Large-Scale Hydrological Changes in Tropical Asia: Prospects for Riverine Biodiversity

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Various anthropogenic activities threaten the biodiversity of rivers and their associated wetlands at global and regional (Asian) scales and may well impair or significantly reduce the ecosystem services those rivers and wetlands provide. These threats can be placed in four categories: flow alteration or regulation (including impoundment by dams, water extraction for irrigation, and so on); pollution; drainage-basin alteration (especially deforestation); and overharvesting (mainly of fishes).

Researchers, increasingly aware of the potential impact of hydrologic alterations on biodiversity, have begun to focus on the environmental and social consequences of large-scale hydroelectric development (Rosenberg et al. 1997). Their attempts to predict the consequences of flow alterations on biodiversity in Asia, however, are confounded by the trend in the region toward more, and bigger, dams, as exemplified by the Three Gorges Scheme in China (Dudgeon 1995a).

In 1950 Asia had 1541 large dams (more than 15 m high), accounting for 30% of the global total (van der Leeden et al. 1990); by 1982 that figure had grown to 22,701 (65% of the global total). Most—18,595, or 82%—were in China. India, ranked fifth in the world (and second in tropical Asia) in number of large dams, had a comparatively modest total of 1085. Absolute numbers of dams have changed over the last several years, of course, but Asia's proportionate share of the global total of dams remains high.

[1]Tropical Asia is used here to refer to that area experiencing a monsoon climate and broadly overlapping with the Oriental biogeographic region (i.e., the part of Asia to the south of a line extending from the Indus River in the west [longitude 70° E] along the Himalaya and ending at the mouth of the Chang Jiang [Yangtze] River in the east [longitude 150° E]). This area includes China south of latitude 30° N, Southeast Asia, the East Indies, and the Indian Subcontinent. A bias toward Southeast Asia and southern China (i.e., Asia east of longitude 93° E) reflects my familiarity with this area.

THE CONSTRUCTION OF LARGE DAMS WILL HAVE AN IMPACT ON THE BIODIVERSITY OF TROPICAL ASIAN RIVERS AND THEIR ASSOCIATED WETLANDS

The natural hydrologic cycle

Table 1 lists the major rivers of tropical Asia.[1] Some of them—Chang Jiang, Mekong, Indus, Brahmaputra, Ganges, Irrawaddy, and Zhujiang, for example—are among the world's greatest rivers, in terms of their discharge and length and thus in terms of the biodiversity they might support. Discharge seasonality influences the biota and land–water interactions of tropical Asian rivers (Dudgeon 1992, 1995a, 1995b, 1999, Dudgeon and Bretschko 1996). The dominant influence of monsoons gives rise to a characteristic pattern (Figure 1) whereby predictable periods of drought in the dry season alternate with periods of increased discharge, spates, and floodplain inundation in the wet season. For many animals, especially fishes, these changes result in alternating periods of resource scarcity (during the dry season) and resource glut (during the wet season). The monsoon drives flood pulses (*sensu* Junk et al. 1989)—the predictable advance and retraction of water over the floodplain—and the life histories of aquatic organisms are timed to take account of

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Table 1. Features of major tropical Asian rivers.[a]

	Length (km)	Drainage area (km^2)	Mean discharge (m^3/s)
Chang Jiang (= Yangtze)	6300 (3)[b]	1,942,500	34,000 (3)
Mekong	4350 (12)	802,900	11,048 (15)
Brahmaputra	2900 (34)	934,990	19,824 (4)
Indus	2900 (34)	927,220	5533 (23)
Ganges	2510 (50)	1,051,540	18,691 (5)
Salween	2400 (52)	279,720	1493 (45)
Zhujiang (= Pearl)	2197 (62)	425,700	12,500 (14)
Irrawaddy	1992 (72)	429,940	13,565 (12)
Godavari	1465 (>100)	297,850	3597 (29)
Krishna	1290 (>100)	308,210	1954 (39)
Red	1200 (>100)	120,000	3900 (26)

[a]Raw data from van der Leeden (1975) and van der Leeden et al. (1990).
[b]Figures in parentheses indicate world rank.

land–water interactions and transfers of material that occur during the inundation phase. As Bayley (1995) has stressed, the flood-pulse is not a disturbance. Instead, a significant departure from the usual hydrological regimen—the prevention of floods, for example—can be regarded as a disturbance.

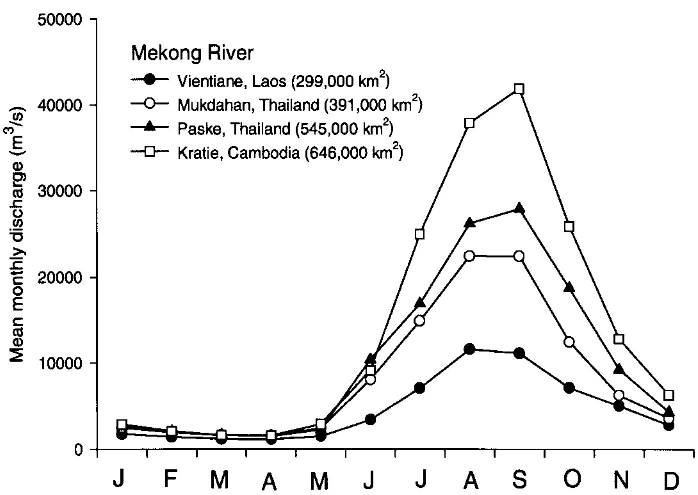

Figure 1. Discharge of the Mekong River at four stations along its course. The area of the drainage basins upstream of each station is given also. Raw data were averaged over at least 6 years and are derived from van der Leeden (1975).

This observation crystallizes the conflict between human modification of river flows and biodiversity conservation. Human populations in monsoonal Asia experience periods of water scarcity that alternate with months when water is plentiful or excessive and floods are frequent. The engineering response has been to capture and store water during flood times to use during the dry period. The benefits are amelioration of peak flows (i.e., flood prevention) and increased water availability during the dry season. In effect, the natural variability in the system, to which the biota are adapted and on which they depend (Dudgeon 1995a, 1999), is smoothed out. This averaging of the annual flow is especially significant because many geomorphic and ecological processes show nonlinear responses to discharge (Poff et al. 1997). Fish breeding migrations, for example, may not begin until flows have passed a critical threshold; a 25% increase in discharge may fail to initiate any population response.

Environmental degradation in Asia

Hydrological changes caused by dams do not occur in isolation. Typically, they interact with other threats to biodiversity. Reduced discharge downstream of dams, for instance, may concentrate pollutants, and deforestation alters flow regimes within drainage basins. In addition, climate change and global warming will alter precipitation and evapotranspiration across Asia, inevitably affecting river flows. Unpredictable and complex synergistic interactions among all of these anthropogenic influences can be anticipated in the light of ongoing and profound environmental change in Asia. Much of the region is characterized by large and rapidly growing urban complexes with associated problems of potable water supply, sanitation, water pollution, flooding, and depletion of groundwater aquifers.

A major challenge, therefore, is to reconcile the needs of the Asian populace with global interests in biodiversity conservation, and to match the pressures for economic growth with what the environment requires for maintenance and what it can supply at a sustainable rate. This situation will be difficult to achieve while demands on the resource base continue to increase. Total water consumption in Southeast Asia rose from 82 km^3/yr in 1900 to 187 km^3/yr in 1950, and to 609 km^3/yr in 1990. It will rise to a projected 741 km^3/yr in 2000 (Niacin 1992). Irretrievable water losses (mainly as a result of irrigation) increased from 65 km^3/yr (1990) to 142 km^3/yr (1950) to 399 km^3/yr (1990). The projected loss in 2000 is 435 km^3/yr. Water pollution and contamination degrade and reduce the resource base further.

Information on domestic wastewater treatment in Asia is fragmentary (Dudgeon et al. 2000) but treatment certainly covers very much less than 50% of the population; almost all sewage entering the River Ganges is untreated, and pollution from agricultural areas and nonpoint sources is largely uncontrolled. Legislation concerning discharge of untreated industrial effluents is in place in several countries (e.g., Thailand, Indonesia, and Malaysia) but is weakly enforced (Dudgeon et al. 2000). There is little evidence that Asian policymakers take into account the benefits that arise from nonconsumptive or nonextractive uses of the environment.

It is important to bear in mind that even unregulated rivers and streams in Asia do not have natural hydrologic regimes. Flow patterns have already been altered by changes to vegetation cover within catchments. The deleterious consequences of drainage-basin misuse and forest clearance are evident throughout the region, resulting in increased runoff, sedimentation, and flash floods (Dudgeon 1992, 1999). Deforestation in Asia, estimated at between 0.9% and 2.1% per annum (Fu et al. 1998), is a major regional issue and, when coupled with the natural patterns of high wet-season and low dry-season river discharge, has direct and profound impacts on floodplains and their inhabitants. In essence, large-scale changes in flow are an inevitable result of deforestation. In turn, they encourage the construction of dams to protect against floods, which further alter the hydrological regime.

However, there are signs of change in this cycle. In China, for example, devastating floods in 1998 (and the preceding 2 years) along the Chang Jiang drew attention to the link between catchment conditions and runoff. The official media blamed the floods on environmental destruction caused by years of uncontrolled logging (see also Dudgeon 1995a). Consequently, in September 1998, the national government introduced curbs on logging in natural forests and the Forestry Bureau announced plans to achieve 45% forest cover over the next 30 years in the upper Chang Jiang basin.

The consequences of drainage-basin degradation have been felt elsewhere in Asia. After devastating floods claimed several hundred lives in 1988, the Thai government banned logging in 1989 and revoked all logging concessions. Unfortunately, this decision has had detrimental effects on Burma, Laos, and Vietnam because it caused logging companies to shift their activities into these countries (Dudgeon et al. 2000).

Biodiversity overview

Tropical Asia is host to a disproportionate amount of the world's biodiversity, with tremendous species richness and high levels of endemism (Braatz et al. 1992). Nevertheless, it was not until the devastating Indonesian forest fires of 1997 that biodiversity in Asia received the same level of media attention that has been lavished on the Neotropics. Indonesia is among the top 10 countries in the world for numbers of species of flowering plants, birds, reptiles, and amphibians. It has more species of plants and birds than does the African continent. Indonesia supports at least 15% of the world's species and, in terms of aquatic biodiversity, has 900 species of amphibians and more dragonflies (666 species) than any other country (Braatz et al. 1992, Caldecott 1996). Because many of the Indonesian islands have been isolated for long periods, there is a high degree of endemism in the freshwater fauna.

Invertebrate biodiversity in Asian rivers has not been inventoried thoroughly and most species are probably undescribed. Nevertheless, surprisingly high diversity is manifest in certain taxa. The Mekong, for example, contains endemic species-flocks of stenothyrid and pomatiopsid gastropods (over 110 species) and a similar radiation has occurred in the Chang Jiang. Likewise, freshwater crabs are astonishingly diverse, comprising six families with more than 80 genera in Asia; at least 185 species occur in China and many more remain undescribed (see Dudgeon 1999).

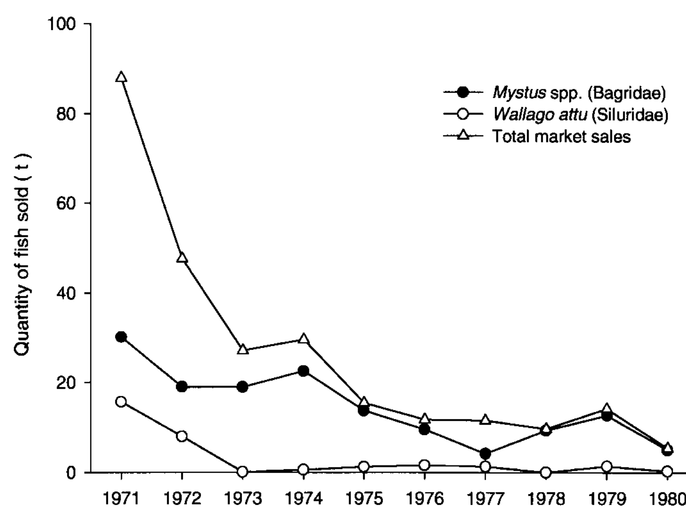

Figure 2. Sales of fishes captured from the rivers of Perak State, Peninsular Malaysia, 1971–1980. Figures are based on the quantities of fish sold in markets and exclude consumption by subsistence fishers. Raw data were obtained by the Fisheries Division, Ministry of Agriculture, Malaysia, and are derived from Khoo et al. (1987). These authors attributed the decline in fish sales to overfishing, pollution, and the effects of dams.

Apart from fish and invertebrates, the animals associated with tropical Asian rivers include freshwater dolphins, crocodilians, and a host of other herpetofauna. An array of mammals and many species of birds also rely on riverine habitats. Tropical Asia is particularly rich in freshwater turtles and supports the world's most diverse assemblage of these animals (Thirakhupt and Van Dijk 1994). Turtles are widely harvested across the region; Chinese communities provide a ready market for turtles and terrapins because many species are believed to have medicinal value. In combination with habitat degradation and flow modifications, detrimental impacts of harvesting on regional and, perhaps, global biodiversity of turtles and terrapins can be anticipated, and some species are already threatened (Belsare 1994, Thirakhupt and Van Dijk 1994).

Eight species of crocodilians. Among other aquatic reptiles, there are eight species of crocodilians in the region (Table 2). All but one (*Crocodylus porosus*, which also occurs in Australia) are endemic. The eight species are a significant portion of global crocodilian diversity (23 species).

Hydrologic alterations are among the human activities that threaten Asian species. Habitat destruction, human displacement, and hunting (especially for skins) are certainly contributing factors, but accidental capture in fisheries nets is an important cause of declines in mugger crocodile populations. The gharial is especially at risk from flow regulation because it prefers fast-flowing river habitats, which are prime sites for dams. This crocodilian is very scarce in the wild and numbers are dangerously low (Emanoil 1994). Likewise, the entire population of the Philippine crocodile consists of approximately 500 animals at a single site. Survey data for the critically endangered Siamese crocodile are inadequate, and the status of wild populations of the False gharial are uncertain because there are no estimates of population sizes.

Normally, juvenile crocodiles move into flooded areas to escape harassment or cannibalism from larger conspecifics, which remain in the main channel. When inundation is reduced as a result of flow regulation, juveniles will be confined within channels where they are unable to escape the depredation of adults (Montague 1983). Species such as the Chinese alligator (numbering about 400 in the wild) are dependent on river floodplains and marshes, areas that have been gradually converted to agriculture to the extent that this species is now "an animal without a habitat" (Thorbjarnarson and Wang 1999).

Terrestrial mammals. Many terrestrial mammals, including elephants, tigers and smaller cats, bears, and leaf monkeys, depend on the riverine habitat in the dry season for water, green fodder, cover, and refuge from fire. This fact seems to have been largely overlooked in the literature (Dudgeon 2000, but see Belsare 1994). Habitats used by terrestrial mammals include seasonally inundated grasslands and marshes on floodplains, as well as swamp forest, gallery forest, and peatswamp. Other mammals (such as orangutan, rhinoceroses, tapirs, pigs, deer, and otters) are associated with riverine wetlands throughout most or all of the year. These mammals include a variety of endangered, rare, or poorly known species of uncertain conservation status. Hydrological changes are likely to be detri-

Table 2. The conservation status of crocodilians in the Oriental Region.

	Range	IUCN status[a]	CITES appendix[b]
Chinese alligator (*Alligator sinensis*)	Chang Jiang (Yangtze) only	Critically endangered	I
False gharial (*Tomistoma schleglii*)	Malay Peninsula, Borneo, Sumatra, and possibly Sulawesi	Data deficient	I
Philippine crocodile (*Crocodylus mindorensis*)	Linguasan Marsh only (Mindanao, Philippines)	Critically endangered	I
New Guinea crocodile (*Crocodylus novaeguinea*)	New Guinea endemic	No listing	II
The mugger (*Crocodylus palustris*)	Indian subcontinent	Vulnerable	I
Fresh- and saltwater crocodile (*Crocodylus porosus*)	Widespread but nowhere abundant north of New Guinea; information on populations lacking over much of range	No listing	I/II (New Guinea)
Siamese crocodile (*Crocodylus siamensis*)	Mainly confined to Cambodia but a few animals in Vietnam, Thailand, and (possibly) Indonesia	Critically endangered	I
The Gharial or gavial (*Gavialis gangenticus*)	Indian subcontinent (excluding Sri Lanka)	Endangered	I

[a]International Union for the Conservation of Nature (now World Conservation Union) status refers to listing by WCMC (1996).
[b]CITES appendix refers to inclusion in the Convention on International Trade in Endangered Species of Wild Flora and Fauna. Appendix I includes endangered species, trade in which is normally prohibited. Appendix II includes threatened species, trade in which is controlled by permits.

mental to these mammals and may interact with other human impacts to further restrict their populations and habitat use. The proboscis monkey (*Nasalis larvatus*), which has webbed fingers and toes to facilitate swimming, depends on forested riverine wetlands and sleeps in tall trees along river banks. Swamp forest in central Kalimantan (Borneo) is key habitat for orangutan (*Pongo pygmaeus*). Malayan tapirs (*Tapirus indicus*) are riverine animals *par excellence*. They inhabit dense vegetation and swamp forest by day but venture onto marshy grasslands or floodplains to feed at night. Other mammals, such as otters (which are exceptionally well represented in Southeast Asia), otter civets (*Cynogale* spp.), the fishing cat (*Prionailurus viverrinus*), the flat-headed cat (*Prionailurus planiceps*), and the bay cat (*Captopuma badia*) are largely restricted to riverine wetlands. Hydrological changes on these animals and the gallery forest on which they depend cannot be predicted accurately, but are unlikely to be positive.

All three species of Asian rhinoceros are associated with rivers. Their combined total number is approximately equal to that of the rarer of the two African species, the black rhino (*Diceros bicornis*). Fewer than 100 Javan rhinos (*Rhinoceros sondaicus*) remain in the wild, dwelling in swampy forest along rivers. They are the scarcest of the three Asian rhinos and probably the rarest large mammal in the world. The Sumatran rhino (*Dicerorhinus sumatrensis*) makes seasonal movements into the hills when lowlands flood, descending at the end of the rains and spending much of the day wallowing in water. The Indian rhinoceros (*Rhinoceros unicornis*) is confined to grassy floodplains, a habitat preference confirmed by historical records indicating a range along the Indus, Ganges, and Brahmaputra Rivers.

In the recent past, expanses of swampy grassland mixed with sparse forest covered river floodplains in parts of Asia, providing ideal habitat for a complex of large grazing animals including Indian rhinos, various deer, and buffalo. During the nineteenth century, there were thousands of marshland deer living along the major rivers of India and Thailand. Until the seventeenth century, ecologically equivalent species were present in southern and central China. These deer are larger than congeneric species from drylands because of the high primary productivity of grassy floodplain. They have narrow habitat preferences that preclude the use of dry grassland, and have declined in numbers as floodplains have been drained, settled, and converted to agriculture, especially rice. Species or subspecies of marshland deer (e.g., *Cervus duvauceli*, *Cervus eldi*, and *Cervus schomburgki*) are, or were, confined to particular river systems. Some have splayed or unusually large hooves (e.g., *Cervus eldi eldi* and *Elaphurus davidianus*) that are sensitive to hard ground but are adaptive in marshy alluvial grasslands. Others have antlers bearing acutely angled tines or radial branching that restricts movement in forest and overhanging vegetation. *Cervus schomburgki*, now extinct, had the most elaborate antlers of any marshland deer, which effectively confined them to open floodplains (in Thailand) and magnified the risk of endangerment by humans. Père David's deer (*E. davidianus*) was exterminated from wetlands along the Chang Jiang, but captive-bred stock has been successfully reestablished in a small part of its original range. Further information on the status of mammalian biodiversity along Asian rivers is given elsewhere (Dudgeon 2000), but it is clear that many of these animals have declined in abundance due to human modification of the natural flood-pulse cycle in riverine wetlands.

Chinese stamps depicting endangered, migratory fishes of the Chang Jiang (Yangtze River), illustrating the flagship species approach to the conservation of aquatic biodiversity. Unfortunately, such stamps are generally marketed for sale as tourist souvenirs and are seldom used in China.

Fish biodiversity. The Indochinese Peninsula has more than 930 fish species in 87 families (Kottelat 1989), although existing inventories of the Asian fish fauna are far from complete. The Mekong Basin supports well over 500 species, placing it among the top three rivers in the world (after the Amazon and Zaire) in terms of fish biodiversity. Species totals for other Asian rivers are lower but impressive nonetheless: 290 species in the Kapuas River

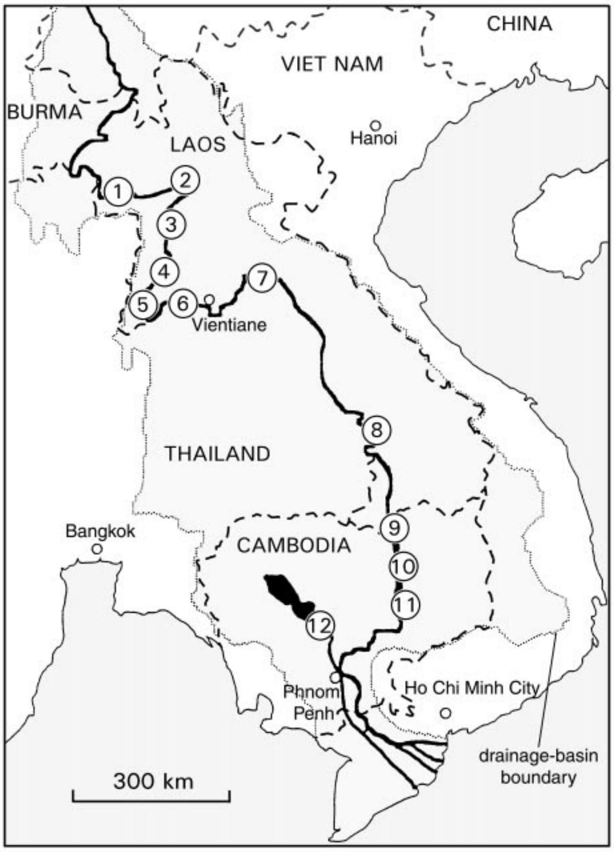

Figure 3. Locations of proposed hydropower projects along the Mekong mainstream in Laos, Thailand, and Cambodia (redrawn from Roberts 1995). The boundary of the Mekong drainage basin is shown also. Site characteristics are given in Table 4. Locations are as follows: 1, Pak Beng; 2, Luangprabang; 3, Sayaburi; 4, Pak Lay; 5, Chaing Khan; 6, Pa Mong; 7, Bung Kan; 8, Ban Koum; 9, Khone Falls; 10, Stung Treng; 11, Sambor; 12, Tonlé Sap.

(Borneo), 262 species in the Zhujiang (Pearl River, China), 150 species in the Salween River (Thailand), 147 species in the Mahakam River (Borneo), and 115 species in the Baram River (Borneo; Kottelat 1989, Liao et al. 1989, Dudgeon 2000 and references therein). If we consider richness of higher taxa, tropical Asia has 105 families of freshwater fishes compared to 74 in Africa and only 60 in South America. A summary of the generic diversity of freshwater fishes in tropical Asia (Table 3) highlights the richness of the fauna (292 genera), which differs substantially in composition from faunae in the Neotropics and Africa. The dominance of cyprinids, the importance of balitorids, and the lack of characids and cichlids are striking.

The potential fisheries production of tropical Asian rivers and their floodplains is extremely high (Scott 1991). The lower Mekong Basin, for example, produces an annual yield of 500,000 t in Cambodia, providing 40–60% of the animal protein intake of the human inhabitants of that region. In Bangladesh, where floodplains and the Ganges–Brahmaputra Delta (the largest deltaic system in the world) occupy approximately 80% of the land area, 5 million people depend on fishing for their livelihood. The annual harvest of fish, prawns, and frogs may reach 725,000 t, 64% of which comes from rivers and 16% from floodplain lakes.

Despite the manifest importance of inland fisheries, there is a trend throughout tropical Asia toward decline and species loss. Attention was drawn to this matter three decades ago (Johnson 1968), but anthropogenic threats (pollution, river regulation, overharvesting, deforestation, and other land-use changes) have persisted and have been exacerbated in recent years (Dudgeon 1992, 1999, 2000). The loss of fish biodiversity in tropical Asia has parallels in streams and rivers in all countries (Allan and Flecker 1993, Bruton 1995, Maitland 1995), and 20% of the world's freshwater fish fauna is already extinct or in danger of extinction in the foreseeable future (Moyle and Leidy 1992). There is a critical shortage of information on the conservation status of Asian freshwater fishes (Kottelat and Whitten 1996); one conclusion that could be drawn here is that extinction or endangerment of freshwater fishes on a global scale has been underestimated because little attention has been paid to Asian fishes.

The precarious state of many species and the contributions of hydrological alterations to their decline is exemplified by the Acipenseriformes (sturgeons and paddlefish) of southern China, especially in the Chang Jiang. Spawning migrations of the anadromous Chinese sturgeon (*Acipenser sinensis*) were blocked by the Chang Jiang Low Dam at Gezhouba in 1981, and fish passages were not provided. This dam has fragmented populations of the endemic Yangtze (or Dabry's) sturgeon (*Acipenser dabryanus*), which is now virtually extinct downstream of the dam (Wei et al. 1997, Zhuang et al. 1997). Populations of these potamodromous (i.e., migrating within river systems) sturgeons stranded below the dam were unable to spawn successfully because breeding was associated with an upstream migration. Even in upstream reaches, increasing sedimentation has negatively affected stocks of the Yangtze sturgeon.

Populations of the Chinese sturgeon below the dam have declined because changes in flows and riverbed characteristics have reduced spawning success. Dam building has also contributed to the greatly reduced abundance of Chinese sturgeon in the Zhujiang River (Liao et al. 1989), which is significant because the species occurs nowhere else but the Chang Jiang. The anadromous Chinese paddlefish (*Psephurus gladius*: Polydontidae) declined drastically in the Chang Jiang after the Gezhouba Dam blocked access to its upstream spawning sites and, because it occurs nowhere else, this fish will almost certainly dwindle to extinction (Wei et al. 1997). The loss of these three species will have potential impacts on the global biodiversity of Acipenseriformes, given that none of them occurs outside Asia and that *P. gladius* is one of only two paddle-

Table 3. Number of freshwater fish genera in major Asian rivers. Taxa that live in both fresh and salt water have been excluded. Certain species-poor families with restricted distributions are not listed but are included in the sum of total genera.[a]

	Ga[b]	Br	Ir	Sa	CP	Me	Re	CJ	MK	PM	Su	Bo	Ja	Total
Cyprinidae	23	22	25	30	42	54	52	84	32	37	31	35	16	147
Balitoridae	3	6	7	8	7	13	8	21	3	7	5	10	3	38
Sisoridae	13	10	13	11	3	4	4	4	2	2	2	2	2	19
Cobitidae	4	5	4	4	5	8	4	4	4	5	3	5	2	12
Bagridae	3	5	3	3	4	4	3	3	2	5	3	5	2	10
Belontiidae	2	2	2	0	3	3	1	1	3	6	6	6	4	10
Siluridae	3	3	3	3	6	6	1	1	4	7	7	8	4	8
Pangasiidae	1	1	1	1	6	5	0	0	2	3	3	2	2	6
Schilbeidae	5	4	3	3	0	0	0	0	0	0	1	1	0	6
Akysidae	0	0	1	1	1	1	0	0	1	3	4	4	2	4
Mastacembelidae	2	2	2	2	2	2	0	1	2	2	2	2	2	3
Nandidae	2	2	2	2	2	2	0	0	2	2	1	2	2	2
Clariidae	1	1	1	1	1	1	1	0	1	2	1	2	1	2
Anabantidae	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Channidae	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Notopteridae	1	1	1	1	1	1	0	1	1	1	1	1	1	1
Acipenseridae	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Polydontidae	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Catostomidae	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Osteoglossidae	0	0	0	0	0	0	0	0	0	1	1	1	0	1
Total genera	71	73	78	77	91	112	80	129	67	93	77	90	47	292

[a]Raw data from Kottelat (1989).
[b]Ga, Ganges; Br, Brahmaputra; Ir, Irrawaddy; Sa, Salween; CP, Chao Phraya; Me, Mekong; Re, Red; CJ, Chang Jiang; MK, Mae Khlong, PM, Peninsular Malaysia; Su, Sumatra; Bo, Borneo; Ja, Java.

fishes in the world. *Myxocyprinus asiaticus*, the sole catostomatid species in Asia (and the Old World), was greatly reduced in abundance following completion of the Gezhouba Dam, and the future of this potamodromous fish in the wild may be further threatened by the Three Gorges Dam (Dudgeon 1995a).

Changes in the status of fish stocks in the Chang Jiang River have been reasonably well documented, but data on fish populations or fisheries statistics for Southeast Asian rivers are scant. This situation exists despite the fact that countries such as Laos are landlocked and must depend entirely on freshwater fisheries; some monitoring of stocks

Table 4. Characteristics of 12 hydropower projects along the Mekong mainstream in Laos, Thailand, and Cambodia. Site locations are given in Figure 3. Site numbers refer to that figure.[a]

Project name and site number	Distance from sea (km)	Dam height (m)	Extreme flood level under natural conditions (m asl)[b]	Existing low-water level (m asl)	Length of inundated area behind dam (km)	Height of operating pool above extreme flood level (m)	Projected impact on river fisheries
1. Pak Beng	2188	39	345	301	120	0	Substantial
2. Luangprabang	2036	46	294	274	200	26	Major
3. Sayaboury	1930	36	254	234	80	16	Major
4. Pak Lay	1818	39	227	211	130	23	Substantial
5. Chiang Khan	1772	34	213	196	140	17	Substantial
6. Pa Mong	1651	37	188	170	120	19	Substantial
7. Bung Khan	1418	—[c]	—	—	—	—	Substantial
8. Ban Khoum	928	30	120	90	140	0	Major
9. Khone Falls	722	—	—	—	—	—	Major
10. Stung Treng	670	—	—	—	—	—	Major
11. Sambor	560	32	23	4	75	17	Major
12. Tonlé Sap	360	—	—	—	—	—	Major

[a]Data from Roberts (1995).
[b]m asl, meters above sea level.
[c]Dashes, data projections not available.

The Mekong: A case study

The Mekong (Figure 3) is ranked second in Asia in length, third in drainage-basin area, and fifth in discharge (Table 1). Plans to dam the Mekong date back to 1957 when a United Nations commission identified seven sites suitable for the development of water resources. The Mekong Committee was set up to coordinate water resource development of the lower Mekong Basin.

The Mekong Committee drew up a list of schemes on Mekong tributaries in Cambodia, Laos, Vietnam, and Thailand. War and political instability stalled the work for three decades but, as the situation stabilized, some small dams were constructed. To date, no dams cross the mainstream of the Mekong in its lower portion (i.e., south of the Burma–Laos border, which constitutes 75% of the total drainage basin).

This situation is unlikely to persist. In 1994 the Mekong Commission (successor to the Mekong Committee) identified 12 potential sites for hydropower dams along the mainstream in Laos, Thailand, and Cambodia (Figure 3, Table 4). Large dams have already been completed in the upper course. China, which is not a member of the Mekong Commission, completed the 1500-megawatt Manwan Dam in Yunnan Province in 1995. At least 14 more dams are planned. One prediction is that by 2010 the dams on the Chinese Mekong (the Lancang Jiang) will reduce downstream flows during the wet season and result in dry season discharges up to 50% greater than under natural conditions (Chapman and He 1996). The data for making informed decisions about the effects of flow management in the Mekong are still lacking, insufficient, or unreliable (Roberts 1993a). Nevertheless, enough is known about the ecology of the river to anticipate some of the effects of large-scale flow alteration. Here, I consider only effects on fishes, although consequences for other elements of the aquatic biota may be profound.

Many fishes in the Mekong River make upstream breeding migrations when water levels rise during the wet season; downstream migrations occur when water levels fall in the dry season. Upstream migrants spawn in inundated areas during the wet season and gather in the river channel or lateral lakes during the dry season. Other fishes follow the rising water and enter flooded forests, rice fields, oxbows, and swamps, which serve as feeding grounds, shelters, and spawning sites (for details, see Roberts 1993a, Roberts and Warren 1994, Roberts and Baird 1995). As a generalization, pelagic fishes, which have large silvery scales (whitefishes; Table 5) cover a greater distance when migrating than bottom-dwelling species (blackfishes; Table 5). Blackfishes have small scales or lack them entirely. They favor floodplains and inundated forest, making lateral movements between the main channel and fringes (Welcomme 1979, Regier et al. 1989). Many blackfishes can tolerate deoxygenation when waters far from the main channel become stagnant. They practice parental care (e.g., mouthbrooding, bubble-nest building), which reduces the death of eggs and fry in anoxic conditions. Whitefishes, by contrast, are egg scatterers that avoid severe conditions by long-distance migration. An expanded whitefish–blackfish classification includes an intermediate assemblage, the greyfishes (Table 5). They are scarcer than the other two groups of fishes in unmodified parts of the Mekong. Their behavior is facultative, with both migratory and static/territorial components, and they respond readily to changing hydrological conditions.

Dam construction on the Mekong mainstream will cause changes in discharge and floodplain inundation patterns that may suppress or fail to stimulate fish migration or reproduction. Any change in the timing and extent of inundation will have significant implications for biodiversity because fish production in tropical rivers is positively correlated with floodplain area and it fluctuates in relation to interyear variations in flood peaks (Welcomme 1979, 1995).

Dams will block the passage of whitefish migrants, including cyprinids and pangasiid catfish (*Pangasius* spp.). The latter makes up around 20% of total landings from the river. The impacts will be particularly severe on Mekong endemics such as the 3 m giant catfish, *Pangasius* (formerly *Pangasianodon*) *gigas*, which has already declined greatly as a result of overfishing, and *Pangasius krempfi*, which has a life history like that of a salmon and can exceed 1 m in length. In essence, these catfishes, as well as the large carps *Aaptosyax grypus* (a 1.3 m-long predator!) and *Probarbus labeamajor*, and the endangered freshwater herring *Tenualosa thibaudeaui*, could be driven to extinction by a single dam on the Mekong mainstream (Roberts 1995, Roberts and Baird 1995). Fish ladders, which may serve as a means to mitigate the impacts of dams on migratory fishes, are unlikely to be successful in the Mekong because most species in the river do not jump. Moreover, ladders are designed for species (e.g., salmon) that swim upstream only. Without provision of appropriate fish passages, adults returning on downstream migrations would have to pass through the dam turbines.

Other impacts of dams result from the effects of thermal stratification, which is typical of tropical Asian reservoirs with dams over 15 m high (Bernacsek 1997). Water released from the reservoir depths is cool and oxygen poor, or may be anoxic containing toxic hydrogen sulphide. All 12 dams proposed for the Mekong mainstream are at least twice the height needed to cause thermal stratification of impounded waters (Table 4).

One of the major dams proposed for the Mekong will block the Tonlé Sap River between Le Grand Lac of Cambodia and the Mekong mainstream (Figure 3). In the dry season, Le Grand Lac is 2500–3000 km^2 in extent; water drains from it into the Mekong. During the wet seasons, the Mekong rises and flows into Tonlé Sap River. Floodwaters enter the lake, swelling it to as much as 15,000 km^2 and inundating tracts of swamp forest. Fish move into the inundated area to feed and breed. This seasonal inundation maintains the lake's productive fishery. A dam on the Tonlé Sap River will alter this situation profoundly.

The impacts of smaller dams on Mekong tributaries have already been severe. For example, construction of Nam Theun Hinboun, a 210-megawatt hydropower project on a tributary of the Mekong (the Theun River) in Laos, began in 1994 after consultants had concluded that there would be no negative effects on fish (Usher 1996). This conclusion ignored a prediction that the river below the dam would be reduced to a series of pools during the 3-month dry season and degrade the habitat of 140 fish species that inhabit the Theun basin. Indeed, fisheries declined greatly following dam completion in 1998. The Pak Mun Dam on the Mekong in Thailand (completed in 1994) has likewise been extremely damaging to fish populations (Roberts 1993b, 1995). Such impacts are predictable and, given the right political will, can be ameliorated or avoided.

The deleterious effects of dams on river fisheries are often ignored because, supposedly, they can be compensated by the development of fisheries in newly created reservoirs. Fish yields can be enhanced by river impoundment, especially where low-order tributaries (not the river mainstream) are involved (Bernacsek 1997), but this increase usually depends on cage culture, stocking, or introduction of exotic species. It is invariably accompanied by a loss of native biodiversity.

What of the effects of global climate change on the annual flow regimes and biodiversity in the Mekong? The influence of water quantity on the life history of tropical river fishes parallels the importance of temperature to fishes in temperate latitudes. This water quantity consideration is important because one climate-change scenario derived from general circulation models (GCMs) of the atmosphere is that a doubling of carbon dioxide concentrations could change rainfall across the tropics by up to 2 mm/day (Meisner and Shuter 1992).

Different GCM models make varying predictions. One recent study projects changes in wet-season rainfall over tropical Asia in the range of –5% to +18% (McLean et al. 1998). Dry-season changes may be smaller and less consistent, but higher temperatures will increase evapotranspiration, reducing dry-season river flows. Extreme weather events will become more frequent; such changes seem likely to stimulate construction of additional dams for flood control and irrigation. Small changes of 0–15% have been projected for the annual discharge of the Mekong in the decade beginning in 2030 (Riebsame et al. 1995), but will be accompanied by greater seasonal differences in flows and delays in the flood peak. A reduction in hydropower generation from the dam cascade planned for the river mainstream may result. Modification of dam operation procedures (and some structural changes) will restore planned performance but will increase the impact of dams on fishes because of reduced downstream flows during the dry season. Indeed, one GCM scenario predicts that two tributary dams at Yali and Pak Mun will run dry for significant periods (up to 10% of the time at Yali; Riebsame et al. 1995).

Regardless of the details of GCM predictions, changes in the quantities and timing of water in the Mekong will have deleterious effects on fishes and other elements of the riverine biota. Impacts will be increased by the synergistic interactions of changed hydrology with other anthropogenic influences such as overfishing and habitat degradation.

Table 5. A comparison of the characteristics of the three ecological categories of river fishes.[a]

Characteristics	Whitefishes	Greyfishes	Blackfishes
Respiratory organs	Gills	Gills with some physiological adaptation to low dissolved oxygen	Gills plus supplementary air-breathing organs; adaptation to low dissolved oxygen
Respiratory tolerance	Well-oxygenated water	Medium to low oxygen tensions	Low oxygen tension (even anoxic)
Dominant sense	Eyes	Eyes; smell	Tactile; smell
Muscle-fiber type	Red	Red/white	White
Migratory behavior	Long-distance longitudinal	Short-distance longitudinal; relatively long lateral	Local and/or lateral
Reproductive behavior	Nonguarders, open substratum spawners, or egg scatterers	Guarders; nest spawners or open substratum spawners	Guarders; mouthbrooders and complex nest builders
Appearance	Round, streamlined, or fusiform; silvery or light	Laterally compressed; spines and/or heavily scaled; dark but often ornamented	Body form various (compressed or elongated); scales reduced or absent; dark or black
Main habitats	Main channel or flooded plain (may enter sea in dry season)	Main channel fringes, back-waters and floodplain	Floodplain water bodies, floodplain and marshy fringes

[a]Modified from Regier et al. (1989).

would seem prudent. As Figure 2 shows, the limited data indicate a long-term trend toward declining stocks despite considerable interyear variation in fish catches. Although information on catch quantities is lacking, there have been manifest declines in Mekong River fisheries (Roberts 1993a, Roberts and Warren 1994). Decreases in fish size at maturity (for 16 species) and reductions in total catches and catch per unit effort have been interpreted as evidence that the Mahakam River (Borneo) fishery is also overexploited (Christensen 1993). Fish catches from the Zhujiang (southern China) peaked during the 1950s but have declined since and, by the early 1980s, had fallen almost 40% (Liao et al. 1989). Landings of the migratory clupeid *Tenualosa reevesii* were reduced by 80%, and it has been almost eliminated from parts of the river.

Dam building, plus the effects of pollution and overfishing, are contributory factors. Dams blocked the migration routes of *Clupanodon thrissa* (Clupeidae) and *Cirrhinus molitorella* (Cyprinidae), reducing stocks to levels where they can no longer sustain a fishery in the Zhujiang. Elsewhere in the region, the effects of structures that alter natural flow regimes have been equally damaging. Fisheries in the Jamuna River (Bangladesh) have been reduced by more than 50% since 1983 (Smith et al. 1998) because flood-control embankments reduce fish access to floodplains. One outstanding study of Bangladesh fisheries suggests that annual losses as a result of flood-control and drainage projects approximate 65 kg/ha (Mirza and Ericksen 1996; see also Sultana and Thompson 1997). Similar consequences of flow regulation have been noted along the River Ganges, where the major carp fishery virtually disappeared after seasonal inundation of the floodplain was prevented by flood control structures (Natarajan 1989). Likewise, landings of anadromous *Tenualosa* (formerly known as *Hilsa*) *ilisha* (Clupeidae) from this river dwindled to virtually nothing after completion of the Farakka Barrage in 1975.

River dolphins. Asia is home to three species of true river dolphins (i.e., dolphins that never enter the sea) out of a global total of only five species (the others being Amazonian *Inia* spp.). River dolphins are indicators of environmental health (Smith et al. 1998), and the fate of these animals may be an apt metaphor for the devastation of river environments. Among Asian river dolphins, the baiji, or Yangtze dolphin (*Lipotes vexillifer*), is almost extinct (fewer than 200 individuals; Zhang et al. 1995) and is listed by IUCN (IUCN–The World Conservation Union; WCMC 1996) as critically endangered. The total population of the Indus dolphin (*Platanista minor*) is estimated at fewer than 1000 individuals, perhaps in the low hundreds (Reeves and Chaudhry 1998). Both this species and *Platanista gangetica* are listed as endangered by IUCN. *P. minor* is confined to the highly regulated Indus River (67–75% of the flow is diverted into irrigation canals); essentially, the dolphins are living in an artificial waterway and populations are fragmented by dams (Reeves and Leatherwood 1994).

A particular problem is that, during floods, some of the river dolphins enter irrigation canals or channels downstream of dams, where they perish when water levels fall during the dry season. Other threats to *P. minor* include deliberate and incidental capture, pollution, and other habitat degradation (Reeves and Chaudhry 1998). *P. gangetica* is more abundant (occurring in Nepal, Bangladesh, and India) but populations have been fragmented by dams. River embankments prevent access to productive floodplain habitats, and the dolphin populations are reduced by pollution, dredging, directed hunting, and fisheries bycatch.

P. gangetica shows highly specific use of feeding habitats such as scour pools in the river mainstream and, in the Brahmaputra, dolphins migrate from the mainstream to tributaries for feeding during the wet season (Mohan et al. 1998, Smith et al. 1998). Reproduction is stimulated by increased discharge and turbulent river flows and may be accompanied by migrations (Belsare 1994). *P. gangetica* does not breed in impoundments; one isolated population in the Brahmaputra showed annual reductions of 14–29% between 1992 and 1995 (Mohan et al. 1998). Thus, unregulated or near natural flows are required to ensure the survival of dolphin and the fishes they feed upon. Habitat changes in the Chang Jiang caused by the construction of dams and floodgates, which prevent exchanges between the river and its lateral lakes, create unfavorable conditions for *L. vexillifer* (Reeves and Leatherwood 1994). Hydrological alterations, in combination with mortality caused by fishing and river-traffic accidents, may well drive this dolphin to extinction.

The Irrawaddy dolphin (*Orcaella brevirostris*) occurs in estuaries and enters rivers in many parts of tropical Asia but has disappeared from areas of former habitat in recent years (e.g., the Chao Phraya in Thailand; Baird and Mounsouphom 1994). This dolphin can live permanently in fresh water and appears to be an ecological equivalent of the Amazonian dolphin *Sotalia fluviatilis*, which thrives in riverine and estuarine habitats. The Irrawaddy dolphin is less threatened than the true Asian river dolphins. It is widespread but highly localized at low population densities within its range (Belsare 1994); Dhandapani (1997) believes that this dolphin should be classified as rare by IUCN. Recent research suggests that populations of *O. brevirostris* in the Mekong River have fallen because of declines in fish prey and death of animals trapped in gill nets. Large-scale dams proposed for the basin (see pages 800–801) will pose significant threats to these dolphins because they will restrict movements and block access to habitats upstream (Baird and Mounsouphom 1994). Asian rivers (such as the Chang Jiang) are also home to the finless porpoise (*Neophocaena phocaenoides*), which travels far upstream from the sea. When inland, they are affected by the same anthropogenic factors as river dolphins.

Research needs: Opportunities and initiatives

Conservation efforts in tropical Asia are piecemeal and reactive, as evidenced by the state of Asian inland waters. Conservation action would be far more effective if we could avoid species loss and habitat degradation. This approach would require an ability to predict the elements of the river biota that are most vulnerable to extinction and to identify their ecological attributes (e.g., obligatory breeding migrations, use of different habitats at different stages of the life cycle, extent of habitat occupancy). A related point is the need to assess the health of the river community and to monitor changes in it over time. Measurement of fish diversity offers an obvious and relevant indicator of health. There is an evident need to develop indexes of biotic integrity, as formulated for North American fish (Karr 1991, Simon and Emery 1995), that are relevant for the Asian river biota. For instance, the occurrence of exotic fishes seems likely to signal disruption in community integrity. Further refinement might involve a scoring system for the presence of an array of functional groups (e.g., predators, benthivores, algivores, surface-insectivores, detritivores/macrophyte feeders). This knowledge is important because most biomass in the lower reaches of rivers is concentrated in comparatively few species adapted to process detritus or fine organic particles (Welcomme 1995). If these key species are reduced in number or eliminated, trophic pathways will change drastically and total fish productivity will fall. On the other hand, elimination of predators may result in the proliferation of smaller species.

The initial development of an index of biotic integrity for Asian rivers could make use of broad generalizations about the breeding strategies of river fishes. Flow alteration tends to make river channels more homogeneous, restrict access to the floodplain, and limit long-distance migrations, but the diversity of fishes in the system depends on maintenance of a variety of habitats. Blackfishes and whitefishes have specific requirements for fluctuating river water levels and unimpeded access to upstream or floodplain sites. Greyfishes, by contrast, are more flexible and can adapt to altered flow regimes (Table 5). The relative proportions of the three categories of fishes will alter in response to changes in river hydrology, with greyfishes (or generalists) becoming more abundant in modified systems and the abundance and diversity of blackfishes and (especially) whitefishes decreasing in proportion to the extent of flow modification.

An appropriate biotic index for Asian rivers seems likely to be based on fish species richness, breeding habits, and feeding behavior rather than on alterations in relative abundance or population size. Detecting the onset of environmental degradation resulting from flow regulation is problematic because subtle but important trends in the abundance of individual species (especially rare species) are rarely discernable early enough to permit appropriate remedial action. The initial stages of impact are likely to produce effects that fall within the range of natural variability observed in lotic communities. We lack data on the magnitude of natural variation among seasons or years. How then can we detect annual decline in abundance (or species loss) of, say, 1–5%? Obviously such a loss would have devastating cumulative effects over time. The imprecision inherent in assessment procedures has implications for river fishes in Asia, which often have a complex life cycle and different habitat requirements at various stages of their life history. As a result, there are many routes of exposure to toxins, direct harvesting, and other detrimental influences.

A major obstacle to reliable prediction of the effects of changed hydrology on riverine biodiversity is the paucity of information on the breeding habits, productivity, and seasonal dynamics of tropical Asian river fishes (Roberts 1993a). Basic ecosystem data, such as the contribution of different habitats and taxonomic groups to production, is almost entirely lacking for the major rivers of the region (Dudgeon 1999). Although a shortage of knowledge is an obstacle to effective conservation and management, this problem should not be overstated. Fish assemblages throughout the world *seem* to behave in a similar manner in response to externally imposed biotic and abiotic stresses (Welcomme 1995), although our understanding of the dynamics of large rivers is limited by the amount of data available from these complex systems. What action can be recommended now? Given the importance of flow fluctuations in determining the breeding adaptations of the lotic animals, it seems obvious that water allocation strategies that mimic natural discharge will be needed to maintain biodiversity (Poff et al. 1997). However, there is considerable year-to-year variation in river discharge, and deforestation (as well as the possible effects of climate change) has made hydrographs increasingly flashy in recent years. Thus, mimicking existing flow regimes may be less important than maintaining a pattern of alternating low and high flows. This water allocation strategy does not, unfortunately, take account of threshold effects of changes in flow, but it will be better than none. Moreover, it may have a better chance of implementation than a requirement to maintain a natural hydrograph and could be refined when (and if) detailed data on responses of the biota to flow become available.

Even with good predictive ability and biomonitoring strategies with the sensitivity to detect the onset of habitat degradation, the progression from knowledge to conservation action is not automatic. Clearly, we must provide policymakers with the best scientific information, but we cannot assume that they will act on it because sociopolitical considerations constrain conservation of riverine biodiversity in Asia. Pressure on governments and policymakers to regulate the flow of rivers to control flooding, provide irrigation water, and generate hydroelectric power is intense. As a result, flow regulation, habitat degradation, and fragmentation are epidemic.

Effective habitat conservation will require forceful demonstrations of the benefits to be gained from the integrated use of rivers, floodplains, and riparian habitats *as wetlands* if we are to prevent their conversion to other uses. Provision of information on the value of these environments and their biota is an essential first step in this process. Moreover, if the continuous increasing endangerment of aquatic biodiversity, especially fishes, is to be halted, then the economic costs of environmental degradation to future generations will need to be included as part of the cost of doing business today (Moyle and Moyle 1995).

One possible conservation initiative would be the identification of flagship species, which can be used to increase the environmental profile of riverine biodiversity. The flagship approach has been employed in conservation of fishes in the Amazon River. For example, because of its fruit- and seed-eating habits, the Tambaqui (*Colossoma macropomum*: Characidae) has become an ichthyological symbol of the Amazonian rainforest and the need to protect floodplain habitats (Araujo-Lima and Goulding 1997). Application of the flagship-species approach in Asia could involve the clown loach (*Botia macracanthus*) of Kalimantan and Sumatra, whose colors rival those of the gaudiest coral-reef fish and which is (in biomass terms) possibly the most important wild-caught aquarium fish in the world (Kottelat and Whitten 1996). Because the clown loach is heavily exploited and undertakes breeding migrations, it can represent a diversity of river fishes occupying a range of habitats. The Mekong giant catfish also has appeal as a potential flagship species; it is listed in *The Guinness Book of Records* as the largest freshwater fish in the world. The Malayan tapir might be adopted to represent mammalian biodiversity of Asian riverine wetlands.

The identity of flagship species is less important than the use of such emblems: Biodiversity icons are needed to provide a focus for conservation action and media attention. As the photo on page 797 shows, the Chinese government has taken some initial steps to highlight flagship species and enhance conservation awareness by portraying the endangered Yangtze sturgeon, Chinese sturgeon, and Chinese paddlefish on attractive stamps. Although this gesture will not by itself save any sturgeons, the very fact that the Chinese government supports conservation efforts is a minor success story.

Concluding remarks

Economic constraints in Southeast Asia may prevent construction of dams along the Mekong and other rivers in the near future. However, given the potential benefits to the human population of the region, the development of hydropower and other water resource schemes are likely. Laos, for example, is one of the world's poorest countries (annual per capita income less than US$300) and depends largely on rain-fed agriculture; average life expectancy is only 49 years (Jacobs 1994). Similar poverty has led the Thai government to formulate a master plan for dam building and drainage-basin development in the northern and northeastern parts of Thailand, the poorest parts of the country. Without hydropower to underpin economic development, Thailand will burn more lignite and Cambodia and Laos will continue to clear their forests for fuelwood. Thus, environmental damage and some loss of biodiversity seem inevitable.

Although understanding of the natural dynamics of tropical Asian rivers is still extremely limited and information on the most basic aspects of the biology of many important or endangered species is lacking, enough is known to permit some predictions. River fishes, crocodilians, dolphins, and other fauna face an array of threats. The present situation is one of species loss and declining biodiversity; foreseeable developments seem likely to exacerbate these trends. The prognosis is grim. Dam building will alter patterns of flow and inundation, block migration routes, and fragment populations. Projections from climate-warming models suggest that river discharge patterns will change, perhaps resulting in more severe floods and lower flows during the dry season. Hydrologic behavior will also be altered by deforestation and other land-use changes in the densely populated drainage basins that characterize tropical Asia. Pollution, already ubiquitous, is likely to increase as a result of the stimulus industry will receive from hydroelectric power generation. In essence, the annual pattern of flood flows, to which river fauna is adapted, will alter irreversibly.

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