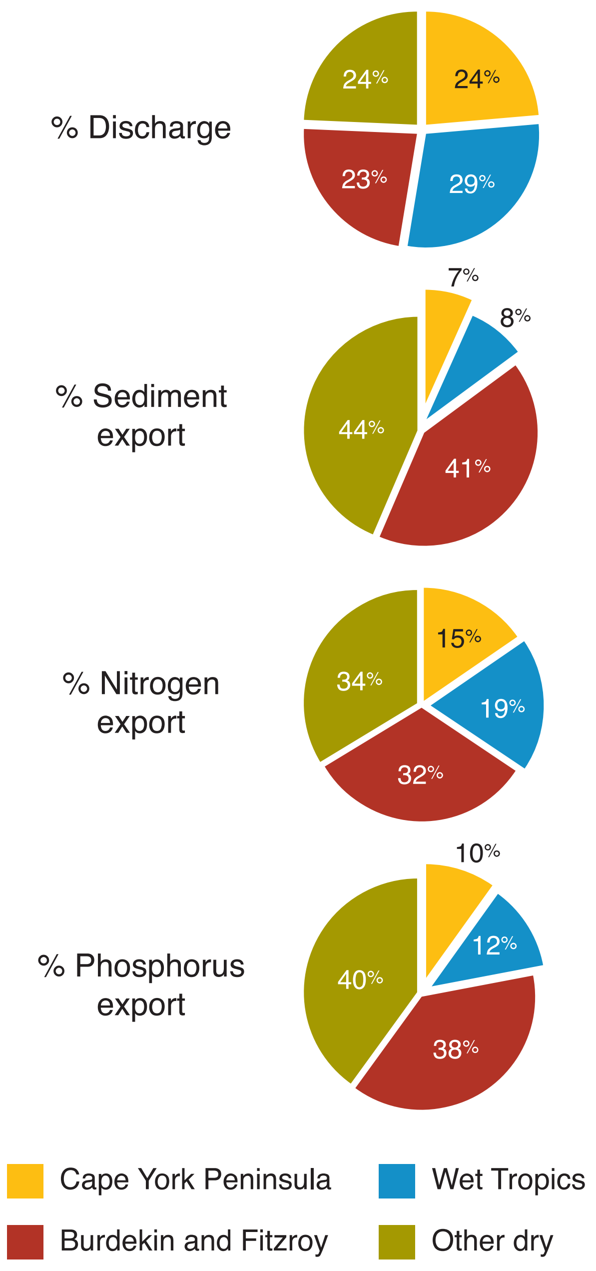
Total terrestrial exports of nitrogen and phosphorus to the GBR lagoon are dominated by runoff from the Burdekin and Fitzroy River basins due to their large average annual discharges and the higher suspended sediment loads in these rivers. Collectively, the Burdekin and Fitzroy River basins account for 32% of total terrestrial nitrogen inputs and 38% of phosphorus inputs to the GBR lagoon. Dry- or largely dry catchment rivers between the Herbert and Mary Rivers (56% of annual runoff volume) are estimated to deliver 77% of terrestrial nitrogen inputs and 92% of terrestrial phosphorus inputs to the GBR. The smaller wet-tropical drainage basins (29% of runoff volume) deliver just 19% of the riverine nitrogen and 12% of the phosphorus. The remaining 15% of nitrogen and 10% of phosphorus inputs are sourced from drainage basins on Cape York Peninsula (24% of runoff volume).

As with sediment, terrestrial inputs of nitrogen and phosphorus will vary from year to year depending on the total volume of freshwater runoff and how that runoff is distributed between drainage basins. For the 25-year period between 1968 and 1994, estimated total nitrogen inputs to the GBR from land runoff would have varied between 11,000 tonnes (1987) and 126,000 tonnes (1974). Over the same period, estimated terrestrial phosphorus inputs would have varied between 1,400 tonnes (1987) and 22,000 tonnes (1974). It is no surprise that the highest levels of nitrogen and phosphorus inputs came in the years with the greatest freshwater runoff (1974, 1991). The large proportion of nitrogen and phosphorus associated with suspended sediment means that years with massive floods will also leave large amounts of nitrogen and phosphours stored in coastal sediments. These stores will influence coastal nutrient dynamics and water quality for years as the nutrients are mineralised and dispersed by currents.

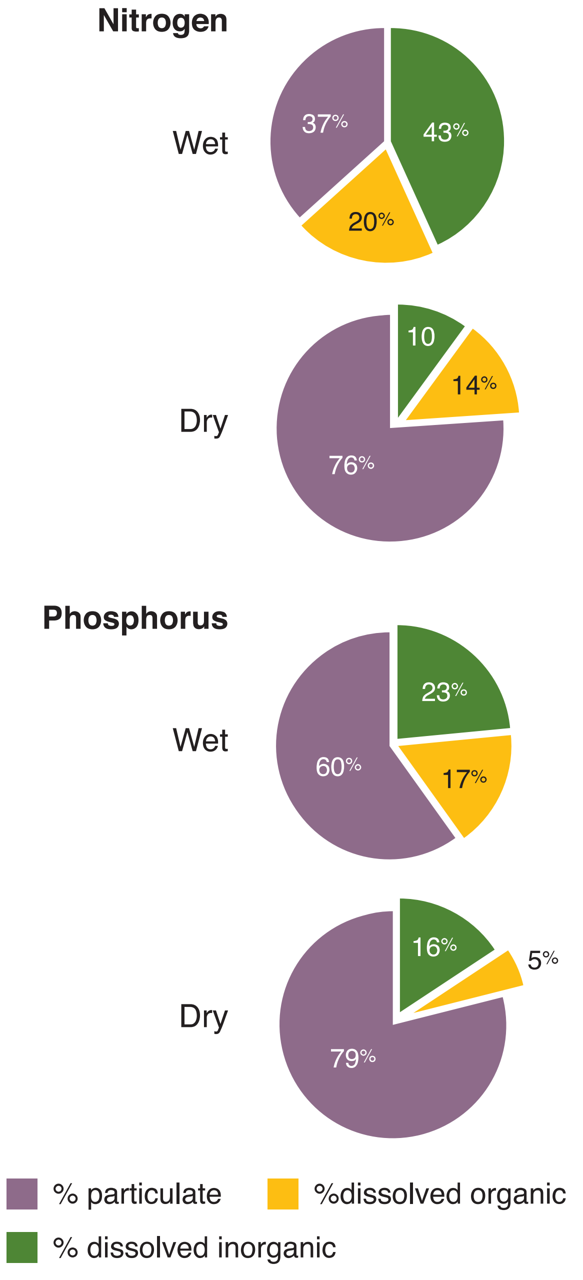
Pre-1850 nutrient exports to the Great Barrier Reef

As with sediments, there is only limited information about nutrients in rivers and streams that drain pristine or largely undisturbed catchments (Table 34). These limited measurements show that nutrient concentrations in pristine streams are lower than concentrations in streams or rivers influenced by clearing and agricultural land use. One indication comes from smaller tributary creeks of the Herbert and Tully Rivers which drain largely undisturbed rainforest catchments. Dissolved and particulate nutrient concentrations in these tributary streams are lower and less variable than nutrient concentrations measured contemporaneously in the main river channel.

Longitudinal sampling in the Herbert River (Chapter 7), shows dissolved nutrient concentrations increase as the river water flows through the floodplain. The upper Herbert River catchment is used for cattle grazing, but as yet, levels of tree clearing are relatively modest. At present,



Relative proportions of the current average annual exports of freshwater, sediment, nitrogen and phosphorus from drainage basins on Cape York Peninsula, the wet tropics, the Burdekin and Fitzroy River basins and other drainage basins of the dry tropics.



Relative proportions of the current average annual nitrogen and phosphorus exports from wet- and dry-tropical drainage basins of the GBRCA in dissolved inorganic, dissolved organic and particulate forms.

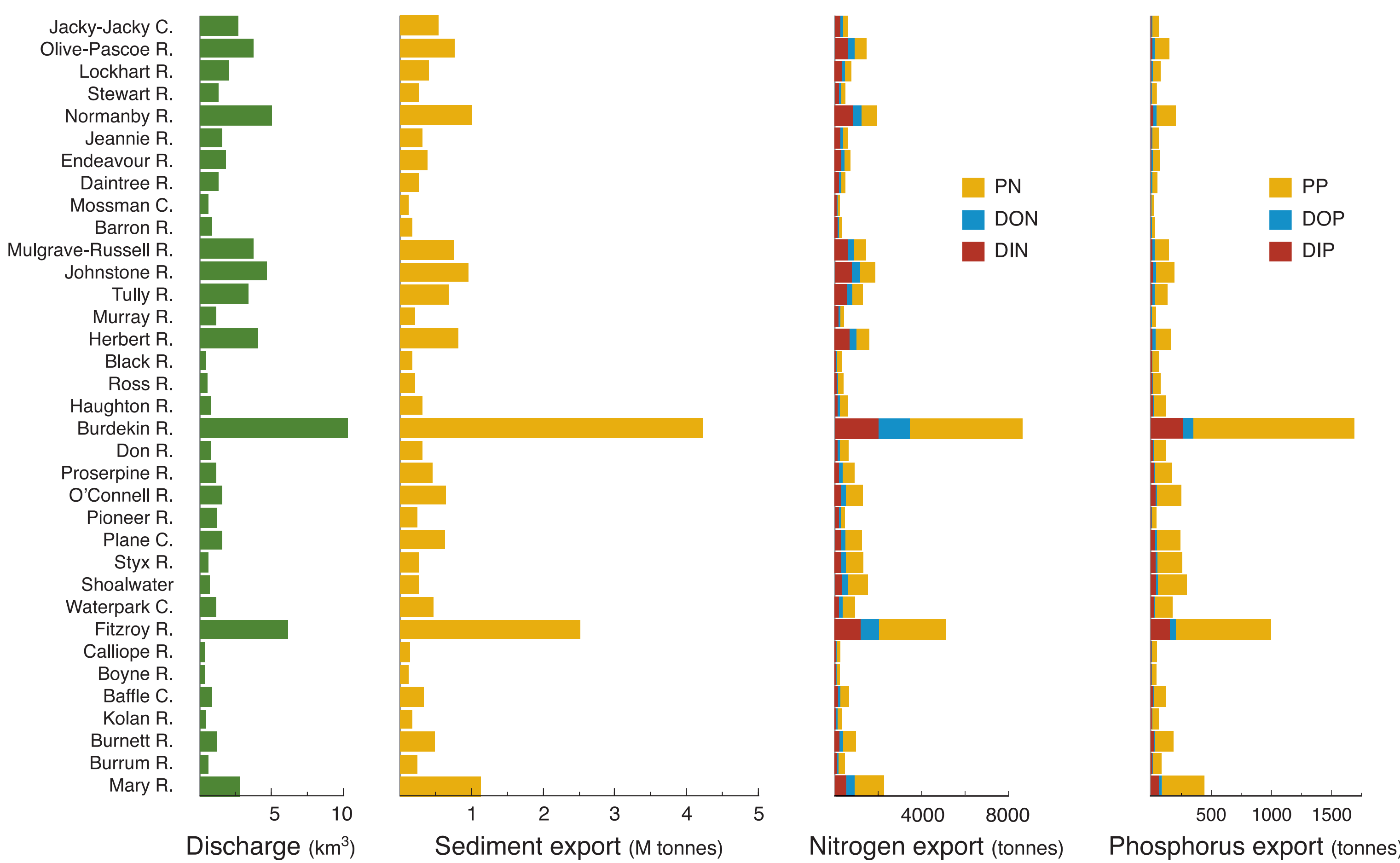
there are no similar longitudinal time series of nutrient concentrations in dry catchment rivers. Nutrient concentrations in the Normanby River, the least-disturbed dry catchment sampled to date, are considerably lower than concentrations recorded in the Burdekin and Fitzroy Rivers.

Nutrient concentrations in nominally pristine or little-disturbed catchments such as Dalrymple Creek (Herbert River basin) and the Normanby River are most likely to represent nutrient levels in wet- and dry-catchment rivers prior to 1850. Pre-1850 nutrient inputs can be estimated by the same catchment weighting approach used for calculating current suspended sediment and nutrient inputs. Using this approach, total nitrogen exports from all catchments under the presumed pre-1850 land cover and burning regime are estimated to be 23,000 tonnes per year or 54% of the current estimated exports of 43,000 tonnes. The disparity between pre-1850 and current phosphorus exports is greater. The estimated pre-1850 phosphorus export of 2,400 tonnes per year is 34% of the estimated current input (7,070 tonnes). The difference in phosphorus inputs largely reflects modern increases in soil erosion and fine sediment losses from catchments because 60-80% of the phosphorus is sediment-bound.

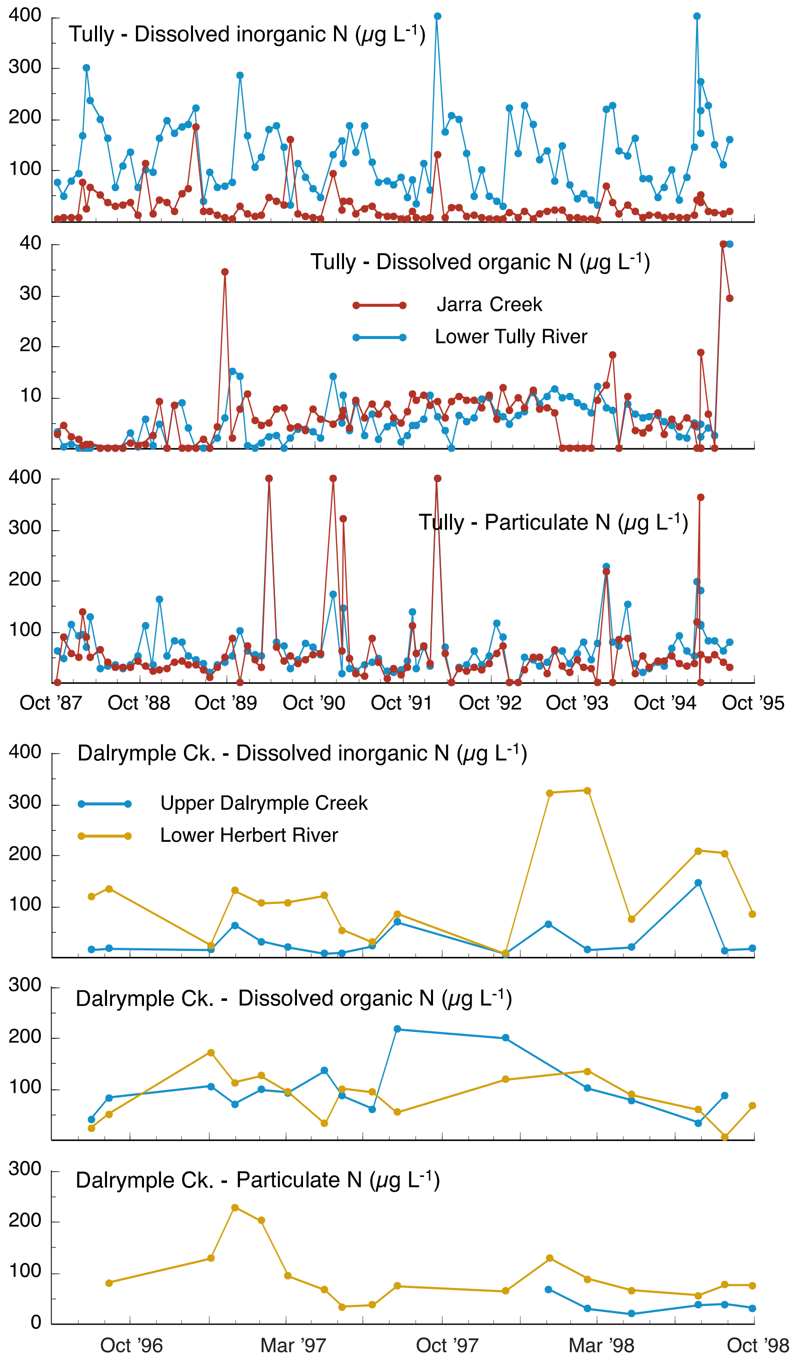
Under both current and pre-1850 conditions, estimated exports of sediment and nutrients from catchments are largely dominated by the dry river basins of the central and southern GBR catchment. The small wet-tropical catchments, with their heavily fertilised sugar crops, export less than 20% of the terrestrial nitrogen and phosphorus reaching the GBR (Table 35).

Nutrient inputs from other sources

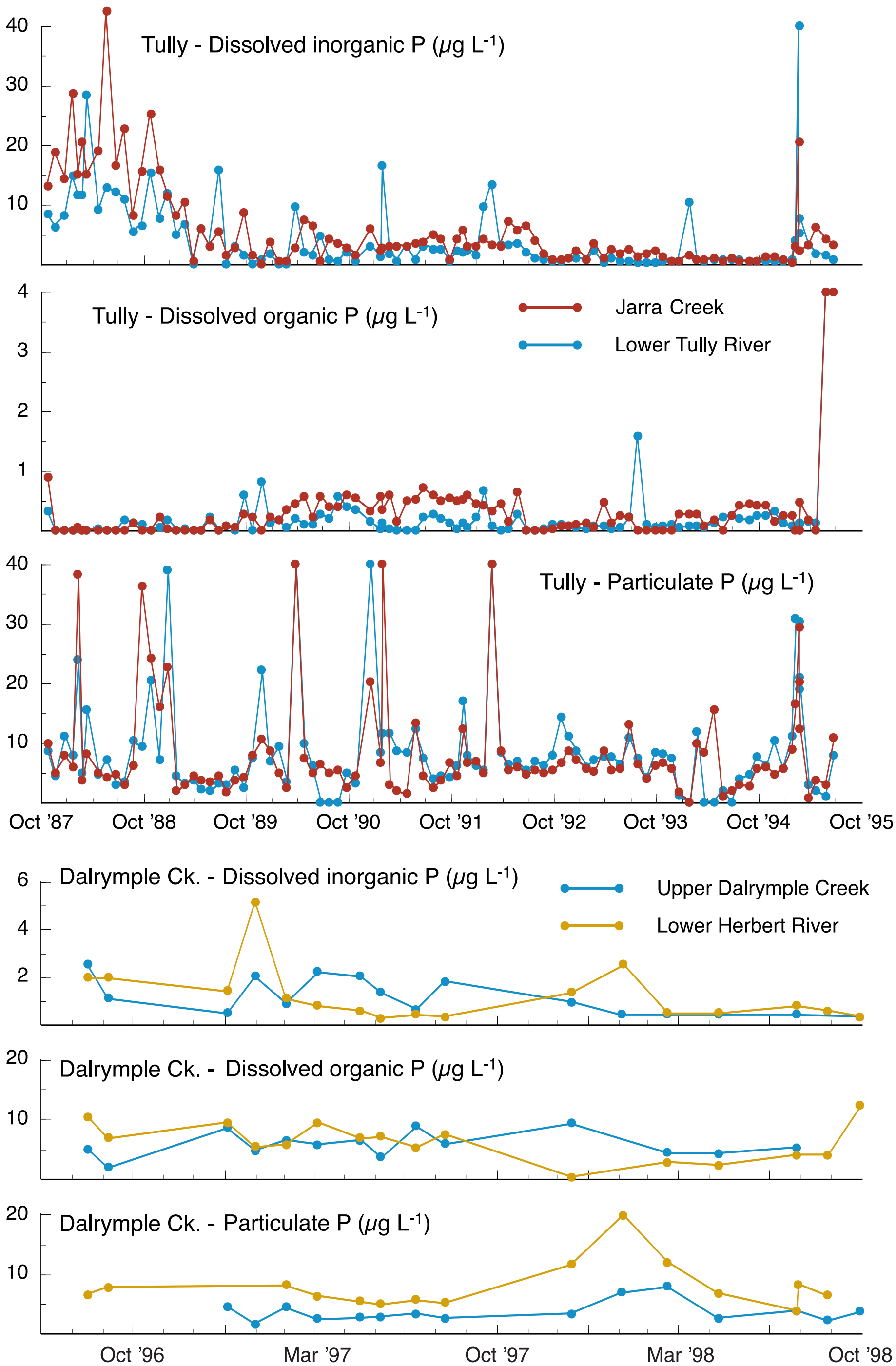
The GBR receives nutrient inputs from a variety of sources, including land runoff, upwelling from the Coral Sea, rainfall, sewage discharge and nitrogen fixation by cyanobacteria [146]. Over the long-term, these inputs balance losses from tidal mixing of shelf waters into the



Current average annual freshwater discharge, and sediment, nitrogen and phosphorus exports from drainage basins of the GBRCA.



Longitudinal changes in nitrogen concentrations measured in streams draining pristine sub-catchments. Top: Concentrations of dissolved inorganic nitrogen, dissolved organic nitrogen and particulate nitrogen measured in Jarrah Creek (Tully River basin) and the lower Tully River (Euramo) between Oct 1987 and July 1995. Bottom: Concentrations of dissolved inorganic nitrogen, dissolved organic nitrogen and particulate nitrogen in Dalrymple Creek (Herbert River basin) and the lower Herbert River (Ingham) between Aug 1996 and Oct 1998.



Longitudinal changes in phosphorus concentrations measured in streams draining pristine sub-catchments. Top: Concentrations of dissolved inorganic phosphorus, dissolved organic phosphorus and particulate phosphorus measured in Jarrah Creek (Tully River basin) and the lower Tully River (Euramo) between Oct. 1987 and July 1995. Bottom: concentrations of dissolved inorganic phosphorus, dissolved organic phosphorus and particulate phosphorus in Dalrymple Creek (Herbert River basin) and the lower Herbert River (Ingham) between Aug 1996 and Oct. 1998.

Table 34. A summary of nutrient concentration at upstream or nominally pristine sites. n = number of samples DIN=(NH_4+ NO_2+NO_3), TDN=DIN+DON, TDP=PO_4^{3-}+DOP

	NH_4^+	NO_2^-	NO_3^-	DIN	TDN	DON	PN	PO_4^{3-}	TDP	DOP	PP	$Si(OH)_4$
							μg L^{-1}					
Upper Dalrymple Creek (Herbert River)												
average	14	0.5	16	31	127	98	36	1.1	7.3	5.6	3.5	10,800
n	17	17	17	17	16	15	6	16	16	14	16	12
median	11	0.4	4	16	114	86	33	0.9	7.4	5.3	3.0	10,800
Yamani Falls (Herbert River)												
average	15	0.7	23	38	186	141	146	1.5	7.0	5.4	20.9	8,500
n	107	107	106	106	98	95	80	107	98	96	111	28
median	11	0.5	6	21	174	133	89	0.5	6.4	4.5	7.2	8,700
Upper Tully River												
average	34	0.9	42	77	165	86	57	1.7	7.5	4.3	7.5	4,870
n	102	102	102	102	98	98	93	102	98	98	95	39
median	26	0.6	38	701	158	84	40	0.6	5.8	2.7	5.6	4,860
Jarrah Creek (Tully River)												
average	27	0.7	24	52	137	88	69	5.6	13.0	7.9	9.2	10,000
n	102	102	102	102	91	91	94	102	90	90	101	37
median	20	0.5	13	41	130	83	42	2.9	12.0	7.0	5.6	10,300
Lakefield (Normanby River)												
average	23	2.9	17	43	314	271	270	11	10.0	1.4	47	5,300
n	29	29	29	29	29	29	17	29	29	29	17	29
median	21	2.8	15	40	262	221	230	11	9.0	0.6	44	4,760

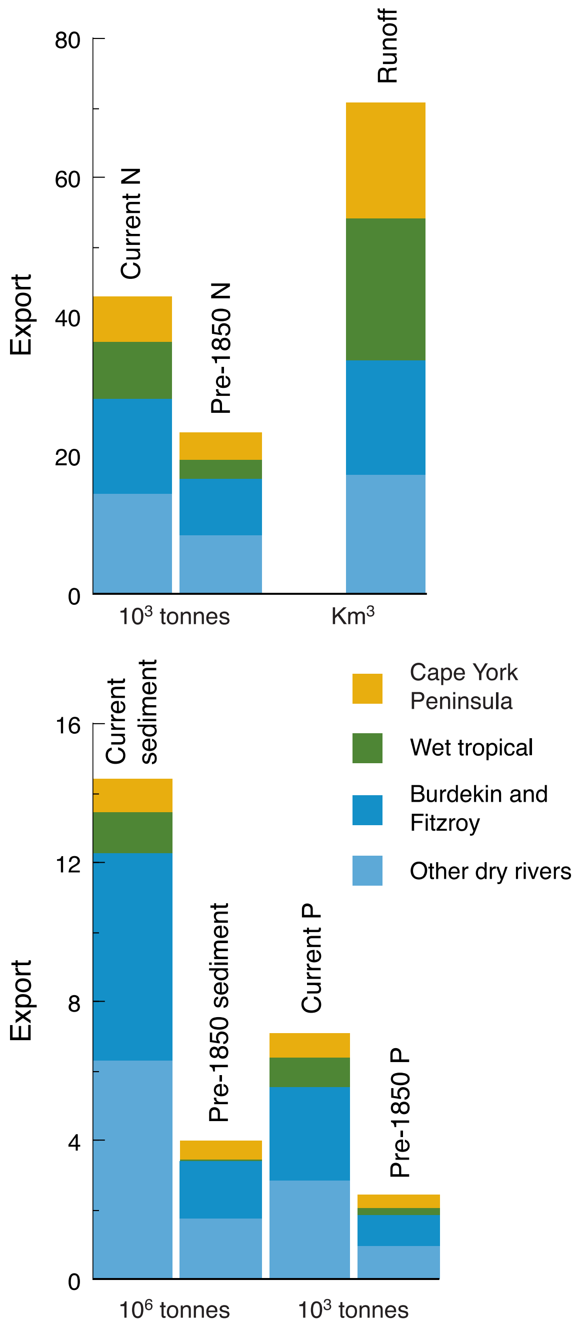
Coral Sea, burial in sediments and denitrification. The GBR extends parallel to 2,000km of coastline. Current average nitrogen and phosphorus inputs from runoff (43,000 and 7,000 tonnes per year) translate to an average of 21 tonnes of nitrogen and 3.5 tonnes of phosphorus per km of coastline.

Annual nutrient inputs from Coral Sea upwelling depend on the number and size of upwelling events during the summer upwelling period [143] and the density of reefs along the shelfbreak. Most of the nutrient inputs from upwelling are dissolved inorganic nutrients (NO_3^- and PO_4^{3-}), with net exports of dissolved organic (DON, DOP) and particulate forms (PN, PP). Net annual inputs of nutrients by upwelling into the central GBR (16-18°S) vary over a 10-fold range (2.8 - 28 tonnes of nitrogen and 0.4 – 4.4 tonnes of phosphorus per km of shelf). The upper ends of these ranges encompass the estimated average annual inputs of nitrogen and phosphorus in river runoff. The higher rates of upwelling and associated nutrient inputs are unlikely to occur along the full length of the GBR because shelfbreak reefs in the northern and southern GBR are more closely packed and restrict onshore movements of upwelling water to narrow passes [498, 575].

Each year, between 140 and 440 km^3 of rainwater falls directly on the GBR lagoon [144]. This rainwater contains approximately 100 µg L^{-1} of inorganic nitrogen (100 tonnes km^{-3}) and 7 µg L^{-1} (7 tonne km^{-3}) of phosphorus [146]. The estimated volume of rainfall would deliver 14,000 – 44,000 tonnes of nitrogen and 1000 – 3,000 tonnes of phosphorus per year to GBR waters. This is equivalent to 7-22 tonnes of nitrogen and 0.5 - 1.5 tonnes of phosphorus per km of coastline. As with upwelling, the upper end of the range of rainfall nitrogen inputs to the shelf are of similar size to the average annual nitrogen input from land runoff. Phosphorus inputs in rainwater, not surprisingly are considerably lower than those from runoff.

Table 35. Proportions of water, sediment and nutrients exported by catchments in major habitat regions of the GBRCA.

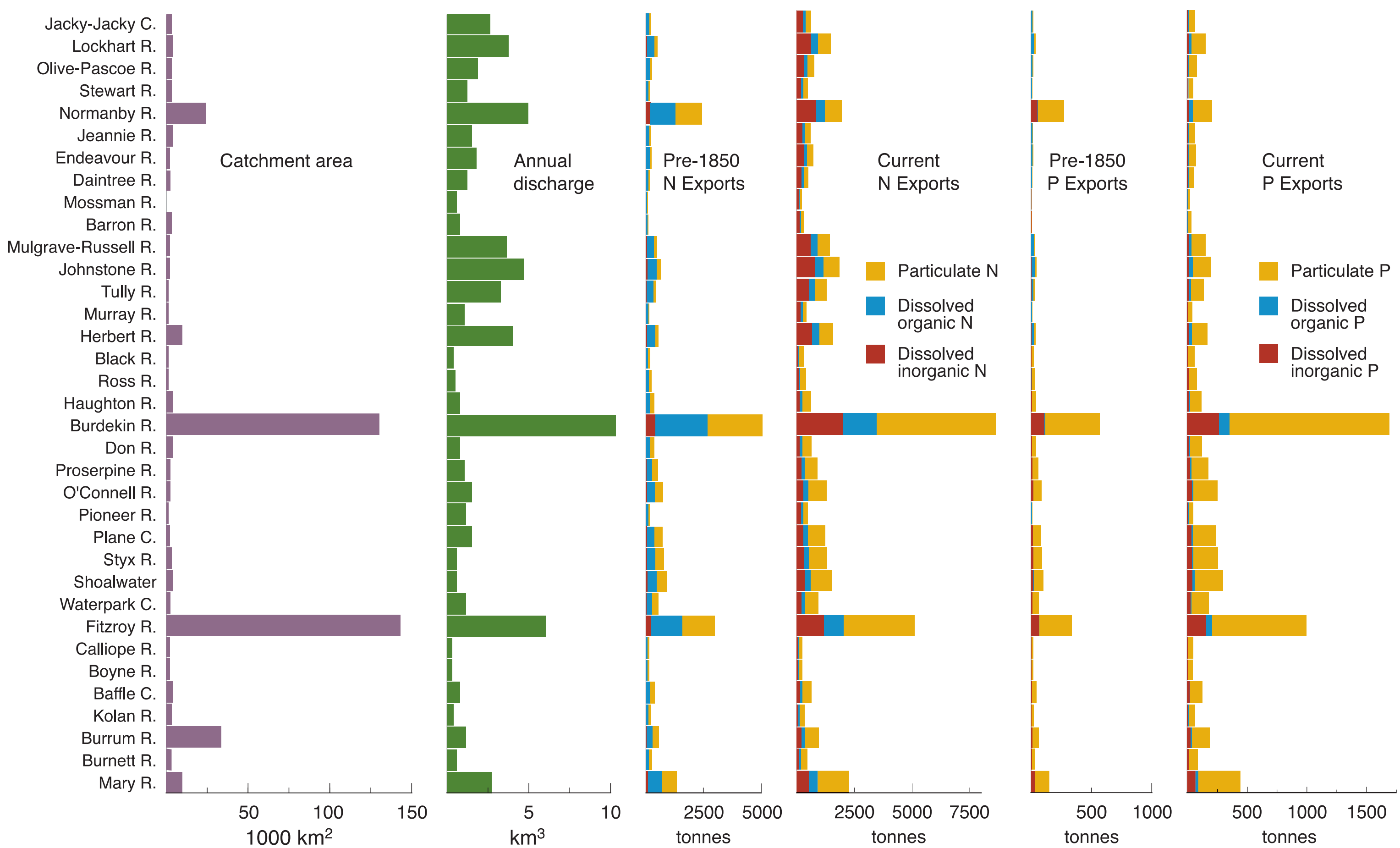
		Pre-1850	Current
Discharge	Cape York	24	24
	Wet Tropics	29	29
	Dry Tropics	47	47
Sediment	Cape York	13	7
	Wet Tropics	1	8
	Dry Tropics	85	85
Nitrogen	Cape York	17	15
	Wet Tropics	12	19
	Dry Tropics	72	66
Phosphorus	Cape York	16	10
	Wet Tropics	8	12
	Dry Tropics	77	78



Estimated current and pre-1850 exports of nitrogen, sediment and phosphorus from catchments of the GBRCA to the GBR lagoon.

Direct nutrient inputs from human sources are considerably smaller than those from natural upwelling, rainfall or river runoff. At present, there is no consolidated estimate of nitrogen and phosphorus inputs to the GBR lagoon from urban areas or all sewage treatment plants discharging directly into marine waters and streams flowing into the lagoon. It is possible to estimate the likely upper limit of such an input. Approximately 40% of the 1 million people living in the GBR catchment live in coastal urban centres with established sewerage systems and treatment plants. Modern secondary treatment plants discharge approximately 5 kg nitrogen and 1.5 kg phosphorus per person per year [66], although this varies with the type of plant and operating factors. Using these values, maximum nutrient inputs associated with sewage discharges from urban centres to the GBR would be 2,000 tonnes of nitrogen and 600 tonnes of phosphorus if all sewage was discharged via ocean outfalls or into coastal waterways. This is only 5% of the estimated average nitrogen and 9% of the average phosphorus inputs from river runoff. A significant proportion of urban sewage is now tertiary-treated to remove nitrogen and phosphorus, or disposed on land. The estimated sewage inputs above are therefore almost certainly greater than actual urban nutrient inputs to the GBR lagoon.

Prawn aquaculture farms in Queensland (ca. 500 ha of ponds, including inactive ponds) discharge about 1 kg of nitrogen and 0.1 kg of phosphorus per ha of ponds per day [382]. The quantity of discharge varies between farms and during the year with rainfall and farm operations. Initially, effluent was discharged to coastal waterways [520]. Increasingly, however, effluent is being treated on-site. At the nominal effluent production rates above, prawn aquaculture farms adjoining the GBR would discharge approximately 200 tonnes of nitrogen and 20 tonnes of phosphorus per year (0.4% of river nitrogen inputs and 0.3% of river phosphorus inputs).



Catchment areas, average annual freshwater discharges and estimated pre-1850 and current exports of nitrogen and phosphorus from drainage basins of the GBRCA..

Current information clearly shows that river runoff is the largest source of "new" nitrogen and phosphorus to the GBR lagoon (Table 36). At the scale of the whole GBR, terrestrial inputs of nitrogen and phosphorus are greater than combined inputs from upwelling, rainfall, sewage plants and aquaculture pond effluent. The range of nutrient inputs from upwelling is most likely an over-estimate because it does not account for the resistance to onshore-offshore water movement presented by the dense network of shelfbreak reefs in the northern and southern thirds of the GBR.

A significant proportion of the nitrogen and phosphorus in runoff to the GBR is associated with particulate matter, and is deposited or buried for at least some time in coastal sediments. As a result, short-term disparities between runoff, rainfall and upwelling inputs are probably smaller. Estimated runoff inputs of soluble readily bio-available forms of nitrogen (DIN, DON) and phosphorus (PO_4^{3-}, DOP) are closer in magnitude to the upwelling inputs of nitrogen and phosphorus. Estimated pre-1850 terrestrial inputs of total nitrogen and total phosphorus are also closer in magnitude to the estimated upwelling inputs of nitrogen and phosphorus. Again the pre-1850 runoff inputs include particulate nitrogen and phosphorus, some of which are probably stored in shelf sediments, while the upwelling inputs are largely of dissolved nutrients. The evidence suggests that prior to modern increases in runoff of nutrients related to vegetation clearing and land use, the GBR shelf ecosystem received nitrogen and phosphorus inputs of similar magnitude from terrestrial runoff and upwelling. Modern changes in the composition of terrestrial runoff have changed this balance.

The relative nutrient input from rain is larger (especially for nitrogen). Rainfall inputs are unlikely to have changed much since 1850 because most of the rain comes from moisture produced in the South Pacific Ocean which is

Table 36. Relative annual inputs of N and P to the GBR from natural and anthropogenic sources. Ranges are shown where inputs naturally vary from year to year. Runoff ranges are based on 1968-1994 average of annual discharges.

Source	Tonnes N	Average	Tonnes P	Average
Current Land Runoff (Total)	10,000-120,000	43,000	1,300-22,000	7,000
Current Land Runoff (Soluble)	6,000-60,000	20,000	300-4,700	1,500
Pre-1850 Land Runoff (Total)	4,000-66,000	23,000	360-7,000	2,400
Pre-1850 Land Runoff (Soluble)	2,900-38,000	12,000	160-1,800	600
Coral Sea Upwelling*	4,400-40,000		630-6,300	
Rainfall	14,000-44,000		840-2,600	
Sewage Discharge**	2,250		600	
Aquaculture Effluents**	200		20	

* Upper end of ranges likely an over-estimate.
** Likely over-estimates.

distant from significant human sources of pollution. The nutrient input from rain is spread over the entire GBR. In contrast, nutrient and sediment inputs from land runoff are initially delivered to the relatively small volume of shallow water (295 km^3 - less than 4% of the water volume of GBR lagoon) adjacent to the coast, concentrating its effect.

Chapter 9

River plumes
in the Great Barrier Reef

Floodwaters carry most of the terrestrial sediment and nutrients that reach the Great Barrier Reef. During floods, river waters push seawater out of the estuaries so that fresh and salt waters mix together in the GBR lagoon. The chemical and biological processes that normally occur when fresh water and seawater mix in estuaries take place in the low-salinity and often turbid waters of river plumes. The size, movement and persistence of river plumes in the GBR lagoon changes with the volume of discharged freshwater and the strength of oceanographic forces which move and mix coastal waters.

Freshwater runoff, is much less dense than seawater and typically contains less than 0.1 gm of dissolved salts per litre. As a result, freshwater and freshwater-seawater mixtures in river plumes float in a buoyant layer above the saltier and denser water of the GBR lagoon. The rate and extent of mixing between the two layers depends on the density difference between them, and the energy of turbulence created by wind and bottom friction. Ultimately, turbulent mixing erodes the salinity and density differences and disperses the plume.

River plume
Photo: GBRMPA

Salinity and the density of seawater:

The density of water depends on its temperature and the quantity of salts dissolved in it. Normal seawater contains approximately 35 grams of dissolved salts per litre, mainly sodium chloride (NaCl) and magnesium sulfate ($MgSO_4$). By definition, pure water at 0°C has a density of 1.0 gm per cm^3 (specific gravity = 1.000). In contrast, seawater (35‰) at 0°C has a density of 1.028 gm per cm^3.

At 25°C (A typical early-summer seawater temperature in the GBR)

Salinity	Density (gm cm^{-3})
0‰	0.996
10‰	1.004
15‰	1.008
20‰	1.011
25‰	1.015
30‰	1.019
35‰	1.022

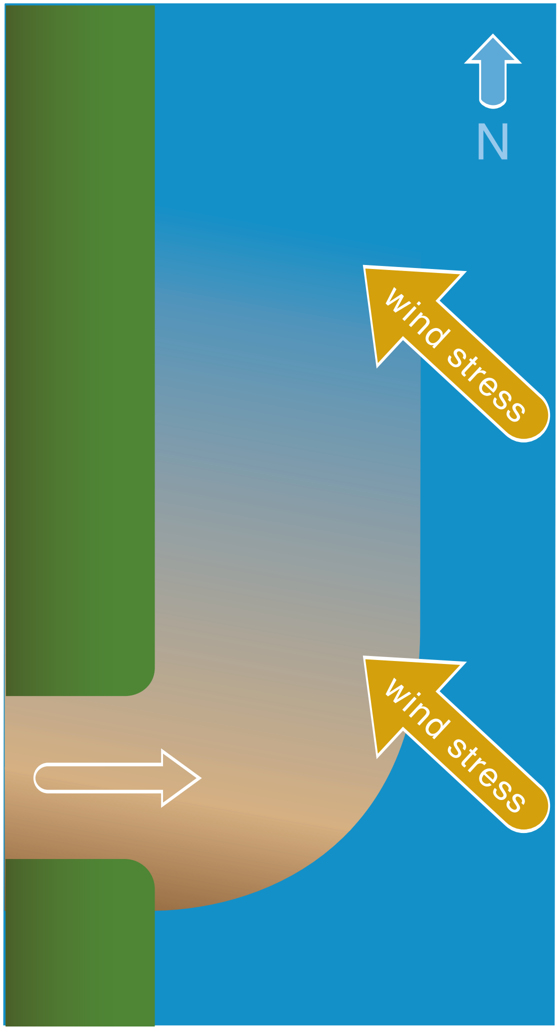
Initially, low-density freshwater flowing out of rivers spreads across the surface of the lagoon. Because of the turbidity caused by fine suspended sediment and organic matter in floodwaters, plumes stand out against the clearer shelf waters. In calm conditions, the horizontal transition between clear shelf waters and turbid plume waters can be very sharp, with boundary zones only a few metres or even centimetres wide.

Freshwater flowing out of a river does not spread evenly across the lagoon or flow directly offshore to the coral reefs on the outer shelf. River waters literally "pile up" at the river mouth, forming a buoyant wedge of low salinity water. The thickness of the fresh layer can vary considerably, from 5-10 metres near the mouth of a flooding river to a thin layer only a few centimetres thick at the boundary of the plume. This coastal wedge is squeezed seaward as gravitational and buoyancy forces work to flatten it. When the freshwater layer of water moves in the flattening process, the rotation of the Earth induces a force on it, the Coriolis force. In the Southern Hemisphere, the Coriolis force pushes the water moving offshore to the left, or northward along the coast. In the absence of winds and the southward flowing East Australian Current (Chapter 2), the Coriolis force causes river water entering the GBR to form a northward-flowing coastal boundary current. This boundary current progressively widens and slows as the plume waters mix with adjoining shelf waters. When there are floods in a number of rivers, plumes from each river join the low-salinity water of the northward flowing coastal current.

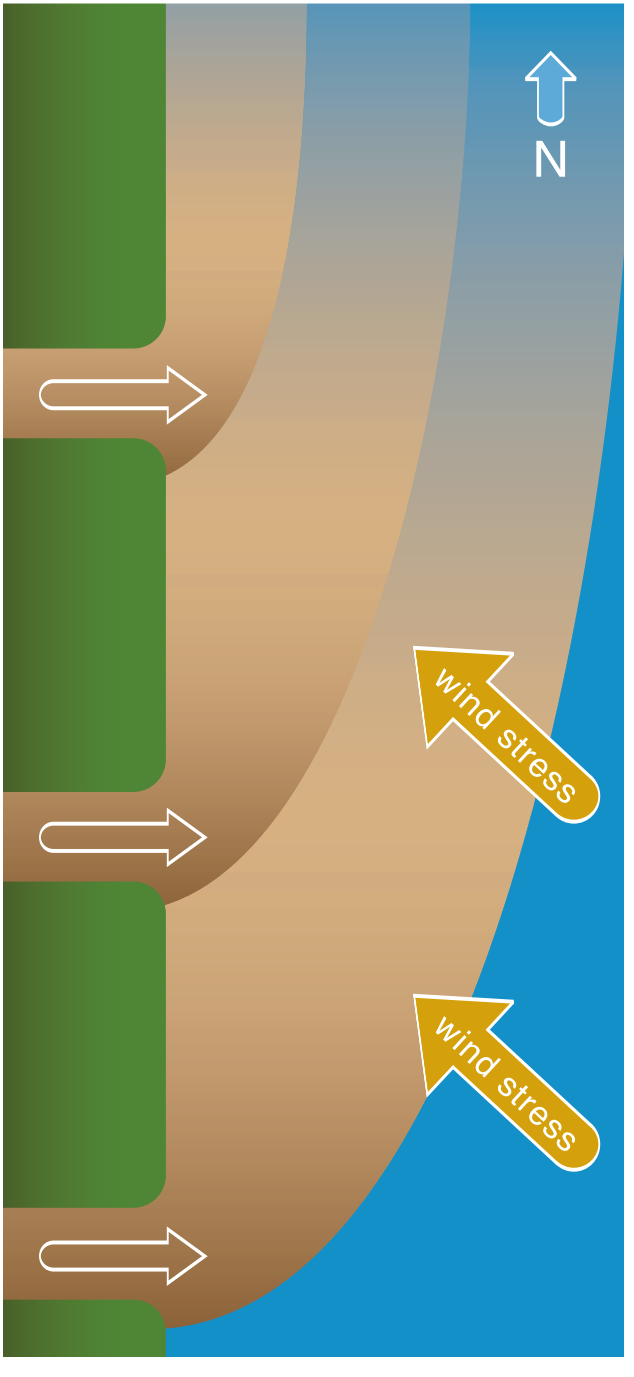
Winds greatly influence the movement and mixing of river plumes. Wind stress creates the waves and turbulence that mix the surface water downward. As with the low-salinity wedge, the Coriolis force also turns surface water pushed by wind friction to the left. The dominant wind direction in the GBR is from the southeast (SE trade winds). Under SE wind conditions, surface waters and low-salinity plumes, are pushed northward and toward the shore. When winds blow from the north, surface waters are pushed southward and offshore.

The Coriolis force and the dominant SE trade winds concentrate buoyant low-salinity plume waters with their associated sediment and nutrients into a narrow coastal band. Near-fresh river plumes only directly affect mid- and outer-shelf reefs under extreme cyclonic conditions. During extreme flood events, river waters flowing onto the continental shelf have sufficient cross-shelf momentum to push across narrow sections of the lagoon to mid-shelf reefs [105]. Persistent northerly and westerly winds can also deflect surface waters offshore [69]. North-flowing plumes from large rivers such as the Burdekin are ultimately dispersed across the lagoon by horizontal mixing over north-south distances of 100s of kilometres. [306, 581].

In some cases, most of a plume comes from a single river. During episodes of widespread rainfall, however, plumes from adjoining rivers and coastal creeks merge into a continuous band along the coast. In cases when winds predominantly come from the southeast and the plume flows northward, the seaward boundary stays within 20 km of the coast [111]. These nearshore plumes principally affect coastal reefs, fringing reefs on nearshore islands and coastal seagrass beds. Distinct plumes from the smaller wet tropics rivers only extend into the mid-shelf reef zone under northerly wind conditions [111]. Because of local geography, however, a few midshelf reefs are more regularly influenced by runoff. Green Island, off Cairns, is inundated with diluted plume waters almost every year because Cape Grafton, south of Cairns, deflects northward flowing river plumes offshore [111].



Northward deflection of a river plume in response to south easterly winds and buoyancy effects.

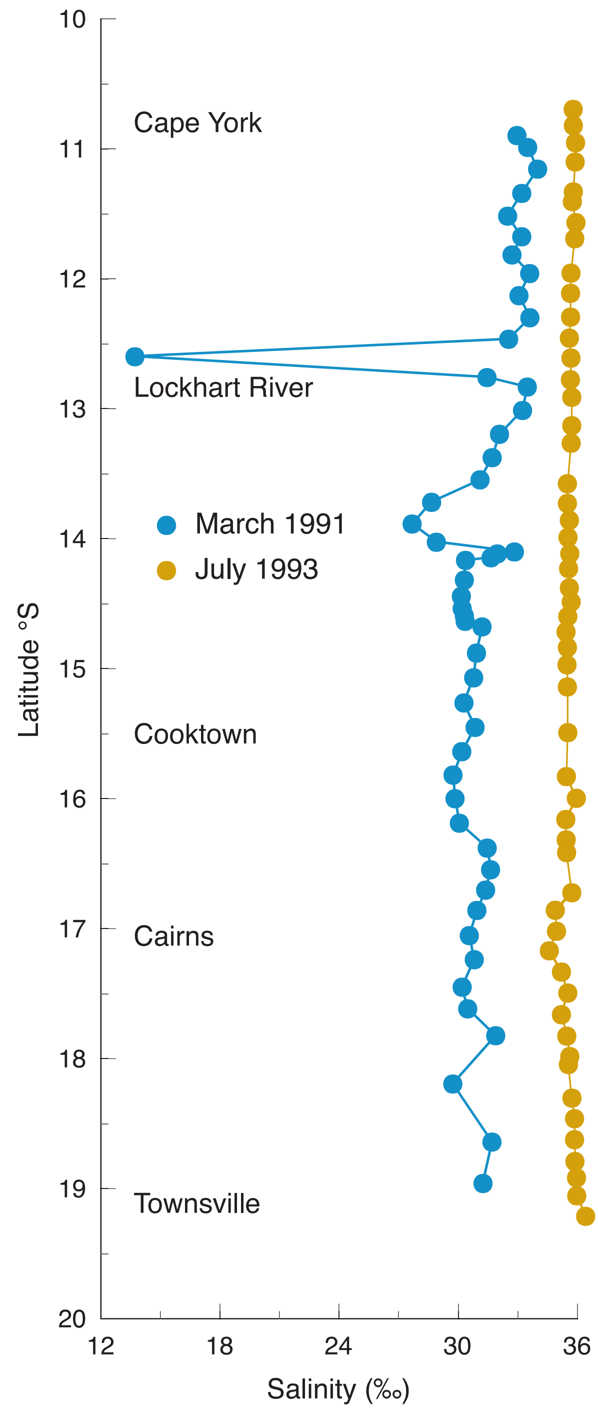


Overlapping plumes from adjoining rivers.

Major floods in the Burdekin River (e.g. 1974, 1981, 1991) episodically produce large and long-lived plumes which can extend for hundreds of kilometres along the coast. Mapping, monitoring and modelling of river plumes in the central GBR lagoon between the Burdekin River (19°S) and Cairns (17°S) has provided a clear picture of where the plumes go. The most complete record of flow in the Burdekin River over the last few centuries has been derived from coral cores collected in the Palm Islands [223] and at Rib Reef (J. Lough, AIMS, pers. comm.) approximately 200 km north of the mouth of the river. Low-salinity water from the Burdekin River has been tracked as far north as Cape Grafton [581]. As plumes drifts northward, they break up into lobes of low salinity water which expand and disperse, engulfing mid-shelf reefs to the north of Hinchinbrook Island (18°S). When there are large floods, the plume from the Burdekin River merges with plumes from the smaller rivers of the wet tropics as it moves northward [250]. Computer models which simulate the influence of winds and tidal currents on the movement of reef waters have reproduced the behaviour of these plumes, showing how they flow along the coast and spread outward after major flood events. These large plumes last sufficiently long (weeks) that large-scale phytoplankton blooms develop from the entrained nutrients.

Extensive runoff also occurs in the far northern GBR after periods of heavy monsoonal rainfall. Because of its remote location, the extent and persistence of freshwater runoff and flood plumes along Cape York Peninsula are not well known. In March 1991, following an extended period of monsoonal rain, low salinity water (less than 33‰) extended along the coast for over 1,000 km between Cape York and Townsville (19°S). With one exception (Lockhart River on Cape York), the lowest lagoonal salinities on this transect, were measured between Townsville and Cooktown because of the extensive discharge from the Burdekin and smaller wet-tropical rivers. To the north of Cape Melville, where northerly longshore water flow is partially blocked by reefs, the freshwater in the lagoon would have come from the largely undisturbed catchments on Cape York Peninsula. During one of these large runoff events, logs, woody debris and dislodged banana plants were observed in turbid waters close to the outer shelf reefs off Cape Tribulation (16°S).

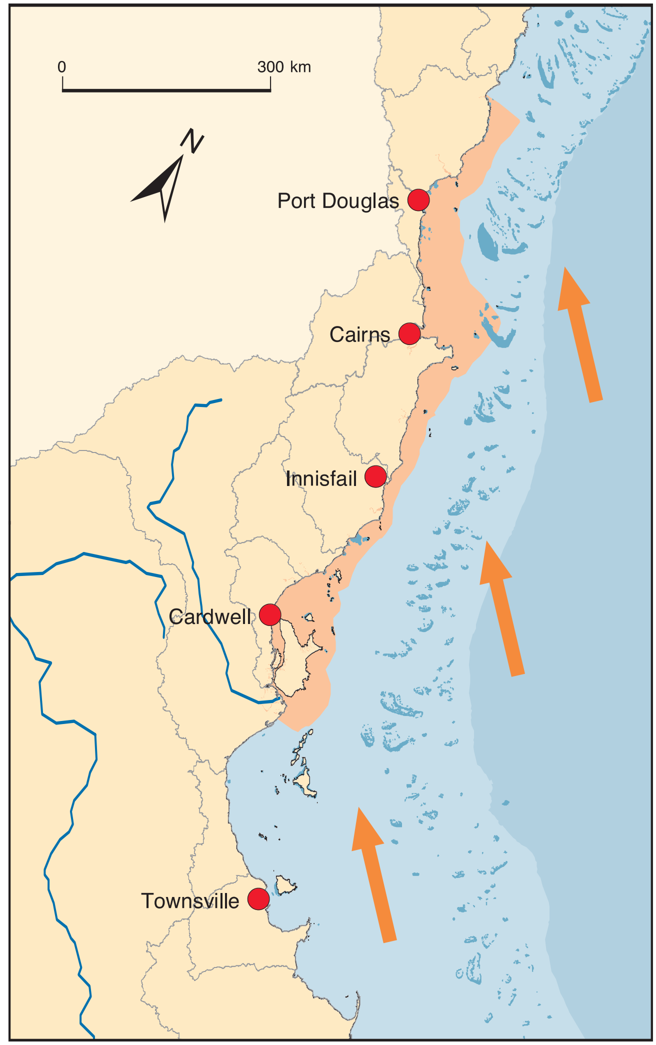
The frequency of flood plumes along the coastline is related to how often flood-producing rains fall in adjacent or more southerly catchments. Rivers draining wet-tropical catchments typically have several flow events or floods of varying size each year. As a result, flood plumes occur annually along the wet-tropical coast, although they may not be large or long-lived. The Burdekin River floods to some degree in most years, the discharge volume varying with the quantity and location of rainfall in the catchment. During the last 50 years, the Burdekin River has produced a very large flood about once per decade (e.g. 1946, 1958, 1974, 1981,1991). These large floods influence the GBR lagoon as far north as Cairns or even Cooktown. Rivers in the dry southern GBR catchments flood less frequently, with moderate to significant floods only occurring every 10-20 years. Nearshore and coastal reefs adjacent to the wet-tropical coast between Hinchinbrook Island and Cooktown are influenced by flood plumes derived from rivers between the Burdekin and Daintree Rivers at least once per year. Reefs and coastal habitats in this region are exposed to low-salinity water with elevated nutrient and sediment loads for periods of several days to weeks. Because they are repeatedly inundated with runoff plumes, reefs and other nearshore habitats to the north of the wet-tropical rivers are most affected by disturbances or stresses caused by freshwater and other materials in runoff.



Latitudinal changes in surface salinity measured in the shipping channel of the GBR lagoon between Townsville and Cape York in March 1991 (wet season, post-Cyclone Joy) and July 1993 (dry season).

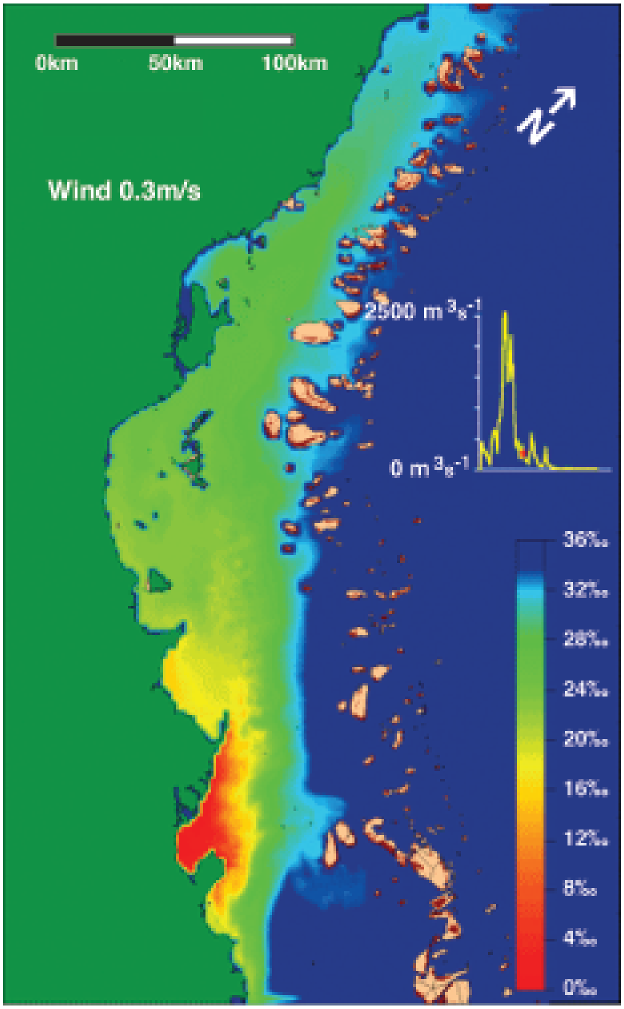
Right: The extent of the runoff plume following cyclone Ethyl (6 March 1996) under southeasterly wind conditions. Plume boundaries were mapped from the air.
Data source: Devlin et al., 2001

Mapped extent of plume
Reefs
Continental shelf (depth < 80 m)
GBR catchment

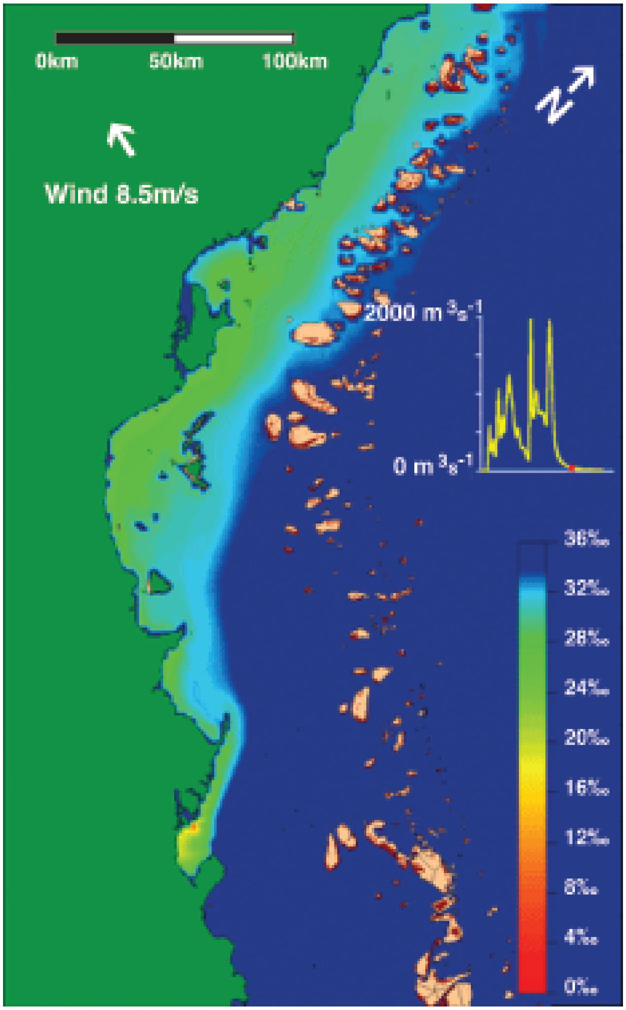


Left: The extent of the runoff plume following cyclone Sadie (1 February 1994) under northerly wind conditions. Plume boundaries were mapped from the air.
Data source: Devlin et al., 2001

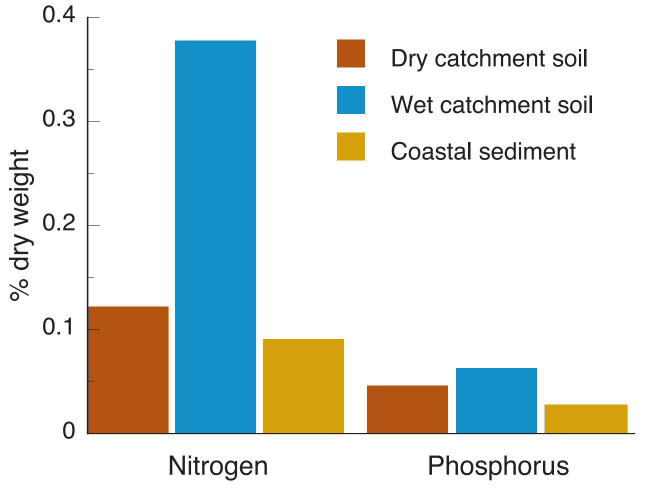
Mapped extent of plume
Reefs
Continental shelf
GBR catchment



Left: Modelled extent of the Burdekin River plume on 12 February 1974. Surface salinities were calculated with a 2-dimensional computer model of surface currents in the central GBR region which incorporated effects of wind stress and tidal currents. The model was calibrated using field data collected during 1981 (Wolanski and van Senden, 1983). Source: McAllister et al., 2000.



Right: Modelled extent of the Burdekin River plume on 14 March 1991. Surface salinities were calculated with a 2-dimensional computer model of surface currents in the central GBR region which incorporated effects of wind stress and tidal currents. The model was calibrated using field data collected during 1981 (Wolanski and van Senden, 1983). Source: McAllister et al., 2000.



The average nitrogen and phosphorus content of surface soils in dry and wet catchments and nearshore sediments bordering the GBRCA.

Terrestrial sediments in river plumes

Rivers flowing into the GBR lagoon carry eroded soils, organic detritus, particle-associated nutrients and a variety of other materials. Suspended soil particles transport a large proportion of the nutrients and other materials (e.g. pesticides) exported from catchments. Suspended particulate matter in rivers accounts for ca. 40% of the nitrogen and 60-80% of the phosphorus exported from the GBR catchment. The particle-associated nutrients are mostly ions and organic molecules attached to the surfaces of fine clay and colloidal (<0.01 µm) particles.

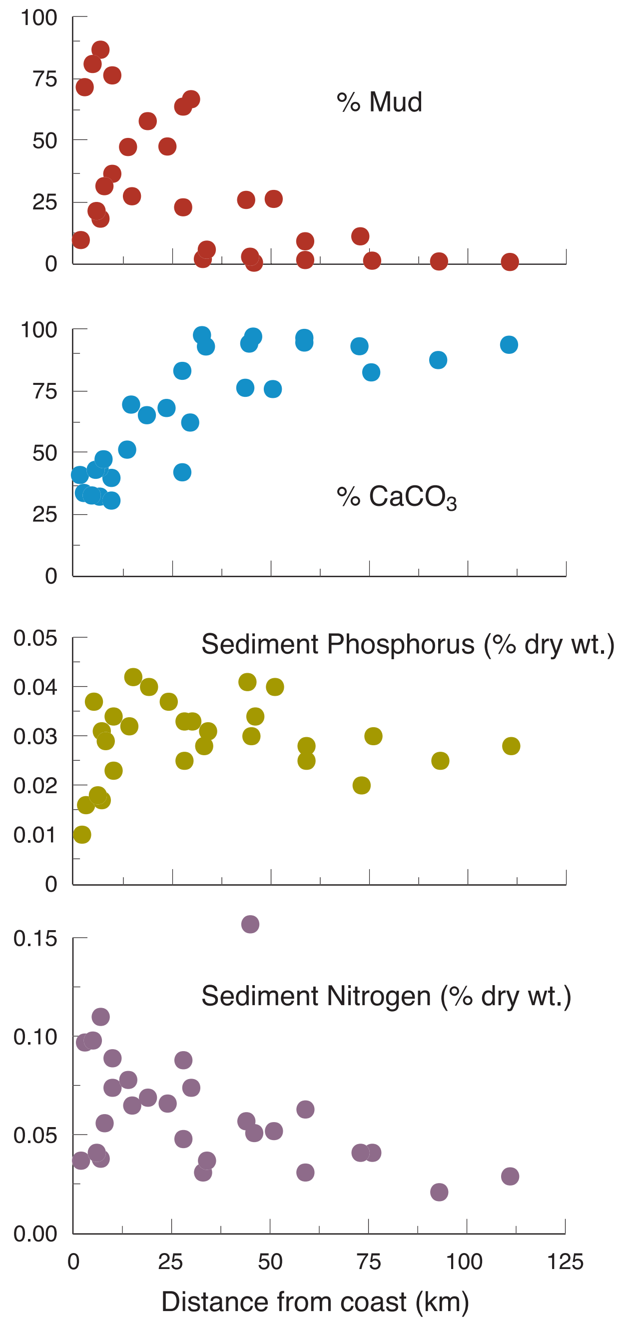
When river waters reach the sea they rapidly slow down. Fine sand and larger silt-sized particles quickly drop out of suspension as the turbulence is dissipated. Under low-flow conditions, sand and silt accumulate in the estuary [19, 208]. During floods, the strong river flows carry silt and sand out of the estuary and deposit them at the river mouth. Smaller silt- and clay-sized particles are deposited at progressively greater distances. Over the last 5,000 years, eroded soils have built a nearshore band of terrigenous sediments along the coast [41, 229, 230, 275].

Slight increases in salinity (ionic strength) due to mixing between fresh and salt water cause even the smallest clay particles, colloids and dissolved humic acids to aggregate and rapidly sink out of river plumes [152, 470, 577]. Because of their small size, individual colloids and clay particles sink very slowly (as little as a few mm per day). When disaggregated in fresh water, very slight amounts of turbulence are sufficient to keep them in suspension for significant lengths of time. The fine mineral and organic particles aggregate as river and ocean waters mix in estuaries or river plumes . The aggregates sink rapidly and cause the bulk of the fine sediments carried by rivers to be initially deposited within a few kilometres of the river mouth [266, 364, 577]. The effect of salinity on particle aggregation is more important than the reduction in turbulence in removing small particles from river plumes. The aggregation process can be accelerated by organic matter produced by bacteria and planktonic algae growing on nutrients carried within the river plume [26] or in some places, by organic matter washed out of mangrove swamps [582].

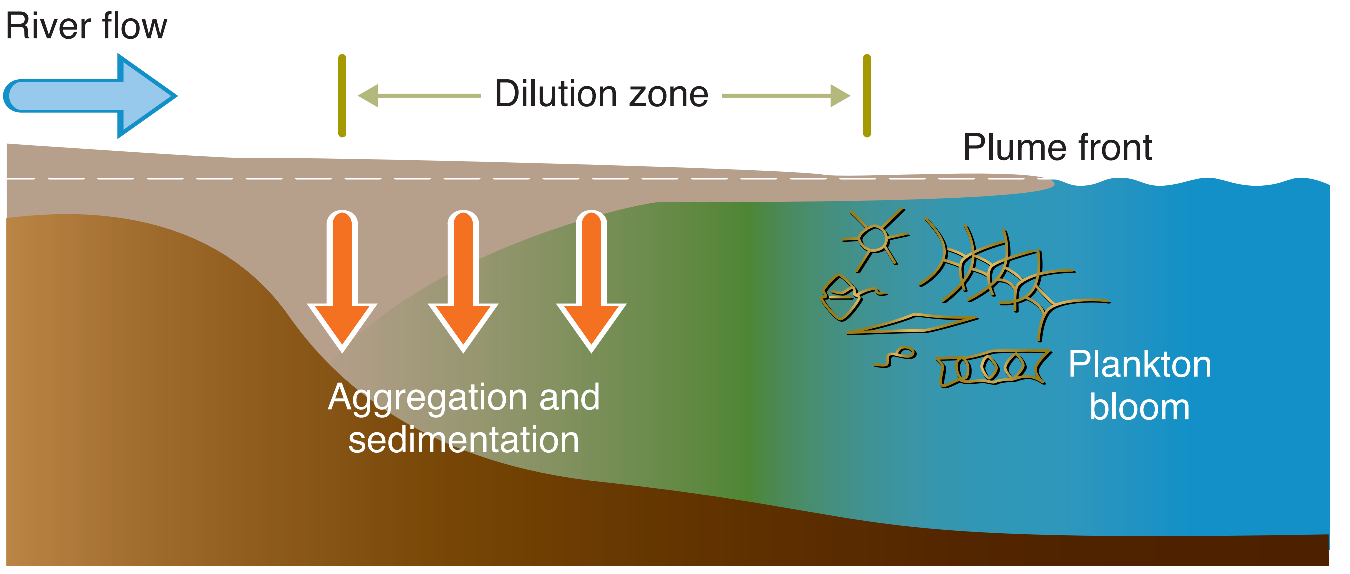
Concentrations of suspended sediment in river plumes can range from several grams per litre near the mouth of large dry catchment rivers, such as the Burdekin, to a few milligrams per litre after the plume has travelled for some distance. Suspended sediment concentrations measured in GBR plume waters [111] generally range between 1 and 20 mg L^{-1}. Even at such low concentrations, particle-laden plume waters are readily visible against the clearer blue waters of the GBR lagoon. Depending on weather conditions and the degree of mixing, the sediments in plumes can be concentrated in a layer only a few metres thick. This layer primarily interacts with the upper few metres of reefs, but also increases shading of algae, corals and seagrasses living below. Despite their visibility, suspended matter concentrations in plumes are low relative to near-bottom suspended sediment concentrations in shallow coastal waters caused by wave-driven sediment resuspension [264]. Because strong winds (greater than 15-20 knots) causing resuspension occur throughout the year, corals and algae on nearshore reefs experience turbid water conditions and sedimentation stress far more frequently from wave-driven resuspension than from flood plumes [264, 265, 365, 576].

Nutrients in river plumes

Dissolved and particulate nutrient concentrations in river plumes [68, 111] are higher than those normally occurring in GBR coastal waters (Table 3). Ambient nitrogen and phosphorus concentrations in shelf and coastal waters are usually on the order of 1s to 10s of µg L^{-1} (Chapter 2). In contrast, nitrogen and phosphorus concentrations in flood plumes can reach several 10s and 100s of µg L^{-1}. Not surprisingly, nutrient concentrations are greatest near the



Changes in the mud, $CaCO_3$, nitrogen and phosphorus content of surface sediments with distance from the coast in the far-northern GBR.
Data source: Furnas et al., 1990

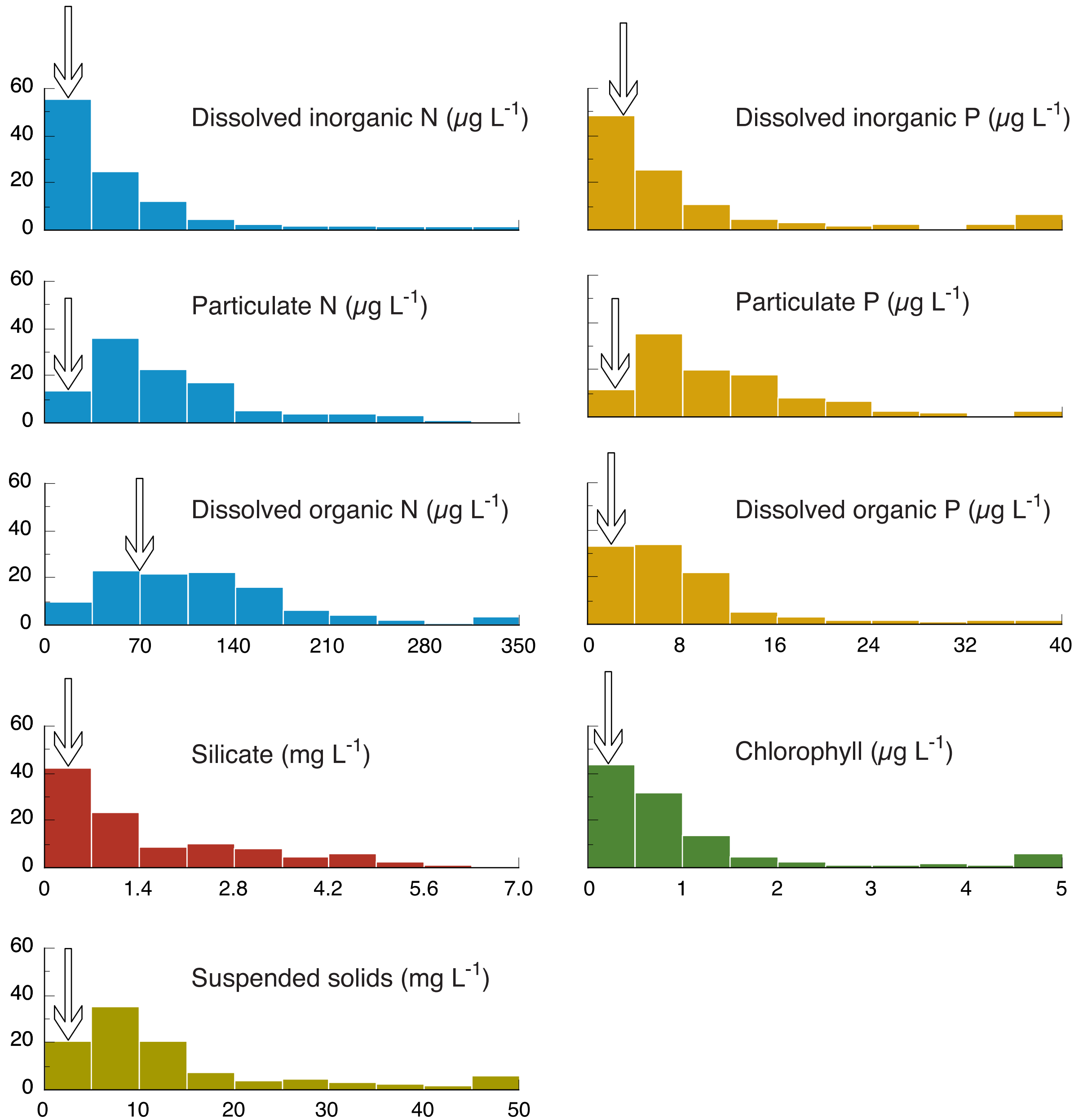


Physical and biological processes associated with river plumes.

river mouth in undiluted plume waters. Suspended sediment and nutrient concentrations in undiluted plume waters follow concentration changes in river waters (Chapters 7 and 8). As plumes spread, mix and age, nutrient concentrations decline as a result of dilution, sedimentation, biological uptake and chemical reactions. In fresh plumes, where biological activity or chemical interactions have not greatly influenced in situ nutrient levels, dissolved and particulate nutrient concentrations are directly related to the salinity of the plume water, reflecting the degree of dilution by low-nutrient shelf waters [111]. There is an inverse linear relationship between salinity and nutrient concentration. Where the initial river source concentration is known or can be estimated from linear nutrient-salinity relationships in field data, measures of salinity provide a useful means for estimating potential nutrient concentrations in plume waters.

What happens to nutrients in river plumes?

To date, most studies of river plumes in the GBR have focused on the concentrations and distributions of nutrients in coastal waters and their relation to salinity [69, 111, 484, 491]. We know less about the fate of nutrients and organic



Numbers of surface water samples collected from river plumes in the GBR lagoon with the nutrient, suspended solids and chlorophyll concentrations in the ranges shown. Arrows show median nutrient, chlorophyll and suspended sediment concentrations in central GBR inshore waters under non-plume conditions.
Plume nutrient data source: Devlin et al., 2001

matter associated with plume waters, or sediment particles and biological responses of reef and benthic communities to nutrients in plumes. The basic physical, chemical and biological processes which influence or are influenced by nutrients in river plumes are the same as those which operate in coastal waters and ecosystems throughout the year, but their effect may be magnified by changes in salinity and nutrient availability.

Several things happen to the nutrients carried by rivers when they reach the GBR lagoon. A large proportion of the organic matter, nitrogen and phosphorus bound to fine soil particles in river water stays attached to those particles and is deposited as they aggregate and settle in the coastal zone. Coastal sediments act as a nutrient bank, storing and releasing nutrients slowly over long periods.

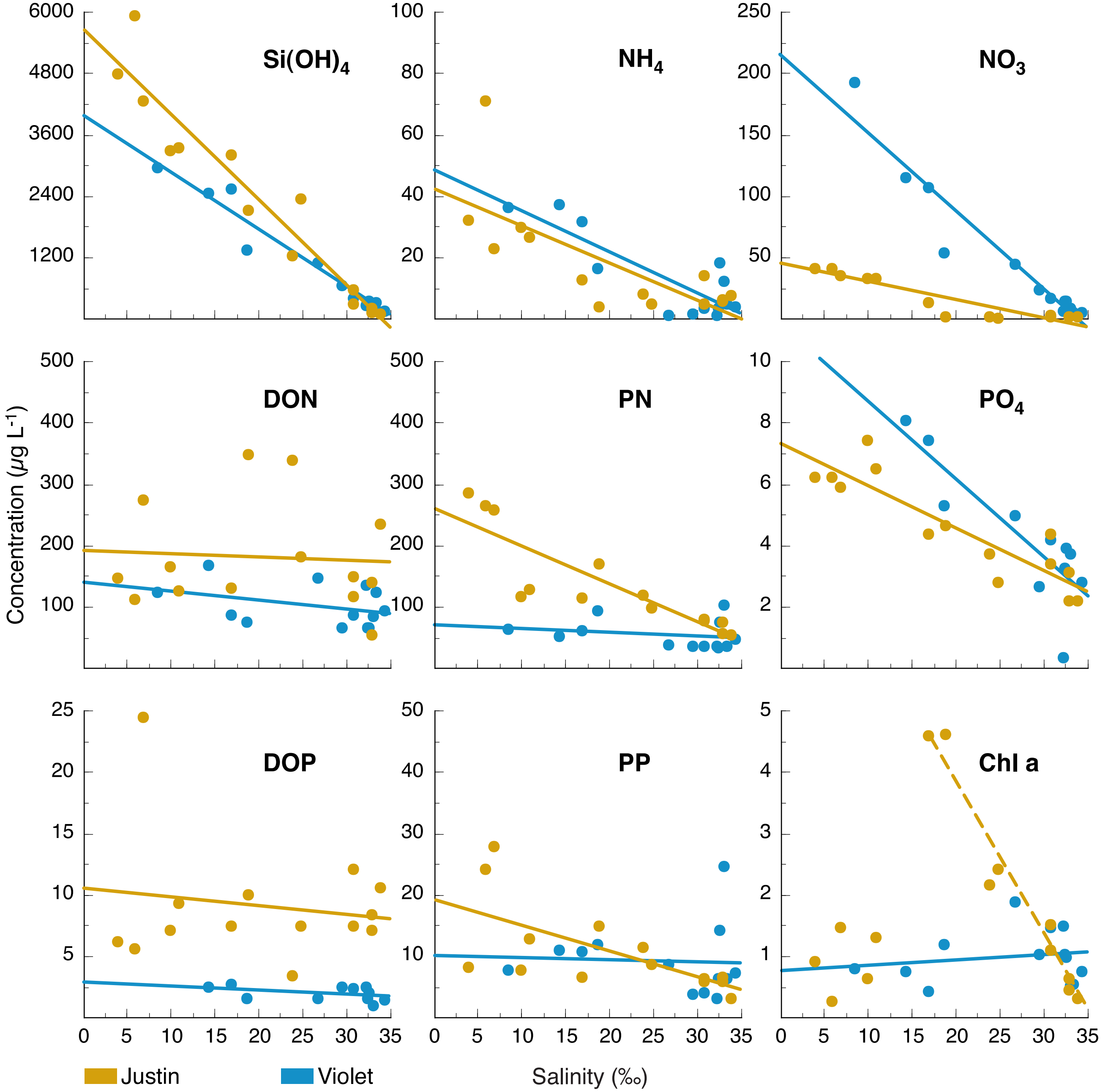
The tendency for nutrients and organic matter to remain associated with sediments depends on salinity, the chemical properties of each nutrient species, the mineralology of the dominant sediment particles, and particularly, microbial activity in the sediments. Nearshore sediments of terrigenous origin have a nitrogen content intermediate between that of soils and offshore (carbonate) sediments. Coastal sediments lose fixed nitrogen over time through microbial mineralisation and denitrification [288]. These microbial nutrient processes are related to the organic content of the sediment. The organic matter is supplied by terrestrial runoff, sedimentation of plankton from overlying waters and exports from adjacent reef, mangrove and seagrass ecosystems.

In contrast to nitrogen, the phosphorus content of coastal sediments is typically lower than both riverine suspended matter and offshore carbonate sediments [145]. Phosphorus is accumulated in carbonate sediments because it binds with calcium to form insoluble minerals (apatites). As a result, the proportion of readily bio-available phosphorus in offshore sediments is lower than in nearshore sediments [369, 371].

Sharp boundary of a river flood plume
Photo: GBRMPA

Measurements of decay-resistant organic molecules derived from plants (waxes and natural hydrocarbons) and carbon stable isotope ($^{13}C/^{12}C$) ratios of organic matter in sediment show that most of the particulate organic matter carried into the GBR by rivers is deposited within 20 kilometres of the coast [150, 452]. The stable isotope composition (^{13}C, ^{15}N) of organic matter on coastal reefs also shows a definite terrestrial influence [428, 451]. Very little particulate matter of terrestrial origin is transported offshore to the mid-shelf reef zone, either directly in river plumes or by subsequent sediment dispersal [114, 150, 452].

In estuaries of tropical river systems such as the Amazon River, phosphate (PO_4^{3-}) ions attached to soil particles



Relationships between nutrient concentrations, chlorophyll and salinity in surface water samples collected from river plumes after cyclones Violet (Johnstone River, 1 Mar 1995) and Justin (Herbert River, 26 Mar 1997).
Data replotted from Devlin et al., 2001

progressively dissociate from the sediment as the sediment passes through the estuary and onto the continental shelf [137, 139]. The sediments provide an ongoing source of phosphorus. As plankton takes up the phosphate and concentrations are depleted in the estuary and offshore river plume, more phosphorus is released from the sediment.

Less is known about the chemical behaviour of particle-associated nitrogen and phosphorus in GBR river plumes. Experiments carried out using soils, sediments and river water from the Fitzroy and Herbert Rivers do not show evidence for rapid estuarine desorption of phosphorus from soil particles [61, 373]. The difference largely appears to be due to the soils involved.

Nearshore coral reefs and seagrass beds in the path of river plumes episodically experience elevated nutrient concentrations for periods lasting days to weeks. However, the elevated dissolved nutrient concentrations in most plume waters, do not directly contact reefs or seagrass beds. The nutrients in plumes are primarily taken up by microscopic bacteria (bacterioplankton) and planktonic algae (phytoplankton) which can form widespread blooms in coastal waters [140]. In the relatively clear and warm waters of the GBR lagoon, and with enhanced nutrients, phytoplankton and bacteria can grow at or near their maximal rates. Under ideal conditions, populations of individual phytoplankton and bacteria species may double between one and four times per day [102, 141]. To support this rapid growth, phytoplankton and bacteria have high affinities for dissolved nutrients and rapidly use available nutrients in plume waters until they are reduced to concentrations which are barely detectable by sensitive chemical methods (less than one part per trillion). Plankton biomass (but not growth rate) is normally held in check by low nutrient availability (Chapter 2) and the rapid consumption of phytoplankton by planktonic grazers and predators. The nutrients in river plumes primarily support the

Runoff plume from a rainforest catchment, Daintree
Photo: GBRMPA

production of additional organic matter in coastal plankton and benthic ecosystems.

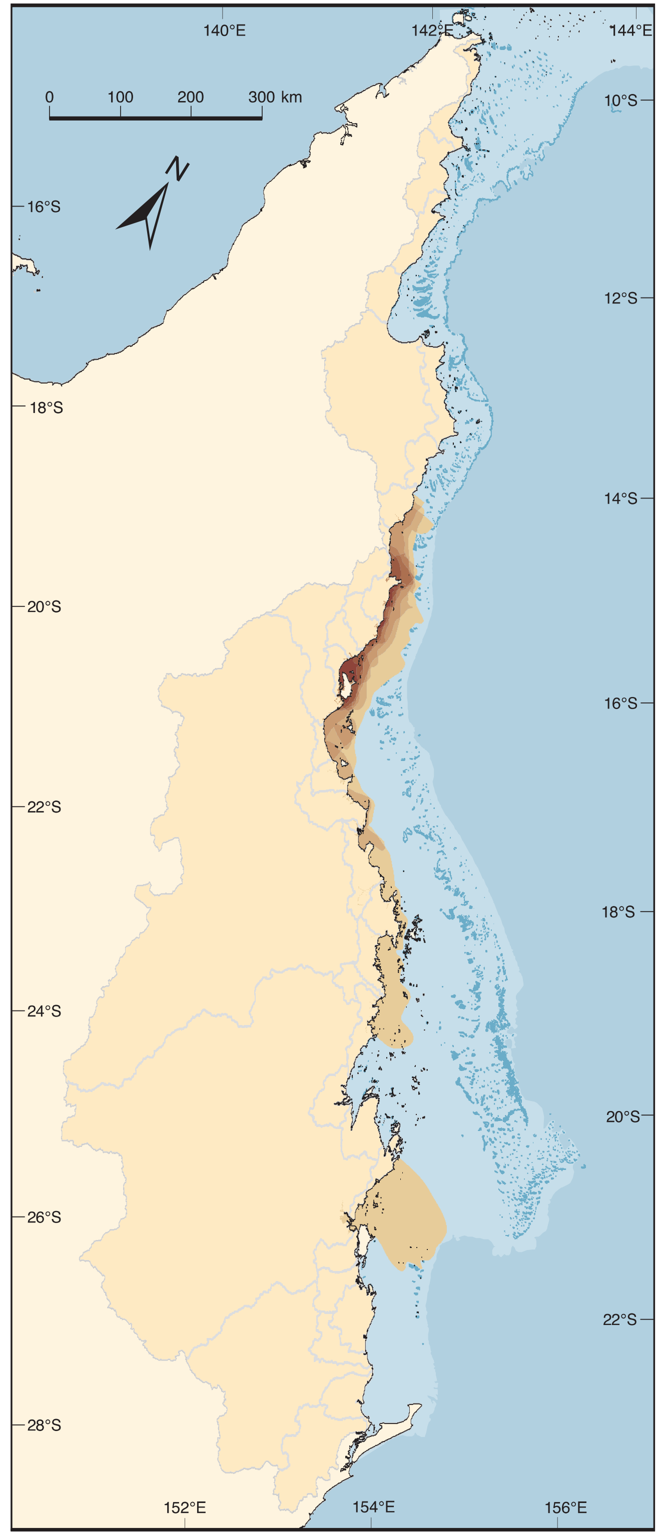
While river plumes are relatively young, phytoplankton growth and nutrient consumption are restrained by the turbidity of plume waters which limits light penetration to a shallow surface layer. Nutrient concentrations in young plumes reflect concentrations in the source waters and the extent of dilution by low-nutrient lagoonal seawater. As particle aggregation and sedimentation remove suspended sediment from the plume, turbidity decreases and phytoplankton can grow over a wider depth range. Plankton will grow fastest around the periphery of the plume where turbidity is lowest. The tan hue of turbid river water is replaced by the greenish-brown of chlorophyll and other phytoplankton pigments. The density of phytoplankton blooms in plume waters depends on the initial quantity of nutrients in river waters and their subsequent degree of dilution in the lagoon. The highest chlorophyll concentrations will usually be found in plume waters of moderate salinity (ca. 20‰). Waters of lower salinity (e.g. 0 – 20‰) are either too turbid to support rapid phytoplankton growth or those phytoplankton which have been mixed into the plume have not had sufficient time to grow. Lower chlorophyll concentrations at higher salinities (over 30‰), reflect cessation of active growth due to nutrient exhaustion, further dilution with low-nutrient lagoon waters and consumption of phytoplankton by grazers [321].

Significant phytoplankton blooms can form in the GBR lagoon within a few days [140] following major floods or sediment resuspension events caused by cyclones, stripping soluble nutrients from the water. Microscopic grazers, which feed on bacteria and the smaller phytoplankton, crop the growth and recycle nutrients (NH_4^+, PO_4^{3-}) back into the water. Larger grazers, such as crustacean copepods rapidly consume the larger phytoplankton [295].

The extent and overlap of mapped river plumes in the central and southern GBR between 1991 and 2000. Darker shades indicate specific areas affected by more than one plume. Plume boundaries were mapped from the air.
Data source: Devlin et al., 2001

Numbers of plumes

1, 2, 3, 4, 5, 6, 7



Herbivorous copepods growing in lagoon waters which are enriched by plume nutrients produce more eggs (a measure of biomass production) than copepods in normal low-nutrient, low-phytoplankton lagoon waters [321]. The zooplankton, in turn, attract larger predators such as larval and juvenile fish which feed on the more concentrated prey [506].

As plumes age and disperse, living plankton and dead organic matter produced by plankton are dispersed through reef and lagoon waters. A significant, but not well-resolved proportion of this organic matter ultimately settles to the lagoon floor, both in the coastal zone beneath the plume and across the continental shelf. Organic matter produced by plankton is a major food source for animals and microbes living in sediments throughout the GBR. Organic matter produced in plumes also settles on reefs and is captured by reef-associated filter and detritus feeders. Although nearshore reefs, experience elevated nutrient concentrations for brief periods when flood plumes wash over them, most of the nutrients they receive have been used and recycled in lagoon waters and sediments. While plumes are prominent symbols of the effect of the land on the sea, they are only the beginning. Terrestrial nutrients may be used and recycled many times by plankton, reef communities and in the benthos before being buried in deeper sediments or flushed into the open Coral Sea.

Gardens of Coral

Brammo Bay has its garden of coral – a border of pretty, quaint and varied growth springing up along the verge of deep water. It is not as it used to be – no less lovely than a flower-garden of the land. Terrestrial storms work as much if not greater havoc in the shallow places of the sea as on land. Pearl-shell divers assert that ordinary "rough weather" is imperceptible at a depth of two fathoms; while ten fathoms are generally accepted as the extreme limit of wave action, however violent the surface commotion. Yet in the shallow sea, within the Barrier Reef in times of storm and stress, not only are groves of marine plants torn and wrenched up, but huge lumps of coral rock are shattered or thrown bodily out of place and piled up on "uproarious beaches."

A storm in March 1903, which did scarcely any damage to vegetation ashore, destroyed most of the fantastic forms which made the coral garden enchanting. In its commotion, too, the sea lost its purity. The sediment and ooze of decades were churned up, and, as the agitation ceased, were precipitated – a brown furry, slimy mud, all over the garden – smothering the industrious polyps to whom all its prettiness was due. Order is being restored, fresh and vigorous shoots sproutting up from the fulvid basis; but it may be many years before the damage is wholly repaired and the original beauty of the garden restored, for the "growth" of coral – the skeletons of the polyps – is methodical and very slow.......(pg. 129)

Banfield, E.J. 1908 The Confessions of a Beachcomber, T. Fisher Unwin Ltd., London.

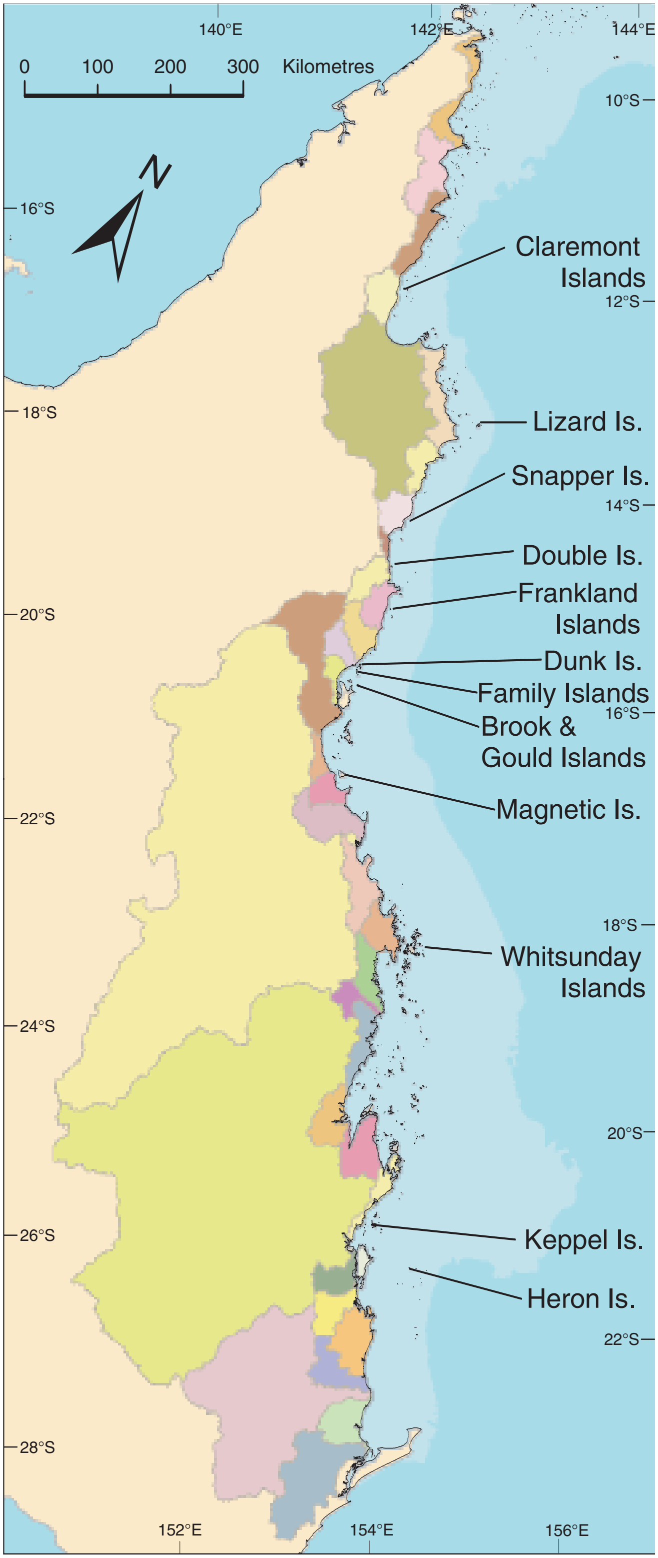
Chapter 10

Ecosystem effects
of increased sediment and nutrient runoff

Freshwater, and the sediment and nutrients carried with it, have always influenced nearshore reef and seagrass communities of the Great Barrier Reef. Disturbances caused by floods and land runoff have shaped the evolution of reef and seagrass communities as sea levels have risen and fallen over geological time [267, 377, 537]. While floods can be disruptive, coastal ecosystems, including coral reefs, use nutrients derived from the land [283, 357]. Rivers are also the major source of the sediments in which mangrove and coastal seagrass communities grow.

Cyclones and floods are a recurrent, if not always predictable feature of the GBR ecosystem [406]. Storm-related disturbances of coral reefs at Dunk Island were recorded prior to extensive land clearance in adjacent catchments [30]. Runoff volumes [223] and rainfall intensity [591] vary over decades to centuries, but it is unlikely that the frequency of flooding has markedly changed in the last 150 years. Year-to-year changes in runoff volume during the last few decades are primarily related to climate variability and weather rather than human activities.

Photo: GBRMPA



Islands or island groups in the GBRWHA with reefs influenced by plumes from regional river systems.

While the frequency of floods has not changed greatly over the last few centuries, modern land-use practices have increased the quantity of sediment and nutrients carried in runoff (Chapter 8). There is now a range of evidence that sediment and nutrient exports from catchments have increased several-fold since 1850 [339, 387, 390]. Apart from industrially produced chemicals based on refined hydrocarbons (fuels, lubricants, paints, solvents, herbicides, insecticides) [182, 192, 193, 540], the elements or materials in modern runoff are the same as those occurring prior to 1850. The changes in exports are of quantity. Modern ecological changes in coastal reefs and benthic habitats have been produced by transient disturbances (cyclones, floods, bleaching, crown-of-thorns starfish) in parallel with less obvious changes in background sedimentation and nutrient availability over longer time frames.

Freshwater inundation, sedimentation and enhanced nutrient availability all affect marine organisms and ecosystems. Their effects often occur simultaneously. To understand how these factors influence ecosystems, it is useful to first consider them separately.

Effects of freshwater

Inundation by freshwater or highly diluted seawater stresses and sometimes kills seagrasses [380], corals [31, 95, 170, 206] and other reef organisms. In the GBR, floods from the 1918 Mackay cyclone killed corals in the Whitsunday Islands and near Bowen[195, 413]. More recently, coral kills due to freshwater have been observed at Magnetic Island (Townsville) following Cyclones Althea and Rona (1971) [94]. The 1991 Fitzroy River flood killed corals in the Keppel Islands [531, 532, 533]. Extensive coral mortality was also observed at Snapper Island (Daintree River) following floods in 1996 [25]. Low salinities, in conjunction with high water temperatures were implicated in coral bleaching during 1994 on nearshore reefs of the central GBR [109].

Redfield Ratios making comparisons

The average chemical compositions of marine phytoplankton and attached algae fall within predictable ranges. The relative abundances of carbon (C), nitrogen (N) and phosphorus (P) in plankton or multicellular marine plants is known as the Redfield ratio after the American oceanographer who discovered this characteristic. To produce biomass containing a given amount of organic C, predictable amounts of bio-available N and P are required as nutrients. Conversely, if a given amount of biomass is broken down and mineralised through respiration, predictable amounts of N and P will be given off as ammonium and phosphate. Redfield ratios can be expressed as relative numbers of atoms (atoms) or by weight (mass).

For marine phytoplankton [419]:

C:N:P (atoms) = 106:16:1
C:N:P (mass) = 41:7:1

For marine macroalgae [24]:

C:N:P (atoms) = 550:30:1
C:N:P (mass) = 213:14:1

In the case of plankton, photosynthetic production of biomass with 106 atoms of carbon requires 16 atoms of nitrogen and one atom of phosphorus. Alternatively, each 41 micrograms (µg) of organic C in phytoplankton biomass is accompanied by 7 µg of N and 1 µg of P. As a general rule, 10 µg of nitrogen (0.7 µmoles N) will produce phytoplankton containing 1.4 µg of phosphorus (0.1 µmoles P) and 1 µg of the photosynthetic pigment chlorophyll a. Macroalgae have a different Redfield ratio because more carbon is needed to produce the multicellular structure of the algal plant. Animals and bacteria have relatively more N and P because they contain more protein than algae

Redfield ratios are useful for estimating quantities of nutrients associated with plankton biomass and ecosystem metabolism. Individual plants or communities often have chemical compositions which deviate from Redfield ratios. This is normal. Understanding why deviations occur provides clues about the physiological state of organisms and their nutrient status. Departures from Redfield ratios are useful indicators of nutrient limitation. Dissolved inorganic nutrient concentrations deviating from Redfield ratios also point to potential nutrient limitation. For example, a DIN: PO_4^{3-} ratio of 4 in lagoon waters means that bio-available nitrogen will be exhausted before phosphorus.

Nearshore coral reef near Princess Charlotte Bay
Photo: K. Fabricius, AIMS

Freshwater kills marine organisms adapted to high salinities through osmotic disruption. Reduced salinities can also stress organisms sufficiently that they die from other causes such as infections. Low salinity appears to reduce survival of coral larvae [426]. Low salinities may cause corals to eject their internal algae (bleaching) [109], leading to death by starvation if the symbiosis is not re-established. During the 1991 Fitzroy River flood, near-surface coral colonies in the Keppel Islands that were exposed to low-salinity water for two or more weeks suffered high mortality [531, 532, 533]. There was non-fatal bleaching of corals in a narrow band below the low-salinity surface layer while colonies at greater depth that remained at near-normal salinities were hardly affected. Mortality varied greatly between coral genera. Exposed colonies of some genera (e.g. *Acropora, Pocillopora*) suffered high mortality, while other genera (e.g. *Goniastrea, Turbinaria*) were much less affected. The dead corals were immediately overgrown by turf algae.

Regardless of the quantity of sediment and nutrients carried in runoff, freshwater in river plumes has always been a factor in the ecology of the GBR. Shallow-water seagrass beds grow near to the mouth of some river systems [273]. These beds are affected nearly every wet season. Living and non-living coral reefs can be found within a few kilometres of rivers. In particular, nearshore reefs bordering the wet tropics are affected by freshwater runoff nearly every year [111, 250]. Coastal reefs adjoining Cape York Peninsula are also influenced by annual monsoonal runoff. Their existence indicates that freshwater inundation at these sites is short or infrequent enough that established reef communities can survive, or at least recover between major floods. In contrast, coastal habitats in the southern GBR may only be affected by one major flood in a decade (Chapter 4). Apart from the Burdekin and Fitzroy Rivers, floods in most rivers are of relatively short duration, although rivers in the wet tropics are more likely to have several floods of varying size in any year and flow to some degree throughout the wet season.

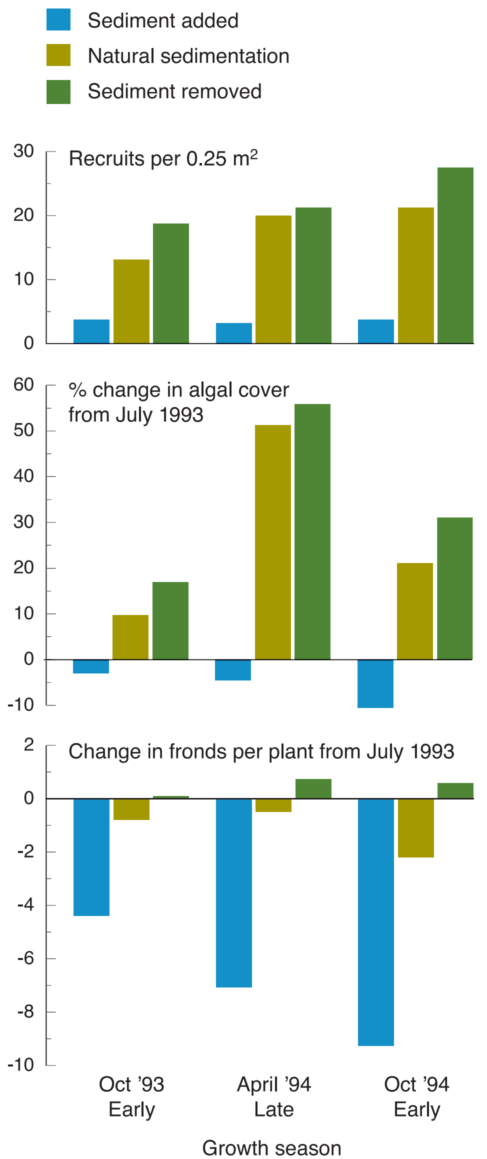
Recovery after a major disturbance can take more than twenty years [31, 514]. It took several decades for coral communities at reefs in the Whitsunday Islands and near Bowen that were killed by freshwater in 1918 to recover [538]. Some reefs (e.g. Stone Island, Bowen; reefs in the southern Whitsunday Islands), however, have endured further kills or disturbances and remain in a degraded state [534, 538].

Effects of sediment in runoff

Virtually all of the sediment carried into the GBR by runoff is initially deposited near a river mouth and stays close to the coast (Chapter 2). Little, if any terrigenous sediment in plumes finds its way to mid- and outer-shelf reefs [266, 362]. When it does, it is only for brief periods. As a result, direct effects of terrestrial sediment are restricted to nearshore coral reef and seagrass habitats. Most of the sediment that affects nearshore reef communities is produced by local resuspension [264, 265, 267]. At coastal sites, wind waves resuspend sediments many times through the year. In contrast, significant resuspension at mid- and offshore reefs only occurs during cyclones [148, 149].

Despite higher soil loss rates from catchments during the last century, there is little evidence of increased sediment accumulation along the coast. If the 11-14 million tonnes of sediment now carried by rivers each year into the GBR were deposited in an even layer within 5 km of the shoreline, annual sediment accumulation would be between 0.5 and 0.7 mm (5-7 cm over the last century). The estimated pre-1850 sediment input of 1-4.4 million tonnes per year would produce an average accumulation of 0.05-0.2 mm per year (0.5-2 cm over the last century). This latter range is similar to the average sediment accumulation rate (< 0.1–0.4 mm per year) at coastal sites between Cape

Relative settlement of coral larvae on the top, bottom and sides of settlement plates exposed to increasing levels of sedimentation. Replotted from Babcock and Davies, 1991



Effects of sediment load on the recruitment, density and growth form of Sargassum microphyllum *plants living on the reef flat at Geoffrey Bay, Magnetic Island. Plants in experimental plots were subjected to enhanced sedimentation (sediment added), natural sedimentation (control) and reduced sedimentation (sediment removed) Top: The mean number of new* S. microphyllum *plants in 0.25 m^2. Middle: Changes in* S. microphyllum *cover relative to cover in July 1993. Bottom: Changes in mean numbers of fronds growing on tagged plants relative to July 1993.*
Replotted from Umar et al., 1998.

Upstart and Halifax Bay which receive the sediment load from the Burdekin River [584]. Sediment accumulation rates of this magnitude cannot be directly measured over short (ca. 50 year) time frames because of sediment mixing by burrowing animals and large sediment movements during storms and cyclones. Indirect measurements using natural and fallout-derived radioisotopes (^{14}C, ^{210}Pb) or geochemical tracers are required to infer modern sediment accumulation rates [148, 540]. These methods work best at sheltered coastal sites with high sediment accumulation rates (e.g. Bowling Green Bay, Hinchinbrook Channel) that are not typical of the general coastal environment.

Terrigenous sediment does not accumulate evenly along the coast. Less than 7% of the current sediment input (ca. 1 million tonnes per year) comes from drainage basins north of Cape Flattery (15°S) which border 36% of the GBR coastline. The Burdekin and Fitzroy River catchments are the largest sediment sources, delivering approximately 42% of the mean annual input. The sediment from the wet tropics and southern dry catchments is deposited along the central and southern GBR coast. Spread over the inner 5 km of the shelf south of Cooktown, this input would produce an accumulation rate of only 1 mm per year. High modern sedimentation rates would only have occurred for a few decades and would be hard to detect due to sediment movement and mixing.

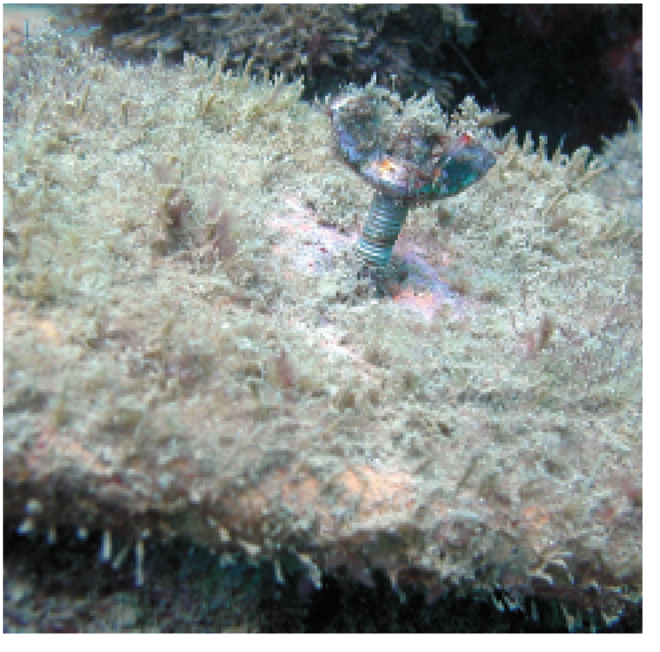
Once sediment reaches the coastal zone, waves and coastal currents continually move the fine sediment northward to traps in sheltered embayments [275, 365]. While plumes of freshwater from the Burdekin River extend as far north as Cairns [581], most of the sediment only goes as far as Bowling Green Bay, just south of Townsville [584].

Wind and waves continually resuspend and re-work nearshore sediments [264]. Unconsolidated silt- and clay-sized sediment particles are most readily resuspended. The extent of resuspension increases as waves become larger relative to water depth. Resuspension is most intense in the nearshore wave zone (depth < 5 m). Under rough conditions [264, 267], waves in shallow water can produce near-bottom suspended particle concentrations exceeding 100 mg L^{-1}. Most of the time, however, near-bottom concentrations of resuspended sediment are much lower (although still higher than at the surface). Seaward of the coastal zone (depths >20 m), larger sand-sized sediment particles are predominantly moved by major storm waves [148, 149]. While rivers are the primary source of coastal sediments, wind-driven resuspension of shallow-water sediments largely determines the turbidity and sedimentation regime that affects nearshore coral reef and seagrass habitats [265].

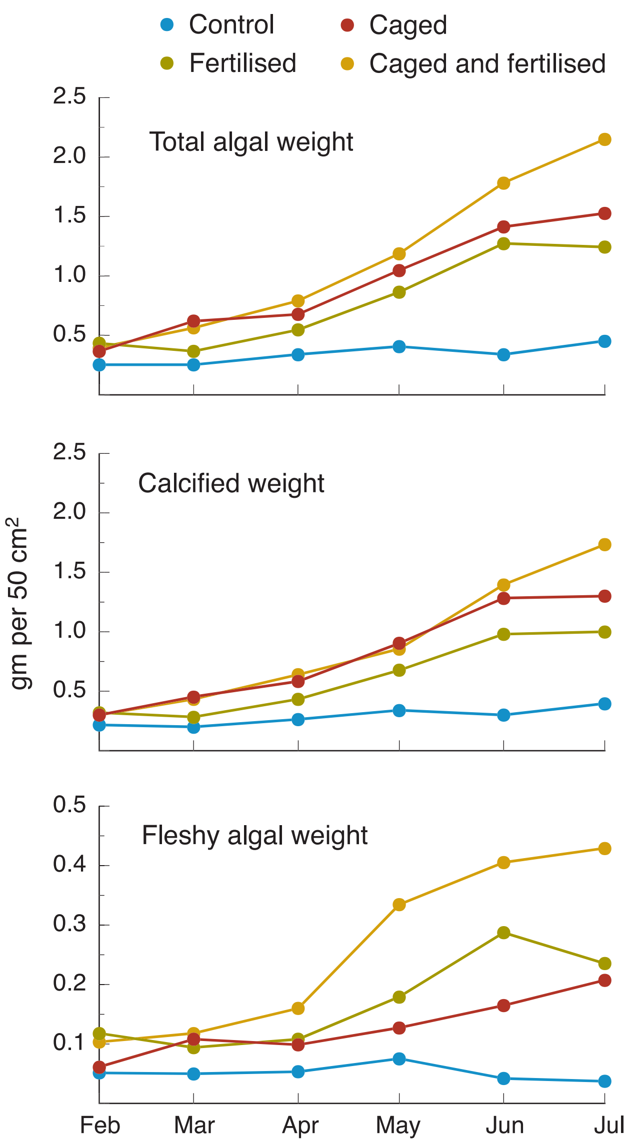
Sediments affect reef organisms and communities in several ways. Suspended particles contribute to water turbidity which reduces light penetration and photosynthesis by seagrasses, benthic algae and algal symbionts in corals [108, 427, 433, 434, 435, 480], cutting their major energy source. Sticky organic matter and rough surfaces on coral polyps, turf algae and epiphytes trap sediment and further reduce the light reaching plants. The viable depth range of coral reefs in turbid waters is strongly influenced by light penetration [203, 255, 289, 323, 480, 512]. Depth ranges of seagrass communities also contract with increasing water turbidity [1, 108]. Light-limited corals grow at slower rates [10], build less reef framework [255] and produce less organic matter for energy storage and reproduction [427, 480]. Distributions and diversity of hard corals, soft corals and coralline algae in nearshore habitats of the GBR are inversely correlated with water turbidity [123, 124, 535].

Corals and other attached animals need extra energy to remove or tolerate sediment [427, 496]. The costs of sedimentation are greater for small or juvenile animals [127] and corals living at greater depths [427]. Corals deal with sedimentation in a variety of ways [479, 480, 481]. Some

Juvenile coral on inshore reef surrounded by sediment-loaded turf algae
Photo: L. Smith, AIMS



Fouling community and sediment on settling tile, Frankland Islands
Photo: L. Smith, AIMS



Effects of nutrient addition and herbivore exclusion (caging) on algal communities developing on settling plates deployed on a Hawaiian fringing reef. Top: Total algal weight. Middle: Calcium carbonate deposited by calcareous algae. Bottom: Weight of decalcified algal tissue.
Replotted from Smith et al., 2001

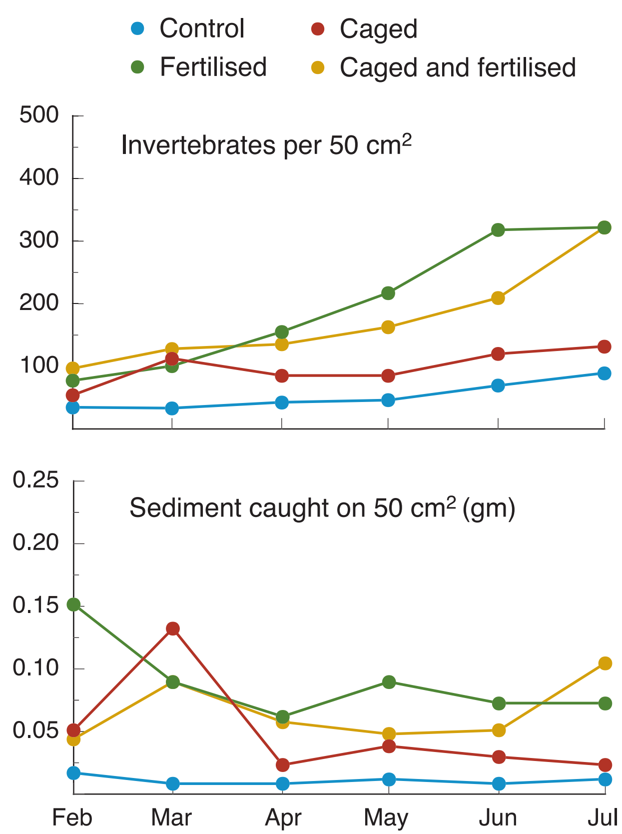
species cope with sedimentation by tolerating light sediment cover and self-cleaning. Other species have colony forms that minimise sediment accumulation. Corals can live in turbid habitats [255, 264] because most fine sediment is continually resuspended and moved by currents and wave-generated turbulence. Fine sediments do not accumulate in high-energy environments. Suspended sediment loads decrease rapidly within a few kilometres of the coast as water depths increase [264]. Coral reefs growing around nearshore islands more than a few kilometres from the coast receive the nutritional benefits of the productive coastal zone, but are less influenced by sedimentation. As a result, nearshore reefs can support well-developed and highly diverse coral communities [537].

Enhanced sedimentation also affects the growth of macroalgae in nearshore reef habitats [526]. Sedimentation in *Sargassum* habitats reduces recruitment of new plants by covering suitable attachment sites or smothering small recruits, and inhibits frond production by established plants. Despite this, macroalgae can be dominant in highly turbid nearshore habitats (e.g. Broad Sound) [255, 316] because corals are affected to a greater degree, or there is reduced grazing on the algae by herbivores.

The greatest impact of enhanced sedimentation comes from the burial or alteration of hard substrate suitable for the attachment and growth of algal spores or animal (e.g. coral) larvae [405]. Sediment covers the surface, fills protective depressions or clogs algal turfs much as sand fills a carpet. Newly-settled coral larvae (ca. 1-2 mm) and microscopic algal germlings (<20 μm) require little space to attach, but they are readily buried and will be less likely to survive if their attachment site is covered by sediment, dislodged by waves or browsed by grazers. Fewer algae and corals successfully recruit as sedimentation increases [27, 28, 162, 201, 214, 526, 572]. Coral larvae preferentially choose attachment sites that are less likely to be covered by sediment, even if those sites are not optimal for their zooxanthellae [27, 28]. Increasing sedimentation or habitat changes that increase the retention of fine sediment will reduce the substrate available for larval recruitment and therefore, rates of habitat recovery after a disturbance.

Although reef kills following burial by sediment are well-documented [202, 252, 265, 301], small amounts of loose sediment do not kill corals or coral reef communities. Shallow-water reefs can recover if the sediment coverage is thin and short-lived [72] However, when combined with loose aggregates of organic matter ("marine snow") [9] that are often abundant in nearshore waters, sediment can have a potent effect on small reef animals. The organic matter binds loose sediment particles and other materials, forming sticky aggregates ("muddy marine snow") [127] that resist the clearing efforts of coral polyps and other small animals. Animals may die if they exhaust themselves trying to remove the attached aggregates. Small sessile animals such as juvenile corals are most vulnerable. Indeed, smothering is likely to be a major natural source of recruit mortality on coastal reefs. The organic matter which forms aggregates in coastal waters comes from a variety of sources, although it is overwhelmingly of marine origin [114, 569]. These sources include the gelatinous houses produced by some zooplankton, coral mucus, and organic remains or excretions of algae, phytoplankton and benthic microorganisms. Much remains to be learned about the production [24, 44], concentrations [125], composition [114] and fate of particulate organic matter in GBR waters, and the nutrients which support its production.

Corals and other reef organisms living in turbid coastal environments can benefit from suspended particles. The organic matter associated with suspended sediment and marine snow provides a low-grade energy and nutrient resource [16, 17, 18, 457, 527, 568]. Some corals living in the



Effects of nutrient addition and herbivore exclusion (caging) on numbers of mobile invertebrates living in (top) and sediment trapped (bottom) by algal communities developing on settling plates deployed on a Hawaiian fringing reef. Replotted from Smith et al., 2001.

Nearshore reef community (Frankland Islands) with healthy corals and older dead corals covered by turf algae
Photo: L. Smith, AIMS

Coral reef in an urbanised embayment of the GBR (Townsville)
Photo: GBRMPA

nearshore environment ingest and utilise this particulate matter [16,17,18]. These nearshore corals are better able to derive nutrition from sediment-associated organic matter than the same species collected at offshore sites [17]. The energy derived from the organic matter in sediment cannot supply the total metabolic needs of the coral. The energy supplement can however, partially offset reductions in the productivity of the coral's algal symbionts due to increased water turbidity [18]. This feeding adaptation may influence which coral species survive or predominate in turbid coastal habitats.

Changes in turbidity and sedimentation in the nearshore environment

Intuitively, one might expect that the modern increase in sediment exports from catchments would lead to greater coastal turbidity and sedimentation, and is therefore a direct threat to nearshore reefs and other habitats [576]. High sediment accumulation rates have been measured in a number of sheltered coastal sites [540, 576, 584]. These sites, however, are not typical of the coastal zone as a whole. Turbidity and sedimentation in most nearshore habitats are largely controlled by wave-driven resuspension of shallow-water sediments [264, 267]. Modern inputs of terrestrial sediment have not significantly increased the amount of fine sediment in most nearshore deposits or its likelihood of resuspension [264, 267, 584]. While modern human land use in catchments adjoining the GBR has increased sediment exports three- to four- fold over the last 150 years, the additional sediment input since 1850 (less than 500 million tonnes) is small relative to the large pre-existing sediment stocks (more than 10,000 million tonnes) in the nearshore zone.

Nearshore coral reefs and seagrass beds have developed over the last 500 years in a naturally high-sedimentation environment. Current levels of turbidity and sedimentation in most coastal areas would not be materially different from what it was pre-1850. The coastal environment is dynamic, changing with floods, storms and particularly, tropical cyclones [149].

Under normal conditions, wave energy and wind-driven currents move fine sediments away from high energy, open coastal settings and deposit them in low-energy, sheltered locations such as mangrove swamps, the lee of islands and in northward-facing bays (e.g. Bowling Green Bay, Cleveland Bay, Rockingham Bay, Trinity Bay, Princess Charlotte Bay) [584]. Modern (post-1850) increases in fine sediment delivery to the coast are therefore unlikely to greatly increase near-bottom turbidity and sedimentation along open sections of the coastline. Much of the modern sediment load is being quickly moved to natural deposition zones. Habitats at greatest risk from increased turbidity and sedimentation (e.g. reefs on Magnetic Island, Dunk Island, Double Island) are located near the edges of these sheltered bays where they are influenced by encroachment or leakage from sediment deposition sites.

At present, there is not enough data about modern (post-1850) regimes of sedimentation and turbidity in GBR waters [264, 267, 576] to clearly identify trends caused by human activities within the natural fluctuations associated with climate, seasonal weather and unpredictable cyclonic storms. Cyclones deliver, resuspend and move enormous volumes of sediment in the coastal and continental shelf environment [148, 149]. In the absence of repeated measurements which demonstrate steadily increasing turbidity or sedimentation, our observations can only provide an index of the natural range of conditions which occur in nearshore waters. If current levels of accelerated soil erosion and fine sediment export to the shelf continue, the amount of fine sediment within the coastal zone will increase. Problems associated with modern increases in fine sediment inputs will take a long time to develop, but an equally long time to disappear.

Effects of nutrients in runoff

Corals, algae and seagrasses require nutrients whether they live in the turbid nearshore zone or in the clear waters of the Coral Sea. The amount, form and availability of nutrients affect water quality, ecosystem productivity and ecosystem structure. Only plants (phytoplankton, benthic microalgae, symbiotic algae, macro-algae, turf algae, seagrasses) and bacteria take up dissolved inorganic nutrients. Animals meet their energy and nutrient needs by consuming organic matter (living or dead) produced by other organisms. Some important reef animals (e.g. sponges, corals, giant clams) obtain a significant portion of their organic and energy needs through symbiotic relationships with algae and bacteria. Here, the symbionts take up inorganic nutrients and produce organic matter for their hosts.

Regardless of location, coral reefs in the GBR exist in an environment that is normally characterised by low concentrations (µg L^{-1}) of bio-available dissolved nutrients (NH_4^+, NO_3^-, PO_4^{3-}, trace metals). There are small and persistent regional variations in average concentrations through the GBR (Chapter 2) [144], but nutrient concentrations in GBR waters are usually at the low end of the ranges found in the ocean. Reef and benthic ecosystems of the GBR have evolved to live in this low-nutrient environment.

Low nutrient concentrations do not necessarily mean low nutrient availability. The ecosystems of the GBR receive frequent inputs of nutrients from several external sources (e.g. terrestrial runoff, Coral Sea upwelling, sediment resuspension, rainfall) [85, 111, 129, 143, 146, 525, 541]. On a day-to-day basis, however, most of the nutrients used by bacteria, plants and animals within the GBR come from decomposition and recycling of living and non-living organic matter. In the warm (20-30°C) waters of the GBR, mineralisation of organic matter can be very rapid. The currents which move and mix water on the continental shelf also carry large quantities of nutrients at low concentrations over and through reef ecosystems [15, 20, 573, 578]. Bio-available dissolved inorganic nutrients remain at low concentrations because phytoplankton, algae and bacteria rapidly use them [147].

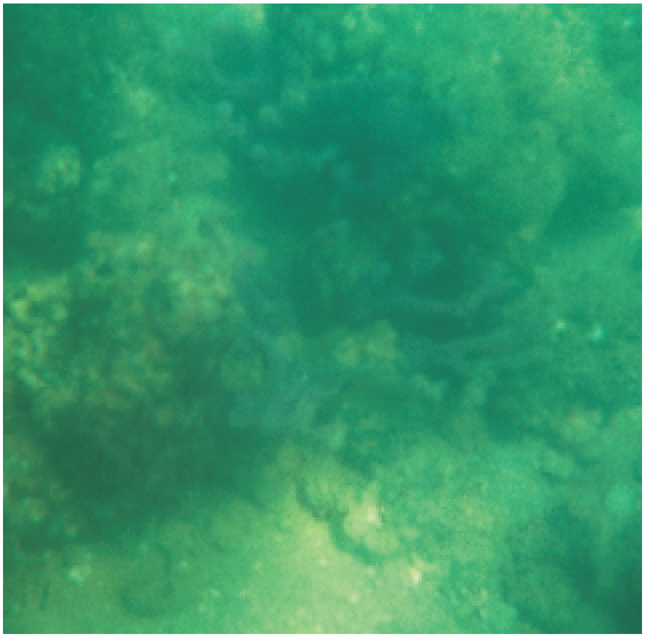
As a result, dissolved organic and particulate nutrients are usually the principal forms in GBR waters. When there are increases in inorganic nutrient concentrations, it is because short-lived disturbances (e.g. floods) have created temporary imbalances between supply and demand.

Changes in reef systems caused by eutrophication – extreme cases

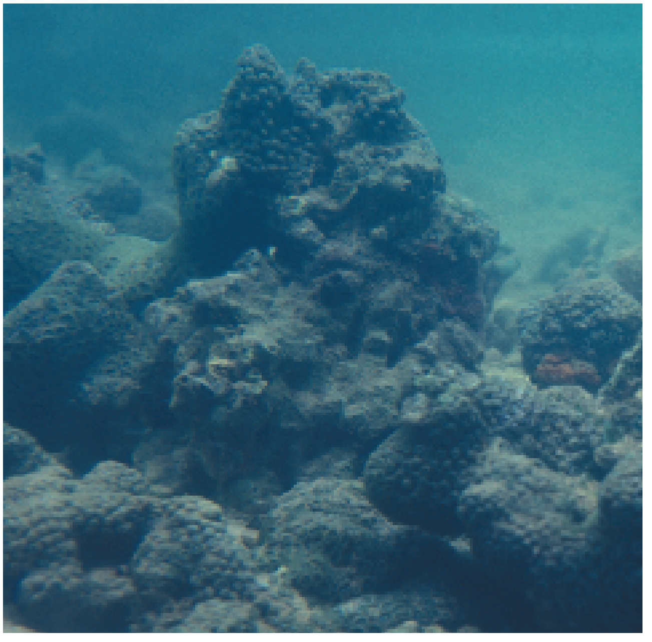
There is clear evidence that eutrophication caused by large inputs of organic material or nutrients change or degrade coral reef ecosystems. The GBR is fortunate. The most dramatic examples of degradation occur at locations outside of Australia. Kaneohe Bay, Hawaii provides the best-documented case. Here, localised eutrophication caused by sewage discharge profoundly altered a nearshore reef ecosystem [32, 215, 477]. Examples of reef ecosystem changes or degradation associated with eutrophication have also been documented in Indonesia [121, 512], elsewhere in Hawaii [92, 176], Hong Kong [203, 338] and Barbados [214, 507-511, 572], among others [120, 372]. At present, extreme cases of eutrophication have not occurred in the GBR, though it has been argued that some degree of eutrophication has occurred [35, 36, 37].

Kaneohe Bay is a small (ca. 31 km^2, 0.26 km^3) embayment on the northeast side of Oahu Island, Hawaii. In the 1950s, sewage outfalls were constructed to discharge treated sewage into the bay from a growing population in the adjoining catchment. By the 1970s, the outfalls were discharging approximately 0.5 tonnes of nitrogen and 0.13 tonnes of phosphorus daily [477]. These nutrients supported a dense and persistent plankton bloom in the semi-enclosed southern end of the bay. After coral kills caused by extreme freshwater runoff and sedimentation [31, 206], reefs near the outfalls were covered by macro-algal mats and filter feeders which fed on the dense plankton. Boring organisms destroyed a significant portion of the carbonate reef structure near the outfalls.

Undisturbed Hawaiian coral reef dominated by Porites compressa. Communities of this type typified the reefs in Kaneohe Bay prior to sewage inputs
Photo: D. Kinsey



Heavily bio-eroded reef substrate in SE Kaneohe Bay after 20 years of sewage inputs (late 1970s). The green tint comes from the thick phytoplankton population growing in the bay
Photo: D. Kinsey



Heavily bio-eroded reef substrate in SE Kaneohe Bay covered by filter-feeding zooanthids (late 1970s). Filter-feeders and macroalgae covered the remaining reef substrate, preventing hard corals from re-establishing.
Photo: D. Kinsey

Hard corals (1985) re-established on degraded reef substrate in Kaneohe Bay after the offshore diversion of the sewage outfall.
Photo: D. Kinsey

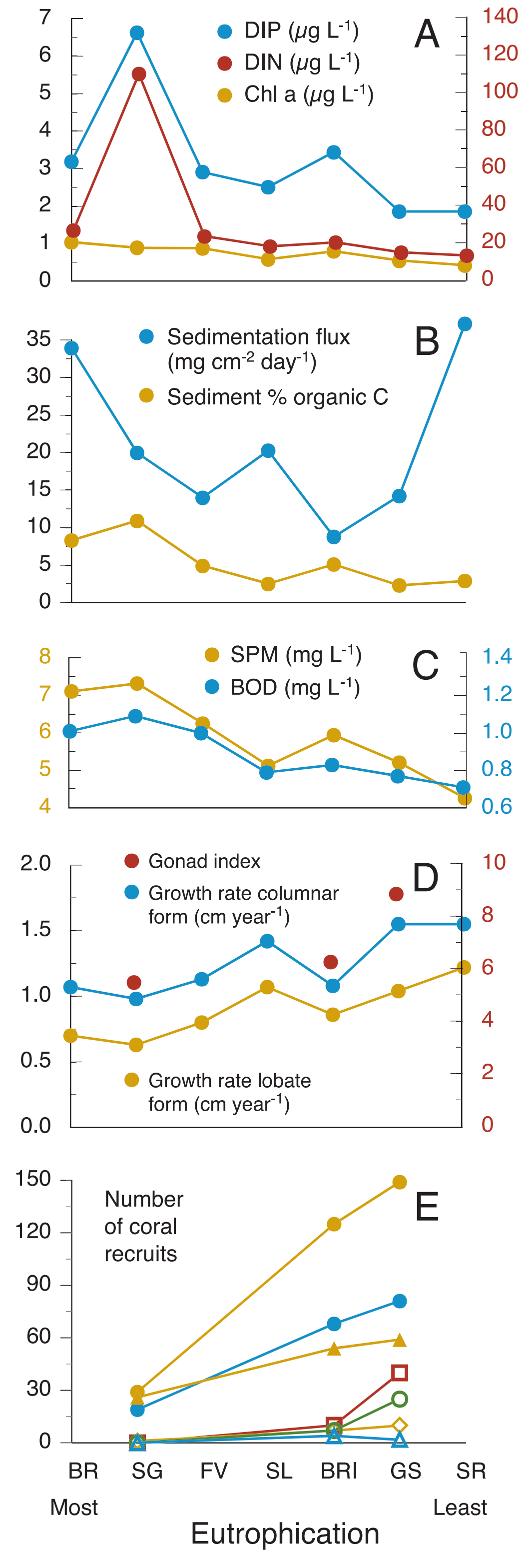
The nutrients in the sewage did not directly kill the corals. Rather, hard corals could not re-colonise disturbed reefs after the freshwater kills due to algal overgrowth, competition for space with plankton feeders and loss of suitable substrate as the reef structure crumbled. Reefs at greater distances from the outfalls had a normal reef structure, but supported elevated populations of algae, filter feeders and detritus feeders living on recycled nutrients and the dispersed plankton bloom.

In the late 1970s, the sewage was diverted to an offshore outfall, cutting off the largest nutrient source to the bay. The plankton bloom ended. Dense populations of macroalgae persisted in the bay as nutrients and organic matter stored in bay sediments were mineralised [477, 486]. Herbivore grazing, largely by fish, strongly influenced the dominance and species composition of the remnant space-occupying macroalgae [485]. As the nutrients stored in bay sediments ran down, water quality improved and hard corals began to re-establish on the remaining substrate, starting the process of reef regeneration. Since the early 1980s the recovery process has been interrupted several times by new disturbances. Water quality has again deteriorated due to additional nutrient inputs from the ever-growing urban population in the surrounding catchment [215]. As a result, some reefs in Kaneohe Bay have not fully recovered.

Eutrophication-induced changes to reefs in Barbados are a second instructive example [214, 507-511, 572]. Here, nutrients and organic wastes from a localised urban-industrial source are transported along the west side of the island by coastal currents. Measurements of water quality, reef community structure, coral growth and coral recruitment were made on coastal reefs downcurrent from the pollution source. Average nutrient concentrations decreased with distance from the source, as did concentrations of suspended particulate matter and organic matter. The coral communities at sites closer to the pollution source had fewer species, while

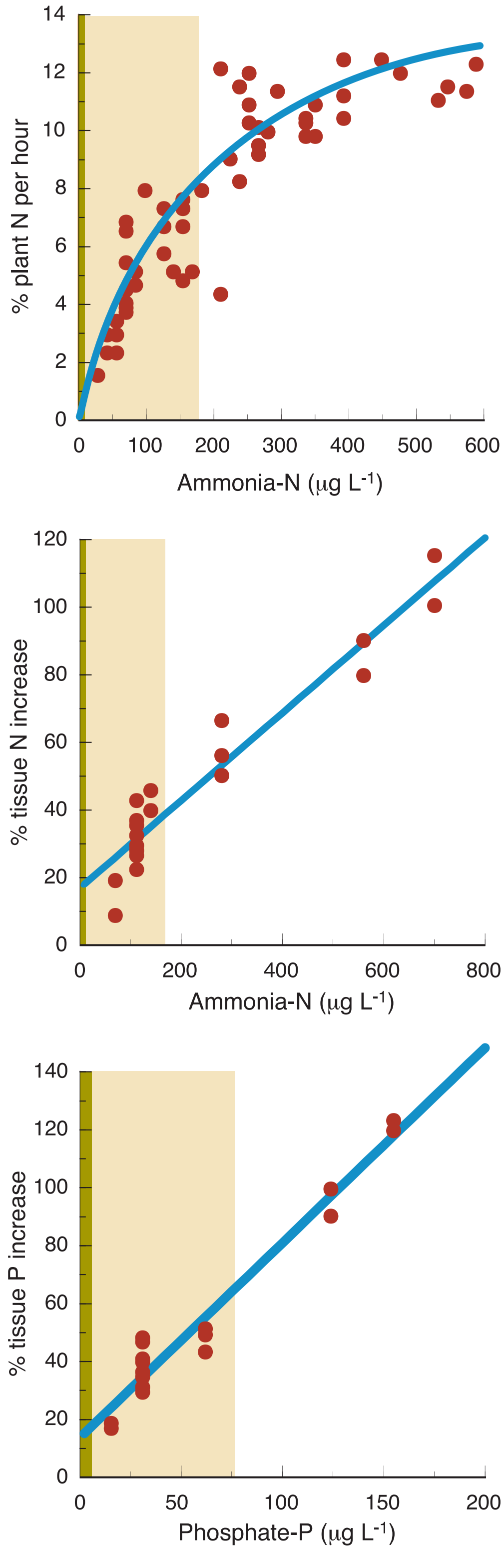
Growth and reproductive responses of corals on Barbados fringing reefs growing in a longshore water quality gradient. Data replotted from Tomascik and Sander, 1985, 1987; Tomascik, 1990, 1991a,b.

A. Concentrations of DIN, DIP and chlorophyll a in surface waters.
B. The organic carbon content of sediment at study reef sites and the average annual sedimentation flux measured with sediment traps.
C. Surface water concentrations of suspended particulate matter (SPM) and the biological oxygen demand (BOD) of organic matter in the water.
D. Growth rates (skeletal extension) of two growth forms of the coral Monastrea annularis *and the average gonadal index (number of male and female gonads per 0.25 cm^2 of coral tissue) for colonies of the coral* Porites porites.
E. Numbers of coral recruits from seven species collected on terra cotta settling plates.



abundances of fleshy macroalgae increased. Coral growth rates, reproductive potential, larval settlement and juvenile survival increased with distance from the pollution source. Concentrations of suspended organic matter, rather than dissolved nutrients were most closely (negative) correlated with measures of reef health and performance.

These examples indicate that eutrophication primarily affects coral reefs through ecosystem responses to organic enrichment. Corals and other animals primarily respond to enhanced organic matter availability rather than elevated nutrient concentrations. At the concentrations found in Kaneohe Bay or in GBR flood plumes, inorganic nutrients are not directly harmful to corals or other reef organisms [489]. Corals and coral reefs can grow in places which naturally experience elevated concentrations of inorganic nutrients [164-167, 187, 476]. At some of these locations (e.g. Canton Atoll, Central Pacific), elevated nitrate and phosphate concentrations are probably due to growth limitation of phytoplankton in surrounding waters by shortages of other nutrient elements (e.g. iron). In the GBR, high inorganic nitrogen concentrations regularly occur in One Tree Island lagoon [187] because of rapid microbial mineralisation processes in a largely enclosed system. Coral reefs grow in upwelling



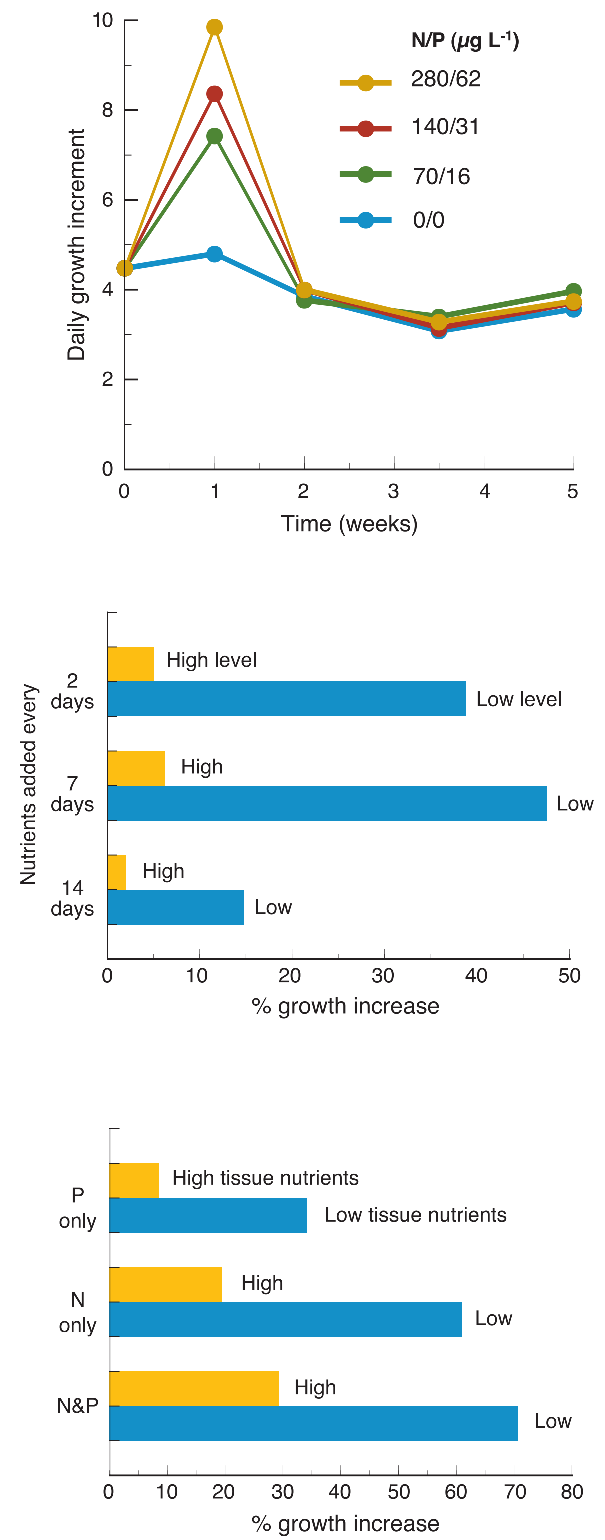
Responses of the macroalga Sargassum baccularia *to enhanced nutrient availability. Top: Ammonium (NH_4^+) uptake by* S. baccularia *in relation to the concentration in surrounding waters. Mid: Relative increases in the tissue nitrogen content of* S. bacillarium *shoots exposed to elevated NH_4^+ for 24 hours. Bottom: Relative increases in tissue phosphorus of S. baccularia shoots exposed to elevated PO_4^{3-} concentrations for 24 hours. The light coloured band in each plot indicates the range of NH_4^+ or PO_4^{3-} concentrations observed in GBR flood plumes. The dark shaded band in each plot indicates the normal range of NH_4^+ or PO_4^{3-} concentrations in central GBR coastal waters. Algal data replotted from Schaffelke and Klumpp, 1998.*

areas (Gulf of Panama, Oman, Bali) where there are large seasonal or daily changes in nutrient inputs, phytoplankton production and water temperatures. Likewise, corals can grow near significant urban sources of nutrients which are not large or are well-dispersed [203].

Where reef degradation has been associated with eutrophication, the ecosystem has been primarily affected by organic enrichment [92], or the elevated local production of organic matter by algae [477]. Reef systems have recovered when the direct or indirect source of organic enrichment was greatly reduced [477]. In the GBR, nutrient-stimulated primary production by phytoplankton is likely to be a major source of the organic matter in reef waters. Because the GBR is a large and open ecosystem, the degree of persistent organic enrichment will be small and the changes often difficult to detect.

Reef responses to low-level nutrient inputs – the Great Barrier Reef situation

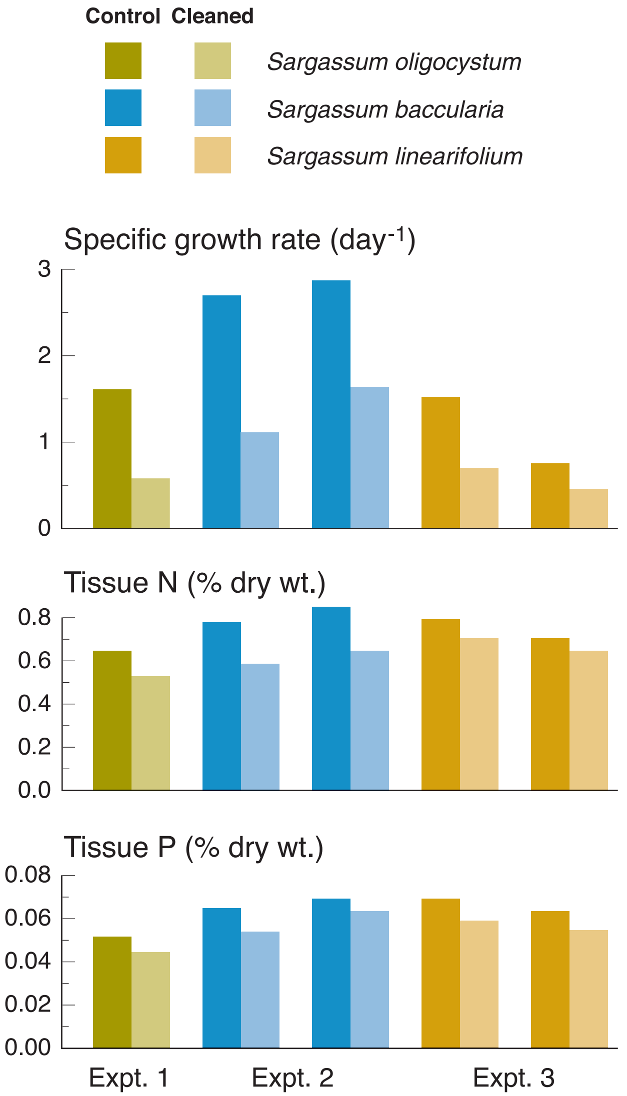
Corals and coral reefs in the Great Barrier Reef are fundamentally no different from corals and reefs in other parts of the world. They will respond to high levels of sedimentation and eutrophication in a similar manner. However, care must be taken when extrapolating extreme examples of the eutrophication-related degradation seen in Kaneohe Bay and Barbados to the GBR. These overseas examples are clear and well documented because they are



Growth responses of the macroalga Sargassum baccularia *to nutrient enrichment. Top: Growth rate of* S. baccularia *shoots after a 24 hr exposure to elevated NH_4^+ and PO_4^{3-} concentrations. Mid: Growth enhancement in* S. baccularia *shoots after short (1 hr) exposures to high (140 µg NH_4^+-N, 30 µg PO_4^{3-}-P) and low (42 µg NH_4^+-N, 9 µg PO_4^{3-}-P) nutrient levels at different intervals. Bottom: Growth enhancement of* S. baccularia *shoots with high and low tissue nutrient levels after short (1 hr) exposures to elevated N (280 µg NH_4^+-N) and P (62 µg PO_4^{3-}-P). Replotted from Schaffelke and Klumpp, 1998.*

extreme. They clearly show that excess organic or nutrient loading can cause degradation of reef ecosystems. The much larger size of the GBR, the open coastal zone and the episodic nature of terrestrial runoff mean that development of eutrophic conditions is unlikely. Instead, elevated nutrient inputs will affect coastal ecosystems slowly as they respond to persistent, low-level enrichment from mineralised nutrients released from sediments, detritus and biomass. Effects are only likely to become evident after disturbances. Reef and plankton communities in the GBR only experience elevated nutrients during infrequent and short-lived upwelling, runoff and cyclonic resuspension events. Only fast-growing plankton and turf-algal communities can change significantly during or immediately after these events. Over the long term, changes in coastal and nearshore reef ecosystems will come from the overall level of coastal nutrient loading rather than as direct responses to elevated nutrient concentrations in river plumes. Some of these nutrients will be immediately active (e.g. NH_4^+, NO_3^-, PO_4^{3-}) and others (e.g. sediment-bound nitrogen) will only gradually enter the ecosystem food webs through mineralisation and recycling.

After floods or other disturbances, algae and bacteria rapidly take up the bio-available inorganic nutrients (NH_4^+, NO_3^-, PO_4^{3-}) in plume waters [111, 140]. Nutrient concentrations in the water fall rapidly as nutrients are incorporated into phytoplankton and sediments, or dispersed by currents. Over a longer period (months), nutrients in coastal sediments, detritus and biomass are recycled to bio-available forms



Benefits gained by macroalgae living on nearshore reefs from the nutrients (N, P) in suspended particulate matter that settles on algal plants. Top: Effect of sediment removal (cleaned treatment) on mean growth rates of three Sargassum *species on the reef at Little Cannon Bay, Great Palm Island. Middle: Concurrent differences in tissue nitrogen levels of plants of three* Sargassum *species with and without removal of settling particulate matter. Bottom: Concurrent differences in tissue nitrogen levels of plants of three* Sargassum *species with and without removal of settling particulate matter. Replotted from Schaffelke, 1999a.*

(e.g. NH_4^+, PO_4^{3-}). These mineralised nutrients sustain a low level of coastal enrichment and the slightly higher levels of nutrients measured in coastal waters (Chapter 2). The degree of enrichment and its persistence depends on the size of the input. The after-effects of a massive flood from the Burdekin River (e.g. 1991) will be greater and last longer than those from a smaller flood from the Tully River. The persistent flow and frequent floods in the wet-tropical rivers, however, maintain an ongoing nutrient enrichment in the local nearshore region. The continual supply of nutrients allows phytoplankton and algae in coastal ecosystems to maintain higher levels of production and growth. Small increases in mean dissolved inorganic nitrogen and phosphorus concentrations on the order of 1 µg L^{-1} (0.07 and 0.03 µmol L^{-1}, respectively) are sufficient to sustain phytoplankton growth rates at near-maximal levels [102, 141].

Responses of plankton and reef communities to nutrient enrichment

Nutrient availability has less to do with nutrient concentration than the quantity of nutrients which are being actively cycled in the ecosystem. Tropical algae, including symbionts in corals and other reef animals, have structural and physiological characteristics which help them extract nutrients from low-nutrient waters [20, 21, 168, 307, 385, 457]. In the plankton, nutrient demand almost always exceeds supply [147]. Benthic algae also show signs of nutrient limitation [458, 459, 461, 462, 463].

Phytoplankton efficiently assimilate dissolved nutrients at very low concentrations (< 0.5 µg N L^{-1}) [168, 307]. Many phytoplankton species can maintain near-maximal growth rates (one to four population doublings per day) at these low, natural nutrient concentrations [102, 141]. Because of their ubiquitous distribution, high affinity for nutrients and rapid growth rates, phytoplankton are the primary consumers of the nutrients delivered to the GBR in runoff. Virtually all of the nutrients in river plumes are quickly taken up and converted into phytoplankton biomass. Measures of phytoplankton biomass, therefore, usually provide a better index of the nutrient status of reef waters than dissolved nutrient concentrations. Chlorophyll *a* is the most commonly used measure of phytoplankton biomass. Despite taking up most of the dissolved nutrients, however, phytoplankton usually comprise only a minor part of the organic matter in GBR waters. Most is detritus. While chlorophyll *a* is generally a good predictor of phytoplankton biomass and nutrient availability, it is a poor predictor of total particulate organic matter in reef waters.

Tropical macroalgae also take up dissolved nutrients at low concentrations, although not with the affinity shown by phytoplankton. Frondose and turf-forming algae only have direct contact with nutrients in the thin turbulent layer near the bottom, but they have first access to nutrients mineralised by microbial populations in sediments and turf algal mats. Benthic algae can achieve only a fraction of their uptake potential at the nutrient concentrations normally occurring in GBR coastal waters. This inefficient uptake, however, is still much faster than plant growth. Macro-algal growth rates depend more on nutrients stored in plant tissues than nutrient concentrations in surrounding waters. Growth will only be limited by dissolved nutrient concentrations when plant growth exceeds uptake rates.

The ability of macroalgae to rapidly take up and store nutrients allows them to take advantage of the extra nutrients present in the water during small, but frequent disturbance events. Macro-algae can take up and store nutrients for future growth in the brief intervals when higher concentrations of nutrients occur during resuspension events [85, 543], river plumes [111] or when other environmental factors such as low light levels (turbid waters) slow growth rate. For example, *Sargassum* plants on coastal reefs have higher nutrient levels in their tissues and grow faster when additional nutrients are supplied in brief

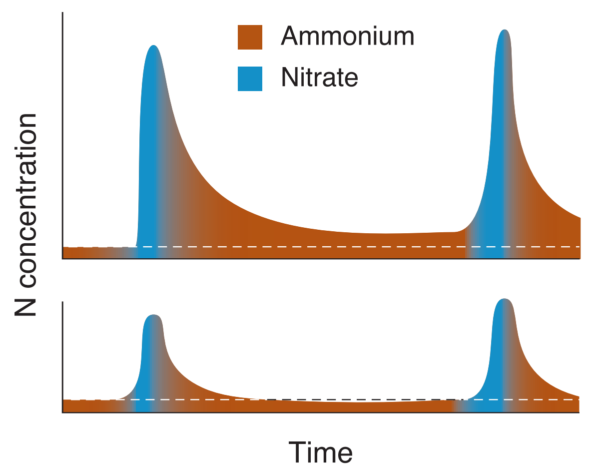


Illustration of the relative abundance and persistence of bio-available nitrogen in nearshore waters following large (top) and small floods (bottom). After a large flood, nitrate in river plume water (blue) is rapidly taken up and replaced by ammonium and dissolved organic nitrogen (brown) produced through mineralisation. Continual mineralisation of large stocks of flood nitrogen stored in sediment and biomass after a major flood keeps nearshore concentrations above the pre-flood level (dotted line) until the next flood. Following a small flood, nitrogen concentrations quickly decline to pre-flood levels.

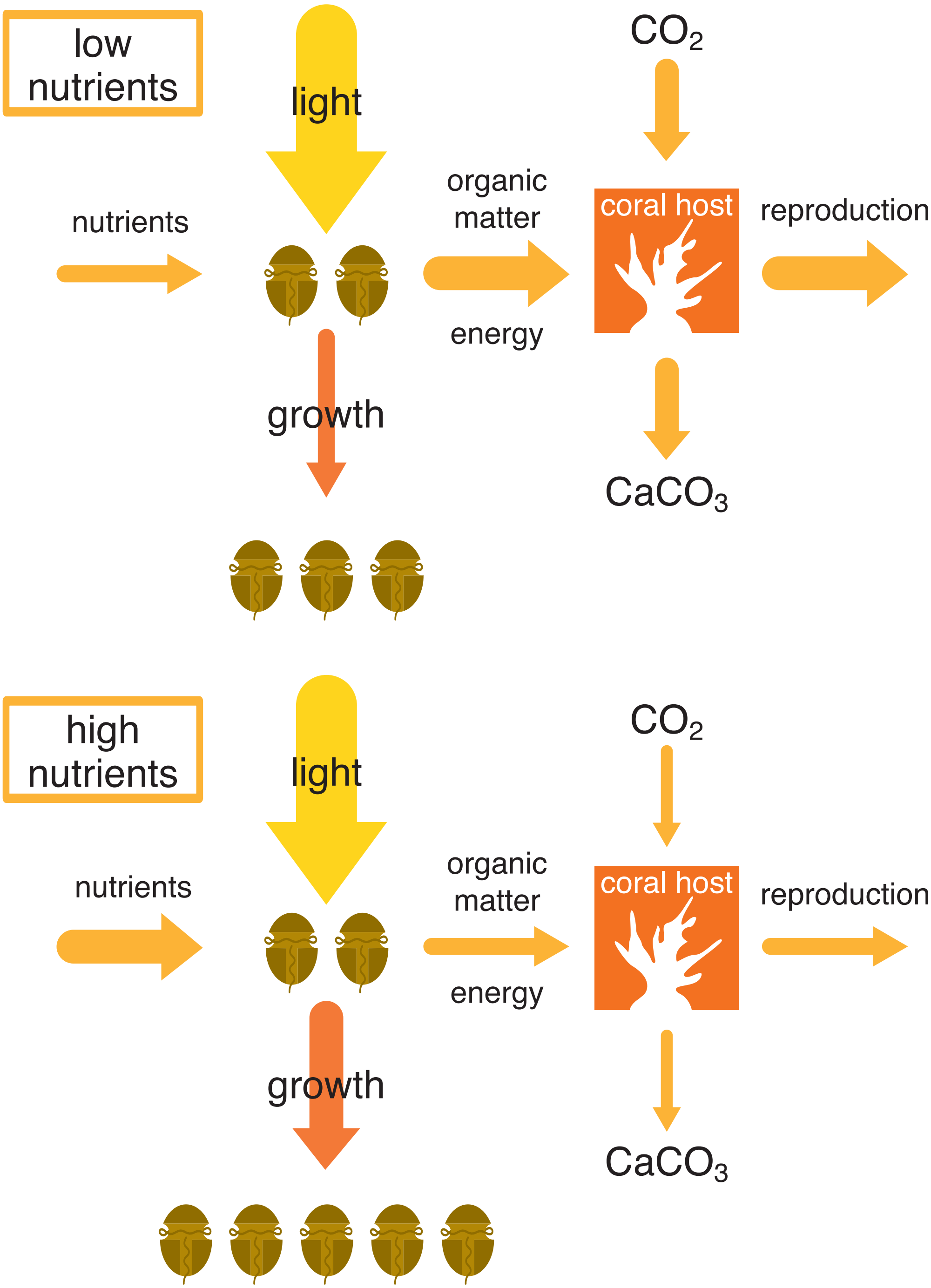


Illustration of how increased nutrient availability can change the relationship between coral hosts and their micro-algal symbionts. Top: Under "normal" low-nutrient conditions, symbionts photosynthesise and produce organic matter in excess of their capacity to assimilate nutrients. The excess organic matter is excreted by the algal cells and used by the coral host for growth, calcification and reproduction. Bottom: With greater nutrient availability, the algal symbionts preferentially retain organic matter produced by photosynthesis for their own growth, reducing transfers to the coral host and limiting the coral's potential for growth and reproduction.

pulses [458, 463]. The extent of growth enhancement for both juvenile and mature algae is directly related to the duration and frequency of exposure to enhanced nutrient concentrations [458, 462]. Nutrient-starved plants, not surprisingly, show a greater response to pulses of enhanced nutrients than nutrient-replete plants.

Like corals, benthic algae can use some of the organic nutrients in marine snow and suspended particles [457]. Many types of macroalgae have shapes or features which trap nutrient-rich organic particles. For example, fine hairs on the surface of *Sargassum* plants catch small particles of “muddy marine snow” [127]. As bacteria and protozoa decompose the organic matter in the particles, nitrogen and phosphorus are released near the plant surface where it is taken up. *Sargassum* plants carrying enhanced sediment and organic particle loads have a higher tissue nutrient levels and grow faster than plants from which particles have been removed [457]. Algal turfs also trap sediment and organic particles [405]. Nutrient mineralisation rates are enhanced in these turfs. Like *Sargassum*, the turf-forming algae have first access to the newly mineralised nutrients.

Elevated nutrient concentrations (usually ammonium, nitrate or phosphate) can affect corals in a number of ways [489]. These responses include changes in the density of algal symbionts [120], the biochemical composition of the corals [304, 482], skeletal growth rates (both positive and negative) [130], calcification [303] and reproductive potential [507].

As with field observations of reefs in eutrophied ecosystems, experimental tests of direct nutrient effects on corals need to be interpreted carefully. Most experiments testing nutrient effects are only run for short periods and use nutrient additions which greatly exceed levels that occur in nature. Important ecosystem properties such as pH or alkalinity (which regulate calcification) are often unreported or not controlled. In most cases, the observed effects of experimental nutrient additions suggest that the algal symbionts in the corals change their composition and growth at the expense of the organic matter and energy normally supplied to the coral host. The long-term ecological implications of these often-subtle re-distributions of organic matter and energy away from coral growth and reproduction have not been explored.

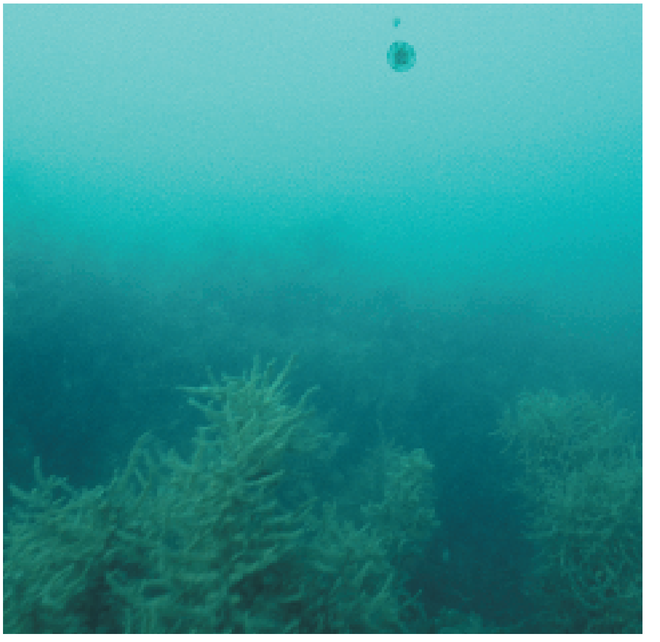
Corals and algae on nearshore reefs

Dense stands of macro-algae are commonly observed on nearshore reefs in the Great Barrier Reef, usually during the early summer. Algal-covered reefs in turbid coastal waters present a strong visual contrast to clear-water offshore reefs that are dominated by hard corals. Macroalgae are an integral, if not always apparent part of natural reef communities. Algal dominance is one of many states that reefs can pass through [115, 313]. Because macro-algae are often conspicuous at eutrophied sites [120, 372], algae were thought to have a competitive advantage over corals in high-nutrient habitats. However, interactions between corals and algae are more complex [116, 211, 234]. Many factors influence the real or apparent dominance of algae on reefs [211, 315]. Elevated nutrient availability is just one of these factors.

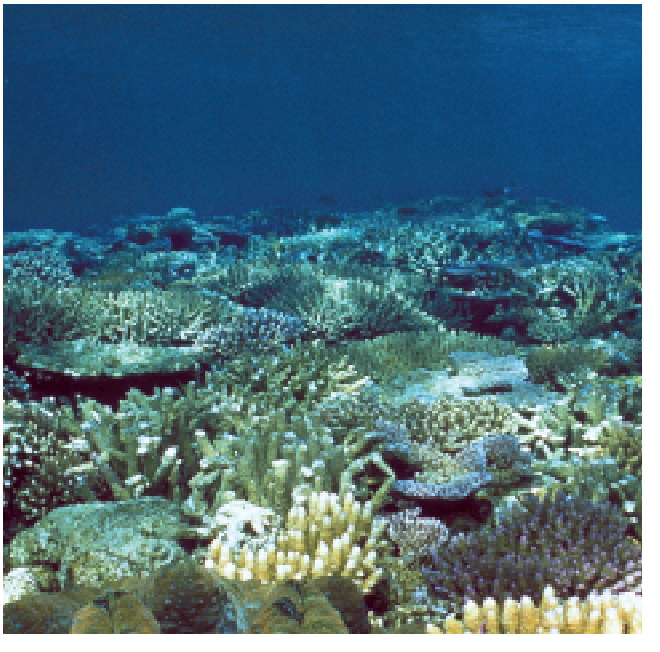
There are two major hypotheses to explain controls on algal dominance in coral reef ecosystems and the relative importance of enhanced nutrient availability and herbivore grazing. The "nutrient threshold hypothesis" [262, 263] states that when nutrient inputs (or availability) to a reef system exceed a critical level for that location, fast-growing macro-algae will take advantage of these nutrients and eventually dominate the system by smothering corals and monopolising space that would otherwise be available for corals to grow on. The alternative, "grazer control hypothesis" [210, 212, 312, 488] is that significant macro-algal populations only develop and persist when grazing, especially by herbivorous fish, is greatly reduced. To some extent, both mechanisms may operate [263]. Experiments in the GBR [312, 442] and elsewhere [308, 309, 475] show that macroalgal and turf algal biomass typically increases when fish grazers are excluded. The increases occur over a range of ambient nutrient levels. Algal and coral communities go through major changes when grazing pressure collapses [210]. Nutrient stimulation of algal biomass production is only clearly seen when herbivores are absent or excluded, so that ungrazed biomass can accumulate [442, 475].

Herbivorous fish are major consumers of algae in many reef ecosystems [191, 561]. As a result, there are often inverse correlations between biomass of macroalgae on coral reefs and herbivorous fish abundance [560]. When herbivores are abundant, all accessible surfaces are cropped, sometimes on a daily basis [191]. Even when herbivores are not obviously abundant, there may be enough to consume small or transient increases in algal biomass [442]. In some situations, however, algal populations can escape strong grazing control when their biomass exceeds the demand by local grazers (more algae, or fewer fish and invertebrates), when particular algal species are less palatable than alternatives, or algae grow in habitats that are inaccessible to or avoided by grazers (shallow reef flats).

The ability of herbivores to control algal cover largely depends on the balance between herbivore numbers (or biomass) and the extent of algal cover [561]. Abundant herbivores can graze algal cover down to very low levels, even when algal production is nutrient-stimulated [188, 442]. Where algal productivity is low or algal area is restricted, smaller numbers of herbivores can consume the production. Algal "blooms" occur when local production outstrips consumption. Experimental manipulations of "coral cover" show that there are limits to what herbivorous fish at one location can consume. Beyond that threshold, algal production exceeds consumption, so that algal biomass can increase [561]. The abundance of herbivorous fish and the extent of algal cover at a site can vary for many reasons. Disturbances such as cyclones, bleaching



Sargassum dominated nearshore reef
Photo: L. McCook, AIMS



Coral dominated offshore reef
Photo: D. Wachenfeld, GBRMPA

Four of many types of herbivorous fish found on the GBR. Top: Siganus doliatus*; Middle:* Scarus globiceps *and* Ctenochaetus striatus*; Bottom:* Paracanthurus hepatus*. Photos: AIMS*

or crown-of-thorns starfish can create large areas of open space (including dead coral) for algal colonisation. Cyclones can also kill or displace herbivorous fish, or destroy the three-dimensional reef structure that allows fish to hide from predators.

Major algal blooms on several Caribbean reef systems were preceeded by decimation of invertebrate grazers (chiefly sea urchins) through disease, or by removal of herbivorous fish by over-fishing [210]. In the GBR, other factors must apply. Sea urchins are not significant herbivores on nearshore reefs and there is essentially no fishing for herbivorous reef fish. Nearshore reefs in the GBR naturally have fewer herbivorous fish than offshore reefs [441]. Natural abundance and recruitment cycles of herbivorous fish on these nearshore reefs and the effect of major disturbances on fish are not well understood. It is likely that the balance between algal production and consumption on nearshore reefs is tenuous and more susceptible to disruption.

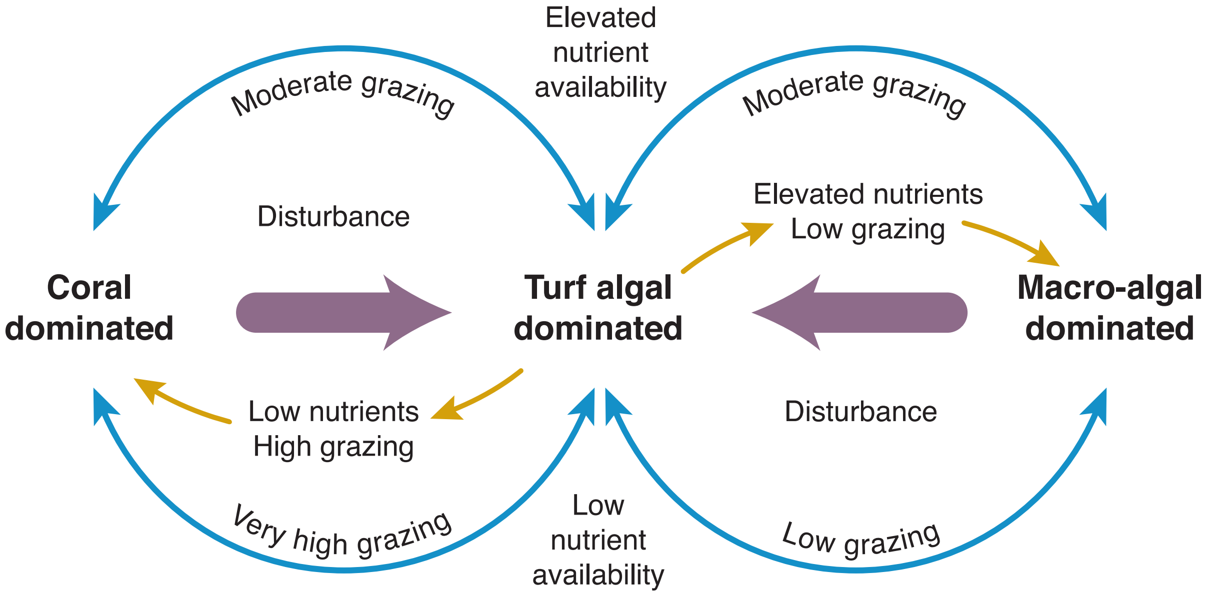
Changing the pathways of recovery

Disturbance and recovery are a natural part of the ecology of coral reefs, regardless of their location. All reefs or parts of reefs are disturbed at one time or another. There can be many types of disturbance and they may have a number of causes: burial by sediment, pathogens, cyclones, freshwater inundation, bleaching, grazing or crown-of-thorns starfish outbreaks. In some cases, it is relatively easy to recognise the disturbance and its effect. Often, however, the degree of disturbance and when it occurred is difficult to determine.

Disturbances affect reefs at many scales (cm^2 to km^2) depending on the cause (fish bite to cyclone) and alter the physical structure of the reef or species composition of reef communities to varying degrees. At one extreme, cyclones may disrupt an entire reef or group of reefs. The disturbance is readily apparent because living corals are smashed or dislodged. Alternatively only a portion of a reef may be affected by small, low-level disturbances that leave dead coral skeletons standing (e.g. crown-of-thorns starfish, bleaching) and only some corals, a single species or small number of species may be affected. The disturbance may not be apparent until the affected area exceeds a threshold, a conspicuous species disappears or another event finally affects the remaining corals.

In open, low-nutrient ecosystems such as the GBR, changes in water quality due to runoff alter natural disturbance-recovery processes by influencing the rates and pathways of recovery from disturbance. Depending on the extent and nature of the disturbed community and degree of disturbance, recovery can take days (turf algae) to decades (massive corals). Turf algae are fast-growing pioneers, quickly colonising and covering bare surfaces. The growth of turf algae is regulated by temperature, light and nutrients. Standing turf biomass is largely determined by grazing pressure [442, 475]. During a "normal" recovery from disturbance on an offshore reef, pioneer turfs are eventually cleared and displaced by slower-growing coralline algae and hard corals. Hard corals re-establish from settlement of planktonic larvae and fragments of broken or partially dead corals. Coral larvae need to settle and attach to a solid surface. When turfs cover the hard surfaces, they block or slow recruitment. Newly settled coral larvae (1–5 mm in diameter) face an uncertain future [450]. They can be smothered by algae, eaten by predators and indiscriminate algal browsers, or be overgrown by surface encrusting filter feeders (e.g. broyzoans). As with most sessile marine organisms, few coral larvae and juveniles survive.

The usual view of a healthy coral reef remains one of living hard corals covering much of the reef surface. Perceptions of reef "recovery" are largely based on a return to a habitat dominated by mature hard corals and other sessile organisms. Recovery will be slowed if fewer juvenile corals can successfully settle on sediment or turf-covered surfaces,



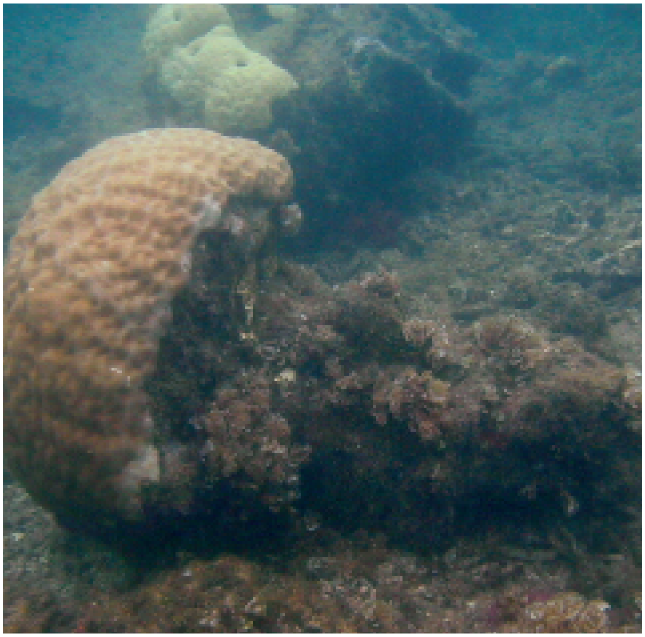
Suggested relationships between disturbance, nutrient availability and relative grazing pressure as determinants of dominant structural cover on nearshore coral reefs. Double-ended arrows indicate situations where the outcome depends on the relative magnitude of grazing pressure and algal production.

are smothered, or eaten. Some species of corals may require decades to fully re-establish themselves in the reef community [116, 211]. Hard corals are the key organisms in reef recovery because they build the reef, providing a structure for many other organisms to live in and on. Longer recovery periods increase the probability of re-disturbance before substantial regrowth [211]. Reef communities may fail to recover if the interval between substantial disturbances are shorter than the time needed by dominant coral species to re-establish and grow [116, 211]. Small shifts in the number of surviving juvenile corals can greatly change the time span needed to re-establish a high level of cover. Under ideal conditions, five to ten years are required to regrow a high level of coral cover on bare surfaces [116, 514], although these species will be fast-growing, "weedy" species [116]. Intervals between cyclonic disturbances in the central GBR are on the order of two to ten years [406]. A particular location within this region, however, may only experience a severe cyclonic disturbance every 10-20 years. Crown-of-thorns starfish outbreaks which can remove up to 90% of coral cover occur at approximately 10-15 year intervals. Since 1982, severe bleaching events, which particularly affect nearshore reefs, have re-occurred at intervals between two and seven years [43]. Reef recovery will be halted by the combination of increased algal growth potential, slower coral recruitment rates, lengthened community recovery times and frequent, recurrent disturbances [116, 211].

Enhanced nutrient availability and grazing pressure influence the abundance of macro- and turf-forming algae on nearshore reefs, and therefore, recovery pathways after disturbances. Their effects are not necessarily equivalent. Turf algae, particularly cyanobacteria, colonise new or dead surfaces after disturbances, regardless of water quality or site. Nutrient availability influences the short-term growth potential of the algae. Turf biomass and space coverage is subsequently controlled by grazers who actively crop the new production. If there are few grazers relative to production, turf biomass will accumulate. Turfs will cover available surfaces, trap sediments and change the suitability of surfaces for recruitment of other reef organisms such as corals. Slower-growing corals need reef surfaces to be cleaned by grazing and remain clear for long enough so that they can grow large enough to re-dominate the benthos. When nutrient levels are enhanced, even slightly, higher algal growth rates improve their capacity to cover and monopolise reef surfaces. Disturbances (cyclones, bleaching events, crown-of-thorns starfish outbreaks) which open up new surfaces, or processes (disease, fishing, predation) which reduce grazer stocks increase the tendency for reefs to become dominated by algae and stay that way until the next disturbance event.

Terrestrial runoff and disturbed nearshore reefs

Well-developed fringing reefs grow, or recently grew, along much of the coast and on nearshore islands within the GBR where suitable substrate exists. Disturbed reefs are now found at several coastal and nearshore island locations (e.g. inshore Whitsunday Islands – 20.5°S, Stone Island – 20°S, Cockle Bay, Magnetic Island – 19°S, coastal reefs on



Reef substrate heavily damaged by a cyclone
Photo: LTMP, AIMS

Reef substrate lightly damaged by a cyclone
Photo: LTMP, AIMS

nearshore islands between 17 and 18°S (e.g. Frankland Islands, Dunk Island, Double Island – 16.5°S). Previously undisturbed nearshore reefs north of Princess Charlotte Bay (14°S) have recently suffered significant levels of coral bleaching.

Most of the known disturbed reefs lie within the nearshore band where river plumes occur most frequently [111]. Most are also close to or downcurrent from drainage basins where there has been significant vegetation clearing, agricultural activity or fertiliser application. These reefs are influenced by river plumes at yearly (wet tropics) to decadal intervals (southern GBR). Because of their nearshore location, natural recovery processes will also be influenced by recurrent disturbance due to cyclones, floods and enhanced organic loading based on runoff-sourced nutrients.

At some locations, the cause of the disturbance is known (e.g. 1991 Fitzroy River flood - Keppel Islands [531, 533]; Cyclone Althea – Cockle Bay [94]). In others (e.g. southern Whitsunday Islands [534]), it is not. Reefs at particular coastal sites have been disturbed more than once in the last century and have recovered (e.g. Stone Island, near Bowen) [538]. Others have not recovered, even over several decades (e.g. southern Whitsunday Islands) [534].

At present, linkages between disturbed nearshore reefs and adjacent catchment land use are circumstantial. Most disturbed reefs are located within the nearshore zone adjacent to catchments with significant levels of clearing or fertiliser use and are subject to recurrent runoff plumes from these catchments. Persistently disturbed reefs indicate that there has been a considerable reduction or failure of natural recovery processes which re-establish a dominant hard coral community [206, 534]. In this respect, the disturbed nearshore reefs of the central GBR resemble, to some degree, reef systems in other parts of the world (e.g. Kaneohe Bay, Barbados, Indonesia) which are known to be affected by human eutrophication or enhanced sedimentation [214, 215, 477, 510-513, 572].

Regardless of a site's current health or status (disturbed or undisturbed), the presence of a carbonate reef framework or coral rubble shows that active growth of reef-building corals once took place over 100s to 1,000s of years [206]. The capacity of reefs to regenerate and maintain themselves ultimately depends upon the presence of long-lived framework-building hard corals [206]. Reefs or coral community sites dominated by fleshy soft corals, fleshy algae and turf algae do not produce calcium carbonate to make up for structural losses due to storm damage or bioerosion by populations of boring or perforating organisms [218, 436].

Seagrasses

Seagrass beds grow in shallow waters along much of the north Queensland coastline [273]. Seagrasses provide habitat and food for many species such as prawns and dugongs. Coastal seagrass beds often grow on muddy sediments characterised by resuspension, high turbidity and enhanced nutrients [261, 582]. Because they require light, the depth range in which seagrasses can grow is inversely related to turbidity [1, 108]. Elevated nutrients and suspended organic matter typically encourage the growth of small encrusting animals and algae (epibionts) on seagrass leaves which shade the leaves and restrict light availability to the plant. Greater light penetration in the clearest offshore waters allows seagrasses to grow at depths exceeding 60 m. Conversely, seagrasses in highly turbid waters may also grow in intertidal habitats where they are exposed at low water.

Seagrass beds in shallow waters of the Great Barrier Reef are subject to recurrent disturbance by cyclones [47, 380], sediment resuspension and freshwater inundation [380]. The local setting strongly influences the time frames for recovery. Because individual species have differing habitat requirements and growth characteristics, complete recovery of a disturbed seagrass bed may take more than 10 years [47]. Two events illustrate the progression of seagrass recovery in the GBR.

In December 1971, Cyclone Althea denuded the intertidal seagrass bed at Cockle Bay, near Townsville [47]. Within a year, two pioneer species of *Halophila* began to re-colonise the original bed. Over the following decade, two additional species, which were dominant prior to Althea (*Halodule, Cymodocea*), increased in abundance as the bed was re-established. Both species, however, grew slowly and had still not returned to their original abundance after ten years. Distributions of species in the recovering seagrass bed were related to water depth and sediment thickness. Sediment accumulation in the habitat, in turn, was directly related to the presence of the seagrasses and algae.

Storm seas and freshwater inundation created widespread disruption of seagrass beds in Hervey Bay in 1992 [380]. Approximately 1,000 km^2 of shallow (< 10m) and deepwater (>10 m) beds largely disappeared. Despite lower in situ light levels, the deep beds began to recover within two years. Recovery of shallow beds has been considerably slower due to recurrent wave disturbance of shallow sediments.

Although seagrasses often grow in muddy sediments, characterised by enhanced pore water nutrients most are nutrient-limited, chiefly by nitrogen [522, 524]. A modern seagrass bed at Green Island (off Cairns) formed on sediments deposited on the northwest (leeward) side of the island where particulate matter would naturally collect. The bed was first recorded in the 1930s and has gradually expanded [324, 524]. It is believed that nutrients from septic systems on Green Island, and later, from a sewage outfall discharging onto the reef flat supported the initial growth of the seagrasses. The bed has persisted following diversion of all treated sewage to a deep-water outfall in the early 1980s. Geochemical tracers [523] now show no evidence of sewage-derived nitrogen in the seagrasses. This does not preclude sewage nutrients having a role in the initiation and early growth of the seagrass bed. Over the fifteen-year period following diversion of the sewage outfall, the original sewage nitrogen would have been metabolised and dispersed while the established seagrasses stabilised sufficient sediment to persist. The nutrients now supporting the Green Island seagrass bed are derived from surrounding waters, including near-annual river plumes coming from rivers in the wet tropics [523]. In its sheltered location, the seagrass bed acts as a collector of nutrient-enriched suspended particulate matter that is mineralised within bed sediments.

Agricultural herbicides along with nutrients and sediment are likely to have an effect on nearshore seagrasses in the GBR. Elevated, though not extreme, levels of the herbicides atrazine [2-chloro-4-ethylamino-6-isopropyl-amino-s-triazine] and diuron [3-(3',4'-dichlorophenyl)-1,1-dimethyl-urea] have been found in coastal sediments and intertidal seagrasses in beds adjacent to the wet-tropical coast between Townsville and Cairns [192]. This distribution is consistent with their extensive use in sugarcane-growing catchments of the wet tropics [182] and the high runoff rates from these catchments. Little or no herbicide is found in coastal sediments adjacent to drainage basins largely used for grazing. Diuron and atrazine have been found in drainage channels and waterways near sugarcane-growing areas, whereas insecticides are more common in cotton-growing areas [341]. Maximum diuron concentrations in nearshore sediments near wet tropics catchments approach 10 µg per kg, while at most other locations, concentrations were below the 0.1 to 0.5 µg per kg analytical detection limit of particular surveys. Where it was found, diuron concentrations in seagrass tissues were higher than in the surrounding sediments. In contrast, relatively little atrazine was found in coastal sediments despite extensive use. This is consistent with its greater solubility and faster breakdown [192]. Diuron reduces photosynthesis of tropical seagrasses at concentrations of 0.1-10 µg per litre of seawater [193]. Concentrations of this magnitude are currently unlikely to occur in open coastal waters. Direct effects of herbicides on seagrasses are more likely to occur through build-ups in less rapidly mixed sediment pore waters which are in close contact with seagrasses. In situ effects of diuron in natural seagrass beds and other organisms are as yet, unresolved. Seagrasses are the principal food resource for dugongs and support food chains containing a number of commercial fish and invertebrate species. The presence of this potent herbicide in coastal seagrasses, its close association with areas of known agricultural use and the importance of seagrasses to dugongs are cause for concern.

Chapter 11

Catchments and corals:
the land and the sea

Terrestrial runoff, and the sediment and nutrients carried in it, have always influenced the Great Barrier Reef ecosystem. Nearshore coral reefs and benthic communities have long grown in habitats affected by freshwater runoff. The volume of freshwater runoff affecting the GBR has always been naturally variable. Terrestrial nutrients support the productivity of coastal ecosystems. Over the last 150 years, however, human activities in the GBR catchment have changed levels of nutrients and sediment in runoff to a degree comparable with that caused by climate or sea level variations over much longer time periods. Modern sediment and nutrient exports from the catchments adjoining the GBR have increased with the extent of land clearing, grazing, farming, fertiliser applications and population growth. Unless there are major changes in how land in the GBR catchment is used, these increased levels of runoff and the resulting ecosystem responses to them will become the norm.

Nearshore fringing reef, wet tropics
Photo: GBRMPA

The Great Barrier Reef is one of Australia's and the world's great natural wonders. Its early designation as a World Heritage Area is clear recognition of the value placed on the GBR. Because of its outstanding scenic and

Mulgrave River
Photo: M. Furnas, AIMS

Paddock near Charters Towers, Burdekin River catchment during 1982-83 drought
Photo: M. Furnas, AIMS

biological values, the GBR forms the centrepiece of a major regional tourism industry, drawing visitors from around the world. The value of the GBR as a centre of marine biodiversity and as a sustainable economic asset is steadily increasing as coral reefs around the world are degraded by inappropriate coastal development, over-fishing, enhanced sediment runoff and eutrophication due to rapidly expanding human populations in coastal regions and poor land management in adjoining catchments [558]. If we are to preserve this value, then we must take a long-term view of the health of the GBR and the full range of human activities which affect it.

Much has happened in the GBR catchment since the 1850s, when European-style land use began in Queensland. At that time, most of the GBR catchment was covered by savanna woodland. Eucalypt forests and rainforest grew on the coastal mountains and wetter sections of the coastal plain. Vegetation communities were structured by the broad distribution of soils, terrain and rainfall, in conjunction with fire and the burning practices of the Indigenous inhabitants of the catchment [356]. Drought and fire, then as now, episodically exposed the soil in drier regions to direct rainfall and erosion. The nutrients carried in pre-1850 runoff came from the seasonal rains, the slow leaching of catchment soils and biological nitrogen fixation. The best evidence, derived from modelling and sampling in minimally disturbed streams and rivers, indicates that pre-1850 runoff carried, on average, 1 to 5 million tonnes of sediment (24-120 kg ha^{-1}, 14 g m^{-3} of runoff), 23,000 tonnes of nitrogen (0.5 kg N ha^{-1}, 320 mg m^{-3}) and 2,400 tonnes of phosphorus (0.06 kg P ha^{-1}, 34 mg m^{-3}) each year to the GBR. Higher concentrations prevailed for brief periods during floods. The volume-averaged concentrations of sediment and nutrients in pre-1850 runoff are three to four times the average concentration of suspended sediment (1.7-3.3 g m^{-3}), nitrogen (100-120 mg m^{-3}) and phosphorus (9-15 mg m^{-3}) (particulate + dissolved) in nearshore waters of the central and southern GBR. Then as now, the highest suspended sediment and nutrient concentrations, and the largest sediment and nutrient loads, came from the dry catchments bordering the central and southern GBR.

Most of the GBR catchment is now used to some degree for cattle grazing and cropping. Beef cattle grazing on native and improved pastures is the principal land use, with approximately 75% the GBR catchment owned or leased for grazing purposes. Substantial clearing of native vegetation has taken place throughout much of the GBR catchment to develop pastures and increase cattle productivity, particularly in the last 50 years. The most recent estimates of tree clearing indicate that overstory vegetation has been cleared from approximately one third of the GBR catchment (BRS, 2000; Queensland EPA, 2001; QNR&M, 2001). Most of this clearing has taken place in the dry catchments draining to the central and southern GBR. Today, the highest rates of tree clearing in the GBR catchment continue in the Burdekin and Fitzroy River drainage basins [410,411,412].

Many studies (Chapter 5) clearly show that the density of vegetation cover, particularly of grasses, has a major influence on water infiltration, soil erosion and nutrient loss from pastures and savanna woodlands. Grazing directly affects the natural level of grass and shrub cover. The degree of grass cover is often more variable than tree cover and estimates of grass cover within the GBR catchment at any time are less certain. Grass cover naturally varies with rainfall, season, climate cycles (drought), soil fertility and grazing pressure. Overall, interactions between grazing pressure (cattle numbers) and climate variability (drought) recurrently reduce effective groundcover in large areas of the GBR catchment. Significant soil and nutrient losses can be expected when heavy, drought-breaking rains fall on landscapes with little or no effective ground cover.

Cattle grazing. wet tropics
Photo: M. Furnas, AIMS

Cattle grazing, dry tropics
Photo: QDPI

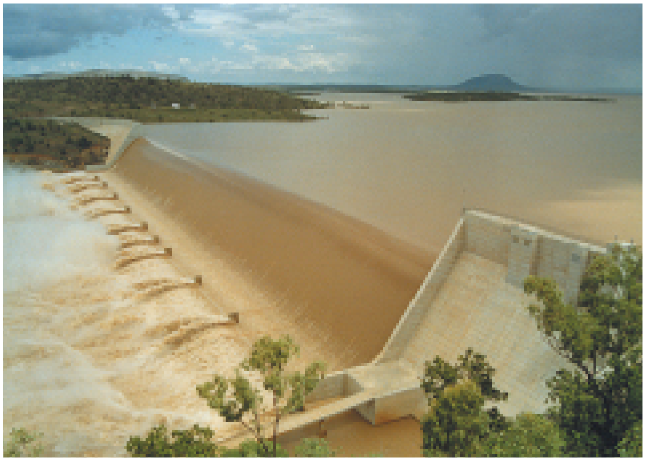
Sugarcane, near Innisfail
Photo: M. Furnas, AIMS

Sugarcane is the most valuable crop cultivated in the GBR catchment. The current harvested area is close to 4,400 km^2, or slightly more than 1% of the GBR catchment. Importantly, the sugar crop receives approximately 60% of the estimated 100,000 tonnes of nitrogen and 40% of the 20,000 tonnes of phosphorus applied as fertilisers within the GBR catchment [414]. Additional nitrogen and phosphorus are added through recycling of mill mud and other bio-solids [414]. These nutrient applications are much greater than current nutrient runoff estimates and are greatly in excess of crop uptake. Some of the added nitrogen is lost to the atmosphere, but significant amounts of both nitrogen and phosphorus have been steadily building up in catchment groundwaters and soils [414,416]. While some forms of nitrogen (nitrate) are mobile in soils [334,401], the phosphorus largely remains bound to soil particles [414,416]. This build-up has produced a long-term reservoir [414] supplying enhanced exports of nutrients from fertilised catchments, as tilled soils are eroded and nutrient-enriched groundwater drains into watercourses. However, as the area of sugar cultivation has expanded over the last few decades, there have been parallel improvements in sugar cropping methods to reduce soil erosion and nutrient loss at the farm scale. In particular, the widespread adoption of green-cane trash blanketing in harvesting and no-tillage cultivation have greatly reduced soil erosion in canelands and aided the retention of soil nutrients.

The best estimate of current sediment runoff to the GBR, based upon multi-year sampling in wet- and dry-catchment rivers (Chapters 6 & 7) and modelling of catchment-scale sediment fluxes [391], is now close to 14 million tonnes per year (330 kg ha^{-1} $year^{-1}$ or 200 g per m^3 of freshwater runoff). Concurrent nitrogen and phosphorus exports are estimated to be 43,000 tonnes per year (~1.0 kg N ha^{-1} $year^{-1}$ or 600 mg N per m^3 of runoff) and 7,000 tonnes per year (~0.17 kg P ha^{-1} $year^{-1}$ or 100 mg P per m^3 of runoff). The volume-averaged suspended sediment concentration in modern runoff is 20-40 times the average suspended sediment concentrations in central and southern GBR coastal waters (Table 3). Most of the sediment is initially deposited close to the river mouth, but over time, the finer particles are resuspended and carried along the coast to sheltered sites and northward facing bays [275]. Volume-averaged nitrogen and phosphorus concentrations in modern runoff are 5-10 times greater than average nearshore concentrations. As with fine sediments, higher concentrations may prevail during floods (Chapters 6 & 7).

The amount of fine sediment and nutrients transported by runoff each year into the GBR is directly related to the volume of freshwater discharge. The close relationship between discharge and material exports from similar types of catchments makes it possible to estimate exports from unsampled rivers using measurements of annual discharge. During the 27-year period (1968-94) when comprehensive gauging records are available for most of the important rivers and streams in the GBR catchment, annual discharge has varied over a nine-fold range (22–186 km^3). Year-to-year variations in runoff from individual rivers range from 5-fold (Tully River) to over 100-fold (Burdekin River). Annual exports of sediment and nutrients from individual river drainage basins, or the total GBR catchment, will vary over similar ranges. Large wet seasons or major flood events in the larger drainage basins will have widespread and long-lasting influences on water quality and shelf ecosystems [250, 581]. There is circumstantial evidence that large-scale changes in salinity and nutrient availability following major rainfall and runoff events in the central GBR may also contribute to the initiation of recurrent crown-of-thorns starfish infestations [49,67].

Terrestrial runoff is the largest quantified external source delivering "new" nutrients to the GBR ecosystem. These nutrient inputs and their effect are initially focused into the shallow nearshore zone. On average, the nutrients in



Floodwaters overflowing the Burdekin Dam
Photo: J. Faithful, JCU

Mouth of the Burdekin River in flood
Picture: GBRMPA

freshwater runoff (volume = 70 km^3) are equal to 6% of the total fixed nitrogen (DIN+DON+PN) and 11% of phosphorous (DIP+DOP+PP) in all GBR shelf waters (volume = 7,600 km^3). Soluble, more bioavailable forms of nitrogen (DIN+DON) and phosphorus (DIP+DOP) in runoff equal only 4% of soluble nitrogen and phosphorus pools in shelf waters. However, these average runoff inputs are equivalent to 140% of the fixed nitrogen in nearshore waters (depth < 20 m, volume = 295 km^3) and 260% of nearshore phosphorus stocks. For soluble, more bioavailable forms, average annual river inputs equal 85% of the readily bio-available soluble nitrogenous nutrients (DIN) in coastal waters and 82% of the soluble phosphorus (DIP+DOP). During seasonal periods of heavy runoff, these inputs have a large effect upon nutrient availability in nearshore ecosystems [111]. The effects of runoff on nearshore water quality and ecosystems vary between regions due to differing runoff characteristics of wet- and dry-catchment rivers. The nearshore reefs bordering the wet tropics (16-18°S) are affected to the greatest degree, and are at greatest risk from runoff-related damage as they are influenced by river plumes nearly every year, while nearshore ecosystems bordering the drier catchments to the south may only be strongly influenced once in a decade. While coastal systems in the wet tropics are likely to be more adapted to freshwater runoff; the greater availability of nutrients from modern runoff will have an increasing effect on the capacity of reefs to recover from disturbances.

The relative contribution of individual catchments or types of land use to total sediment and nutrient exports varies greatly. Most of the terrestrial sediment (85%) and nutrients (66-80%) entering the GBR come from the drainage basins bordering the central and southern GBR. The Burdekin and Fitzroy River basins dominate these inputs because of their size. Grazing lands in these catchments receive little, if any, fertiliser. The bulk of nutrients exported from grazing lands still come from rainwater and soils. Annual discharges from dry-catchment rivers, and associated sediment and nutrient exports vary considerably between infrequent wet years and droughts. Because of this variability, longer periods of river monitoring (more than 10 years) are necessary to make accurate estimates of sediment and nutrient export. The current estimates of nutrient and sediment exports from the Fitzroy River drainage basin (Table 32) are almost certainly conservative because a large flood (e.g. post-Cyclone Joy; Jan. 1991) has not been sampled. This variability will also make it difficult to establish trends in water quality over time.

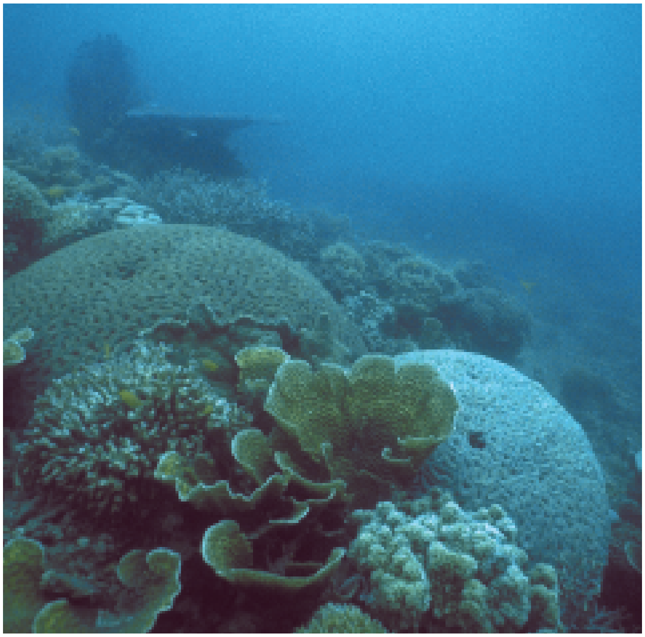
While it only takes up a small portion of the GBR catchment (ca. 1%), the land used for sugarcane cultivation contributes a disproportionate fraction of the total sediment and nutrients in runoff. Canelands are estimated to be the source of 1.25 million tonnes of sediment (9% of runoff exports), 8,800 tonnes of nitrogen (20%) and 1,300 tonnes of phosphorus (18%) [414]. Prior to 1850, runoff losses from the woodland and forest-covered coastal floodplains now planted with sugarcane and bananas were likely less than 100,000 tonnes of sediment, 1,500 tonnes of nitrogen and 500 tonnes of phosphorus.

Water quality and nearshore ecosystems

How much has water quality changed within the Great Barrier Reef lagoon as a result of human activities? If we consider the entire GBR lagoon, the answer is probably not a lot. This is because the GBR lagoon is very large and the biological communities in the lagoon rapidly assimilate new inputs of bio-available nutrients. The effects of land runoff will be greatest near the coast. Concentrations of dissolved nutrients derived from runoff are highest near river mouths and in the nearshore zone. The degree of change will depend upon levels of input, water depth and the occurrence of disturbance events (flood plumes, resuspension). Changes in nutrient inputs are manifested as changes in plankton and algal biomass rather than nutrient concentrations. The biological uptake of nutrient

Sargassum bed on a nearshore coral reef: a natural part of the GBR ecosystem
Photo: L. McCook, AIMS

inputs from runoff happen very quickly. Plankton blooms can develop within days after a major cyclone or flood event [111,140]. Light penetration, or water clarity, which are strongly influenced by suspended sediment concentration, are major factors behind the initiation and development of these post-disturbance algal blooms [140]. In shallow nearshore waters, wind-driven sediment resuspension has a greater effect on suspended sediment concentrations than river plumes. After a bloom, the nutrients incorporated into plankton biomass are then distributed throughout planktonic and benthic food webs. A large part of the particle-associated nutrients transported by suspended sediment in rivers are deposited, at least initially, in the coastal zone. Of this, a significant, but as yet unresolved, proportion is ultimately buried in the sediment.



Undisturbed nearshore reef in turbid waters near Princess Charlotte Bay
Photo: K. Fabricius, AIMS

It is suggested that the GBR lagoon has become eutrophied [35,36,37] and more turbid [576] in recent decades as a result of modern runoff of sediment and nutrients, although this view has not been fully accepted [70,253,264,266, 542]. There are persistent regional differences in average concentrations of suspended sediments, nutrients and phytoplankton biomass in the lagoon (shown by chlorophyll a – a proxy measure of nutrient availability) [144], with higher concentrations near the coast. Relatively higher concentrations of dissolved nutrients and chlorophyll are found in the nearshore zone bordering the central and southern GBR which also receives the largest proportion of land runoff and runoff-associated nutrients. The available information, however, does not yet show that these concentrations have increased or are increasing. Monitoring data (Furnas; unpubl. data; GBRMPA, unpublished) covers too short a period (ca. 10 years) to detect subtle trends within the natural range of variability. Despite some appreciable, but short-term fluctuations, average chlorophyll concentrations in the more open central GBR lagoon (18° - 20°S) have largely remained at the same level over the last twenty years (1976-1995 inclusive) [70.]

It has also been suggested that phosphate concentrations in the central GBR lagoon have increased, based on a comparison of measurements carried out near Low Isles (Port Douglas) in 1920s [300,366] and Townsville (19°S) in the 1970s [36,422,423]. Considerable care must be taken when making comparisons between data collected 50 years apart. Average environmental conditions differ naturally between years due to climatic and oceanographic variability. There will also be differences between data sets if samples are not collected at the same sites, or as sampling, storage and analysis methods have changed. In the case of the Low Isles-Townsville nutrient data, the differences between concentrations measured in the 1920s and 1970s are similar in magnitude to natural year-to-year fluctuations in local waters and to systematic differences between nutrient data sets due to handling and analytical procedures. The differences are interesting, but not definitive.

The absence of obvious trends in water quality within the GBR lagoon despite increasing inputs of sediment and nutrients is not surprising. Lagoonal nutrient and chlorophyll concentrations will not be sensitive indicators of terrestrial influence. The GBR lagoon, even the shallow nearshore section, is a very large (10,000s of km^2 in area and 100s of km^3 in volume) and well-mixed body of water. Sediment and sediment-associated nutrients are initially deposited in and remain concentrated within the nearshore zone. A significant fraction of the sediment-associated nitrogen and phosphorus will remain there, buried or cycling in coastal sediments. Soluble nutrients and suspended particulates, in contrast, will be dispersed by currents along (north-south) and across the continental shelf. Because phytoplankton and algae rapidly take up any available nutrients (e.g. NH_4^+, NO_3^-, PO_4^{3-}), regardless of concentration, dissolved nutrient concentrations must be expected to be very low or decrease rapidly. Nutrient inputs will be rapidly converted to biomass and detritus. The slightly elevated nutrient and chlorophyll concentrations near the coast are due to high rates of mineralisation within particle and plankton-rich nearshore waters, and to nutrient exchanges between coastal waters and the large nutrient stocks stored in coastal sediments. Higher coastal nutrient concentrations in the central and southern GBR reflect the greater extent of sediment and nutrient runoff from dry tropical drainage basins and larger stores of terrestrial sediment in shallow coastal waters.

Because of the considerable capacity of the GBR lagoon to absorb nutrient inputs, the detection of any persistent upward trend in concentrations of dissolved nutrients or nutrient proxies (chlorophyll) must be regarded with the greatest concern. Such an increase represents a change driven by very large amounts of nutrients, acting over a large area, in the face of significant dispersive processes. The conditions necessary to produce even slight eutrophication of the GBR lagoon will have taken many years to develop and will take decades to go away. The resulting biological effects on reef and benthic communities in GBR ecosystems will also be slow to develop and likewise take many decades to disappear.

The absence of measurable changes in nutrient or chlorophyll concentrations in GBR lagoon waters does not mean that sediment- or nutrient-driven changes in nearshore reef and benthic ecosystems have not occurred or are not occurring. Our current understanding of and ability to detect change in nearshore ecosystems is limited by the lack of detailed and long-term study of these systems. It is very clear, based on overseas examples (Chapter 10) that large or chronic local increases in sediment or nutrient inputs will change or degrade coral reef ecosystems. The biology of GBR ecosystems and the communities in them are no different from those elsewhere. They will respond to the same pressures in a similar manner. Because of their adaptation to local factors, however, species and communities on reefs in the GBR will almost certainly have thresholds to environmental change or stress that differ from species or communities growing elsewhere. Large changes in nutrient or sediment loading will create large changes in communities or ecosystems. Smaller changes in loading will produce smaller responses. Subtle changes will produce subtle responses that may not be apparent over short periods (< 1 decade), or until a significant disturbance event (e.g. a cyclone or bleaching event) changes relationships between species in a community or creates free space for colonisation. Over time, changes in water quality, nutrient inputs or organic loading in the GBR lagoon will gradually alter species distributions [123,124], excluding some species from habitats in which they could once grow, or giving other species an increased competitive advantage to colonise new habitats and hold this space as new dominant species.

While there is good evidence that high turbidity, sedimentation or eutrophication can adversely affect corals and seagrasses, it is much more difficult to say exactly when small changes in inputs or concentration harm coral reef and seagrass ecosystems. Ecological community changes will either reflect the level of environmental alteration, or no change may be apparent until the community is disturbed and recovery takes a different path [252], producing a changed community. It would be inappropriate to describe slightly elevated levels of inorganic nutrients as being "stressful" to coral or reef communities any more than holiday overeating or consuming a diet overly-rich in fat or sugars is stressful to humans. Over time, however, the cumulative effects of over-eating or consuming a narrow, calorie-rich diet can be seen in both individuals (over-weight, increased risk of heart disease) and populations (e.g. the increasing incidence of obesity, diabetes). Increased nutrient availability may cause analogous changes in the health of coral reef communities or individual organisms.

There have been attempts to define water quality thresholds for undesirable change in coral reef ecosystems [190,262]. These proposed thresholds are derived from observations on reefs in the Atlantic Ocean. While it is highly desirable to set standards for water quality in order to provide benchmarks for management, there are obvious problems with applying threshold values derived elsewhere to the large and heterogeneous GBR as they may not take full account of the wide range of conditions that naturally occur in GBR nearshore ecosystems. For example, average concentrations of chlorophyll (0.5-1 $\mu g\ L^{-1}$) and suspended sediment (1.5-3 $mg\ L^{-1}$) in central and southern GBR coastal waters are likely naturally at or approaching levels regarded as inhibitory to coral growth at sites on islands in the Caribbean [190]. A number of hard coral species living in the nearshore zone of the GBR [255,265,537] appear to be better adapted to enhanced nutrient availability (organic loading) and sedimentation than corals living on isolated reefs or islands. The degree of reef development in turbid coastal areas is related to historical sealevel, resource availability, disturbance frequency and environmental stress (including sedimentation). Coral reefs, including nearshore reefs exist where suitable conditions for coral establishment and growth persist, on balance, for extended periods of time. Reefs stop growing and may ‘die’ where environmental conditions or recurrent stresses reduce their capacity to recover from disturbances.

Where are we now?

Our current inability to detect clear changes in water quality within the GBR lagoon and the capacity of nearshore reef communities to tolerate locally elevated levels of turbidity, sedimentation and nutrient availability (at least temporarily) should not be grounds for complacency. Increased inputs of terrestrial sediment and nutrients have and will continue to influence nearshore regions of the GBR ecosystem. The degradation seen in overseas coral reef systems such as Kaneohe Bay or Barbados gives an indication of what could eventually occur in the GBR if sediment and nutrient inputs increase still further or continue at a high level. We do not know exactly what sediment and nutrient input levels will trigger a similar degree of decline in water quality within the GBR lagoon or the resulting degradation of nearshore reef and benthic ecosystems. It is obviously not desirable to find out. The clear lesson from observing water quality-related changes in reef ecosystems overseas is that once community- or habitat-scale degradation become obvious, major ecosystem changes have already occurred and the time frame for recovery is likely to be decades or longer. Now is the best time, while many of the coastal ecosystems of GBR are still in relatively good condition, to make changes in land use practices that will reduce sediment and nutrient loads in runoff. Because of the size of the GBR, ecosystem rehabilitation will become ever more expensive, disruptive and difficult to implement in the future. The present degraded state of the Murray-Darling River system, the salinisation of the West Australian wheat belt and the decrease in water flow from the Great Artesian Basin provide sombre signposts to one possible future for the GBR. The early signs of trouble in those systems were small, easily overlooked and easily dismissed. If the present situations in those systems had been foreseen and their consequences appreciated, relatively small and straightforward decisions about land and water management could have done much to alleviate the current environmental problems. Such decisions could have greatly reduced the enormous economic and social costs that must now be incurred to restore and maintain the assets, health and productivity of these regions. We have the opportunity to make changes for the GBR's sustainable future while they are achievable.

The pronounced seasonal, inter-annual and regional variability in the climate and hydrology of the GBR catchment means that the results of efforts to reduce sediment and nutrient runoff may not be immediately apparent. Some actions, such as replanting of riparian vegetation or upgrading sewage works may take only a few years to implement and produce local results. Running down the large stocks of fertiliser phosphorus bound to caneland soils will take decades. The vision and effort must be for the long term. The detection of trends, whether of progress or not, will also take extended periods. Land management practices which work under "normal wet season" or dry conditions may be overwhelmed during extreme flood events or undermined by extended droughts. Once changes are made and as improvements occur, it will be necessary to continue their implementation to ensure the long-term health of the GBR

The large size, natural variability and diversity of both the GBR and its catchment mean that a long-term, large-scale and cooperative approach to their preservation, utilisation and management is essential. The relationship between nutrient runoff and the health of nearshore ecosystems is not just an issue for banana farmers in Tully, homeowners in Cairns or cane farmers in Mackay. Land use by graziers in Pentland and cotton farmers near Emerald also has an impact on the GBRWHA. Everybody in the GBR catchment has an influence on runoff and water quality. Because of the size of the GBR catchment, and of individual drainage basins within it, no single level or department of government, industry, community or catchment can unilaterally solve the problem. Each catchment, community, industry or level of government does, however, have an important role to play.

What should be done?

The two most important actions which can be taken to reduce the amount of terrestrial sediment and nutrients reaching the Great Barrier Reef are to:

- reduce the rate of soil loss from grazing and farming lands in adjoining catchments, and
- minimise the loss of nutrients applied as agricultural fertilisers to pastures and farming lands within the GBR catchment.

These actions involve the greatest land area within the GBR catchment and the greatest exported tonnages of sediment and nutrients.

The smaller inputs of nutrients from point sources such as sewage treatment plants and aquaculture farms can be locally important. However, urban and industrial point sources of nutrients (< 2,500 tonnes of nitrogen and < 600 tonnes of phosphorus per year) are small compared to diffuse sources associated with soil erosion and agricultural land use (ca. 43,000 tonnes of nitrogen and 7,000 tonnes of phosphorus per year). Industrial and urban point sources of nutrients and pollutants are largely known and are subject to regulation. There are well-understood engineering solutions and management practices available to reduce and control point source inputs.

Although the quantities are no where near as great, it is also highly desireable to:

- minimise the use of pesticides, herbicides and other toxic chemicals within the GBR catchment and GBRWHA, and where use is necessary, to avoid the contamination of neighbouring habitats or ecosystems.

Reduction of erosion and subsequent soil loss from GBR catchments will have the largest effect on terrestrial nutrient inputs to the GBR and on water quality in both fresh and marine waters. Fine sediments carry approximately 50% of the terrestrial nitrogen and 80% of the terrestrial phosphorus reaching the GBR. Approaches to minimising sediment input to the GBR must therefore be focused on sediment sources in the catchments and the processes which move it. Most of the sediment (85%) entering the GBR comes from the drier catchments or parts of catchments where grazing is the principal land use. The largely dry river basins of the central and southern GBR catchment also export 50% of the immediately bio-available nitrogen (DIN) and 80% of the directly bio-available phosphorus (PO_4^{3-}, DOP) in runoff. Overall, unfertilised, grazing-dominated catchments are the source of 65% of terrestrial nitrogen inputs and 78% of phosphorus inputs to the GBR. Although the absolute exports of sediment and nutrients from the wet tropics are lower, these wet catchments have higher area-specific soil and nutrient loss rates, reflecting their generally steeper topography and greater rainfall. Wet tropics catchments flood more frequently than the dry catchments and deliver a higher proportion of their nitrogen output in soluble bio-available form.

This provides a strong case for more active management of fertiliser inputs of nutrients to cropping lands in the GBR catchment. Current annual fertiliser applications of nitrogen (100,000 tonnes) and phosphorus (20,000 tonnes) considerably exceed the post-1850 increases in nitrogen (ca. 20,000 tonnes) and phosphorus (ca. 4,600 tonnes) exports in runoff. These fertiliser inputs do not include nutrient recycling through application of biosolids and sugarcane mill mud [414]. Significant amounts of fertiliser appear to be applied as a matter of course, without regard to soil nutrient status or the likelihood that significant production gains will result [414]. At present, most of the nutrients applied to agricultural lands in fertilisers are lost to the atmosphere, groundwater and runoff, or remain bound in the soil. The link between soil erosion and phosphorus exports is especially strong. Soil phosphorus is overwhelmingly bound phosphorus. Most of the phosphorus in fertiliser applied to GBR catchment soils over the last 50 years has remained in the soil [416]. Phosphorus losses from catchments are therefore directly related to soil erosion and sediment runoff. Efforts to control terrestrial phosphorus exports to the GBR must focus on minimising soil erosion and sediment loss.

There are a number of approaches to reducing fertiliser losses from agricultural lands. Some are relatively easy to implement through voluntary action, while others require a higher level of management and control [414]. These approaches include: increased soil testing to identify which land does and (especially) does not need fertilisation to maintain economic productivity; inclusion of mill mud and bio-solids in farm nutrient budgets so as not to over-fertilise cropped paddocks; continued research and development toward producing more efficient and cost-effective fertiliser products; developing improved application technologies and application strategies; training and certification of agricultural fertiliser users in improved farm nutrient management, and development and certification of nutrient management plans as part of wider property and catchment management planning. In extreme cases, however, where excess fertiliser applications are clearly affecting catchment water quality or adjacent marine habitats, it may be necessary to place caps on fertiliser use in source catchments.

Loss of groundcover due to fire
Photo: QDPI

Maintaining adequate vegetation or other ground cover is central to minimising soil loss from both wet and dry catchments. Plot- and paddock-scale studies clearly show that, freshwater runoff, soil erosion and soil loss increase as vegetation or litter cover decreases (Chapter 5). The degree of increase depends on several factors, including topography, soil type, the quantity and rate of rainfall, and the type of vegetation (or litter) cover. In cultivated landscapes, crops and crop residues (e.g. leaf and stalk materials discarded during green-cane harvesting) behave like vegetation and litter cover in retarding soil erosion. Soil loss rates are relatively low while vegetation cover remains above 30-40% of surface area, then increases rapidly at lower cover levels.

Recently planted sugarcane paddock, wet tropics
Photo: M. Furnas, AIMS

Vegetation clearing, overgrazing, drought and fire are the principal factors contributing to low vegetation cover and enhanced soil erosion in the drier portions of the GBR catchment. These pressures often interact (e.g. overgrazing before or during droughts) and contribute to a greater loss of vegetation cover than one process on its own. Vegetation clearing and agricultural tilling of cleared land are the principal causes of low ground cover in wet tropical settings.

In both wet and dry catchments, riparian vegetation is the final barrier between eroding landscapes and the river network. Well-vegetated riparian borders of sufficient

Coastal freshwater wetland, wet tropics
Photo: GBRMPA

width trap soil moved by overland water flows and protect the riverbank during floods. The effectiveness of riparian borders vary with the slope of the land, the width of the border and the degree of surface roughness in the border. Riparian vegetation is particularly important in the headwaters of stream networks, the source of most eroded soil during heavy rainfall events.

The sediment trapping efficiency of riparian borders has been tested in several locations in the GBR catchment [238,239,320,386]. Properly designed and well-established riparian borders can trap a significant proportion of the eroded soil moving across them. Their efficiency falls during major rainfall and flood events if borders are degraded or when barriers are physically overwhelmed. Barriers to improving the extent and status of riparian vegetation along river and stream networks within the GBR catchment include: current economic and social incentives to continue and maximise cropping or grazing on cleared riverside soils; costs associated with riparian revegetation; and particularly in grazing lands, the high capital costs of fencing off riparian zones, while providing alternative shade and watering points for stock. There needs to be strong incentives for restoring the extent and quality of riparian vegetation in all habitats through the GBR catchment and to improve their soil trapping efficiency.

Adaptive pasture-management strategies that focus on retaining significant levels of grass cover (at least 40%) must be a central part of minimising soil and nutrient losses from grazing lands [593]. These strategies need to take the monsoonal and ENSO-driven climate variability of the region and their effect on grass production into account. There will be years and seasons with enough grass to support large, productive and profitable cattle herds, just as there will be drought periods when the land lacks the capacity to tolerate even light grazing. Appropriate grazing strategies must be based on prudent stocking rates, the capacity to quickly adjust herd size to pasture condition and a willingness to remove cattle from the land before paddocks are over-grazed. Business strategies for grazing enterprises need to manage significant swings in sustainable herd size, provide incentives and mechanisms to move cattle (and grazing pressure) off the land well before groundcover is denuded and preserve enterprise capital during drought periods to finance property maintenance and herd rebuilding when the rains come again.

A detailed consideration of adaptive grazing, farming and agricultural business strategies for the GBR catchment is beyond the scope of this book. Both government (Commonwealth and State) and industries are actively involved in research and extension activities to develop and foster adoption of improved land use practices [593]. Much work remains to be done. The development and implementation of sustainable grazing, farming and land use practices will, and must, incorporate both changes in land use and the financial management of agricultural enterprises to ensure their profitability. Inevitably, this will influence the economic and social structure of agricultural industries and the communities they support. This need not be bad. The preservation of viable and ecologically sustainable rural industries must involve land users (graziers and farmers); the industries which buy, sell and process rural products; governments (at all levels) and financial institutions associated with the rural industries. In particular, financial incentives that reward sustainable land stewardship as well as prudent business management must be developed and implemented.

The process of reducing runoff of sediment, nutrients and pesticides to the GBR, which is now occurring as a result of inappropriate levels or types of land use is, overwhelmingly, a social and economic process. The major agricultural and land-using industries in the GBR catchment are long established and make significant economic contributions to the nation [597]. The rural industries of the GBR catchment and the infrastructures

Well-grassed woodland pasture in the dry tropics
Photo: P. O'Regain, QDPI

Reef tourism
Photo: GBRMPA

(physical, social, economic) which support them were largely established before the degree of connection between land use, terrestrial runoff and the health of the GBR were appreciated. It is very unlikely, therefore, that the current enhanced inputs of sediment and nutrient runoff to the GBR, and the effects they cause can be fully wound back to pristine levels. This is no reason for not working toward such reductions. While the communities and industries within the GBR catchment are significant generators of national product and wealth, they also draw upon the amenity values, economic activity and wealth generated by the GBR World Heritage Area [597].

An essential first step in managing and fixing runoff-associated problems is identifying what is known about the sources, magnitude and effects of runoff, and to communicate these to affected parties. That is the objective of this book. Practical approaches to reducing exports of sediment and nutrients in runoff are known. The challenge is to design better and affordable solutions to a wide range of land management problems (e.g. erosion control, water management, groundcover retention, fertiliser management and minimisation). A far larger effort is also required to understand social, economic and management barriers to implementing solutions, and to develop the attitudes, mechanisms and incentives to achieve the best possible land management practices.

It is essential that all residents and land users throughout the Great Barrier Reef catchment, from the wet tropics to the dry inland understand that what they do influences the reef. We all have a stake in the Great Barrier Reef and have an essential part in the process of conserving the ecosystems of the Great Barrier Reef World Heritage Area. In doing so, we all will sustain the long-term benefit that is derived from the GBR. Ultimately, doing what is best for the land is also doing what is best for the Great Barrier Reef.

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River Flow (selected rivers):
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Spatial Data:
- GBR and Wet Tropics World Heritage Area boundaries
- Reefs in the GBR Marine Park
- Bathymetry of the GBR Marine Park
- Population centres in the GBR catchment
- Land tenure in the GBR catchment
- Sugar, cotton, horticulture cultivation areas
- Forest Reserves, National Parks, protected areas

AUSLIG (Geosciences Australia)

Spatial data:
- Topography
- Rivers
- Coastline

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Bureau of Meteorology

Spatial data:
- Queensland gridded rainfall: 1969-1999

Rainfall:
- Annual Rainfall (selected sites)
- Monthly Rainfall (selected sites)
- Maximum Daily Rainfall (selected sites)
- Pan Evaporation (selected sites)

University of Sydney (Dr. C. Jenkins)

Spatial data:
- Carbonate content of sediments in the GBR Marine Park (via GBRMPA)

Glossary

alkalinity
The capacity of a solution to neutralise acidity (H^+). Seawater is slightly alkaline (pH ca. 8.1). The alkalinity of marine waters is largely determined by the concentrations of bicarbonate (HCO_3^-) and bicarbonate ($CO_3^=$) ions

alluvium
Soil or sediment deposited by floodwaters

ambient
Conditions or concentrations normally occurring in the environment

anaerobic
Biological metabolism not requiring oxygen

anoxic
Devoid of free oxygen

bacterioplankton
Bacteria living suspended in seawater or freshwater

baseflow
Low-water flow in a river or stream sustained by non-seasonal rainfall inputs to headwater catchments and groundwater inputs

beche-de-mer
Sea cucumber or holothurian. A slug-like, mobile echinoderm (related to starfish) which feeds on organic matter in sediments. Some species are harvested for food

bedload
Coarse sediment carried along the bed of a stream or river by the current

benthic
Associated with the sea bottom

benthos
The biological community living on and closely associated with the sea bottom

biogenic
Formed by living organisms

biodiversity
The range of species and genetic variability within species in a biological community or ecosystem

bryzoan
Aquatic colonial encrusting filter feeders. Bryzoans are important members of the fouling community in GBR waters and their skeletons contribute to sediments

calcareous
Formed of calcium carbonate ($CaCO_3$)

carbonate
Formed of calcium carbonate ($CaCO_3$)

catchment
The land area draining into a particular stream or river at a defined point

clastic
Sediment largely formed of terrigenous sand and gravel

cnidarian
The aquatic phylum of organisms containing the corals, jellyfish and anemones

commensal
The relationship between two organisms living in close physical association without apparent metabolic benefit or harm to either species.

community
A recognisable group of species which live in the same habitat over long periods of time.

continental shelf
The shallow subsurface area adjoining a continental land mass between the coastline and where the bottom begins a steeper descent into the deep ocean (continental slope). In the GBR, the seaward edge of the continental shelf (shelfbreak) typically occurs at 40 to 80 m depth

cyanobacteria
Photosynthetic bacteria containing chlorophyll a or close derivatives. There are both planktonic and benthic cyanobacteria. Some species fix atmospheric nitrogen. So-called because some species have pigments giving them a dark blue, green or purple coloration

cyclone
Intense low-pressure rotating storm system (equivalent to hurricane or typhoon). Minimum wind speeds in a cyclone exceed 138 km per hour

denitrification
Microbial conversion of nitrate (NO_3^-) to inert di-nitrogen gas (N_2) in order to obtain the oxygen for metabolism. Denitrification is only carried out by specialised bacteria under anoxic (oxygen-free) conditions

detritus
Non-living organic matter once part of or produced by living organisms

duricrust
A hard crust on or layer in tropical soils predominantly formed from residual iron and aluminium oxides after soluble minerals (e.g. silicates) have been leached out

EAC
East Australian Current – the ocean current flowing southward along the seaward margin of the GBR and eastern Australia from about 15–16° S to southern New South Wales

echinoderm
An aquatic phylum containing the starfish, holothurians (sea cucumbers) and crinoids (sea lilies)

ENSO
El Nino-Southern Oscillation – a global-scale ocean-atmosphere interaction driven by oceanographic processes in the equatorial Pacific which strongly influences weather and climate in northern Australia. In Australia, ENSO events are characterised by a reduction or failure of the summer wet season as the Inter-tropical Convergence Zone (ITCZ) shifts eastward from Indonesia to the central West Pacific Ocean and the summer monsoon trough largely stays to the north of Australia. ENSO events typically occur every 2 to 7 years

eukaryotic
Organism comprised of one or more cells characterised by a complex internal structure, particularly with the genetic material (chromosomes) enclosed within a nucleus

eutrophic
Characterised by elevated nutrients, organic matter and plant productivity

eutrophication
The enrichment of a water body or ecosystem with organic matter or nutrients (eg.N,P), generally leading to an increase in biological productivity

evapotranspiration
Loss of water from a vegetation community through evaporation of surface and soil water and losses of plant water through pores in leaf tissues

foraminifera
Protozoan (both benthic and pelagic) producing a calcium carbonate shell. Some benthic foraminifera produce disklike calcium carbonate shells exceeding 1 cm in diameter

freehold
A land tenure status whereby a parcel of land and specified rights for its use are owned by an individual, family or corporate body

fringing reef
Coral reef growing along the coastline or margin of an island or continent

front
The horizontal boundary zone between two water or air masses

GCTB
Green Cane-Trash Blanketing – a now-common sugarcane harvesting practice where the mature cane is not burnt before harvesting. During harvesting, the cane leaves are mechanically stripped from the stalks and left to lie in the paddock, forming a blanket of leaf trash

groundwater
Water held in saturated sub-surface soil and porous rock

hard coral
A solitary or colonial coral species producing a hard skeleton of calcium carbonate

igneous
Rock formed directly from volcanic activity or solidified magma (e.g. granite)

isobath
Points at the same depth. Usually refers to a depth contour line

krasnozem
A deep reddish soil derived from basaltic rock, generally characterised by high levels of iron and other minerals (e.g. phosphorus)

laterite
A highly weathered and leached tropical soil largely formed of insoluble aluminium and iron oxides. Laterites often form crusts on the surface or layers and nodules within soils

leasehold
A land tenure status whereby a parcel of land remains the property of the state, but an individual, family or corporate body pays for the right to use the land for specified purposes

mangrove
A woody tree or shrub adapted to living in saline marine waters

marine snow
Large organic aggregates (visible to the naked eye) suspended in seawater. When viewed in situ, marine snow resembles floating snowflakes

median
An alternative statistic for the central value in a collection of data where half of the measured values exceed the median and half are less. Useful in place of a numerical average (mean) where a small number of large outlying values overly influence the value of the calculated average

metamorphic
Igneous or sedimentary rock transformed by intense heat and pressure to a different form (e.g. marble formed from limestone)

mineralisation
Biological conversion of organic matter to inorganic components (e.g. CO_2, NH_4^+, PO_4^{3-})

MYBP
Million Years Before Present

nearshore zone
Shallow marine waters, generally within 10-15 km of the coastline

nitrogen fixation
The microbial conversion of inert di-nitrogen gas (N_2) to metabolically useable forms of nitrogen. Nitrogen fixation is only carried out by specialised bacteria

no-tillage cultivation
Farming practice where the land is not plowed or tilled between crops in order to maintain the natural soil structure. When a new crop is planted, seeds are sewn directly into the ground. In the case of sugarcane, the next crop (ratoon crop) grows from the cut bases of the previous crop

oligotrophic
Low-nutrient, low-organic, low-productivity

paddock
Enclosed field or pasture

parasite
An organism living in close association with individuals of another species which derives benefit from that species without providing any benefit to its benefactor or host

PDO
Pacific Decadal Oscillation – a global-scale ocean-atmosphere interaction which influences global climate. The PDO is primarily driven by movements of large oceanic circulation gyres and mean atmospheric pressure over the North Pacific Ocean. Fluctuates over time scales of 10 to 20 years

pH
A shorthand measure of acidity. The pH of a water sample = –1 times the natural logarithm of the hydrogen ion (H^+) concentration. A neutral solution has a pH of 7. A low pH (< 7) indicates acidity while a high pH (>7) denotes an alkaline sample

phytoplankton
Plant plankton; generally microscopic single-celled algae and photosynthetic bacteria

plankton
Bacteria, plants and animals which live drifting in marine or freshwater. Many types of plankton can swim, but do so to move about in the water rather than stay in one location. Many benthic plants, animals and fish have spores or larval stages which live, drift and develop for days to months in the plankton before settling to the bottom and maturing

platform reef
Free-standing (unattached) coral reef rising steeply to the surface from a flat seabed

recruitment
A life process for many organisms when a larval or juvenile stage matures and is considered to be part of the adult population. For many reef and benthic species, recruitment refers to the changes occurring when planktonic larvae or juveniles attach to or take up residence on the bottom

riparian
The zone immediately adjacent to a stream or other water body. Describing vegetation adjacent to a stream or waterbody

sand slug
A large deposit of sand in a streambed or riverbed, several to many kilometres long which is gradually being moved downstream as bedload

seagrass
One of a group of flowering plants (angiosperms) which have adapted to live submerged in the ocean

sedimentary
Rock formed from deposited sediment (e.g. sandstone)

sessile
Non-mobile or physically attached to the bottom

shear zone
Where two water masses flow horizontally past each other at different relative speeds or directions

shelfbreak
The transition zone between the shallow continental shelf and the continental slope where the seabed slopes more rapidly to greater depths

soft coral
A solitary or colonial coral species lacking a hard carbonate skeleton. Soft corals are in a different family (octocorals) than hard corals

soil water
Water adhering to or trapped between soil particles

standard deviation
A statistical measure of variability in a group of measured values

symbiont
An organism living in a symbiotic relationship

symbiotic
Two or more organisms living in close physical association, with one or both organisms dependent to some degree on the other

taxonomy
Scientific discipline concerned with the identification, description and classification of organisms

taxonomist
A scientist who practices taxonomy. Because of the vast number and diversity of living organisms, taxonomists commonly specialise on one or a few groups of related organisms

terrigenous
Derived from the land

trophic
Relationships of nutrient and energy supply within an ecosystem

upwelling
An oceanographic process which mixes or lifts nutrient-enriched subsurface water into the surface layer

zooplankton
Animals living drifting with the water. Some animals spend their entire life in the plankton, while others spend only part of their life cycle drifting

zooxanthellae
Specialised microalgae (dinoflagellates) living symbiotically within the tissues of corals, giant clams and other reef organisms

Catchments and corals: terrestrial runoff to the Great Barrier Reef (2003)

Index completed by Mary Anne Temby, Feb 2005.