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Processes of wetland loss in India

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Summary

Wetlands in India supply crucial human and animal needs such as drinking water, protein production, fodder, water purification, wildlife habitat, and flood storage. Increased appreciation of uses and threats is essential to protect wetlands where justified. Three quarters of India's population is rural, it places great demands on India's wetlands and losses continue to occur. This paper is based on extensive discussions with natural resource managers, government employees, farmers, academicians, and resource users at dozens of sites in India, as well as an extensive literature search. Twelve important kinds of wetland loss are identified and mechanisms believed to be causing them discussed: (1) agricultural conversion, (2) direct deforestation, (3) hydrologic alteration, (4) inundation, (5) defoliation, (6) altered upper watersheds, (7) accumulative water demands, (8) water quality degradation, (9) wetland consolidation, (10) global climate change, (11) ground-water depletion, (12) exotic species and biodiversity. Wetland understanding, management, and public awareness in India must continue growing if wetland resources are to remain functional.

Keywords: India, Wetland, Habitat Degradation, Causes, Sustainability

Introduction

Human systems are considered to benefit from wetlands through water filtration, flood protection and production of renewable resources (Mitsch & Gosselink 1986). With continuing losses and enhanced appreciation of the values and functions of wetlands during the last 20 years, wetland loss has become a world-wide concern leading to international agreements such as the RAMSAR convention (IUCN 1990). Current loss rates can lead to serious consequences in densely populated countries such as India, where 74% of the human population is rural (World Development Report 1994) and many of these people are natural-resource dependent. Healthy wetlands are essential in India for sustainable food production and potable water availability for humans and livestock. Wetlands are also necessary for the continued existence of India's diverse populations of wildlife and plant species; a large number of endemic species are wetland-dependent.

Most problems in India's wetlands are related to human population. India contains 16% of the world's population, yet the Indian subcontinent constitutes only 2.42% of the Earth's surface. The 1990 Census reported India's population to be approximately 844 million, with a country-wide population density of 267 people per km^2 (Government of India 1993). In the past, ecological impacts and linkages between human population increase and wetland loss have not received sufficient attention in the literature (however, see Singh 1995; Gopal 1994). Understanding the interplay between human activities and ecological responses that cause wetland degradation may provide clearer foci for development planners, natural resource managers, and leaders in the natural resource arena who seek to intervene in the processes of wetland loss. Research needs to be conducted on specific problems, but the lack of management and implementation of wetland protection and restoration is in our view a much greater problem.

Though specific amounts are not well quantified, the landscape of India has contained fewer and fewer natural wetlands over time (Fernando 1984). Restoring converted wetlands is an unlikely prospect once the sites have been occupied for alternative non-wetland uses. Therefore, the demand for wetland products (e.g. water, fish, wood, fibre, natural foods, medicinal plants) that are not provided in abundance by intensive cropping will increase as the population of India increases. Consequently, resource allocation problems are expected to increase, indicating a greater need for advanced planning and organized management of common property resources. Where we discuss wetland values, we refer primarily to ecological values, though overlapping cultural, economic and ecological values may be inseparable.

Wetland loss terminology

We interpret *wetland loss* to mean a physical loss in areal extent of wetlands or a significant and obvious reduction of wetland functions. Loss rates are a function of the total areal extent of the loss, and of the time interval selected over which to examine that loss. True conditions may be misrepresented if the loss of wetlands is not understood in the context of a time span. For example, natural cycles of sea-level rise in the geological record provide evidence of massive changes in coastal wetlands. Hawkins (1986, p. 451) states that many exposed marine terraces indicate higher sea levels; such terraces are present in parts of Gujarat and Tamil Nadu. When coastal wetland loss is annualized, it is shown to be a trivial amount per year over the long time-spans involved, and wetland losses expressed as percentages can also be misleading. For example, the most rapid rate of absolute wetland loss in the world (90 km^2 per year) is currently taking place among the coastal wetlands of the southern United States (Barras *et al.* 1994), but this loss only constitutes an annual loss of 0.83% of the total extent of wetlands present in the region. Even less apparent from wetland loss figures are the associated social and economic consequences for resource-dependent communities. The loss of one km^2 of wetlands in India will have much greater human impacts than the loss of one km^2 of wetlands in low population areas of abundant wetlands such as the

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Amazon basin or northern Canada. Depending upon their presentation, wetland loss figures may serve to alarm or to placate readers.

We have divided wetland loss issues into two broad groups for ease of discussion. *Acute losses*, which will be discussed in the first four issues, result from factors that operate for a brief period, usually less than 1 year. The filling of wet areas with soil constitutes a type of acute wetland loss. *Chronic losses*, which will be addressed in the subsequent eight issues, occur over several to many years and are often the result of multiple impacts which tend to accumulate over time. An example of chronic loss is seen in the gradual elimination of forest cover in a river's watershed with subsequent sediment erosion that fills downstream wetlands, thereby reducing their area over a period of decades.

The term *mechanism* is used here as the combinations of operative factors and processes that result in wetland loss. Mechanisms of loss are usually estimated through observation, then when funding becomes available they are subsequently tested and quantified with an organized research programme. Therefore, a clear understanding of wetland loss requires knowledge of the total area of wetlands existing initially, the amount of wetlands converted to non-wetlands, the time interval of loss, and the mechanisms of wetland loss. This clear understanding of wetland loss is one of the most powerful management, policy, and educational tools available for ecologically-based restoration efforts. In India this understanding is just beginning to develop.

Wetland ecosystems consist of multiple, linked components (waterways, habitat types, plant stands, and animals on the site) that exchange components through energy flows, chemical and physical transfers, moving biota, and water flows. Hence, we consider watershed alteration (Issue 6), grazing (Issue 5), and biodiversity (Issue 12) as crucial influences on the existence and function of India's wetlands. Because there are many strong links between the 12 issues related to wetland loss in India which we identify, we cross reference some of these linkages and our perceptions of their strengths in Table 1.

Table 1 Summary of linkages between 12 Issues by strength of association

Issue	*Issues Strongly Associated*	*Issues Moderately Associated*
1. Agricultural conversion	2, 3, 5, 6, 7, 8, 11, 12	4, 10
2. Deforestation	1, 6, 8, 10, 12	5, 7, 9, 11
3. Hydrologic alteration	1, 4, 6, 7, 8, 9, 11	10, 12
4. Wetland inundation	3, 6, 7, 8, 10, 12	1, 9
5. Defoliation	1, 6, 8, 9, 11, 12	2, 7
6. Alteration of upper watersheds	1, 2, 3, 4, 5, 7, 8, 11, 12	10
7. Accumulated water demands	1, 3, 4, 6, 8, 9, 10, 11	2, 5
8. Reduced water quality	1, 2, 3, 4, 5, 6, 7, 9, 11	12
9. Consolidation of small wetlands	3, 5, 7, 8, 10, 11	2, 4
10. Global climate change	2, 4, 5, 7, 9, 11, 12	1, 3, 6
11. Ground-water depletion	1, 3, 6, 7, 8, 9, 10	2
12. Biodiversity and extinction	1, 2, 4, 5, 6, 10	3, 8

Acute wetland losses

Issue 1. Agricultural Conversion

It is an ecological irony that as a result of rice culture, the gross areal extent of wetlands on the Indian subcontinent is probably greater today than it was 3000 years ago. Rice farming, a wetland-dependent activity, has been developed in virtually all suitable floodplains, riparian zones, river deltas and savannah areas in India. Noteworthy rice paddy conversion areas include DePar bil (Assam), Hokarsar Lake (Kashmir), and the Pyagpur and Sitadwar Jheels (very wet marshy areas) near Lucknow in Uttar Pradesh (Fig. 1). Koleru Lake in Andhyra Pradesh has lost 34 000 ha of natural wetlands to agriculture thus far (Anon. 1991). Furthermore, as a result of captured precipitation and the diversion of stream flows into catchment areas, fish-pond aquaculture and rice farming also occupy areas that were not previously wetlands, thereby robbing water from downstream natural wetlands. There are 1.6 million ha of freshwater fish-ponds in India (Anon. 1993). Rice fields and shallow fish ponds are technically wetlands even though they rarely function like natural wetlands. Energy flows in these systems are very simple and are focused on the crucially important job of food production. Of the estimated 58.2 million ha of wetlands in India there were 40.9 million ha under rice cultivation in 1993 (Anon. 1993). The rich alluvial soils of the Gangetic plain, with their easy access to water, constitute one of the most intensively cultivated regions of the world. Rice fields along the Ganges River can produce great quantities of human food, yet such agricultural wetlands lack many of the other wetland functions that provide benefits to society (Fernando 1977). Functions such as flood-buffering capacities, water-quality enhancement, sediment trapping, sewage filtration, wildlife habitat and small-scale landscape diversity are reduced in these agricultural systems. Conversely, in some regions devoid of wetlands, the construction of fish ponds for private use or the diversion of water for rice culture appear to have improved ecological values by adding a component of habitat diversity to the landscape. In the dry regions of neighbouring Sri Lanka, linked complexes of rain catchments, rice paddy fields and buffalo wallows support fish populations that traditional villagers depend upon (Ulluwishewa 1995).

Coastal wetlands (mangroves and former salt flats) have been converted to salt evaporation ponds in the western coastal zone of the Indian state of Gujarat as well as in eastern Tamil Nadu areas around Lake Pulicat. Salt is extracted from the sea when sea-water is trapped at high tide, then held in expansive shallow ponds to evaporate the water and concentrate brines to form salt crystals. These systems greatly alter the resident biota. Although brine ponds are used by some wading birds such as flamingos (*Phoenicopterus roseus* and *Phoeniconaias minor*), ecosystem losses appear in the form of reduced tidal energy and export of detritus (decaying plant and animal materials) to ocean near-shore areas (de la Cruz 1978; Montague *et al.* 1987). In natural estuaries the flow of detritus and soluble soil nutrients initiates a food-chain where microscopic organisms thrive, shrimps and crabs feed on detritus and micro-organisms, fish forage on the shellfish, and birds, wild mammals and humans feed on the fish and the shellfish. Blockage of such exchanges clearly impacts the ecological dynamics of the estuary (Savenije & Pages 1992).

Issue 2. Direct deforestation in wetlands

Mangroves are specialized, flooding- and salt-tolerant shrubs and trees that grow along the coasts in the tropics. In India, mangrove forests are valued for production of fish and shellfish, livestock fodder, fuel wood, building materials, local medicine, honey and beeswax, and for extracting chemicals used in tanning leather (Ahmad 1980). Alternative land-uses of farming and fisheries production have replaced many mangrove areas and continue to pose threats to the forests. Eighty per cent of India's 4240 km^2 of mangrove forests occur in the Sundarbans and the Andaman and Nicobar Islands (Government of India 1991) where 59 species of mangroves occur

(Singh 1994). However, in many coastal states mangroves are under severe pressure. The demand for shrimp has provided an economic incentive to clear coastal mangroves and develop shallow, open-water shrimp ponds. In the estuaries of Bhitarkanika National Park, the illegal clearing of mangroves for prawn ponds in interior tidal areas constitutes a management and enforcement problem for resource managers (Sanjeeve Kumar Cheda, District Forest Officer of Mangrove Forests, personal communication 1994). Mangrove regeneration can be relatively rapid because mangrove species sort themselves along hydrologic and salinity gradients according to competitive interactions (Smith 1987), however the replacement of an original mangrove species complex may take a long time, especially if the hydrology has been changed.

One estimate is that 85% of India's original mangrove cover has been lost since pre-agricultural times and that only 1894 km^2 remain (Anon. 1991). However, the Government of India (1991) estimated 4240 km^2 of mangroves remain while recognizing that mangrove deforestation in India has not been measured satisfactorily. Whatever the rate, India's mangrove loss is likely to follow the pattern documented by Primavera (1991), who showed that 70% of the Philippines' mangroves have been cleared and replaced by shrimp ponds during the previous 15 years. In Southeast Asia the production of cultivated shrimp in 1990 was almost 7 times the amount measured in 1982 (Conner & Skladany 1991). Crucial ecosystem-level functions such as buffer zones against storm surges, nursery grounds and escape cover for commercially important fish, sustainable levels of minor forest product extraction, and sediment trapping ability were lost. Shrimp ponds also caused excessive freshwater withdrawal and produced pollution (increased lime, organic wastes, pesticides, chemicals and disease organisms) that was flushed into the remaining mangroves adjoining the ponds. The greatest human impacts of habitat losses were borne directly by local people who depended on the mangrove ecosystems for natural materials, fish protein, and revenue (Primavera 1991).

The loss of wetland forests, whether coastal or riverine, reduces the ability of wetlands to slow water and trap suspended sediments. Chilka Lake, in the northeastern India state of Orissa, is the largest brackish lake in the country. The lake is being filled with sediments and the total lake area has been reduced from 860 km^2 to 605 km^2 in the last 60 years due to the growth of shoreline mud flats and an invasion of wetland and upland plants (Malini *et al.* 1993). The entire Chilka wetland complex, including the lake area, covers 1165 km^2 and the lake bottom is being filled with water-borne sediments from the Daya and Bhargavi Rivers (IUCN 1990). Sediments are also clogging the tidal exchange channels which formerly connected the lake to the Bay of Bengal. The downstream effects of erosion in mountainous areas are silt deposition, severe flooding during the wet seasons and lower than normal water levels in the dry season (Hawting & Mateo 1987). In the case of Chilka, the increased sedimentation rate appears to be a result of deforestation in the upper watershed and subsequent erosion of exposed soil. Along with these changes has come a reduction in the fish output from Chilka from 1970 to the present and the impoverishment of the 12 250 fishermen who fish there (Das *et al.* 1990).

The ecological linkages between land alterations, such as deforestation, and the downstream effects on wetlands, lakes, fisheries and people are apparent. There is a striking set of Indian deforestation estimates: India sustained a 4.1% annual loss of forested area which translates into approximately 1.5 million ha of woodlands per year for the 1975–82 period of study (B.B. Vohra, cited in Anon. 1990). Except for the relatively small Costa Rican forests, India sustained the highest rate of (dry) tropical deforestation in the world, primarily through agricultural conversion, fuel wood harvesting and land-uses leading to desertification (however, see Chatterjee [1995] for a restoration case study in India). For more details on deforestation in the upper watersheds, see the discussion under Issue 6.

Issue 3. Hydrologic alteration

Altered hydrology can dramatically change the character, functions, values and appearance of wetlands. The most profound changes in hydrology involve changes which either remove water from wetlands or raise the land-surface elevation to the point where it no longer floods. The growth of India's Salt Lake City, on the eastern outskirts of Calcutta, is an example of wetland filling that has converted over 4000 ha of productive wetlands into a filled area that is ready for development. It is alleged that this wetland replacement led to the loss of 25 000 metric tonnes (t) of commercial fish production from Calcutta's markets (Chopra 1985). Erosion of cleared hillsides indirectly eliminates wetlands by filling ponds and river courses (called 'nullahs') and building up river outwash areas as described in Issue 8 in relation to siltation.

Major canal dredging operations have been conducted in India since the early 1800s. The East Jamuna Canal was opened in 1830 and the Ganges Canal in 1855 to irrigate the land between the rivers (locally known as 'doab'). Canal dredging has continued at a rapid pace. There were 3044 km^2 of irrigated land in India in 1970, whereas by 1990 there were 4550 km^2 (Anon. 1994). Initial increases in crop productivity gave way to reduced fertility and greater water demands to flush the soil salt accumulations inherent in irrigated farming of arid soils. These canals and others like them have impacted the river hydrology and the annual water balance of downstream peatlands, wetland basins and riparian zones. In most cases canal systems are developed to bring water to a farming location, but in some cases they function to drain areas too wet to grow crops. Despite its overall aridity, India has 32 000 ha of peatland remaining (Andriesse 1988) and drainage of these lands usually leads to rapid subsidence of the soil surface. In Southeast Asia 50–100 cm of subsidence normally occurs in the first years of drying through canal drainage (Andriesse 1988) and the local hydrology is altered significantly for centuries.

Issue 4. Inundation by dammed reservoirs

There are currently more than 1550 large reservoirs covering more than 1.45 million ha and more than 100 000 small and medium reservoirs covering 1.1 million ha in India (Gopal 1994). Impoundment of water for controlled release is usually carried out in areas that formerly supported river corridor and backwater wetlands. By impounding water, the hydrology of an area is significantly altered, providing an opportunity to use moving water as a source of energy. In the mountainous regions of India, the government plans to harness that energy with dams and reservoirs for the production of electrical power. While the benefits of hydroelectric power are recognized by the government for areas in India that have inadequate electricity, the long-term costs and benefits in terms of ecological and social impacts are overlooked or are simply unknown (US Government Printing Office 1990).

India has a long history of damming waterways. Irrigation and the impoundment of waters behind human-constructed dams have been influential landscape features since the era of Chandragupta, evidence for which is a dam near Ginar in western India that was dated by stone inscriptions as having been in constant use for over 800 years (Tharpar 1963). The influences of impoundments are on a time scale that spans significant climate, vegetation, and animal species changes within the affected region. In some senses, the human-altered landscape has existed with greater constancy than some natural ecological communities. This is a frame of reference that is generally under-appreciated in industrialized countries. Small earthen dams used for water harvesting are considered ecologically sound with few negative environmental impacts, and no need for relocation of people. In stark contrast is one of the largest damming projects in India. The Narmada Basin Development Programme involves planned construction of 150 large dams and over 3000 smaller tributary dams over the next 40 years it is the largest comprehensive water project in the world and is controversial. It requires international funding, has various projections on benefits and impacts and the subsequent inundation would displace over one million people (US Government Printing Office 1990).

Riparian wetlands and substantial amounts of forest and agricultural land along the corridors of the Narmada project would be inundated and lost to productive use. Due to the large and erratic alterations of impounded water levels, the potential for shoreline wetlands to develop and mitigate the losses of river bottom and riparian zones is minimal. As a result of variable dam releases for power generation, the wetted area does not follow a predictable seasonal pattern, thereby precluding development of a stable wetland flora and wildlife community.

There are some mitigating beneficial effects from reservoir construction for particular biota. Pandey (1993) discovered an increased bird species diversity resulting from the construction of the Pong Dam Reservoir in the State of Himachal Pradesh (Fig. 1). There are also some economic benefits for fishing communities that learn to harvest fish from reservoirs, and the availability of standing water in large reservoirs provides the potential for nearby wetland development, should this become a priority. Furthermore, as high sediment loads fill portions of the reservoir, zones of deep water will be converted to shallow wetlands with the potential for wetland management. Ultimately, reservoir efficiency will be reduced to marginal benefits, and there may be opportunities for restoration of the flooded areas to emergent wetlands. This type of restoration is poorly understood and should be investigated further.

Chronic wetland losses

Issue 5. Defoliation (overgrazing, biomass removal)

India has more grazing animals than any other nation in the world. Worldwide, India supports 20% of all cattle, 50% of all water buffalos and 15% of all goats (Hulkarni 1970). The foraging activities of these animals change the vegetation and soils of the country, especially since over 10% of the cattle graze in forests. Intensive stocking of livestock on wetland soils can directly reduce herbage on the site through grazing, but it can also reduce the ability of the land to produce vegetation through soil compaction and long-term changes in soil structure (Adams & Akhtar 1994), as well as the selective removal of the most palatable plant species, leaving a preponderance of poor forage for wildlife and future grazers.

In simple experiments it was realized that closure to grazing without any planting could effectively check erosion (Stebbings 1962). The contrast between grazed and non-grazed areas is clear and striking to observers who enter many of India's national parks (e.g. Bandavgarh, Gir and Guindy). These parks are largely, if not totally, protected from grazing by the country's 237 million bovines, a number that has increased by approximately 20% since the 1950s (Panwar *et al.* 1992). Less obvious, but still important, are the significantly better conditions regarding watershed stability, soil structure development and the moisture-trapping ability of soils in the protected parks. Improvement of soils contributes to greater wetland vegetation density and health, higher water quality downstream, and more permanence of stream flows. While it is unrealistic to request the elimination of grazing in most areas, moderation of grazing in sensitive areas could provide public benefits and ultimately produce greater long-term support for graziers.

Issue 6. Alteration of upper watersheds (orchard planting, terracing)

Watershed conditions and downstream wetlands are linked. The condition of the land where precipitation falls, collects and runs off or percolates into the soil, will influence the character and hydrologic regime of the downstream wetlands. When agriculture, deforestation, or over-grazing removes the natural moisture-holding vegetation of watersheds, the runoff velocity of water increases and soil erosion is more pronounced. Over 30 years ago Stebbings (1962, p. 291) observed that 'The floods, erosion, and destructive changes of course by a number of rivers tended to increase in frequency and amount, and this seemed to be due to the clearance of both private forests in Bengal and the forests in the neighboring territories of Nepal, Sikkim, and Bhutan.' Fast-moving water poses a much more erosive force on landscapes resulting in the removal of topsoil, siltation of river courses and wetland filling with entrained sediments as discussed in Issue 3.

Large areas of India's watersheds are being physically stripped of their vegetation for human use. The human demands for subsistence fuelwood alone are dramatic; in 1968 India consumed 103 million t of firewood, or 0.23 t per person (Hulkarni 1970). Even though much of the wood removal occurs in non-wetlands, the attributes of catchments are changed and the down-slope wetlands are affected. There are many indicators that the upper watersheds have suffered dramatic changes that influence downstream wetlands, particularly the erosion of sediments from the upper hill-slopes and subsequent sediment deposition downstream. For example, an analysis of maps of different dates showed a sediment spit 30 km long had grown at the mouth of the northernmost of the three river distributaries of Godavari, the second largest river in India (Rao & Sadakata 1993). Mahadevan and Prasada Rao (1958) speculate from the timing of the conspicuous growth of this alluvial outwash that it was due to the increased sediment load resulting from deforestation in the catchment. The alluvial outwash of this delta would have been even greater except for the presence of impoundments along the river that served as sediment settling basins and reduced the sediment transport to the mouth of the river.

Terraces for growing hard grains, pulses, nuts, wheat (*Triticum* sp.), potatoes (*Solanum tuberosum*) and oranges (*Citrus reticulata*), are maintained in steep terrain of the Himalaya Mountains at altitudes from 500 m to more than 2000 m (Rai *et al.* 1994). Apple (*Malus* sp.) orchards replace native coniferous forests at even higher altitudes. Both of these land-uses are expected to reduce snow-holding capacity and to speed the relative rate of precipitation runoff, causing greater erosion. Rai *et al.* (1994) identified farmers under trying economic circumstances as the agents of the degradation and non-sustainability of the mountainous landscapes in the Indian state of Sikkim in the northeastern belt of the Indian

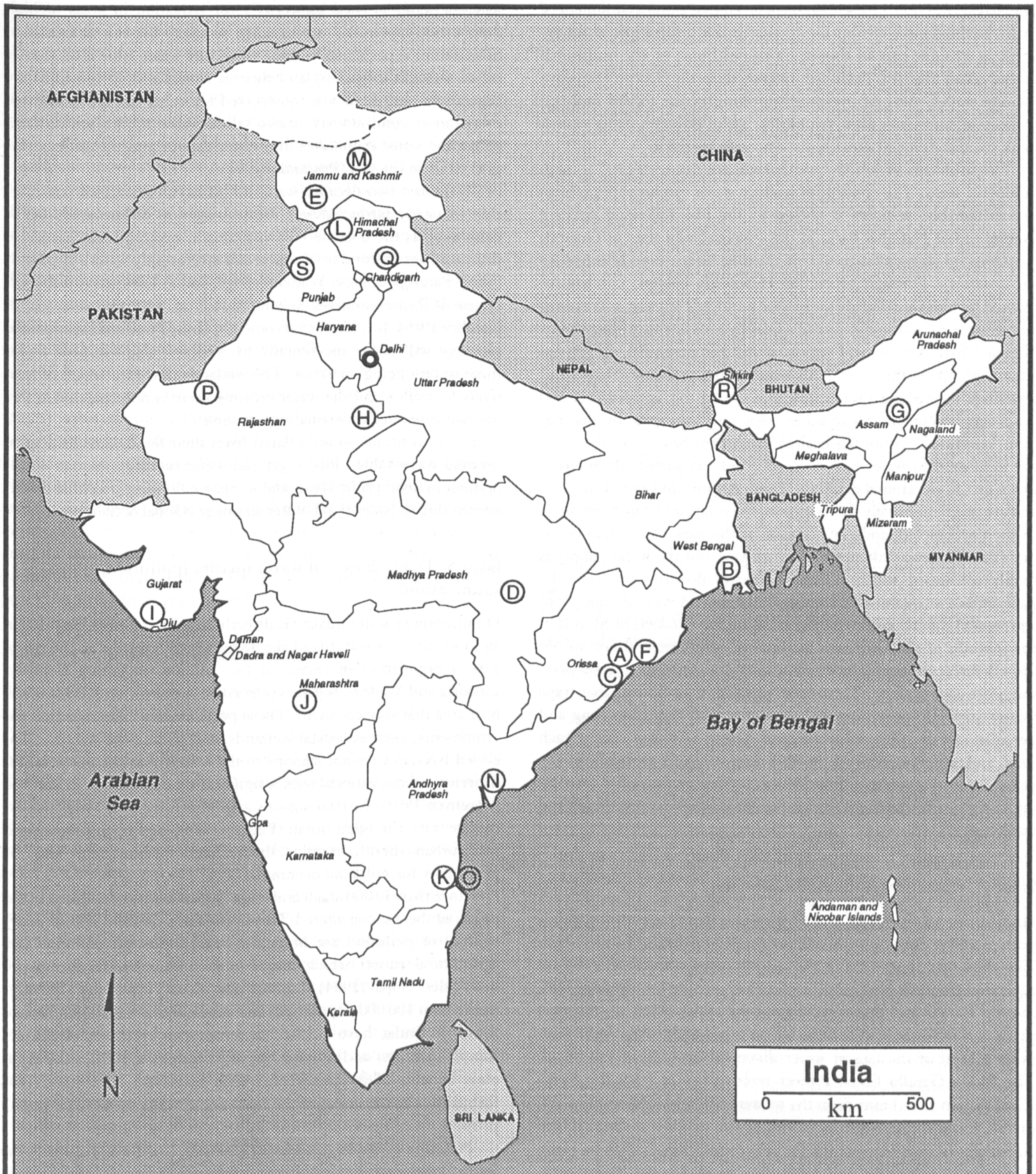

Figure 1 Locations of Indian wetlands mentioned in this article.

A. Bhitarkanika
B. Calcutta wetlands
C. Chilka Lake
D. Bandavgarh
E. Dal Lake
F. Daya River
G. DePar bil
H. Ghana Keoladeo National Park
I. Gir National Park
J. Godavari River
K. Guindy National Park
L. Harike & Pong Reservoirs
M. Hokarsar Lake
N. Koleru Lake
O. Pulicat Lagoon
P. Rajasthan Canal
Q. Shimla
R. Sikkim Himalaya
S. Sutlej River

Himalayas. Rai *et al.* (1994) also recognized that the abandonment of many adaptations contributing to sustainable utilization of watersheds is a major part of this degradation. Some of the traditional conservation practices listed for watersheds in the Sikkim Himalaya include stall-feeding of livestock, agroforestry for fodder and soil protection, terracing, plant symbioses, use of nitrogen fixing plants, bank stabilization and dung replacement fertilization.

The problems of healthy watersheds are not restricted to high mountain areas. The concept of healthy water catchments protecting sustainable wetlands is shown in the two following positive examples. Gir National Park, in the western India state of Gujarat, is famous for its population of free-ranging Asiatic lions (*Pantera leo* var. *asiatica*). Through protection of wildlife habitat, Gir has remained forested and lightly grazed for hundreds of years and as a result it supports soils indicative of a healthy ecosystem. Although Gir National Park is in an arid region, it still has perennial, spring-fed streams that flow through highly ornamented prehistoric baths and dwellings, suggesting a water flow rate similar to that used over 500 years ago. These streams of water are simply precipitation that has been 'harvested' within the healthy catchment basin, absorbed into the local ground-water and released evenly as surface flows lower down on the elevational gradient. These streams flow out of the park and are used intensively for irrigation, livestock, and community use in the unprotected landscape outside of the park. A riparian corridor exists for some kilometres downstream, but the water supply is totally consumed within a few kilometres downstream from the park, ending in a sand-filled seasonal drainage. A second example of a protected watershed catchment exists on the outskirts of Shimla in the foothills of the Himalaya mountains, where several km^2 of old growth forest are maintained under state protection as a preserve on the north-facing slope. This forest serves as a catchment that traps winter snowfall, providing a shaded area with a slow melting and percolation rate. Ground-water and stream recharge occurs each year, and water is available to downstream users throughout the year. These two examples provide an excellent rationale for protecting key water recharge areas that benefit downstream wetlands and water users.

Issue 7. Water demands and diversions

Human-caused alteration to the hydrological regime is the most important and serious cause of tropical wetland damage (Gopal 1992). The abundant waterways in the mountainous regions of India are separated from the arid semi-tropical flatlands by hundreds of kilometres. Canals and diversions have been constructed to transport this water to lower arid regions where crops are grown. India supports several of the largest water diversion projects in the world. The Indira Gandhi Canal Project removes water from the Sutlej River system as it drains from the western Himalaya Mountains and diverts it via a canal system to the desert regions of Gujarat and Rajasthan to provide irrigation for cash crops. Some estimates claim that up to 22 million ha m of water could be made available countrywide (Chopra 1985) by ditching and transferring water from water-rich basins into the adjacent low-flow, or fully utilized basins. Inter-basin water transfers offer great potential for increases in irrigation, yet associated with them are other ecological problems, such as soil waterlogging (Issue 7), soil chemical changes, exotic species introductions (Issue 12), more dam construction to provide increased head to divert water (Issue 4), the interruption of migration routes of people and animals, regional desertification and elimination of culturally sustainable lifestyles. Water diversion projects, wherein water is used improperly for irrigation in areas of high evaporation potential, are usually plagued by soil salinization. Salinization is particularly acute where the water table is artificially raised through irrigation, land clearing removes deep-rooted native vegetation, and dams are constructed (Abrol *et al.* 1988). Surface evaporation continuously draws saline water to the soil surface, where the water evaporates into water vapour and the salt remains as crystals in the soil (Pessarakli 1991).

In the last two decades water tables have been raised considerably in newly farmed desert areas. Irrigation of farmlands below dams such as the Ukai and Tawa Dams in western India has led to decreased agricultural production and increasingly waterlogged soils (Vijay Paranjpye, Ness Wadia College, India, testimony to the US House of Representatives Subcommittee on Natural Resources, 24 October 1989). It is likely that some unplanned wetland creation and recharge will occur incidentally to cropland abandonment under these waterlogging scenarios. The wetlands thus created are of relatively low value and the water creating them is not available to former wetlands in the original watercourse.

Rivers continue to be isolated from their floodplains leading to lowered water tables, loss of ground-water recharge, human development in flood prone areas, and increased flooding potential downstream due to faster flood-water drainage (Gopal & Sah 1993).

Issue 8. Degradation of water quality (pollution, siltation, salinization)

Diminution of water quality is directly related to human population and industry. Two thirds of the 98 metropolitan areas in the world with a population in excess of two million, including Bombay, Calcutta and Madras, began as port cities or are within 100 km of the port area that services them. These ports modify natural coastal environments, such as coastal wetlands, and pollute the waters of enclosed bays and coastal lagoons to the extent that the potential for fisheries and recreational uses is significantly degraded or eliminated (Sorensen 1993). Coastal lagoons are defined by their restricted exchange with the open ocean (Packer 1984), which, in conjunction with urban runoff, explains the reduced flushing rates and the propensity for pollutant accumulation.

More than 50 000 small and large Indian lakes are polluted to the point of being considered 'dead' (Chopra 1985). The primary sources of pollution are human sewage, industrial pollution and agricultural runoff which may contain pesticides, fertilizers and herbicides. Gopal (1994) observed that 'about 70% of the 3100 large (more than 100 000 population) and small (above 50 000 population) towns in India have neither sewerage nor treatment facilities.' Simple siltation, as discussed earlier, threatens to reduce the economic benefits of impoundments such as Harike Lake which was formed by the damming of the Beas-Sutlej watershed (IUCN 1990, p. 307).

Pollution of the largest lake in Kashmir, Dal Lake, has made the water unsuitable for drinking, fishing or bathing. A local government proposal has been developed for an intricate and very expensive clean-up involving dredging, the laying of sewer pipe on the lake bottom, water diversions, and artificial aeration until organic pollution is reduced (Bhargava 1994).

Extreme organic pollution levels from sewage can be put to constructive use in some situations. The Calcutta wetland sewage system is an excellent example of a beneficial use of wetlands to filter sewage and use the nutrients profitably. Since the 1930s water and sewage have been fed into lakes covering an estimated 2500 ha (formerly a much larger area). After a brief algal bloom, fish such as carp (*Cyprinus* sp.) and tilapia (*Tilapia* sp.) are introduced and raised. This sewage fishery produces approximately 7000 t of fish annually for the Calcutta markets or 2.8 t per ha per year (Edwards 1985). Solids in the sewage outfall ponds accumulate, and periodically pond bottom sediments are removed and used as fertilizer for nearby vegetable farms. The rich soils and humid tropical growing conditions allow farmers to produce approximately 30% of the vegetables supplied to Calcutta (Avijit Mitra, Institute of Wetland Management and Ecological Design, Calcutta, personal communication 1994). Unfortunately, the unrestricted dumping of industrial wastes into the sewage stream threatens the health of this nutrient-demanding system. Of particular concern are the waste chromium compounds dumped by the nearby tanneries; dense blue-grey streams of metallic compounds flow into the fishing and gardening areas. What is otherwise a sustainable system may be permanently altered if toxic chemicals accumulate sufficiently, causing a loss of fish production and a tremendous need for waste treatment processing by other means. Pollution in coastal mangroves and lagoons sometimes results from mariculture operations.

India's wetlands have been given a respite in terms of agricultural runoff. The world's other leading grain producers regularly use ten times more fertilizer than their Indian counterparts (Brown *et al.* 1991). If farm consolidation, credit organizations and more modern fertilizer distribution patterns are developed, fertilizer use could increase dramatically. The problems of agricultural runoff would be likely to increase as well.

Issue 9. Consolidation of wetlands

Throughout much of central India, villages and towns were settled around dependable water sources for drinking and stock watering (Vivek Kadpekar, Center for Environmental Education, Ahmadabad, personal communication 1994). Ponds are formed by ditching and capturing runoff from the occasional rains. To minimize evaporation, water is stored in small, deep ponds rather than in the more natural shallow, spreading wetlands. Aerial views throughout central India show a landscape development pattern with livestock trails radiating out, wheel-like from a water source at the wheel's hub where water is available. Wetlands adjacent to a main water source ordinarily provide excellent dry-season foraging opportunities for grazers. Where water sources are consolidated for diversion or collected for irrigation, grazers are usually excluded. However, the focused use of water sources usually precludes this.

Communal village tanks are very important to the rural people to fulfill their day-to-day washing, bathing, drinking and livestock watering requirements as well as for minor irrigation and as social gathering places. Tanks suffer from bank degradation due to overuse, pollution by the introduction of excess nutrients and, frequently, by becoming choked with exotic water plants such as water hyacinth. Many villages formerly carried out annual desilting operations where the tanks were deepened and the material removed was spread on croplands for fertilizer, or used to build mud houses. This practice is much rarer now that many of the traditional springs, seeps and ponds around larger towns have been eliminated or are over-used by the burgeoning numbers of villagers and efforts are underway to relocate these traditional water sources and to refurbish them (Vivek Kadpekar, Center for Environmental Education, Ahmadabad, personal communication 1994).

Issue 10. Global climate change effects

Wetland loss is both a contributing cause and a result of climate change. As a cause, wetlands are the single largest global emission source for methane, a gas which is a major contributor to the atmospheric trapping of heat that leads to atmospheric warming (Office of Technology Assessment 1991). Atmospheric warming leads to drying, desertification and loss of wetlands over regions of the earth as well as predicted increases in global sea levels of 10–21 cm by the year 2025 (Hoffman *et al.* 1986). Because such climate change occurs over decades or centuries, this influence would be operating in addition to direct wetland losses on specific sites. Based on some of the earliest archaeological descriptions of the extensive forests that covered areas now occupied by plains and deserts, India was a much wetter region 2700 years ago (Tharpar 1963). Though speculative, changes in regional weather patterns may be related to land surface change. Entire regions of India's land surface were altered through long-term human use and manipulation (e.g. intensive cropping, deforestation, intensive grazing, and alteration of water flows). Unlike most regions of the world, the population of India has been high enough for long enough to cause such landscape changes. Relatively large populations have accumulated small, incremental effects on wetlands over millennia. Continued degradation of water and wetland resources means that if a warming and drying cycle of global change affects India's climate, extensive regions will be marginalized or rendered less habitable by people and domestic animals.

Issue 11. Ground-water depletion (pumped irrigation, reduced water tables)

Demand for water to irrigate crops has increased dramatically in the last 20 years. The water budgets and desired surface flows of water to sustain wetlands must be put in perspective in the light of the population's needs for water. Between 1980 and 1983 the rapid depletion of ground-water left over 6000 villages in rural India with no source of drinking water (Chopra 1985), requiring that water for household use be brought in by truck. Simple hand-dug wells and hand withdrawal systems did not deplete ground-water significantly in the past, and wetlands continued to exist at recharge and seep areas. With the advent of technological advances in tube wells and large-capacity pumps for crop irrigation, water tables have been reduced quickly over entire regions, drying wetlands, emptying hand-dug wells, and ultimately pumping themselves dry (Chopra 1985). Water pumping continues to reduce ground-water levels by 1.5 to 6 m per year in some areas, and the beds of rivers that once flowed continuously are now dry for most of the year.

The problem of excessive water extraction is becoming apparent world-wide (Anon. 1991, p. 166). This phenomenon is believed to have affected the southern coastal plains of Saurashtra in Gujarat over an area exceeding 100 000 ha (Chopra 1985).

Issue 12. Introduced species, extinction of native biota

Indian wetlands are threatened by exotic plant species such as water hyacinth (*Eichornia crassipes*) and salvinia (*Salvinia molesta*). These free-floating nuisance plants were introduced to India and they pose problems by clogging waterways and outcompeting native vegetation (Mitchell & Gopal 1990). In fertilized waters the water hyacinth may double its size every 2 weeks. In heavily polluted areas water hyacinth may have some benefits though, since it is capable of taking up and sequestering unwanted nutrients and heavy metals in the water column.

As habitats are changed, exotic plants may be favoured over native plants. Some dewatered wetlands only have subsurface flows that may emerge as intermittent saline seeps. These drying sites have been invaded by exotics such as salt cedar (*Tamarix* sp.) and prosopis (*Prosopis* sp.) which may further decrease the water tables through evapotranspiration. Although these weedy opportunists have some benefits in ground cover, and the prosopis is a key fuel-wood source for village use, neither benefits native wetland plants. As wetlands lose valuable species of animals and plants, they are thought to be of lower value and it is harder to justify their defence. India is a focal point of biodiversity and endemism (Singh 1995) and the wetlands add substantially to the diversity of the landscape. Approximately 2400 species and subspecies of birds have been recorded in India out of a world-wide total of around 8600 species (Ali 1979). Unfortunately, India continues to show dramatic species losses as habitats are changed by human activities.

There are several populations of threatened, wetland-dependent animal species in India. The world's largest tiger (*Panthera tigris*) reserve exists in the tidal mangrove wetlands at the mouth of the Ganges River in a region called the Sundarbans (Fig. 1, item B). The endangered Indian rhinoceros (*Rhinoceros unicornis*) depends upon the dense freshwater grass beds in Kaziranga National Park in northwestern India (Hawkins 1986). Several populations of crocodile and turtle species are threatened due to river alterations (Ernst & Barbour 1989). Elimination of forested river corridors needed by Indian elephants (*Elaphus maximus*) around Rajaji National Park in Uttar Pradesh threatens the last free-ranging herd in northwestern India (Chowdhury 1995). The wetland bird fauna has suffered the extinction of the pink-headed duck (*Rhodonessa caryophyllacea*), and in the last four years the Indian population of the Siberian crane (*Grus leucogeranus*) appears to have been extirpated (David A. Ferguson, US Fish and Wildlife Service, unpublished lecture transcript 8 December 1994). These colourful and charismatic examples of threatened wildlife species are merely the obvious ones. There may be many lesser species being lost without notice.

Discussion

Despite the human demands for arable lands, living space, irrigation water, hydroelectric power and wetland materials, India still contains many crucially important wetlands deserving protection and management. There are 170 Indian wetlands covering 580 000 km^2 described in *The Directory of Indian Wetlands* (Anon. 1993). In another listing by Scott and Pole (1989), of 93 key Indian wetlands only 27% of them were protected at 28 sites. According to Scott and Pole's (1989) listing, 45% of all Indian wetlands are considered moderately to highly threatened. No single effort is going to protect these wetlands.

We have narrowed the scope of this paper substantially by non-inclusion of the social forces that lead to wetland degradation in India. There is a substantial body of literature on social systems in India and the natural resource needs of the largely rural population. However, one particular phenomenon has greatly increased the apparent magnitude of all of the 12 wetland issues described, namely the diminution of publicly usable land. Traditionally, the rural population organized to share common property resources in a sustainable way (Agarwal 1992). Through passage of laws, fencing, privatization of land for mechanized farming, water developments and commercial forestry, public access to land and wetlands has been reduced. Jodha (1992) calculated that in semi-arid regions spanning eight Indian states, the area of the commons declined by 30 to 50% between 1950 and 1980, and taking population growth over that span into account, the area per capita declined on average by two thirds. The combination of increasing population, diminished quality of wetlands and decreasing access to wetland functions is an Indian example of 'Tragedy of the commons' (Hardin 1968). Protection of common property resources through restrictions that are not equitably borne by all parties makes for a particularly difficult form of regulation. An unfortunate example of this was seen at Keoladeo National Park where six individuals were killed over the enforcement of a regulation forbidding livestock grazing in this wetland park. In hindsight, the effects of cattle grazing on these managed wetlands were not well understood before the regulation was promulgated (Gopal 1991). When property rights are uncertain, there are few incentives for sustainable use by tenants. International rural development research has shown that people are more likely to moderate their use and to use land more sustainably if they are confident that they will continue to have access to that land in the future (Freeman 1992; Bakker 1995), and an incidental benefit is that good land stewardship by graziers can also help preserve habitat quality and support biodiversity.

Saving or restoring wetland areas is expensive. Some form of decision sequence or prioritization that is compatible with the Indian system of government must be used for project selection. A start in this direction to protect Indian wetlands has already been made along with the country's attempts to establish a protected area network (Rodgers & Panwar 1988), and join the RAMSAR Convention. Six wetland areas of importance, including Chilka Lake, Keoladeo National Park, Loktak Lake, Sambhar Lake, Harike Lake and Wular Lake, have been designated as RAMSAR sites. Despite an emphasis on protection of lakes, some lakeshore wetland complexes are also protected. Given the large demand and the relatively small budget available for environmental issues, it is crucial to seek out projects with the greatest results for the least cost. The cost:benefit ratios so often debated in World Bank projects are frustrating to ecologists because they generally fail to consider the many non-economic values of Indian wetlands. Yet the concept of assessing wetlands, ascribing functional value to them, and costing their preservation, should be part of any efforts to keep these habitats in the landscape. Indian scientists and policymakers desperately need to come to agreement on a definition of what constitutes a wetland. Currently, lakes, lagoons and other deepwater habitats are combined with wetland area estimates and the emphasis on restoration or preserving genuine wetland qualities is diminished by this inclusion.

The amount of political will behind proposed projects influences their success. Without governmental backing and strong links between national, state and local leaders it is rare for projects to succeed. Two contrasting examples show this clearly. A basic component of 'sustainable development', is encouragement of public participation by resource users (Bakker 1995). There are numerous tree-planting cooperatives, agricultural cooperatives, and women's gardening organizations that are supported by local or outside funds, yet political will provides them little support. Conversely, political will in support of the Sardar Sarovar dam construction led to the accumulation of approvals, partial funding, and initial surveying, in the face of tremendous opposition from Indian environmental groups. Fortunately the concerns of local people and environmentalists did play a role in the World Bank's decision to withdraw funds from the project.

The Indian Ministry of Environment and Forests (MOEF) provides financial assistance to the states for carrying out activities related to conservation and management of wetlands. The MOEF has also identified key research institutions to provide scientific and technical inputs. From the authors' observations in India, recognition exists of the need for prioritization and planning. To make this fledgling system effective there needs to be some demonstrable benefit to each of the levels of government in exchange for their participation in or permission for each project. In terms of wetland environmental issues, the easiest and highest calling of managers is to point out how wetlands benefit every layer of government through natural processes to improve the lives of so many rural Indians.

Misdirected, uninformed or misinformed political will can exacerbate ecological problems through the pursuit of special interests or poorly planned projects, thereby squandering resources which could be applied effectively to more pressing problems. Clear biological description and some estimate of values and sustainability are common needs. Three considerations are important in the planning, or mustering of political will, for wetland restoration or protection. Objectivity must be maintained by using Indian experts who have little or no personal stake in the outcome. Mechanisms such as peer review or panels to encourage planners to be accountable for their actions must be put in place. Public participation in the value estimation, planning procedure and formulation of local political will must be insisted upon.

Unfortunately, ecological issues are usually complex and politicians and the media attempt to represent them as simple action-response systems and this means that wetland protection exercises are often based on misinterpreted evidence. The need for research and policy specialists is apparent in wetland issues.

Researchers, including the authors, hold as paramount their mission to answer questions, develop understanding and accumulate knowledge. In developing nations with limited conservation funds, research expenditures must be balanced against application of existing knowledge. It is the authors' view that knowledge accumulation has outpaced implementation of conservation efforts and a strong argument can be made that the 'conservation fields' should be tilled using the tools at hand rather than continuing to build more tools. There remains a niche for applied research, and outside support of basic research should be encouraged.

Training for managers is also needed. In response to this need, programme sectors in wetland management have been added to the Indian Government's Wildlife Institute of India in Dehra Dun. Because wetland research capabilities have not been a priority in India thus far, wetland protection and regulation will likely be aimed at more common-sense, easily interpretable, and simply communicated, approaches.

We end this article with three synthesis points. First, we echo Singh (1995) who points out 'The profound crisis of population growth [in India] is being trivialized by the bulk of society... Ecologists have to tell all concerned people about this, before they recommend doing research on sustainability of natural resource use.' Our second message is that wetlands provide basic, sustainable benefits to people throughout India and they deserve protection and restoration. Third, mistakes are inevitable when conservation attempts are undertaken because our knowledge of wetland ecosystems is so incomplete. The awareness of wetland values and losses puts the consequences of failed conservation efforts in perspective and calls for renewed attempts with more effective methods.

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References

Abrol, A.P., Yadav, J.S.D. & Massoud, F.I. (1988) Salt-affected soils and their management. *FAO Soils Bulletin* 39: 131 pp.

Adams, W.A. & Akhtar, N. (1994) The possible consequences for herbage growth of waterlogging compacted pasture soils. *Plant and Soil* 162: 1–17.

Agarwal, B. (1992) Rural women, poverty and natural resources: sustenance sustainability and struggle for change. In: *Poverty in India – research and policy*, ed. B. Harriss, S. Guhan & R. Cassen, pp. 390–432. Delhi: Oxford University Press.

Ahmad, N. (1980) Some aspects of economic resources of Sunderban mangrove forests of Bangladesh. (abstract). In: *Mangrove environment: research and management*, ed. P. Soepadmo, pp. 50–1. Report of UNESCO Asian Symposium, held at University of Malaya, Kuala Lumpur, Malaysia, 25–29 August 1980.

Ali, S. (1979) *The Book of Indian Birds*. Bombay: Oxford University Press: 187 pp.

Andriesse, J.P. (1988) Nature and management of tropical peat soils. *FAO Soils Bulletin* 59: 165 pp.

Anon. (1990) *World Resources 1990–1991*. New York: Oxford University Press: 383 pp.

Anon. (1991) *World Resources 1991–1992*. New York: Oxford University Press: 291 pp.

Anon. (1993) *Directory of Indian Wetlands*. World Wildlife Federation, New Delhi: 264 pp.

Anon. (1994) *World development report*. World Bank development report 1994. New York: Oxford University Press: 254 pp.

Bakker, J.I. (1995) *Sustainability and International Rural Development*. Toronto: Canadian Scholars Press Inc.: 250 pp.

Barras, J.A., Bourgeois, P.E. & Handley, L.R. (1994) *Land loss in coastal Louisiana 1956–90*. National Biological Survey, National Wetlands Research Center Open File Report 94-01: 4 pp.

Bhargava, D.S. (1994) Dal Lake clean-up strategy: an example for others? *Environmental Conservation* 21: 269–72.

Brown, L., Flavinc, Q. & Pootel, S. (1991) *State of the World. A World Watch Institute report on progress towards a sustainable society*. World Watch Institute India, New Delhi: 260 pp.

Chatterjee, N. (1995) Social forestry in environmentally degraded regions of India: case-study of the Mayurakshi Basin. *Environmental Conservation* 22: 20–30.

Chopra, R. (1985) *The State of India's Environment*. New Delhi: Ambassador Press: 393 pp.

Chowdhury, K.N. (1995) India's Rajaji National Park and threatened elephants. *Environmental Conservation* 22: 79–80.

Conner, B. & Skladany, M. (1991) Aquacultural development in tropical Asia: a re-evaluation. *Natural Resources Forum* 15(1): 66–73.

Das, H.S., Mishra, R.K. & Sinha, B.N. (1990) Some observations on Chilka wetland ecosystem. In: *Ecosystem degradation in India*, ed. B.N. Sinha, pp. 85–93. New Delhi: Ashis Publishing House.

de la Cruz, A.A. (1978) Production and transport of detritus in wetlands. In: *Wetland Functions and Values: the State of our Understanding*, ed. P.E. Greeson, J.R. Clark & J.E. Clark, pp. 162–74. Proceedings of the national symposium on Wetlands, Lake Buena Vista, Florida, 7–10 November 1978. American Water Resources, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota, USA.

Edwards, P. (1985) *Aquaculture: A Component of Low Cost Sanitation Technology*. The World Bank, Washington, D.C.: 45 pp.

Ernst, C.H. & Barbour, R.W. (1989) *Turtles of the World*. Washington, D.C.: Smithsonian Institution Press: 313 pp.

Fernando, C.H. (1977) Investigations on the aquatic fauna of tropical rice-fields with special reference to southeast Asia. *Geo-Eco-Trop* 1: 166–88.

Fernando, C.H. (1984) Reservoirs and lakes of southeast Asia (Oriental Region). In: *Ecosystems of the World* Vol. 23, ed. F.B. Taub, pp. 441–6. Amsterdam: Elsevier Press.

Freeman, David M. (1992) *Choice Against Choice: Constructing a Policy-Assessing Sociology for Social Development.* Niwot, CO: University Press of Colorado: 365 pp.

Gopal, B. (1991) Wetland (mis)management by keeping people out: two examples from India. *Landscape and Urban Planning* 20: 53–9.

Gopal, B. (1992) Tropical wetlands: degradation and need for rehabilitation. In: *Ecosystem Rehabilitation* Vol. 2: Ecosystem analysis and synthesis, ed. M.K. Wali, pp. 277–96. The Hague: Academic Publishing.

Gopal, B. (1994) Conservation of inland waters in India: an overview. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* 25: 2494–7.

Gopal, B. & Sah, M. (1993) Conservation and management of rivers in India: case-study of the River Yamuna. *Environmental Conservation* 20: 243–54.

Government of India (1991) *India 1990: A Reference Annual.* Research and Reference Division, Ministry of Information and Broadcasting, Government of India, Delhi, India: 920 pp.

Government of India (1993) *India 1992: A Reference Annual.* Research and Reference Division, Ministry of Information and Broadcasting, Government of India, Delhi, India: 910 pp.

Hardin, G. (1968) Tragedy of the commons. *Science* 162: 1243–8.

Hawkins, R.E. (1986) *Encyclopedia of Indian Natural History.* Delhi: Oxford University Press: 620 pp.

Hawting, G. & Mateo, N. (1987) *Farming on high.* International Development Research Center, Markham, Ontario. Report 16(1): 4–5.

Hoffman, J.S., Wells, J.B. & Titus. J.G. (1986) Future global warming and sea level rise. In: *Greenhouse effect, sea level rise and coastal wetlands,* ed. J.G. Titus, EPA-230-05-86-013, US Government Printing Office, Washington, D.C.: 232 pp.

Hulkarni, D.H. (1970) *Forestry in India.* Oregon State University Printing Dept, Eugene, Oregon: 38 pp.

IUCN (1990) *Directory of Wetlands of International Importance.* Ramsar Convention Bureau, Gland, Switzerland: 796 pp.

Jodha, N.S. (1992) *Common Property Resources – A Missing Dimension of Development Strategies.* Report No. 169. The World Bank, Washington, D.C.: 87 pp.

Mahadevan, C. & Prasada Rao, R. (1958) Causes of the growth of sand spit, north of Godavari confluence. *Memoirs of Oceanography* 2: 69–74.

Malini, B.H., Rao, K.S. & Rao, K.N. (1993) Evolution and dynamics of the Chilka Lake. In: *The Management of Coastal Lagoons and Enclosed Bays,* ed. J. Sorensen, F. Gable & F. Bandarin, pp. 257–68. Proceedings of the eighth symposium on Coastal and Ocean Management, New Orleans, Louisiana. American Society of Civil Engineers, New York, USA.

Mitchell, D.S. and Gopal, B. (1990) Invasion of tropical freshwater by alien aquatic plants. In: *Ecology of Biological Invasion in the Tropics,* ed P.S. Ramakrishnan, pp. 139–54. New Delhi: International Scientific Publications.

Mitsch, W.J. & Gosselink, J.G. (1986) *Wetlands.* New York: Van Nostrand Reinhold: 539 pp.

Montague, C.L., Zale, A.V. & Percival, H.F. (1987) Ecological effects of coastal marsh impoundments: a review. *Environmental Management* 11(6): 743–56.

Office of Technology Assessment (1991) *Changing by degrees: Steps to reduce greenhouse gases.* OTA-0-482, US Government Printing Office, Washington, D.C.: 354 pp.

Packer, S.P. (1984) *Dictionary of Earth Science.* New York: McGraw Hill: 837 pp.

Pandey, S. (1993) Changes in waterbird diversity due to the construction of Pong Dam Reservoir, Himachal Pradesh, India. *Biological Conservation* 66: 125–30.

Panwar, H.S., Badola, R., Sinha, B. &. Silori, C. (1992) The wilderness factor protected areas and people – compatible strategies. *Sanctuary (Asia)* 12(5): 75–85.

Pessarakli, M. (1991) Formation of saline and sodic soils and their reclamation. *Journal of Environmental Science and Health* A26(7): 1303–20.

Primavera, J.H. (1991) Intensive prawn farming in the Philippines: ecological, social, and economic implications. *Ambio* 20: 28–33.

Rai, S.C., Sharma, E. & Sundriyal, R.C. (1994) Conservation in the Sikkim Himalaya: traditional knowledge and land-use of the Mamlay watershed. *Environmental Conservation* 21: 30–56.

Rao, K.N. & Sadakata, N. (1993) Holocene evolution of deltas on the east coast of India. In: *Deltas of the World,* ed. R. Kay, pp. 1–15. Proceedings of the Eighth Symposium on Coastal and Ocean Management, New Orleans, Louisiana. American Society of Civil Engineers, New York, USA.

Rodgers, W.A. & Panwar, H.S. (1988) *Planning a Wildlife Protected Area Network in India.* Vol. I and II. Field Document No. 7. Wildlife Institute of India Publication, Dehradun: unpaginated.

Savenije, H.H.G. & Pages, J. (1992) Hypersalinity: a dramatic change in the hydrology of Sahelian estuaries. *Journal of Hydrology* 135: 157–74.

Scott, D.A. & Pole, C.M. (1989) *A Status Overview of Asian Wetlands.* Asian Wetlands Bureau, Kuala Lumpur, Malaysia. Publication No. 53.

Singh, B.P. (1994) Biodiversity conservation in mangrove environment. *Indian Forester* 120: 827–36.

Singh, S.P. (1995) India's population problem, a global issue of environment and sustainability: an appeal for cooperation. *Bulletin of the Ecological Society of America* 76: 55–9.

Smith, T.J., III. (1987) Effects of light and intertidal position on seedling survival and growth in tropical tidal forests. *Journal of Experimental Marine Biology and Ecology* 110: 133–46.

Sorensen, J. (1993) The management of enclosed coastal waterbodies: the need for a framework for international information exchange. In: *The Management of Coastal Lagoons and Enclosed Bays,* ed. J. Sorensen, F. Gable & F. Bandarin, pp. 1–17. Proceedings of the Eighth Symposium on Coastal and Ocean Management, New Orleans, Louisiana. American Society of Civil Engineers, New York, USA.

Stebbings, E.B. (1962) *The Forests of India.* Vol. IV. London: Oxford University Press: 485 pp.

Tharpar, R. (1963) *A History of India.* Vol. 1. New Delhi: Penguin Books: 381 pp.

Ulluwishewa, R. (1995) Traditional practices of inland fishery resources management in the dry zone of Sri Lanka: implications for sustainability. *Environmental Conservation* 22: 127–32.

US Government Printing Office (1990) *Sardar Sarovar Dam Project.* Hearing before the subcommittee on natural resources, agriculture research and environment of the committee on science, space, and technology US House of Representatives 101 Congress 24 October 1989. US Government Printing Office, Washington, D.C.: 218 pp.

World Development Report (1994) *World Development Indicators.* Oxford: Oxford University Press: 254 pp.