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Wetland Loss in World Deltas

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ABSTRACT

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Geologic and geomorphic data on 42 world deltas were compiled for a NASA-sponsored research project. Satellite images from 14 of these deltas (Danube, Ganges, Brahmaputra, Indus, Mahanadi, Mangoky, McKenzie, Mississippi, Niger, Nile, Shatt el Arab, Volga, Huang He [Yellow], Yukon, and Zambezi) were analyzed for delta plain wetland loss caused by natural causes and conversion of wetlands for agricultural and industrial use. These analyses indicated that a total of 15,845 km^2 of wetlands have been irreversibly lost during the past 14 years and the average rate of loss is 95 km^2/y. If a similar trend is present in the other deltas, a total wetland loss in the delta plains of the 42 deltas would be on the order 364,000 km^2 over the past 15 to 20 years.

ADDITIONAL INDEX WORDS: Wetland loss, world deltas, coastal change.

INTRODUCTION

The world's deltaic plains contain some of the most productive and sensitive ecosystems found on the planet, but because of natural causes and human-induced changes, these ecosystems are being modified and lost at an astonishing rate. An extensive amount of information was collected for some 42 deltas worldwide through a NASA research contract (Coleman, Huh, and Braud, 2003). One aspect of this project was to detect changes in delta plain wetlands by using change detection techniques on satellite images of 14 deltas. Images from two different dates (generally the early 1980s and 2002) were analyzed by georegistering the high-resolution satellite images. Photoshop software was then used to delineate the two major causes of wetland loss, expansion of open water in the delta plain, and agricultural and industrial expansion in the delta plain. The two images of each delta were then imported into ArcView software for calculation of areas. This data could then be used to quantify the net total wetland loss for each delta in the two major categories. Figure 1 illustrates the results of the analysis of open water comparisons in the Huang He (Yellow) River for the period 1989–2000. Because of the size of some of the deltas and cost and time constraints, only selected images from Ganges-Brahmaputra, Indus, and Mississippi deltas delta were analyzed, while the entire delta plain of the other 11 deltas were analyzed. On those where only one image was analyzed, qualitative review of adjacent images in the entire delta plain tended to indicate that the images analyzed were indeed representative of the entire delta.

The 14 deltas analyzed and the dates of comparison included the Danube (1987–2001), Ganges-Brahmaputra (1989–2001), Indus (1992–2000), Mahanadi (1989–2002), Mangoky (1985–2000), McKenzie (1995–2002), Mississippi (1985–1997), Niger (1987–2002), Nile (1984–2001), Shatt el Arab (1984–2000), Volga (1984–2001), Huang He (Yellow) (1989–2000), Yukon (1985–1992), and Zambezi (1986–2000). These deltas span various climatic regions, display varying rates of subsidence, vary considerably in size, and have varying population densities (Figure 2). The Ganges-Brahmaputra and Shatt el Arab deltas have relatively high population densities, while the Yukon and Mangoky have little or no industrial/agricultural use in the delta plain. The total area of the delta plains examines was 30,225 km^2. Table 1 summarizes the results of these analyses, showing for each delta the net loss due to expansion of open water, net loss as a result of conversion of wetlands by agricultural and industrial expansion, the average rate of wetland loss in each category, and the total net wetland loss and average annual rate of loss.

DELTA DESCRIPTIONS AND LAND-LOSS ANALYSIS

Danube River

The Danube is the second largest river in Europe; it is approximately 2900 km long and drains an area slightly larger than 779,500 km^2. The river rises in the Black Forest Mountains of Germany and empties into the Black Sea. The geology of the drainage basin is complex; the western part of the basin is dominated by Precambrian and Paleozoic sediments, the southern basin is Mesozoic in age, and the central and eastern part of the basin is dominated by Neogene sediments. The western part of the drainage basin lies within the West Molasse and Southwest German basin, while the central basin lies within the Central Pannonian and Caspian-Balkanean basins. The northern basin is bordered by a major zone of faulting, while the southern border of the basin displays a large number of earthquake epicenters. The drainage basin has an extremely dense tributary pattern. The density of the

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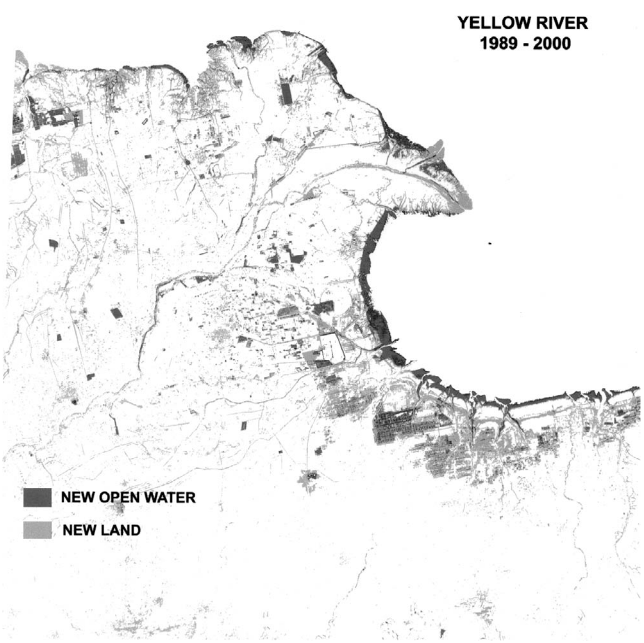

Figure 1. Analysis of open water changes in the Huang He (Yellow) River delta, 1989–2000.

tributary pattern is 0.22 km stream length per 500 km^2, and the average rainfall is 808 mm with a maximum of 1678 mm (July) and a minimum of 457 mm (January). The river, from its headwaters to the mouths of the river in the Black Sea, is 2536 km in length. Relief in the basin is generally low, averaging only 292 m. The average elevation of the drainage basin is 462 m with a maximum of 2600 m and a minimum of 60 m. Most of the western basin lies within temperate broadleaf and coniferous forests, and the central basin consists primarily of temperate grasslands and savannas.

The alluvial valley of the river system is well defined, and meandering of the channel is quite common. Numerous channels exist, and from the satellite images, it is apparent that changes in the river course are quite a common occurrence. The average annual discharge is 6499 m^3/s with a maximum of 8938 m^3/s and a minimum of 4447 m^3/s (VOROSMARTY, FEKETE, and TUCKER, 1998). Floods generally begin in late March and continue into the latter part of July. Lowest discharges occur in September and October. Settlements and population density is quite high within the alluvial valley, and much of the area is under cultivation.

The delta area (4345 km^2) of the Danube was created in recent times. Sediment discharge averages 122 million tons/y, of which 54 million tons consist of bed load (SAMAJLOV, 1956). To the north and west of the river delta, primarily Pliocene and Miocene sedimentary rocks form north-south-

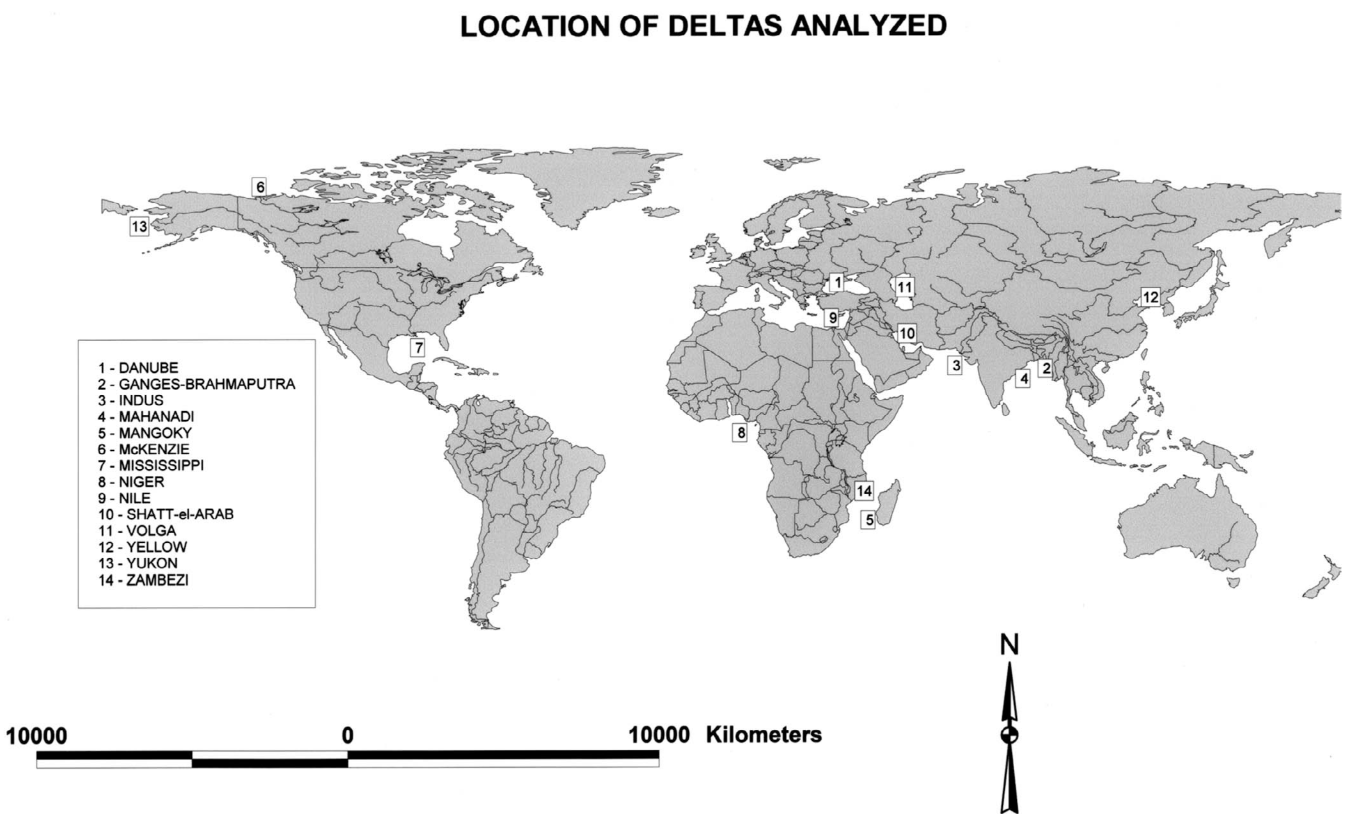

Figure 2. Location of delta comparisons.

Table 1. *Wetland loss (km²) and average annual rate of loss (km²/y) in 15 deltas analyzed.*

Delta	Open Water		Agricultural and Industrial Use		Total Wetlands		Area of Delta Measurement
	Net Loss	Average Rate per Year	Net Loss	Average Rate per Year	Net Loss	Average Rate per Year	
Danube			83	6	83	6	3066
Ganges-Brahmaputra	783	65	3507	292	4290	358	5930
Huang He (Yellow)	8	1	727	66	735	67	1960
Indus	960	120	635	79	1595	199	1380
Mahanadi	116	39	22	7	94	31	1440
Mangoky	43	3	90	6	133	9	1449
McKenzie	24	12			24	12	995
Mississippi	252	21	112	9	364	30	1904
Niger	81	5	7	0.5	88	6	1110
Nile	2.4	0.2	12	0.7	14	0.8	872
Shatt el Arab	1610	101	5089	318	6699	419	1340
Volga	100	6	177	10	277	16	1420
Yukon	1100	157			1100	157	4654
Zambezi	24	2	325	23	349	25	2705
Total Loss	5104		10,786		15,845		30,225
Average Rate		41		68		95	

trending low hills capped by Pleistocene loess up to 200 m high. East of the river and south of the delta, Paleozoic and Mesozoic sediments form high rolling hills that attain elevations of 450 m.

The main channel of the Danube is highly migratory within the lower part of the alluvial valley, so that numerous meander scars are present within the valley. Small stretches of river braiding are found along the valley course. As the Danube turns abruptly east to form its delta plain, sedimentation has blocked numerous valleys of the north-south-trending topography, forming elongated freshwater lakes. The major tributaries of the Danube consist of three major channels: the St. George to the south, the Sulina in the middle, and the Kilia to the north. The St. George arm is 120 km long and has widths ranging from 200 to 500 m. The Sulina arm, before 1860, had a length of 100 km and a width of 250 m. The Sulina was artificially diked in the period 1860–1895 for navigation purposes. The Kilia, the youngest of the tributaries, having formed within the past 600 years, now receives the major part of the flow. It is slightly longer than 100 km and ranges in width from 300 to 700 m. The tributary channels that distribute water are bordered by well-developed natural levees that are quite narrow, generally less than 250 m wide. Offshore of these young prograding tributaries, slope is extremely low (0.152 degrees). The coastline is relatively muddy, although sandy beaches are located along the entire delta coast. A large sandy barrier spit is present south of the St. George tributary.

Predominant in the delta plain are roseau cane (marsh cane, *Phragmites* sp.) marshes and freshwater lakes. The marshes are an important resource of the delta and provide a major nesting place for waterfowl. The marshy areas of the delta plain are the largest continuous marshland in Europe, and they include the greatest stretch of reed beds probably in the world. The roseau cane forms thick root mats and results in organic content being exceptionally high in the delta deposits. Much of the delta area is occupied by freshwater lakes up to 3 to 4 m deep. These lakes are initially filled by overbank flow of organic-rich clays. As filling with organic-rich clays proceeds, the lakes become isolated from the overbank splays, and thick floating organic mats form the final fill.

Tides in the Black Sea are virtually absent, and the only water variations result from wind-driven surges. Wave power is moderate, with average wave power of 0.033×10^7 ergs/s per meter of coast. Wave energy is highest in March–May and September–November. The subaerial delta is much larger than the subaqueous delta (ratio of subaerial/subaqueous delta is 8.6). The abandoned delta is approximately three times the size of the active delta.

In order to detect changes in open water and agricultural and industrial use within the Danube River delta, comparisons were made between a satellite obtained in 1987 and one in 2001. Changes in these parameters were completed for the 14-year period. The delta area covered by the georegistered images was 3066 km² (Table 1) and included a significant portion of the entire delta plain. Thus, before humans influenced the delta plain, there was approximately 4345 km² of wetlands within this portion of the delta plain. By 1987, there was a total of 1630 km² of open water within the delta plain, or a reduction of some 62% of the delta plain wetlands by formation of open water due to subsidence, changes in channel geometry, and obviously some influence by humans. Some 14 years after the 1987 satellite image was obtained, the open water was reduced to 1570 km², mostly because of filling of open water areas by humans. Agricultural and industrial use of the delta plain comprised some 493 km² on the 1987 image. By 2001, the total wetlands loss due to agricultural and industrial expansion was 410 km², or a loss of 83 km² in the 14-year period. Thus, since the delta was first occupied by humans, a total of 3% of the wetlands in the delta plain has been destroyed, and the average rate of wetland loss is 6 km²/y.

Ganges-Brahmaputra River

The Ganges and Brahmaputra rivers are one of the largest river systems on the earth. The river channels drain some of the highest mountains present on the planet, the Himalayans. The Ganges River originates near the Tibet-India border, and then flows southeast across India to combine with the Brahmaputra in the country of Bangladesh. The Brahmaputra River has its source in Tibet along the northern slope of the Himalayas, and flows across Assam into Bangladesh. The drainage basin covers an area of 1,664,700 km^2, and the combined length of the two major rivers exceeds 3900 km. The drainage network is exceedingly complicated and highly dense, one of the highest densities for a large drainage basin. The average elevation in the basin is 1923 m, with maximum and minimum being 6033 m and 180 m, respectively. The combined rivers drain both slopes of the Himalayan mountain chain. Paleozoic and Mesozoic rocks, with scattered outcrops of Precambrian rocks, make up the vast majority of the drainage basin. The headwaters are in the West Indian Shield and the Central Himalayan Foreland basins. In the northern part of the basin, mountain grasslands and alpine meadows are the dominant vegetation. The remainder of the basin is covered by deciduous forests and tropical and subtropical broadleaf forests. Average annual rainfall in the basin is relatively high (1474 mm) with a maximum of 2265 mm and a minimum of 341 mm. The rainy months range from June through September, when monthly rainfall exceeds 100 mm. The dry months have average rainfall between 20 and 60 mm.

The Ganges is primarily a meandering river, whereas the Brahmaputra is primarily a braided channel. Their average annual combined discharge into the Bay of Bengal is approximately 29,692 m^3/s with a maximum during flood of 80,984 m^3/s and 6041 m^3/s during low-water periods. The major floods occur during the months from June through September. The channels of both rivers are extremely unstable, and bank lines can migrate as much as 400 m in a single season (Coleman, 1969). Sediment load is extremely high, with suspended sediment load during flood stage reaching as high as 13 million tons per day (Coleman, 1969). Bedload has never been measured but is obviously extremely high, and consists of fine- and medium-grained sand. Most of the land in the alluvial valley is cultivated in rice and jute, and population density is quite high, with 100 to 500 people per half-degree area.

The delta, which is one of the largest in the world, covers some 105,640 km^2 and has one of the highest population densities of all deltas. Throughout Pleistocene times, the site of active deltaic sedimentation has switched. Today, the Ganges merges with the Brahmaputra, and the site of active sedimentation lies to the eastern side of the country of Bangladesh, where large bell-shaped tributaries are present. The major area of abandoned deltaic plain lies to the west and is the site of one of the largest mangrove regions in the world, the Sunderbans. The abandoned delta is approximately 1.6 times the size of the active delta plain. Numerous abandoned channel scars dominate the surface morphology of the abandoned delta plain. These scars are apparently remnants of former courses of the Ganges River and many of its tributaries. Most of the scars indicate that a meandering channel was dominant, now extensively modified by humans. Channel scars are of similar size to channels presently active along the Ganges and its tributaries. Many of these former riverine channels are now tidally dominated.

The inland part of the tidal plain has been diked, and the former saline lands have been converted to various agricultural and marine farming practices. This reclaimed land has retained some of the general morphology of the original deltaic channel scars, but it has been modified by tidal drainage networks. Originally, the entire surface of the abandoned delta formed an extreme expanse of mangrove forests. The mangrove swamp is dissected by an intricate network of tidal drainage channels. The larger tidal channels form bell-shaped estuaries that are quite deep, and many of them serve as major transport arteries. Inland, the estuarine channels display highly sinuous channel patterns, but they appear to be stable rather than migratory. Comparison of old maps and aerial photographs with present-day imagery indicates that some major channel patterns have not changed in tens of years.

Typical of many high tidal estuaries are the bell- or funnel-shaped river mouths in the active delta plain. The tidal range varies considerably along this coast; mean tidal range is 3.6 m. Wave energy is relatively low, with wave power being 0.585×10^7 ergs/s per meter of coastline and the root mean square wave height 1.4 m. As a result of the low wave energy, few beaches are present along the shoreline, and muddy tidal flats are common. The coastline is extremely irregular as a result of the large number of tidal channels that bisect the coast. Broad mud and silt flats border the coast. At low tide, many of these flats are exposed as fluid mudbanks. Most of the banks display elongated patterns, aligned in an onshore-offshore direction. This type of subaqueous morphology is common along many high tidal estuaries, and these shoals have been called "tidal ridges." The few beach deposits that exist are most commonly composed of reworked shell debris and fine sand. These types of beach ridges have been referred to as cheniers on other delta coasts.

The offshore slope fronting the delta is extremely low, averaging 0.011 degrees. The ratio of the subaerial to subaqueous delta is 2.42, the subaerial delta being nearly 2.4 times the size of the subaqueous delta. Offshore of the delta is a large submarine canyon, the Swatch of No Ground. This submarine feature is a broad canyon that was formed during Pleistocene low sea levels, feeding fluvial sediment to one of the largest submarine fans in the world's oceans.

Georegistered satellite images from 1989 and 2001 were compared to detect changes to the delta plain during this 12-year period. Because of the size of this delta, only three satellite images were analyzed and covered some 5930 km^2 of the delta. In the 12-year period, some 783 km^2 of delta wetlands had been converted to new open water (Table 1). The Ganges-Brahmaputra delta is one of the highest populated delta plains in the world. Wetland loss because of conversion to agricultural and industrial use totaled 3507 km^2 during this same 12-year period. Enlargement of the original high-resolution georegistered image indicates that a high percentage of the agricultural land is divided into small family parcels, generally on the scale of a few acres at most.

Total conversion of wetlands to open water and agricultural lands during the 12-year period is 4290 km^2. The average annual rate of wetland loss by natural causes and human modifications is 358 km^2/y. Although the analysis did not cover the entire delta plain, browse images of the entire delta show a similar use of the delta plain. The only area in which agricultural expansion has not taken place is in those areas where saline tidal waters intrude into the delta plain. The largest such area is the main mangrove covered tidal plain referred to as the Sunderbands. Examination of browse images shows, however, that even in a short period of time, agricultural land is expanding into this region by construction of levees to prevent saltwater intrusion.

Indus River

The 1487-km-long Indus River rises in the Himalaya Mountains of western Tibet at an elevation of about 5700 m. It follows a precipitous course west through Tibet and then northwest across Kashmir. In western Kashmir, it flows down a narrow passage nearly 396 m deep in places through the mountains until it enters Pakistan and proceeds almost due south to the point where it is joined by the Panjnab River. Shifting to the southwest, the Indus follows a contorted path before emptying into the Arabian Sea and creating a complicated protuberance of terrigenous clastic sediments known as the Indus delta. The drainage basin represents an extremely complex basin, the northern basin dominated by an east-west-trending Himalayan fold belt, while the central and southern basin is dominated by relatively low-relief Quaternary sediments. Drainage density of the tributaries is relatively high, averaging 0.37 km stream length per 500 km^2. The drainage basin occupies some 1,086,000 km^2 and has an average elevation of 1721 m with a maximum of 5700 m and a minimum of 30 m. The average relief in the basin is 606 m. The average annual rainfall is relatively low, only some 396 mm with a maximum of 1580 mm and a minimum of 39 mm. The rainy months are late June through September, and the driest months are November through March, when the average monthly rainfall rarely exceeds 30 mm. Most of the vegetation in the drainage basin and the alluvial valley consists of thorn-scrub forests and desert, with the exception of the northern part of the basin, which is dominated by alpine steppe vegetation.

Almost 90% of the water in the Upper Indus River Basin comes from remote glaciers tucked in the majestic Himalayan and Karakorum mountain ranges, which border China and India, and the Hindu Kush, which borders Afghanistan. The rest comes from rains, especially during the monsoon season from July to September. The average annual discharge is 2644 m^3/s with a maximum of 10,128 m^3/s and a minimum of 189 m^3/s—quite a large range, illustrating the erratic nature of the discharge regime. River floods occupy the months of June through September, coinciding with monsoon rains and glacial melt. The river is lowest in December through February when rainfall is lowest. In its upper valley, the Indus flows primarily as a braided stream because of a high gradient associated with the river course and an erratic pattern of discharge. As the river approaches the Arabian Sea, it becomes a meandering system in its lower reaches. Oxbow lakes, meander loops, and abandoned channels, plus ridge-swale scrollwork associated with the deposition of coarse point-bar sediments, are formed during the lateral migration of the river. In historic times, the Indus River has switched its location, thus contributing to the construction of a broad deltaic plain some 29,524 km^2 in area, the largest part of which does not receive active sedimentation from the modern river (Wells and Coleman, 1984). The abandoned delta is some 6.4 times the size of the active delta region, and the subaerial delta is 8.2 times larger than the subaqueous delta. Within the abandoned deltaic plain, many remnants of once-active tributaries and their associated alluvial features are still apparent. Numerous small lakes, representing former intertributary bays, dot the abandoned delta plain. Tidal processes are now the most active process in the seaward-most region of the delta plain.

The delta has formed in an arid climate under conditions of high river sediment discharge (~400 million metric tons of sediment per year), a moderate tide range (2.62 m), extremely high wave energy (14×10^7 ergs/s per meter of coast and a root mean square wave height of 1.84 m), and strong monsoonal winds from the southwest in the summer and from the northeast in the winter. The resultant rather coarse-grained delta, which has acquired a lobate shape, is lacking in luxuriant vegetation and is dissected by numerous mangrove-lined tidal channels in the lower deltaic plain. Estimates of delta building over the last 5000 years indicate an average progradation rate of approximately 30 m/y. Morphology of the Indus River delta lie midway between that of a fluvially dominated delta, with tributaries that protrude into the basin of deposition, and a wave-dominated system, with little tributary expression along the coast, except where characterized by beach and dune deposits.

In recent years, a high proportion of water from the Indus has been diverted for irrigation, thus considerably reducing the effective discharge. Water storage areas and manmade canals for diverting Indus River water are apparent along the west margin of the delta. The lower or active deltaic plain is roughly delineated by the landward boundary of saltwater intrusion. This lower deltaic plain is crossed by a complicated network of meandering tidal channels that daily inundate the region with saltwater and fine-grained suspended sediment. The margins of these tidal channels are commonly lined by salt-tolerant mangrove vegetation on a sand to silt substrate, while barren flats are common in the interchannel areas. Along the creek margins, small crevasses/splays build sediment wedges into interchannel regions. Even though the tide range of the Indus is not extreme (~2 to 3 m), when combined with the effects of the storm tides of the southwest monsoon in summer, vast areas of both the active and lower abandoned deltaic plain are inundated with saltwater. As a result of this yearly cycle, combined with an arid climate, low-relief areas trap saltwater that evaporates to create rather extensive salt flats. The bell-shaped channels associated with river mouths and tidal creeks are other indicators of tidal influence on this delta's morphology.

Waves are the single most important process variable in shaping the Indus delta. Intense monsoonal winds arriving from the southwest (May–September) are responsible for an abnormally high level of wave energy at the coast. The effect of this wave energy has been to concentrate the coarse sediments at the shoreline, produce strong alongshore currents, and generally straighten the configuration of the coastline. The result has been the development of beach, barrier, and dune complexes at the leading edge of the subaerial delta. Sandy sediments that were originally concentrated at the shoreline by wave activity have been transported into dunes by aeolian processes. These dunes reach heights of several meters and are in a state of active migration. They occur along the seaward and western margin of the Indus delta.

Because of human intervention in the natural delta-building processes of the Indus, this delta's future is uncertain. Extensive use of freshwater for irrigation during the 20th century has decreased the Indus River discharge approximately fourfold. If this trend continues, we can expect the delta to evolve into a more wave-dominated form characterized by extensive beach, beach ridges, and dune formation, probably accompanied by substantial coastal retreat.

In 1992, there was 1030 km^2 of open water in the Indus River delta plain. The interior of the delta plain consists mostly of vegetated soils, and little open water is apparent on the satellite images. Most of the open water is located in the tidally dominated lower delta plain. By the year 2000, or some 8 years later, significant changes have taken place. First, small areas of new open water begin appearing within the delta plain. However, the most significant change is taking place in the tidally dominated lower delta plain. In 2000, nearly 1990 km^2 of open water existed, an increase of 960 km^2 of new open water (Table 1). Analysis of the images indicated that shoreline erosion was occurring all along the entire delta front. This erosion is probably the result of a lack of sediment that presently reaches the coast because of dams on the middle and upper channels of the river. Some new land has also been formed, mostly the result of shifting of the river course, which has been significant in this 8-year period. Human intervention in destruction of wetlands has also been spectacular. In the 8-year period, some 635 km^2 of wetlands had been converted into agricultural and industrial use. This represents an average annual rate of wetland loss of 79 km^2/y. In the 8-year period, a total of 1595 km^2 of the wetlands in the Indus River delta has been converted from wetlands to open water or agricultural use, an average rate of 199 km^2/y.

Mahanadi River

The Mahanadi River rises in the hills of central India in the Satpura Brahmani fold belt of the Indian Precambrian Shield. Drainage density is extremely dense and the Hirakud Dam on the river has formed a man-made lake 55 km long. The area of the drainage basin is 141,464 km^2. The interior coastal plain has a relatively low elevation, and relief is extremely low. The average elevation of the drainage basin is 426 m with a maximum of 877 m and a minimum of 193 m. The main soil types found in the basin are red and yellow soils, and mixed red and black soils (laterite soils). The main channel of the river is 900 km long. Average annual rainfall in the basin is 1463 mm with a maximum of 1663 mm and a minimum of 1331 mm. The rainy months are June through September, corresponding to the monsoon season. The remainder of the year, rainfall is extremely low, rarely exceeding 30 mm per month. The basin is heavily populated, with a population density of 3.6 people/km^2, with some areas exceeding 36 people/km^2.

The alluvial valley is poorly defined, and the channel is predominantly meandering in nature. The average annual discharge is 1895 m^3/s with a maximum of 6352 m^3/s during the summer monsoon. Minimum discharge is 759 m^3/s and occurs during the months October through June. The river is one of the most active silt-depositing streams in the Indian subcontinent. The area of the delta is 10,589 km^2. The delta is extremely complex, with numerous abandoned delta lobes. The presently active delta lobe lies to the south, and at least two other abandoned delta lobes are located to the north. The older delta lobe to the north is now dominated by tidal influence, and numerous tidal channels are apparent on the image. Mangrove is the most common type of vegetation along the seaward edges of the delta plain. The delta plain is a major rice-growing region in India, and population density is extremely high. Numerous lakes and bays are present on the delta plain, many of them the remnants of former river courses. Wave energy is quite high along the delta front, and well-developed beaches and barrier islands are present along the coast.

Analysis of satellite images from 1999 and 2002 (only 3 years) indicated that the major change in wetlands was the result of new open water rather than conversion of wetlands to agricultural and industrial use. In the 3-year period, 116 km^2 of new open water was computed, with the annual rate of conversion being 39 km^2/y (Table 1). Agricultural and industrial use is a relatively new use of this delta plain, and in the 3-year period, only 22 km^2 of wetlands had been converted. This is a relatively small delta, and the rate of conversion to agricultural and industrial use is 7 km^2/y. If this rate continues, a high percentage of the delta plain will be destroyed by human activity. Total net loss during the 3-year period by both natural causes and human intervention has been 94 km^2, or a rate of 31 km^2/y.

Mangoky River

The Mangoky River rises in the central Highlands of Madagascar and enters the Indian Ocean in the Mozambique Channel. The eastern half of the basin drains Precambrian sediments, while the central and western basin drains a prominent series of north-south-oriented Mesozoic fold belts. The basin area is 58,155 km^2 in area, and drainage density is relatively low. From its headwaters to the delta mouth, the main channel has a length of 570 km. Average elevation in the drainage basin is 778 m with a maximum of 1440 m and a minimum of 240 m. Most of the higher relief areas are located in the easternmost portion of the basin. Average annual rainfall is 831 mm with a maximum of 1882 mm and a minimum of 240 mm. The rainy months occur from November through March. The average annual monthly rainfall during this period is 130 mm, and the average monthly rainfall during the dry season is only 19 mm.

The channel in the well-defined alluvial valley displays a braided pattern, with numerous midchannel islands. The average annual river discharge is 526 m^3/s with a maximum of 1621 m^3/s, which occurs in January, and a minimum of 93 m^3/s which occurs in October. Thus, the discharge pattern displays extremely erratic discharge characteristics. Examination of satellite images of differing dates indicates that changes in channel pattern is quite common in the alluvial valley and the delta plain. The climate in the alluvial valley is quite dry, and exposed sandy islands dot the main river course.

The delta displays a fan-shaped pattern and has two main tributaries. The area of the delta is 1547 km^2. Braiding is prevalent in the tributary channels, and it is obvious that the tributaries change course frequently: numerous abandoned channel courses can be seen on the satellite images. The abandoned delta is some four times larger that the active delta plain. Most of the delta plain is devoid of vegetation because of the harsh, arid climate; salt pans and barren algal flats are common throughout the delta plain. In the area of the abandoned delta plain to the north, tidal channels are prominent, and mangrove vegetation dominates the lower delta region. Wave energy is quite high, and beach ridges front the entire delta plain. Stranded beaches can be seen in the delta plain, especially in the southern part of the delta. The barrier islands are relatively unstable and are constantly changing their geometry. The barriers average 3–10 km in length (STUTZ and PILKEY, 2002) and occur as new islands that form at active river mouths that grow laterally through the accretion of recurved spits. Along the inactive delta, the barriers are exceedingly narrow and show evidence of active alongshore migration.

Georegistering the 1985 and 2000 satellite images and importing them into ArcView allowed interpretation of various changes between the two dates and to calculate the changes. The delta plain analyzed was 1449 km^2 in extent and thus covered most of the delta plain. In the 15-year period, a net loss of some 43 km^2 of wetlands had been converted to open water, primarily by natural causes (Table 1). This represents a rate of 3 km^2/y. Most of the new open water resulted from shoreline erosion and changes in the channel pattern of the river course. A total of 130 km^2 of the original delta plain had been reclaimed by 1985. Between 1985 and 2000, an additional 90 km^2 of wetlands had been converted into agricultural and industrial use, a rate of 6 km^2/y. Thus, between natural change and human-induced change, a net total change of 133 km^2 of former delta plain had been converted to either open water or human-induced land use. This represents an average annual rate of 9 km^2/y.

McKenzie River

The McKenzie River is the longest river in Canada, covering a distance of 1470 km. The river originates at the Great Slave Lake in the Northwest Territories and flows north in the Arctic Ocean. The drainage basin covers an area of 1,448,400 km^2 and originates in the Canadian Shield of Canada. Precambrian basement rocks are dominant in the eastern part of the basin; Devonian and Cretaceous sedimentary rocks are found with the central part of the basin. Drainage density of the tributaries is quite high, and several large rivers, such as the Peace, Athabasca, Liard, and Slave, are part of the drainage pattern. Average elevation in the basin is 620 m, with maximum elevations of 2167 m and minimum elevations of 80 m. Relief in the upper basin is quite high, with average relief being 730 m. Annual average rainfall is 335 mm with a maximum of 893 mm and a minimum of 119 mm. The rainy months are July through September, when precipitation rarely falls below 30 mm. There are about 300 days during the year when the temperature is below freezing. The drainage basin is covered by boreal forests and taiga and results in an extremely large volume of woody debris flowing down the river.

The channel in the well-defined alluvial valley is predominantly braided in nature, but meandering is present in the lower part of the valley. Average annual discharge is 8561 m^3/s with a maximum of 18,188 m^3/s and a minimum of 2873 m^3/s. Discharge is rather peaked because of the rapid thaw in the drainage basin, and the flood season lasts from May through September, during which monthly discharge generally exceeds 10,000 m^3/s. The month of March has the lowest discharge (2873 m^3/s).

The delta has an area of 8506 km^2 and is formed in a narrow embayment of the general coast. The climate of the area is very cold, with mean temperatures of −29.6°C in January and 13.6°C in July at Inuvik (PANNATIER, 1997). Much of the McKenzie delta is underlain by permafrost. The permafrost is approximately 100 m thick in land areas in the delta and well away from river channels or lakes. The delta is dominated by approximately 25,000 lakes. These lakes are not static features, but are constantly changing. Only northern deltas have such a large number of lakes; most temperate and tropical deltas have large areas of marshes and swamps, and few lakes. The main tributary of the delta is quite complex and displays a sinuous pattern with a few meandering stretches. The delta is home to one of the world's largest concentration of pingos, with about 1450. Pingos are large, volcano-shaped mounds of solid ice, which are thrust up through the permafrost terrain by the growth of their ice cores from below. Most of the delta plain is characterized by patterned ground or ice polygons. Tides are very low in the Arctic Ocean, and spring tides are less than 0.3 m. Wave action is also relatively low, with the root mean square wave height being only 0.15 m. Drill holes reveal that there is about 70 to 80 m of deltaic sediment overlying bedrock. Wood found at a depth of 38 m in one of these holes was dated by radiocarbon techniques and found to be about 6900 years old.

Net sedimentation rates on tributary channel levees vary between 1.3 and 2.3 cm/y in the middle delta, while they range from 0.5 to 1.4 cm/y in the outer delta (PANNATIER, 1997). Lateral channel migration is limited by the development of fine-grained levees covered by vegetation and stabilized by the presence of perennially frozen ground. Net sedimentation rates in lakes connected to the channel system vary between 0.36 and 1.16 g/cm/y in the middle delta and between 0.15 and 0.64 g/cm/y in the outer delta.

Georegistered satellite images from 2000 and 2002 (only a 3-year period) were analyzed to detect changes in open water because little or no parts of the delta plain are used for agricultural and industrial use. In the 3-year period, some 24 km^2 of tundra wetlands were converted to new open water (Table 1). This represents an annual average rate of 12 km^2/y.

Mississippi River

The Mississippi River, the largest river system in North America, drains an area of 3,226,300 km^2; this broad drainage area lies between the Appalachian Mountains (east), the Rocky Mountains (west), and the Precambrian Shield of Canada (north). The river rises in the foothills of the Rocky Mountains and flows southward for a distance of 6211 km and enters the Gulf of Mexico. The density of the tributary network in the basin is relatively dense, the average drainage density being 0.19 km stream length per 500 km^2. Average elevation in the drainage basin is 659 m with a maximum of 2980 m and a minimum of 30 m. Average relief in the drainage basin is quite high, averaging some 915 m. Average annual rainfall in the basin is 688 mm with a maximum of 1532 mm and a minimum of 169 mm. The rainy season lasts from May through August, when the rainfall rarely falls below 80 mm. The driest month is January, with an average rainfall of only 34 mm.

The alluvial valley is extremely well defined all along its course and has a length of 870 km. Meandering is the most common type of channel process, but some braided stretches occur in the upper valley. The lower alluvial valley is characterized by an abundance of abandoned meander belts, each belt marking a former course of the river. Within each meander belt are well-developed abandoned meander loops and oxbow lakes. Separating the meander belts are broad wetlands composed of water-tolerant trees; these are referred to as backswamps. Only fine-grained suspended sediments are deposited in these regions, and organic accumulations are common. The major geologic work on the alluvial valley was conducted by H.N. Fisk of the U.S. Army Corps of Engineers (Fisk, 1944), whose paper is a classic study of processes and sedimentation in alluvial valleys.

The average discharge of the river at the delta apex is approximately 17,704 m^3/s with a maximum and minimum of 28,161 and 9579 m^3/s, respectively. Sediment discharge has been estimated to be about 2.4 billion kg annually. The sediment load brought down by the river consists primarily of clay, silt, and fine sand (approximately 70% of the load).

During the past 7000 years, the sites of maximum deltaic sedimentation (delta lobes) have shifted and occupied various positions (Kolb and Van Lopik, 1966). The currently active delta lobe is the Birdfoot or Balize delta. An older, abandoned lobe, the St. Bernard delta lobe is located north of the active lobe, while a younger abandoned lobe, the Lafourche delta lobe flanks the modern delta to the west. In recent times, the seaward progradation and lateral switching of the deltas has led to the construction of a broad coastal or deltaic plain that has an area of 28,568 km^2, of which 23,900 km^2 is subaerial.

The modern Birdfoot or Balize delta of the Mississippi River is the youngest of the Recent delta lobes; it commenced its seaward progradation some 600 to 800 years ago (Fisk and McFarlan, 1955). This newest delta has prograded over a relatively thick sequence of prodelta clays, and as a result of differential sediment loading, it has built a relatively thick but laterally restricted deltaic sequence. In contrast, the older Recent deltas, mostly built over shallow bay and shelf deposits, are laterally widespread and relatively thin. The main channel of the river is almost 2 km wide, is 30 to 40 m deep, and displays relatively well-developed natural levees. At image top, the natural levees are up to 1 km wide and have heights of 3 to 4 m. Along the active tributaries in the lower delta, the natural levees narrow considerably, to widths less than 100 m, and display heights generally less than 0.5 m.

The channels of actively prograding tributaries in the delta display bifurcated patterns both upstream and near their mouths. This type of pattern normally is associated with extremely low offshore slopes and low wave energy. Situated between the channels are intertributary bays displaying a variety of sizes and shapes. These bays are usually extremely shallow (generally less than a few meters) and contain brackish to normal marine water during periods of low flooding and freshwater during periods of high flooding. Sedimentation rates are relatively low. The bays receive sediment only during periods of overbank flow associated with floods.

Immediately seaward of the actively prograding tributaries are the turbid river mouth effluent plumes (Coleman and Wright, 1971). Deceleration of a turbid plume as it spreads laterally allows the coarser sediment being transported to be deposited, forming the tributary mouth-bar and delta-front environments. The finer grained sediments remain suspended and spread laterally over broad distances, forming a turbid plume that fronts the entire offshore delta; as these fine-grained sediments are deposited, they form the prodelta platform as the tributaries build seaward at rates of 100 to 150 m per year. Wave energy is relatively low offshore of the Mississippi River delta. Wave power is highest during the low-discharge months, and this often results in excessive coastal erosion.

Wetland loss in Louisiana is extremely rapid and has been documented by numerous investigators (see the good regional review by Barras, Bourgeois, and Handley, 1994). Since the 1930s, 2800 km^2 of wetlands have been converted to open water. This loss is primarily the result of the high subsidence rate that is taking place in the delta region. Rising sea level, dredging, and conversion of wetlands for agricultural and industrial uses have also played a major role in this wetland loss. Because of the size of the delta, satellite images of only the active delta were acquired in 1983 and 1995 and were used to detect changes in open water and industrial modification of the delta wetlands in the active Birdfoot delta. The area of the delta analyzed comprised some 1904 km^2. In a 12-year period, some 252 km^2 of wetlands had been converted to new open water, at an annual rate of 21 km^2/y (Table 1). Most of the land loss occurred in the numerous bay fills, especially in the West Bay area (south of the Mississippi River channel). In isolated regions, some new marsh was created. Much of the wetlands of the active delta have been modified by humans and converted into industrial use. In the 12-year period, a total of 112 km^2 of wetlands had been destroyed by human activity. A total net wetland loss by conversion to open water or by industrial use was 364 km^2 during this 12-year period.

Niger River

The source of the Niger River is in the Precambrian West African Shield region of interior Africa. The central part of the basin, where the "inner delta" is located, is in the Central Tertiary Basin. The drainage basin has an area of 2,117,700 km^2, and the drainage density is quite high (0.20 km stream length per 500 km^2), especially in the northern part of the basin. The main course of the Niger River has a length of 4350 km from its headwaters to the mouths of the delta. Average basin elevation is relatively low, some 431 m with a maximum of 1693 m and a minimum of 157 m (in the inner delta region). Annual average rainfall is 672 mm per year with a maximum of 2247 mm and a minimum of only 8 mm. The wet season occurs in July through September, and average monthly rainfall generally exceeds 120 mm. The dry season commences in mid-October and lasts through the month of May, where monthly rainfall rarely exceeds 10 mm per month.

The alluvial valley is generally well defined, especially in the region below the inner delta. River discharge averages some 1045 m^3/s annually, with a peak discharge of 1424 m^3/s in October and a minimum discharge of 750 m^3/s in March. A very pronounced feature within the alluvial valley is the presence of an "inner delta." The total area covered by the inner delta, which is a network of tributaries, channels, swamps, and lakes, can reach about 30,000 km^2 in flood season. The delta area is swampy and the soil sandy. This inner delta has formed in a large cratonic basin, the E1-Djouf or Taoudene.

The delta of the Niger displays a relatively smooth lobate pattern. The delta covers an extremely large area, some 19,135 km^2. The subaerial delta is nearly eight times larger than the subaqueous delta, probably as a result of the relatively high nearshore wave action and the presence of strong littoral currents. As a result of the extremely high density of active tributaries, only about half of the delta is in an inactive state. Wave energy is relatively high along the delta front. Wave energy is relatively uniform along the entire length of the delta shoreline, and the highest wave action occurs in the months of June through October. The lobate nature of the delta generally results from the alongshore wave energy gradients. Root mean square wave height is 1.11 m.

The tributary pattern in the delta is highly complex in nature, and approximately 11 active river mouths exist. Tributary density is quite high, averaging some 0.48 km stream length per 500 km^2—one of the highest of the deltas analyzed. Most of the interior part of the delta is densely vegetated and mangroves dominate the vegetation along the fringes of the delta. One of the most prominent features of the delta is the relatively large and complex tidal channels that front most of the delta. Tidal range is moderate, with an average tidal range of 1.43 m. Intricate tidal channels extend from the shoreline into the interior part of the delta. The active tributaries are tidally dominated and often display typical bell-shaped river mouths. The presence of strong coastal currents is indicated by the deflection of the river mouths in a downdrift direction. Because of the relatively high wave action, most of the coast displays active sandy beaches and barriers along the coast.

Georegistered satellite images acquired in 1987 and 2002 were analyzed to detect changes in open water and agricultural and industrial use during this 15-year period. The entire delta was not analyzed, but 1110 km^2 of the lower delta was included in the analysis. Some 97.7 km^2 of open water existed on the 1987 image and increased to 179.0 km^2 by 2002, a total net increase of 81.3 km^2 in this 15-year period (Table 1). This represents an average rate of conversion to open water of 5 km^2/y. Much of the lower delta consists of mangrove tidal swamps, and agricultural and industrial use is quite low. In 1987, some 97 km^2 of the delta plain was occupied for agricultural usage, and by 2002, this had increased to 104 km^2, an increase of 7 km^2/y, an average rate of 0.5 km^2/y. Thus, during this 15-year period, some 88 km^2 of wetlands had been converted to open water or converted to agricultural usage, an average rate of 6 km^2/y.

Nile River

The Nile River system is the largest river system in Africa, and the drainage basin covers an area of 3,038,100 km^2. From its major source, Lake Victoria in east-central Africa, the White Nile flows generally north through Uganda and into Sudan, where it meets the Blue Nile at Khartoum, which rises in the Ethiopian highlands. From the confluence of the White and Blue Nile, the river continues to flow northward into Egypt and continues to the Mediterranean Sea. The southern part of the drainage basin consists of Precambrian rocks (East African Rift), and the remainder of the basin consists of a variety of Mesozoic, Tertiary, and Quaternary sediments. The southern and central basin is sparsely vegetated, with vegetation consisting of subtropical savannas and grasslands; the vegetation of the northern part of the basin consists mainly of xeric shrubs and deserts. The tributary density in the drainage basin is quite dense (0.20 km stream length per 500 km^2). From its headwaters, the main channel is some 3878 km long. The average elevation in the basin is 737 m with a maximum of 2900 m and a minimum of only 40 m. Average annual rainfall is 664 mm with a maximum of 2703 mm and a minimum of 1 mm. Rainy months occupy the months of April through October, and the dry months are November through March, during which the monthly rainfall rarely exceeds 20 mm per month.

The alluvial valley of the main river channel is well defined, is approximately 1100 miles long, and has an average width of 50 km. The average annual river discharge is 2778 m^3/s with a maximum of 7692 m^3/s in the month of September and a minimum of 979 m^3/s in the month of April. The river is predominantly meandering in nature, and numerous abandoned meander loops are found within the valley. Population within the alluvial valley is quite high, average density being 30 people/km^2.

The term "delta" was first applied by the Greek historian, Herodotus, in approximately 450 BC, to the triangular alluvial deposits at the mouth of the Nile River. The delta displays the classical triangular shape characteristics of numerous large worldwide deltas. The area of the subaerial delta is

12,512 km^2, and the abandoned delta is 8.68 times larger than the active delta. In ancient times, the Nile had seven tributaries: the Pelusiac, Tanitic, Mendesian, Phatnitic (Bucolic), Sebennytic, Bolbitine, and Canopic. There are only two today, the Damietta and Rosetta. Tides offshore are extremely low, averaging only 0.43 m range. Wave energy is relatively high, with an average wave power at the shoreline of 10.25×10^7 ergs/s per meter of coast. The shoreline wave energy is highest during the months from November through April. The highest wave energy is concentrated at the protruding mouths of the two tributaries. The root mean square wave height is 1.53 m. Subsidence is relatively high in the delta region, averaging 1.2 mm/y. A considerable part of the delta coast lies below 1-m elevation, and some parts are below sea level. With continued eustatic sea level rise and continued subsidence, much of the delta will be inundated in the next century. Severe beach erosion is occurring along the coast and will continue and increase in the future, especially at the Rosetta and Damietta headlands. The delta was continuing to prograde at the mouth of the two main tributaries until construction of the Aswan High Dam, when severe coastal erosion commenced.

The delta area is heavily populated, with population densities of 3000 per km^2 being common in some parts of the delta. The region is under heavy agricultural use. Although the area has been greatly modified by humans, the remnants of the former tributaries can still be discerned. Saline salt and algal flats are common behind broad coastal barrier islands and dune fields.

Satellite images from 1984 and 2001 were analyzed to detect changes that occurred in the delta plain during this 17-year period. Conversion of delta wetlands to open water has been very low in the delta, and most of the change has resulted from shoreline erosion. During the 17-year period, only 2.4 km^2 of the shoreline has been lost to erosion, a relatively low rate of 0.2 km^2/y (Table 1). Conversion of delta wetlands for agricultural use, however, has been quite high. By 1984, some 135 km^2 of the delta plain was in agricultural usage; this increased to 147 km^2 by 2001, an average annual rate of 0.7km^2/y. Thus, the total change in the delta plain during the 17-year period has been 14 km^2, representing an average rate of 0.8 km^2/y.

Shatt el Arab River

The Shatt el Arab River rises in the Tertiary and Mesozoic northwest-southeast trending Zagros fold belt. The river is formed by the confluence of the Tigris and Euphrates Rivers, which flow through central and eastern Iraq. A third river, the Karun River, which rises in west-central Iran and drains the Zagros Mountains, joins the Shatt el Arab just north of the modern delta. The Tigris-Euphrates Basin, as well as its extension, the Persian Gulf, occupies a zone of subsidence flanked by mountains and/or desert. This elongate depression was formed during an era of mountain building initiated early in the Tertiary that continues with the movement of the Arabian plate against the stable landmass of Asia. The drainage basin of these three rivers covers an area of 793,600 km^2. The main channel is some 2658 km long and debouches into the Persian Gulf. Tributary density is quite low, and the average tributary density is 0.01 stream length per 500 km^2. The average elevation in the basin is 1090 m with a maximum of 2450 m and a minimum of 60 m. Most of the drainage basin is covered with desert and xeric shrubland, with some temperate coniferous forests in the northeastern part of the basin. The average annual rainfall is 920 mm with a maximum of 1921 mm and a minimum of 599 mm. The wet months begin in June and end in November, but the monthly average rainfall during this period rarely exceeds 100 mm. During the dry months, December through May, there are many months that have no rainfall, and the average monthly rainfall rarely exceeds 50 mm.

The alluvial valley of each of the three rivers are fairly well defined, and the channels display a meandering tendency, with stretches of braiding where tributaries enter the main channels. The average annual river discharge is 1966 m^3/s with a maximum of 3299 m^3/s and a minimum of 849 m^3/s. The delta exists today in an arid climate, with extremely high rates of evapotranspiration and notable fluctuations in temperature and wind, controlled mainly by topographic variations outside the delta. The Shatt el Arab delta is located at the northern end of an elongate shallow sea where semidiurnal tidal variations reach about 2.5 m. Although much of the delta is made up of broad marshes and associated lowlands that are valuable as agricultural lands, most coastal regions are tidal flats and sabkhas devoid of extensive vegetation where salts are deposited. The river mouths are bell shaped, and prominent broad natural levees flank the tributary channels. They support a growth of salt-tolerant vegetation (mainly blue-green algal mats). Freshwater wetlands just north of the active delta support freshwater vegetation; this area is actively subsiding, but it receives a large percentage of the sediments of the Tigris and Euphrates Rivers. The marshlands contain broad expanses of floating cane marsh and bullrush and are inhabited by a unique group of people commonly referred to as the Marsh Arabs.

The modern delta has only two active tributaries, and in its lower course, the natural levees are covered with mangrove vegetation. The intertributary areas consist predominantly of salt flats. The delta area is some 18,497 km^2 in area, and much of the modern delta plain is inactive or abandoned. Immediately to the north of the modern delta is a large tidal basin displaying intricate tidal channels and broad unvegetated tidal flats. The wave energy along the delta shoreline is extremely low, with the average wave power being 0.014×10^7 ergs/s per meter of coast and the average root mean square wave height being 0.99 m. Because of low wave energy, only narrow beaches and small dune systems lie along the leading edge of the delta. Mudflats and sandbars dissected by tidal channels dominate the prograding delta front. Where seawater is trapped during very high (storm) tides, salt pans consisting of gypsum/anhydrite are present. Cultivated areas in the lower delta generally follow the Shatt el Arab and Karun channels. Offshore from the river mouth are broad elongate subaqueous tidal ridges that form in response to tidal fluctuations.

Human activity has profoundly affected the Shatt el Arab and its delta. The network of irrigation ditches in the delta region appears to be responsible for a nearly 64% water loss after contributing sources reach the main channel. Most loss is accounted for by evapotranspiration in the irrigated fields of the lower basin and the Hawizeh marsh. Comparisons of satellite images acquired in 1984 and 2000 allow an evaluation of the changes that have taken place in the delta during the 16-year period. It should be mentioned that tidal range is quite high in the Shatt el Arab, and part of the large amount of open water analyzed on the two images could be the result of tidal differences. Most of the changes have occurred in the marshes to the north of the delta, the tidal basin east of the delta and on the seaward edges of the southwestern part of the delta. In the 16-year period, some 1610 km^2, or 23%, of the former wetlands have been converted to open water (Table 1). This represents an annual rate of loss of wetlands of 101 km^2/y. The most profound change, however, has been conversion of wetlands to agricultural and industrial use. In 1984, some 2760 km^2 of the delta plain had been converted to agricultural use, but by the year 2000, some 7849 km^2 had been converted. Thus, in this 16-year period, some 5089 km^2 marsh and tidal basin regions had been converted to agricultural and industrial use. This represents nearly a 72% loss of wetlands. Total change from natural wetlands to either open water or agricultural or industrial uses has been 6699 km^2, or 36%, of the total delta area in the 16-year period. Thus, the average annual rate of wetland loss in the Shatt el Arab delta is 419 km^2/y, a very significant land-loss rate.

Volga River

The Volga River, the largest river system in Europe, rises in the Valdai Hills northwest of Moscow at an elevation of 225 m and flows through its 2365-km length to discharge into the Caspian Sea. It has a drainage area in excess of 1,553,900 km^2. Over much of this drainage area, the river traverses a broad, often swampy basin, surrounded by low morainic hills. Within its basin lives nearly 25% of the total population of the USSR, and the river and its tributaries carry about two-thirds of all the river-borne freight in the country. The eastern boundary of the drainage basin lie in the Ural-Novaya-Zembya fold belt, while the central part of the basin contains the Moscow basin. The western edge of the drainage basin is bounded by the Baltic shield. Most of the basin drains Paleozoic and Mesozoic sediments. Earthquakes are common along the eastern edge of the drainage basin. Tributary density is quite high, and numerous small tributaries enter the main channel of the river. The average elevation in the drainage basin is 161 m with a maximum of 783 m and a minimum of 30 m. Relief is quite low within the basin, averaging only 32 m. The average annual rainfall is 626 mm with a maximum of 839 mm and a minimum of 395 mm. The wet months are July through August, and the basin has some 240 days with temperatures that are below freezing. Discharge during these periods is extremely low. Boreal forests and taigas cover most of the drainage basin.

The alluvial valley of the Volga River is well defined and displays a meandering pattern. More than 200 tributaries merge with the main river. Today, much of the flow is regulated through a series of dams and reservoirs. The Volga is fed mainly by snowmelt. Average annual river discharge is 8103 m^3/s with a maximum of 24,022 m^3/s and a minimum of 3918 m^3/s. High discharge is in May and June and low discharge is from August through March. Before damming, the river delivered 25.5 million tons of suspended sediment and an unknown quantity of bedload to the Caspian Sea (ZENKOVICH, 1967).

The Volga River flows into the Caspian Sea, the earth's largest landlocked water body, and its isolation from the world's oceans has enabled the preservation of several unique animal and plant species. The Volga provides most of the Caspian's freshwater and nutrients, and also discharges large amounts of sediment and industrial waste into the relatively shallow northern part of the sea. The delta has a classical "delta pattern" and comprises an area of 27,224 km^2. It has both a well-developed subaerial and subaqueous delta components. The ratio of the subaerial delta to the subaqueous delta is 1.97. The river system can be described as an erratically discharging river, flowing into a receiving basin whose water level has varied consistently during the Recent. Within the receiving basin, wave and current energy is extremely low. The level of the Caspian Sea has been fluctuating significantly, and in the last 150 years, water level has fluctuated over 6 m; during the period 1930–1963, water level dropped 2.6 m. This water-level fluctuation has led to three zones in the delta proper. The higher areas of the first zone are referred to as "Behr's mounds," linear ridges of clayey sands ranging from 400 m to 10 km in length and averaging 8 m in height. Between the ridges are elongated depressions (*ilmens* in Russian) that fill with water and become either fresh or saline bays. It is believed that these ridges and swales represent coastal banks now stranded by the falling level of Caspian Sea. The delta proper, comprising the second zone, displays low relief (generally less than 1 m) and is the site of active and abandoned channels, intertributary regions (often containing saline water), small dunes and algal flats, and small, partially vegetated aeolian dunes that derive their sediment from the exposed dry channel courses. The third zone is the submarine part of the delta, which forms a broad platform extending 30 to 60 km offshore.

The main eastern tributary displays a complex anatomizing channel patterns consisting of numerous dry and abandoned channels, as well as active channels. Flow in the channels is so erratic that for much of the year, little or no water flows in the channels. Strong winds erode the channel floors and form linear dunes on the overbank areas. Adjacent to the main channels are well-developed natural levees capped with small aeolian dunes; the source of the sand is the adjacent channel. The active channels that contain river flow are ice bound during the period December through March. Before the construction of dams, these complex channels constantly shifted their position with each flood. North and west of the delta are broad coastal dunes, many of which have been stranded inland by the falling level of the Caspian Sea. Many of these show little or no orientation and are generally devoid of substantial vegetative cover. A similar extensive system bounds the western flank of the delta, in which interdune areas enclose elongate, oriented lakes. The sand ridges have been stranded by the falling level of the Caspian Sea and consist of marine sands reworked by aeolian action; they generally contain a high shell content.

In the lower delta, the small tributaries display well-developed, complex, bifurcated channel patterns, and because of this process, the few major tributaries that enter the head of the delta have split, producing more than 80 active river mouths in the delta. At the river mouths, many shoals and triangular river-mouth bars are the most common geomorphic landform. Relief is very low, rarely exceeding 0.5 m. Immediately offshore is another complex system of subaqueous channels and shallow shoals that forms the delta-front platform. Because of their small size, most of these are barely visible in the image. All along the front of the delta, mudflats, coquina banks, and muddy sand shoals are present, associated with the rapid progradation of the channels before damming. On the lateral margins of the delta are algal flats and salt pans which have accumulated in those parts of the delta that are no longer active or in depressions that have been stranded by the falling level of the Caspian Sea.

Because of the changes in the level of the Caspian Sea, the delta has grown significantly in the past century. In 1880, the delta had an area of 3222 km^2 and by 1920, an additional 2970 km^2 had been added as a result of the falling level of the Caspian Sea (ALEKSEEVSKIY, AIBULATOV, and CHISTOV, 2000). From the period 1920 to 1991, an additional 6580 km^2 of subaerial delta had been deposited.

In order to determine the short-term changes in open water and conversion of wetlands to agricultural and industrial use, images acquired in 1984 and 2001 were analyzed for change detection. In 1984, a total of 1610 km^2 of open water existed in the Volga River delta plain. This represented 10.6% of the delta plain that contained open water. Some 17 years later, in 2001, a total of 1710 km^2 of open water existed in the delta plain, a loss of 100 km^2 of wetlands, and now nearly 12% of the delta plain is open water (Table 1). During this same period of time, new wetlands were being formed, but only 78 km^2 were deposited during the 17-year period. Thus subsidence and other natural factors resulted in a net loss of wetlands on the order of 100 km^2. The rate during this period of time averaged 6 km^2/y. Industrial and agricultural modification to the delta plain has also resulted in significant wetland loss. In 1984, 931 km^2 of delta plain were used for agricultural or industrial use. This represents roughly 6% of the original wetlands that existed in the delta. By 2001, a total of 1108 km^2 of the delta plain had been modified by humans, an increase of 177 km^2 during the 17-year period. Thus, in a 17-year period, a net loss of delta plain wetlands by natural causes and human-induced causes has been 277 km^2 and the loss is occurring at a rate of 16 km^2/y.

Huang He (Yellow) River

The Huang He, or Yellow, River is the largest river in China after the Yangtze and has a total length of 5464 km. The Huang He rises in northern China in the Kunlun Mountains in Qinghai Province, south of the Gobi Desert. The upper drainage basin originates in Ordos Basin and flows through numerous fold belts before reaching the Bohai Gulf. From its source, the river first flows east through deep gorges onto the Ordos Desert and finally through a relatively young valley in deposits of loamy soil known as loess. In this portion of its course, the river picks up and carries in suspension yellow silt, which colors the water. The drainage basin has an area of 865,100 km^2, and the tributary density is extremely dense: 0.23 km stream length per 500 km^2. The average elevation in the basin is 1547 m with maximum elevations reaching 4240 m. Rainfall is relatively low, the average annual rainfall being only 300 mm a year with a maximum and minimum of 754 mm and 6 mm, respectively. The rainy months are May through September and the dry months are December through March, when less than 25 mm of rainfall occurs. Most of the drainage basin is semidesert or steppe grasslands.

The alluvial valley is well defined in the lower part of the drainage basin and is heavily populated. The average annual river discharge is 2571 m^3/s with a maximum of 2858 m^3/s and a minimum of 543 m^3/s. The major high water period is from July through October. More than 100 million people live along the banks of the Huang He. In some places the water level of the river is higher than the land, and dikes have built to try and stop the river from flooding. The river is often called "China's sorrow" because millions of people have been killed by flooding. The worst flood disaster in world history occurred in August 1931 along the Huang He River in China and killed an estimated 3.7 million people. Between July and November, some 88,000 km^2 of land was completely flooded, and about 21,000 km^2 more was partially flooded.

The Huang He has changed course in the eastern portion a number of times. For several centuries before 1852, it emptied into the Yellow Sea, south of the highlands of Shandong Province. The course shifted north that year, and from that time until 1938, the river emptied into the Gulf of Bohai. In 1938, during the Second Sino-Japanese War, Chinese forces, seeking to impede the invading Japanese, destroyed the dikes and diverted the Huang He into its former course. The Chinese rebuilt the dikes in 1946–1947, redirecting the river to the Bohai. The present delta is 36,272 km^2 in size. Although there are several tributary channels, the southern branch is the presently the most active. This tributary has changed considerably in the past 20 years. The delta grew nearly 400 km^2 between 1989 and 1995, then began eroding back (EVANS, 2002). Between 1995 and 1997, the delta area eroded back about 255 km^2. In 1997, a new channel was cut near the tip of the delta. From 1997 to February 2000, the delta tip again grew nearly 100 km^2. Two factors contribute to the changes: first, the river carries a heavy sediment load, leading to clogged channels and frequent river course changes; and second, the river is heavily engineered and water is oversubscribed, resulting in little flow to the coast in recent years (EVANS, 2002).

The river carries one of the largest sediment load of all major river systems. One hundred miles from the river mouth, the sediment discharge has been calculated to be 1.1 $\times$ 10^9 tons/y, exceeded only by the Ganges-Brahmaputra and Amazon Rivers (QIAN and DAI, 1980). The sediment plume that emanates from the river mouth blankets the Bohai Gulf with suspended sediment. The high sediment loads and concentrations of suspended sediment (often greater than 50 g/L) result from the rapid erosion of the loess plateau in the drainage basin and partly from historically poor agricultural practices (YANG *et al.,* 1998). This sediment discharge figure is based on data collected between 1950 and the late 1970s. Recently, during the past 10 years, the sediment load was only 0.018×10^9 tons/y, less than 1% of the annual sediment loads in the early 1950s (YANG *et al.,* 1998). The most likely reason for this decrease is related to the decrease in rainfall and the corresponding increased use of the river's water.

The channel patterns in the delta are extremely complicated and are constantly changing. Intensive modification of the original wetlands have taken place in the delta plain, and few areas are in a pristine condition. Tides at the river mouth are 1.13 m in range, and wave power is extremely low because of the extremely low offshore slope (0.026 degrees) and limited fetch in the Bohai Gulf. Wave power is calculated at 0.218×10^7 ergs/s per meter of coast, and the root mean square wave height is 0.58 m.

Satellite images from 1989 and 2000 were used to determine changes in the delta wetlands. The total open water in the 1989 image was 45.1 km^2, and by 2000, the total open water had increased to 53.1 km^2, a relatively small increase of 8 km^2 in this 11-year period (Table 1). Conversion of delta wetlands resulting from agricultural and industrial use, however, was much more significant. In 1989, some 350 km^2 were in agricultural use, while in 2000, this usage had increased to 1077 km^2, an increase of 727 km^2; the average rate of change was 66 km^2/y. Thus, during this 11-year period, some 735 km^2 of delta wetlands had been converted to open water or used for agricultural purposes; this represents an average rate of change of 67 km^2/y.

Yukon River

The Yukon River rises in Precambrian, Paleozoic, and Carboniferous sediments of Alaska and Canada. The drainage basin covers some 829,700 km^2, and the river flows some 3219 km west and empties into the Bering Sea. The average basin elevation is 740 m with a maximum of 2797 m and a minimum of 50 m. The basin is frozen for nearly half the year, and little or no flow occurs in the channel. Average annual rainfall is 502 mm with a maximum of 2041 mm and a minimum of 77 mm. Drainage density of the tributaries is quite dense.

The alluvial valley of the river is well defined and controlled primarily by the structural grain of the region. Although some meandering is displayed by the main channel within the alluvial valley, it is braided most of its distance. The average annual discharge is 6115 m^3/s with a maximum of 12,988 m^3/s and a minimum of 895 m^3/s. Discharge peaks in May–June after thawing in the basin and declines over the next few months until November, when the basin again freezes. During the winter months, discharge averages less than 1000 m^3/s.

The delta has an area of 5280 km^2 and protrudes into the Bering Sea. Much of the delta plain is inactive, and active deposition takes place mostly at the three active river mouths. Much of the intertributary region consists of small lakes and contains channel scars of former active tributaries. Much of the delta plain is covered by these small lakes. Pleistocene terrace remnants are found just north and south of the active delta. Along the shoreline are ice-pushed beach ridges that contain a large volume of woody debris in the form of large logs. For some 180 days, the entire delta plain is frozen solid, and permafrost can be found almost throughout the delta.

Because there is very little agricultural or industrial use in this remote delta, only changes in open water were calculated. In addition, this was one of the few arctic deltas in which georegistered images were available for analysis, and because no industrial use is present in the delta plain, any changes in open water would be solely caused by natural processes. Satellite images were obtained for 1985 and 1992 and comparisons analyzed by ArcView. The 1985 image contained 1210 km^2 of open water, so roughly 26% of the delta plain consists of lakes and open water channels. Some 7 years later, in 1992, the open water in the delta plain was calculated to be 2310 km^2, an increase in new open water of 1100 km^2, or nearly 48% (Table 1). Only a small percentage of this loss resulted from shoreline erosion; the remainder was lost by enlargement of the numerous small lakes within the delta plain. During this same interval of time, some 316 km^2 of new wetlands were formed at the mouths of the rivers and by infilling of some of the open water lakes. Thus, in this 7-year period, there was a net loss of delta plain wetlands of 1100 km^2, an annual rate of wetland loss of 157 km^2/y. Because there is virtually no influence by humans in the delta plain, this significant loss is solely the result of natural processes. Because a high percentage of the loss is along the shoreline of the lakes that exist on the delta plain and in the creation of numerous small new lakes, it is interesting to speculate that the global warming trend might be the most significant contribution to this wetland loss.

Zambezi River

The Zambezi River arises in central Africa, and the western portion of the drainage basin is located in the Quaternary and Tertiary sediments, while the central and eastern portion of the basin drains the Precambrian Luffillian Arch and the East African Rift. The drainage basin has an area of 1,388,200 km^2 and is sparsely vegetated with grasslands and savannas and flooded grasslands. The main channel of the Zambezi flows for some 2650 km before entering the Indian Ocean. The drainage density is quite high, and numerous dams have been constructed that impound large freshwater lakes. The average elevation in the basin is 1058 m with a maximum of 1847 m and a minimum of 333 m. The average annual rainfall is 955 mm with a maximum of 1518 mm and a minimum of 533 mm. The rainy months commence in November and last through mid-April with an average monthly rainfall of 140 mm. The dry period is from mid-April through October, and the monthly average rainfall rarely exceeds 20 mm. Thus, there are distinct wet and dry periods within the basin.

The alluvial valley is well defined in its lower reaches, and the channel displays a predominantly braided pattern. Average annual discharge is 3341 m^3/s with a maximum of 4558 m^3/s and a minimum of 1954 m^3/s. The delta protrudes slightly into the Indian Ocean and has an area of 2705 km^2. Wave energy is quite high, and numerous beach ridges are found abandoned within the delta plain, alongshore away from the delta, and flanking the river mouths. Tidal influence is best expressed south and north of the delta, where broad tidal basins exist. Within the delta plain, abandoned channels are present, indicating rather active changes in the tributary channels. Extensive mangroves are present in the lower delta and in the tidal basins. Salt flats are common in the intertributary basins, and vegetation is sparse. The river carries a substantial silt and clay suspended load, and distinct sediment plumes are present offshore.

The lower delta plain is virtually free of any agricultural or industrial land use. Comparison of 1986 and 2000 satellite images indicates that coastal erosion is quite high along the delta front. Some 46 km^2 of wetlands and coastal barriers have been lost in the 14-year period between the satellite images. The only significant land gain is along some of the tidal channels and at the mouths of the main channels. In the 14-year period, only 22 km^2 of new delta plain sediments has been formed. Thus, there has been a net loss of delta plain wetland of 24 km^2 (Table 1). This represents an average annual rate of wetland loss of 2 km^2/y.

As mentioned, there is virtually no agricultural or industrial use in the lower delta plain, but at the head of the delta (in the upper delta plain), some agricultural use is made of the delta plain, especially the areas adjacent to the active channel. In 1986, a total of only 22 km^2 of land was under cultivation. But by the year 2000, a total of 347 km^2 was utilized for agricultural purposes, an increase of 325 km^2. This represents an annual rate of delta plain loss of 25 km^2/y. As agricultural practices increase and levees are constructed to block tidal water incursions, it is likely that land reclamation will continue to expand into the lower delta.

CONCLUSIONS

In the 14 deltas analyzed, all deltas showed wetland land loss, but at varying rates. The change in open water areas within the delta plain, and hence wetland loss, ranged from 8 km^2 to 1610 km^2 (Table 1), and the total wetland loss by conversion to open water was 5104 km^2. This loss took place within the last 14 years. Loss of wetlands caused by conversion of the delta plain to agricultural and industrial use was even greater than the loss experienced by natural causes. The range of wetland loss caused by human intervention was 7 km^2 to 5089 km^2. The average annual rate of loss ranged from less than 1 km^2/y to 318 km^2/y. Total wetland loss caused by human modification of the delta plain was 10,786 km^2 in roughly 14 years. Total wetland loss by both natural causes and human intervention was 15,845 km^2, with average annual rates ranging from slightly less than 1 km^2/y to 419 km^2/y.

In the 14 deltas analyzed, approximately 52.4% of the total delta plain area was irreversibly lost by natural causes and by conversion by humans for agricultural and industrial use. Quantitative examination of lower resolution browse satellite images tended to show that this trend is not unique to the deltas analyzed in detail, but is occurring in all of the deltas studied. The total delta plain area in all of the 42 deltas studied is 694,600 km^2. If the wetland loss calculated for the deltas analyzed—52.4% of the total delta plain—is correct, and if a similar loss of wetlands is occurring in the other 42 deltas, the total loss of wetlands would be on the order of 363,970 km^2 in the past 14 years, or an average annual rate of loss of nearly 26,000 km^2/y in the 42 deltas.

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