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Review

Deltas in Arid Environments

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Abstract: Due to increasing water use, diversion and salinization, along with subsidence and sea-level rise, deltas in arid regions are shrinking worldwide. Some of the most ecologically important arid deltas include the Colorado, Indus, Nile, and Tigris-Euphrates. The primary stressors vary globally, but these deltas are threatened by increased salinization, water storage and diversion, eutrophication, and wetland loss. In order to make these deltas sustainable over time, some water flow, including seasonal flooding, needs to be re-established. Positive impacts have been seen in the Colorado River delta after flows to the delta were increased. In addition to increasing freshwater flow, collaboration among stakeholders and active management are necessary. For the Nile River, cooperation among different nations in the Nile drainage basin is important. River flow into the Tigris-Euphrates River delta has been affected by politics and civil strife in the Middle East, but some flow has been re-allocated to the delta. Studies commissioned for the Indus River delta recommended re-establishment of some monthly water flow to maintain the river channel and to fight saltwater intrusion. However, accelerating climate impacts, socio-political conflicts, and growing populations suggest a dire future for arid deltas.

Keywords: salinization; climate change; Colorado river; Tigris-Euphrates river; Nile river; Indus river

Citation: Day, J.; Goodman, R.; Chen, Z.; Hunter, R.; Giosan, L.; Wang, Y. Deltas in Arid Environments. *Water* **2021**, *13*, 1677. https://doi.org/10.3390/w13121677

Academic Editor: Georg Umgiesser

Received: 26 April 2021
Accepted: 9 June 2021
Published: 17 June 2021

1. Introduction

Arid deltas, which often have arid drainage basins as well as delta plains, are among the most threatened deltas globally, with many already in an advanced state of deterioration [1]. In most arid drainage basins, there is a growing demand for water for human use while climate change is leading to further drying in most of these areas. To assess the status of arid deltas and the impacts of climate change, we reviewed the literature on four iconic deltas—the Colorado (Mexico), Indus (Pakistan), Nile (Egypt), and the Tigris-Euphrates (Iran, Iraq) (Table 1). For these four deltas, little fresh water regularly enters the sea. Even though the upper Nile basin is wet, the lower basin is dry, and little water reaches the Mediterranean. For the Colorado and Indus deltas, hypersaline conditions due to freshwater reductions have led to widespread wetland death [2–9]. Subsidence is sometimes increased by groundwater withdrawals. In the Nile delta, almost all river water is diverted into the delta to support agriculture that occupies most of the delta plain and dam construction in the basin further reduces discharge reaching the delta. Much of this agriculture is threatened due to subsidence, increasing salinization, and sea-level rise [5]. In the Tigris-Euphrates delta, river water was used as a political weapon when the Iraq government diverted water away from the delta to punish marsh Arabs [10]. Freshwater has now been reintroduced to some areas, and marshes are recovering [11]. Growing demand in drainage basins combined with climate impacts makes the sustainability of deltas in arid regions unlikely due to hyper-salinity and reduced basin inputs.

Table 1. Characteristics of arid deltas.

Delta	Size of Delta (km^2)	Annual Precipitation (cm)	Decrease in Average Historical River Discharge (%) Reaching Ocean	Decrease in Delta Size (%)	Number of Dams in Watershed	Anthropogenic Modifications and Threats
Colorado	7800	26.7	75	80	15 on Colorado; >100 on tributaries	Dams; Water consumption by municipalities and agriculture; Salinization
Nile	20,000	5–10	>95		25; 4 under construction	Damming; Dramatic water reduction; Salinization, Increased subsidence; Eutrophication
Tigris-Euphrates-Karun	18,500	13.9	96	85	14 on Tigris; 12 on Euphrates; 6 on Karun; >50 on tributaries	Damming; Water consumption by transboundary municipalities and agriculture; Salinization; Military conflict; Effluent; Wetland drainage; Eutrophication
Indus	41,400	25–50	>90	>90	15	Damming; Dramatic reduction in discharge; Salinization, Pollution

The objective of this review is to describe the current status, and projected impacts, of climate change for these four deltas. We chose these deltas because of their importance globally and because of the abundance of literature. We discuss changes in freshwater input, habitat change, and the impacts of changes in the basins. We then generalize our findings to discuss the future of arid deltas.

2. Colorado River Delta

The Colorado River Delta (CRD) was once one of the largest desert estuaries in the world. Historically, the Colorado River discharged up to 6000 m^3/sec of water to the delta, supporting vast riparian forests, fresh, brackish and saline marshes, and an extensive estuary [12]. The CRD covered 780,000 ha of riparian wetlands and marshes, mudflats, and sand beaches that provided a stopover for millions of migratory birds on the Pacific Flyway and habitat for deer, quail, bobcat, jaguar, and waterfowl, including clapper rails, bitterns, mallards, teal, and egrets [7]. During a 1922 canoe trip to the CRD, the naturalist Aldo Leopold famously wrote that "The river was everywhere and nowhere," describing the way the river meandered and braided, nourishing a fertile "milk and honey wilderness" of "a hundred green lagoons" (https://www.nature.org/en-us/about-us/where-we-work/priority-landscapes/colorado-river/restoring-the-delta (accessed on 15 September 2020)). Prior to anthropogenic modification, the Colorado River flowed freely over 2250 km from the Rocky Mountains to the Gulf of California, dropping 3050 m in elevation and draining 626,780 km^2 in the U.S. and 5180 km^2 in Mexico [12]. The drainage basin of the river includes all of Arizona, parts of six U.S. states, and two Mexican states (Figure 1).

The CRD is located almost entirely in Northwestern Mexico in a desert region with maximum summer temperatures of 40 °C and minimum winter temperatures of −5 °C. Evaporation rates are about 1 m per year and the annual average rainfall is only 68 mm [7]. The CRD is a macrotidal estuary with strong tidal currents and the salinity ranges from 35 psu in winter to 41 psu in the summer. Salinity values are higher towards the head of the estuary than at the lower end and, as a result, some consider it an inverse-estuary [7].

Figure 1. Drainage basin of the Colorado River in the Southwestern United States and Mexico (Public domain image from USGS).

Prior to the construction of Glenn Canyon and Hoover Dams, Colorado River water continually reached the CRD and the Gulf of California, providing nutrients and habitat for numerous species. During this time, the silt and water that the river brought to the delta were critical to sustaining dense wetland plant communities. By the late 1970s, hardly any water was reaching the CRD in most years. This changed in the early 1980s due to increased precipitation from El Nino that filled reservoirs and allowed water to once again reach the CRD [13]. However, after 20 years of above-average rainfall, in 2000, a drought occurred in the Southwest region, causing water shortages, and the CRD dried up again. Because of the historical reduction in freshwater and sediment input, the CRD is in a destructive phase with erosion reducing the size of the delta to about 20% of its historic size. Carriquiry et al., (2011) [7] examined sediment budgets for the CRD and concluded that the system was a net exporter of suspended sediment, with export rates as high as 7 tons of sediment per tidal cycle.

2.1. Anthropogenic Modifications

Today the Colorado River is one of the most manipulated and controlled rivers in the world, and the modifications began with the construction of the Hoover Dam in the 1930s. The purpose of the dam was to store high flows from spring runoff to be released during times of low river flow. Because it provided a steady supply of water year-round, the completion of the dam, in 1935, initiated numerous agricultural and construction projects on the river, as well as use for human consumption [12,14].

There are now more than 25 dams on the Colorado River and its many tributaries that store water for use by more than 40 million people and over 5.5 million acres of agriculture [15,16]. The dams store water and control the river's natural fluctuations and, because of this, they impact the habitat of numerous species [14,17]. For example, once dispersed, cottonwood seeds remain viable for only 1–2 weeks and need bare, moist mineral substrate in which to germinate. These conditions are usually produced in the spring by high flows of snowmelt runoff [18]. When flooding is controlled and overbank flooding is reduced, the amount of suitable habitat for cottonwood germination is decreased. In the absence of pulse flood, the river banks have become salinized and overgrown by salt-tolerant shrubs and non-native tree species, such as *Tamarix* sp. and Russian olive, resulting in loss of habitat value for birds and other wildlife [17].

Other environmental impacts of damming the Colorado River and its tributaries include lower mean water temperature and reduced nutrient and sediment concentrations. Before the dams were built, about 374 metric tons of sediment were carried downstream each day but the sediment load was reduced 70 to 80 percent following dam construction [19]. The dams also significantly affect native fish species by blocking migration patterns and altering water temperature regimes, which inhibits spawning and embryonic development, depresses swimming performance and growth, and reduces survival of early life stages [20].

During the 20th century, river flow into the CRD was reduced nearly 75% due to storage and consumption, from an annual average of 20.6 billion m^3 from 1896 to 1921 to an annual average of 5.2 billion m^3 between 1984 and 1999 (https://swdams.wordpress.com/2012/12/03/breaking-a-6-million-year-old-tradition/ (accessed on 15 September 2020)). Flessa et al. [21] estimated that only 1.9 billion m^3 of water crossed the border into Mexico each year, a reduction of nearly 75% in less than 15 years. As a result of river impoundment and water diversions, Colorado River water rarely flows all the way to the Gulf of California, altering the natural salinity balance, decreasing the flow of nutrients that supports upper CRD fisheries and reducing the area of wetlands by 80% [12,22].

2.2. Water Rights and Allocation

Every drop of water from the Colorado River is managed and allocated, even over-allocated, for use primarily by agriculture and municipalities [13]. The river water was first officially allocated in 1922 through the Colorado River Compact, with 9.3 billion m^3 to the Upper Basin and 10.5 billion m^3 to the Lower Basin each year [15]. About 20 years later, under a 1944 treaty, the United States promised Mexico 1.9 billion m^3 annually (about 10 percent of the Colorado's average annual flow) plus 246 million m^3 during flood years. However, by the time the river reaches Mexico, nearly all of its water has been diverted for agricultural and municipal use in the United States by 10 major dams and 80 smaller diversions [13]. Approximately 90% of Mexico's water allocation from the Colorado River is diverted into Canal Reforma at Morelos Dam and distributed for agricultural irrigation through a series of canals [23]. Thus, in most years, virtually no water reaches the CRD, and the relict river channel is ephemeral, with flows only from rainfall or in places where there is significant inflow from irrigation return channels or from groundwater seeping into the river from irrigated areas [21].

2.3. Salinity

Much of the Upper Colorado River Basin is underlain by geologic formations composed of sediments that were deposited or precipitated in ancient inland seas and waterways that concentrated salts in these formations. The Colorado River picks up and dissolves salt along its path from about 50 mg/L at its source to nearly 850 mg/L as it flows from the Rocky Mountains to Mexico. Historically, nearly 10 million tons of dissolved salts passed down the river annually below the Hoover Dam, causing significant environmental and economic damages. Natural and human activities also add to the salt load of the Colorado River, including out-of-basin exports, agriculture, and other consumptive uses, evapotranspiration and evaporation from reservoir surfaces.

Because of concerns over salt concentrations, the seven Colorado River Basin states worked with Federal agencies to pass the Colorado River Basin Salinity Control Act in 1974 [14]. This act was passed "to authorize the construction, operation, and maintenance of certain works in the Colorado River Basin to control the salinity of water delivered to users in the United States and Mexico." Some of the programs outlined in the Act included construction of a desalination plant near Yuma, Arizon and basin-wide salinity control projects. The desalination plant cost $250 million to build in 1992 and it was designed to take saline water from the agricultural drainage system and remove the salt. It began operating in 1992 at one-third capacity but operations were suspended after the 500-year flood on the Gila River in 1993. Since that time, the plant has been maintained but largely not operated due to water surplus and/or average water supply conditions on the Colorado River. Recently, as water demand increases and drought conditions occur in the Colorado River Basin, interest in plant operation has been renewed.

2.4. Restoration of the Delta

Restoration of the CRD, if possible, must rely on collaboration between the United States and Mexico to designate and deliver water to the region, along with help from state governments, universities, non-governmental organizations, and philanthropies [24]. Some marshes in the CRD have been restored and maintained with agricultural drainage, subsurface flows, and effluent from wastewater treatment plants, including the Hardy River marsh, Las Arenitas wastewater assimilation wetlands, Cienega de Santa Clara *Typha* marsh, El Doctor wetlands, and Mesa de Andrade wetlands (Figure 2). Portions of these wetlands are located within the Upper Gulf of California and CRD Biosphere Reserve, and all of them have been designated as Wetlands of International Importance under the Ramsar Convention and Important Bird Areas [22,25].

In 2012, Minute 319 to the 1944 Water Treaty was signed by the United States and Mexico to guide future management of the Colorado River through 2017. Among other things, this agreement included measures to promote the ecological health of the CRD. In keeping with Minute 319, in 2014, 105,392 acre-feet of water was released into the CRD in a one-time event, allowing water to reach the Gulf of California for the first time in 13 years [26]. The flow was designed to simulate historical pulse-flows into the CRD and to enhance wetlands in the area. Minute 319 also provided for a base flow of 52,696 acre-feet of water to be delivered at low flow rates over a longer period of time [27]. Both the pulse flow and the base flow were expected to restore approximately 950 ha of habitat but many of the positive impacts, seen immediately following the pulse, did not last long. The 2014 flow inundated approximately 1600 ha of the main channel and adjacent terraces of the CRD. There was a 17% increase in Normalized Difference Vegetation Index (NDVI), i.e., greenness, throughout the riparian corridor in 2014 following the water release, but this decreased after about one year [28]. The abundance (+20%) and diversity (+40%) of nesting and migratory waterbirds and nesting riparian land birds in the riparian corridor increased following the pulse flow but declined after 2014. Only a small amount of the flow mixed with Gulf of California waters and, thus, hydrologic effects were not detected in the estuary [29].

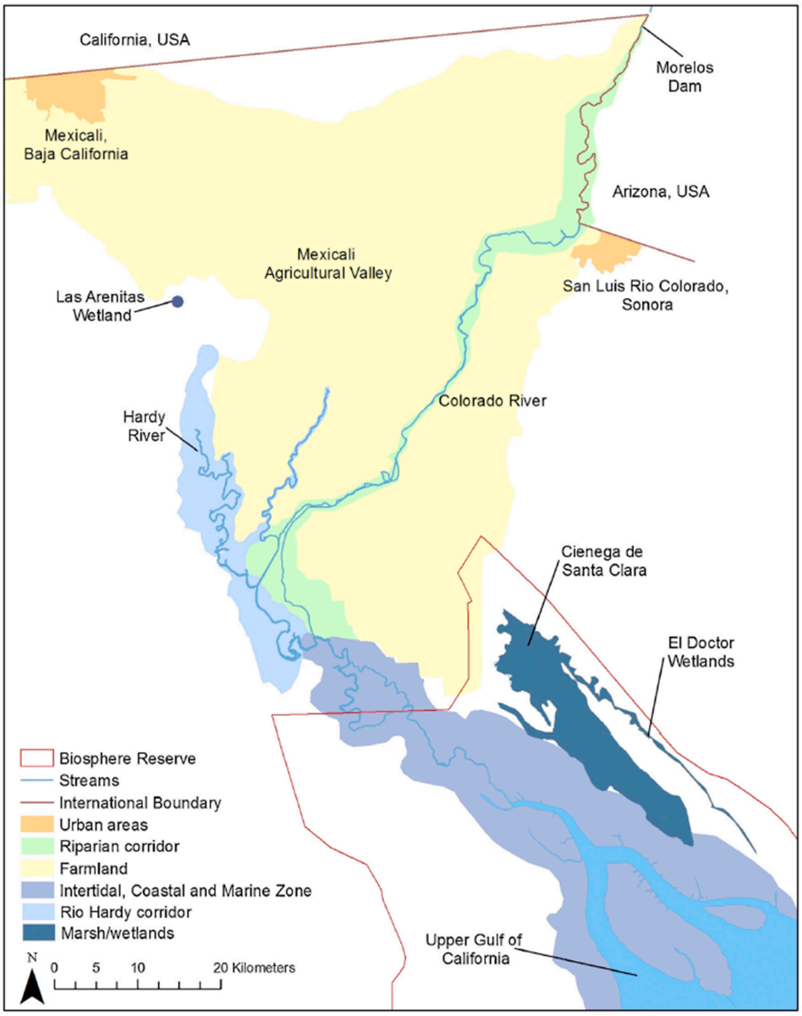

Figure 2. Wetland restoration areas of the Colorado River Delta (adapted from Ref. [22]).

Other restoration activities are planned or completed on the CRD to increase freshwater flows to the region and increase tidal exchange with the Gulf of California. The lower CRD and the upper estuary receive freshwater from the Colorado River, Ayala Drain (agricultural drainage), Hardy River (treated effluent and agricultural drainage), and other agricultural drains and seawater from the Gulf. In 2012, and again in 2016, sediment was removed from a tidal sandbar barrier in the CRD to construct a pilot channel to improve river-sea connectivity, increasing freshwater influx, tidal flooding, and drainage [29].

In 2017, the United States and Mexican governments signed a supplemental agreement to the 1944 Water Treaty, called Minute 323, that provided mechanisms for increased conservation and water storage in Lake Mead to help offset the impacts of drought and to prevent water shortage. This agreement incorporated lessons learned during the river pulse in 2014 and dedicated 210,000 acre-feet of water, over nine years, for ecological restoration in the CRD.

A little more than thirty years ago, the CRD was considered all but a dead ecosystem. However, after flood flows in the 1980s and 1990s helped to revitalize some areas, there was renewed interest in delta restoration. Water is necessary for restoration but, in the Colorado River Basin, water is scarce, and it will likely become scarcer over time. In addition to water, however, collaboration, active management, and science are also needed for sustainable restoration and to optimize the ecological and social benefits of the CRD [24]. Projections for increasing arid conditions, lower river discharge, and greater demand in both the US Southwest and northwestern Mexico do not bode well for the sustainability of the CRD [16,30].

3. Nile River Delta

Among deltas in the world, the Nile Delta of NE Africa is characterized by its distinctive physio-geographical setting [31,32] (Figure 3). The fan-shaped 20,000 km^2 subaerial Nile delta is fed solely by the water and sediment from the African Plateau and Ethiopian Highlands with rainfall from both the Indian and Atlantic oceans of ~1500–2000 mm/yr, whereas the rainfall is only 50–100 mm/yr in the lower Nile basin, including its delta. Human impacts have drastically changed input to the delta [4,33–35] particularly after the completion of the High Aswan Dam in 1964. The ongoing construction of the Grant Ethiopian Renaissance Dam (GERD) on the Blue Nile will make the situation worse. Thus, the Nile delta is increasingly suffering from serious environmental degradation because of reduced sediment and freshwater and increasing nutrients which have negatively impacted the eco-health of the Nile delta coast. Egypt initially benefited by overextraction of water from Lake Victoria when a new hydroelectric dam was built in Uganda, in the early 2000s, at the outlet of the lake that forms the White Nile River, but once the lake level was lowered this benefit stopped [36]. The pre-GERD Nile flow now supplies 97% of Egypt's present water needs with only 660 m^3 per person per year. About 86% of that water is for irrigation and industrial use, so this is one of the world's lowest annual per person water shares. Egypt's population is expected to double in the next 50 years, and this will lead to countrywide freshwater shortages as early as 2025 after the GERD dam is completed. Some form of arbitration is clearly needed to prevent a conflict over water between Egypt, Sudan, and Ethiopia (https://www.npr.org/2018/02/27/589240174/in-africa-war-over-water-looms-as-ethiopia-nears-completion-of-nile-river-dam (accessed on 20 February 2021)).

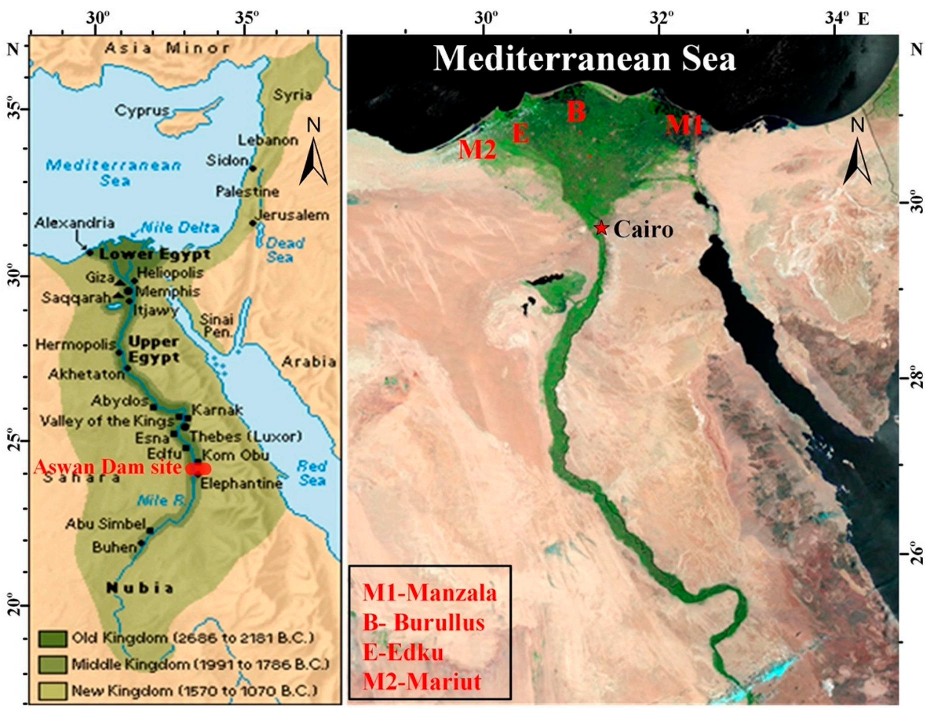

Figure 3. The Nile River basin, where Aswan dam site is shown (**left**); Lower Nile River and Nile Delta, where 4 lagoon Lakes are indicated (**right**).

The Nile Delta extends about 200 km from Cairo to the present coast, and about 250 km wide from west to east (Figure 3). The delta is characterized by low elevation land 1.0–2.0 m or less above mean sea level (MSL), which occurs along a broader delta-coast of about 30–50 km wide. The elevation then increases landward to about 15 m at Cairo.

The higher topography in inland parts of the delta was primarily caused by greater Nile floods occurring during the early to middle Holocene, during the Humid Africa Period (HAP) [37].

There are four large lagoons along the delta cost of the Nile, and from east to west, they are the Manzala, Burullus, Edku, and Mariut lagoons (Figure 3). Manzala lagoon is the largest (c. 700 km^2) [38]. These lagoons formed c. 7000 years ago, when the Holocene sea level rose to nearly the present level. The low tidal range (<1.0 m) combined with strong littoral wave-driven currents has played a key role in long shore sediment transport, forming the typical sand-spit barrier—lagoon system along the Nile coast. The lagoons were important social-bio-ecological reservoirs for the early Egyptian agricultural civilization, and this continues to the present [38].

The population of Egypt increased rapidly from about 70 million in the 1980s to nearly 100 million at present. About 90% of the Egyptian people live on the delta-coast, relying extensively on the natural resources offered by the river catchment and delta. However, the rapid development of agriculture and industrialization in the 20th century in order to meet societal demands has dramatically altered the river-delta system [39]. Dam construction, over-use of bio-chemical fertilizers, and change in land use has dramatically modified the dynamics of delivery of riverine materials to delta coast. A healthy deltaic habitat for both natural and human communities no longer exists as it was in preindustrial times.

3.1. Aswan High Dam and Related Environmental Issues

The Aswan High Dam (AHD) was completed in 1964 in the lower Nile valley about 1000 km south of Cairo (Figure 3). Geologically, the lower Nile River is contained within its valley, and no more tributaries enter the river below the AHD. Thus, the construction of the AHD has dramatically altered the natural hydrological patterns of water and sediment transport downstream to the delta coast. It is estimated that, prior to the construction of the AHD, sediment delivery to delta and coast was about 200×10^6 t annually. With the closure of the AHD in 1964, however, sediment transport below the dam was reduced to nearly zero after damming and in the delta water turbidity decreased [40].

With the completion of the AHD, freshwater discharge to delta and coast was dramatically reduced. As noted above, even though the Nile Delta is in an arid climate, it was nourished and sustained by the high freshwater discharge from the drainage basin. Seasonal floods overflowed the delta and supported high agricultural productivity for thousands of years. Since 1964, the AHD has fundamentally altered the hydrograph of the river (Figure 4), with little freshwater currently reaching the coast.

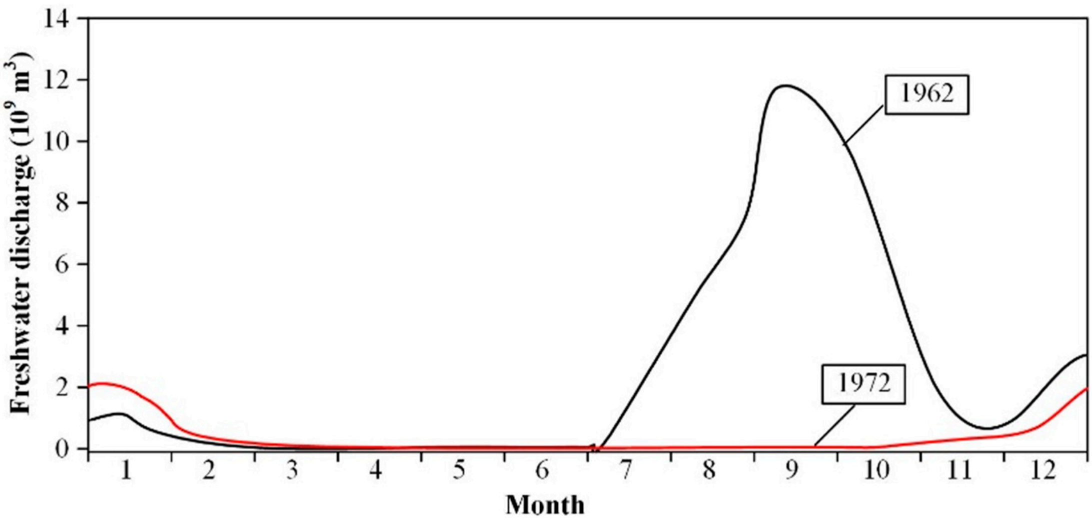

Figure 4. Freshwater discharge before and after construction of the Aswan High Dam [41].

Water diversion has been a great concern in the Nile Delta system. In addition to water use for agricultural irrigation, urban development on the margins of the delta contiguous to the desert has been taking place. These developments have considerable water demand. Thus, the water needs for urban development must now be balanced with agricultural demand. This has become an urgent issue for an increasing population because >90% freshwater released from the Aswan reservoir is already used for irrigation, and much of it is lost to evaporation [40].

On the other hand, nutrient transport, basically nitrogen (N) and phosphorus (P) are not strongly affected by the dam since nutriets are mainly dissolved and do not accumulate in the sediments. However, N and P flux increased due to increase fertilizer use. N and P fertilizer use increased from about 200 $\times$ 10^6 kg N yr^{-1} and 50 $\times$ 10^6 kg P yr^{-1} in the 1960s to about 900 $\times$ 10^6 kg N yr^{-1} and c. 150 $\times$ 10^6 kg P yr^{-1} in the 1990s [42]. Thus, N fertilizer use has increased by a factor of more than four and P-fertilizer has increased by a factor of three. P-use declined after 1990 while N-use increased up until 2000. This indicates that, before the AHD, the Nile Delta aquatic ecosystems were N-limited, but have become P-limited after the closure of the AHD in 1964 [43]. Dissolved silicate (DSi) flux to the Nile Delta was also affected by dam construction. Prior to construction of the AHD, DSi flux from the AHD was about 110 $\times$ 10^3 t yr^{-1}. However, DSi flux was reduced to about 15 $\times$ 10^3 t yr^{-1} after dam construction [44,45]. More recently, DSi flux has increased to about 35 $\times$ 10^3 t yr^{-1} [46]. The reduction in DSi flux and the increase in N and P fluxes has led to widespread eutrophication in delta waters.

3.2. Delta Geo-Ecohydrological Responses

Because of the changes described above, the Nile Delta has been in a destructive phase due to the drastic reduction in sediment and freshwater delivery to the delta as well as global climate change [47]. The coastline has been diked, especially at the promontories of the Rosetta and Damietta river mouths in order to prevent rapid shoreline retreat from coastal erosion. For example, the Rosetta promontory after the AHD had lost 12.29 km^2 of land between 1973 and 2008 and the shoreline retreated southward by about 3.5 km [48]. Most land loss and shoreline retreat occurred between 1973 and 1978 (0.55 km^2 yr^{-1} and 132 m yr^{-1}). The erosion between the river mouth promontories resulted in an overall smoothing of the coastline.

In addition to the forcing from the AHD, sea-level rise, land subsidence, storms, and coastal protection works have intensified coastal retreat [49]. Projections are for increasing salinization and subsidence in the delta. Even under natural levels of sediment, the Nile Delta would not maintain its area with a 1-m sea-level rise [5,34,50]. The Nile Delta is so fundamentally changed that sustainable management will be extremely difficult given the trajectories of major 21st century environmental and socioeconomic trends. Land reclamation has dramatically degraded the environment of coast. Edku Lagoon, in the west-central delta, has vanished after closure of the outlet to the sea.

The reduced sediment and freshwater discharge and increasing nutrients in Nile River water has directly impacted the eco-health of the Nile Delta. The pattern of fish landings off the western Nile coast evidenced a unique change over the past half century. There was a rapid decrease in fish catch after completion of the AHD in 1964, followed by a gradual recovery in 1980s and a significant recovery in 1990s [42]. This pattern was the result of increasing nutrient delivery to the estuary and coastal sea, due to agricultural runoff and urban wastewater effluent, which offset the loss of nutrients due to the AHD, leading to the recovery of the fishery [44,45]. Improved fishing technology likely also contributed to the recovery of the fishery.

Increasing N and P, and reduced DSi, has altered the N:Si:P ratio from prior-dam 12:20:1 to post-dam 14:11:1 (data sourced from [42,44–46]. Therefore, N- and Si-limitation of post-dam is evident referring to the optimum of Redfield ratio (16:16:1) [51]. Water storage in the AHD reservoir favors algae blooms down river due to reductions in DSi. Interestingly, riverine primary production increased dramatically after the 1980s due to the changes in Redfield ratios. The low DSi concentrations resulted in shifts from diatoms to non-silicate algal species, including toxic dinoflagellates in coastal waters [52]. This eutrophication led to low oxygen conditions in coastal water bodies [45]. Low oxygen, or hypoxia, in coastal water has occurred worldwide [53].

Industrial development has led to significant toxic pollution in surficial sediment in coastal lagoons after completion of the AHD [54]. In general, the upper 10–15 cm of lagoonal sediments deposited after dam completion has high levels of heavy metals. For example, Manzala Lagoon is severely polluted by Mn (Max. ~600×10^4 ppm), Pb (Max. ~20×10^4 ppm), Zn (Max. ~50×10^4 ppm) and Cd (Max. ~1.0×10^4 ppm) [54]. It receives runoff from the Cairo metropolitan area, and surrounding urbanized areas, where the petrochemical industry is thought to be a major contributor. Burullus Lagoon on the central delta coast has the lowest concentrations, but Mn and Pb are increasing. Edku Lagoon on the western delta coast seems remote from any major pollution sources, but it has high levels of Mn, Pb, and Zn in the surficial sediments, suggesting polluted runoff from Alexandria. Heavy metals are toxic for species living in the delta, and for humans, due to bio-magnification through food chains [54,55].

3.3. Management Perspectives

The Nile Delta has been key to the development and sustainability of the Egyptian civilization for over 4000 years. Agricultural production in the delta supplied the great majority of Egypt's food for millennia. However, the delta is now in danger due to global climate change, reduced river discharge, and intensifying anthropogenic impacts. The Nile Delta is an example of deltaic non-sustainability in a hyper-arid climate setting, highlighting the urgency for environmental conservation. Little rainfall and lower Nile discharge has resulted in the inability to maintain a healthy coastal environment, which is even more aggravated by a variety of human activities.

In addition to ecological degradation, sea-level rise, in response to climate warming, is threatening the environmental security of the Nile Delta and Egyptian society. Figure 5 shows the vulnerability of extensive coastal lowland below three meters (~7000 km^2), potentially to be affected by saltwater intrusion in coming decades (personal communication, Prof. Khaled Abd El-Kader Ouda).

Given the conditions discussed above, there is a need for coordination among scientists (physical and social), governmental officials, decision-makers, and stakeholders towards a sustainable strategy of delta management, via policy development and implementation. There is a need for cooperation among all nations, in the Nile drainage basin, of integrated river-basin and coastal management. However, given trajectories of climate change, mismanagement of the river, and a growing population, the future sustainability of the Nile delta is uncertain.

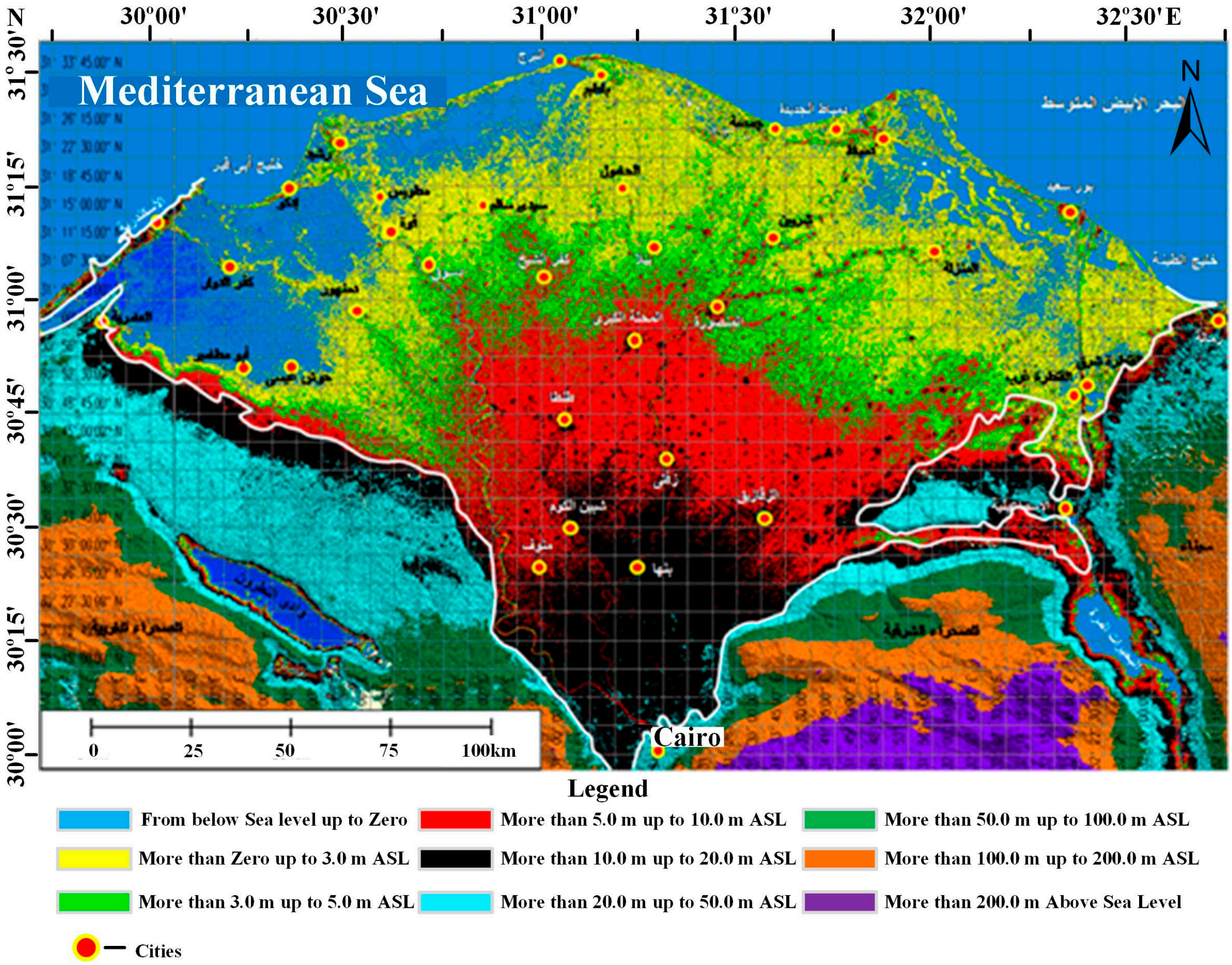

Figure 5. Coastal lowland of the Nile Delta: an extensive area (c. 7000 km^2) ranging between 0–3 m above mean sea level is particularly vulnerable to the sea level rise.

4. Tigris-Euphrates-Karun Delta

The Mesopotamian Delta (also known as the Tigris-Euphrates-Karun Delta) represents a unique fluvio-deltaic complex of inland and marine deltas that have rapidly evolved throughout the Holocene. While the Tigris and Euphrates rivers deposit most of their sediment into a spectacular system of marshes and lakes in southern Iraq, they join the Karun river at Khorramshahr in Iran to form the Shatt al-Arab estuary before entering the Persian Gulf [56,57]. The Shatt Al-Arab's relatively recent formation underscores the intricate yet understudied geomorphological history of the Delta's transition between continental and marine waters. The natural resource diversity of this ecotone encouraged the world's first complex societies [58–61]. Today, its watershed spans six countries, draining a combined area of over 10^6 km^2, from Turkey in the north to Iraq in the south (Figure 6) [62]. The rivers traverse an alluvial plain interspersed with wetlands that grade from fresh to brackish and end in an intertidal zone of sabkha and salt-encrusted mudflat [63]. Three wars, catastrophic draining, and unrelenting sectarian violence over the past four decades have threatened this enchanting landscape's remarkable mix of flora and fauna, and its recent inscription on UNESCO's World Heritage List is an effort to preserve what the historian Fred Donner [64] called "the dichotomy between dry and wet . . . a land which, despite its aridity, can appear in the late spring floods virtually submerged under a shallow, wind-rippled sea."

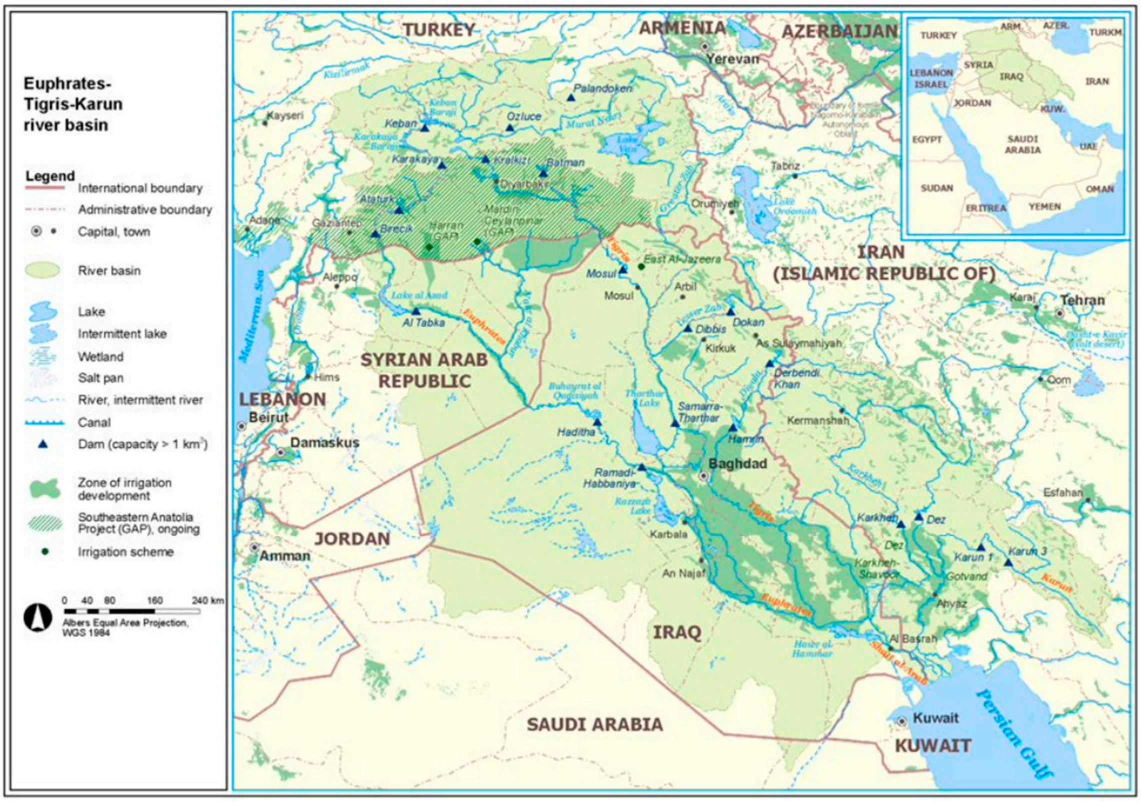

Figure 6. Drainage basin of the Mesopotamian Delta (Tigris, Euphrates and Karun Rivers) and major dams (modified from [65]).

4.1. Anthropogenic Modifications

Archaeological surveys in Mesopotamia have shown that people manipulated levees and built canals for gravity flow irrigation throughout the Delta by as early as 5000 BP [66,67]. Prior, Neolithic communities likely settled along the valley sides of deeply incised Pleistocene rivers that emptied into the Gulf of Oman [68–70]. Nonetheless, it was not until the early first millennium CE that regional-scale hydrology systems and exploding population numbers permanently changed the landscape [71]. From then until the latter half of the twentieth century, the rise and fall of successive state-led irrigation regimes increased both the rate and extent of river avulsion, and upstream sedimentation, throughout the Mesopotamian Delta [72]. As a result, marsh extensification and gilgai soil formation are well documented in the Arabic literature and early colonial sources [73].

More recent damming and diversion in the region have transformed the natural water and sediment fluxes to the delta basin, however. Major construction projects, such as the Ataturk Dam in southern Turkey, have reversed conditions of the preindustrial past, leading to the overall reduction, and even disappearance, of wetlands in the inner delta. Figure 7). From 1976 to 2002, about 7600 km^2 (85%) of Iraq's permanent marshes vanished, while 11,000 km^2 of seasonal marsh were no longer recharged [74]. The Iraq government even made a concerted effort to drain the Central and Al-Hammar marshes after the first Gulf War, home to the famous marsh dwellers, to assert control over a historically independent area, and to expand agricultural lands for export production [75].

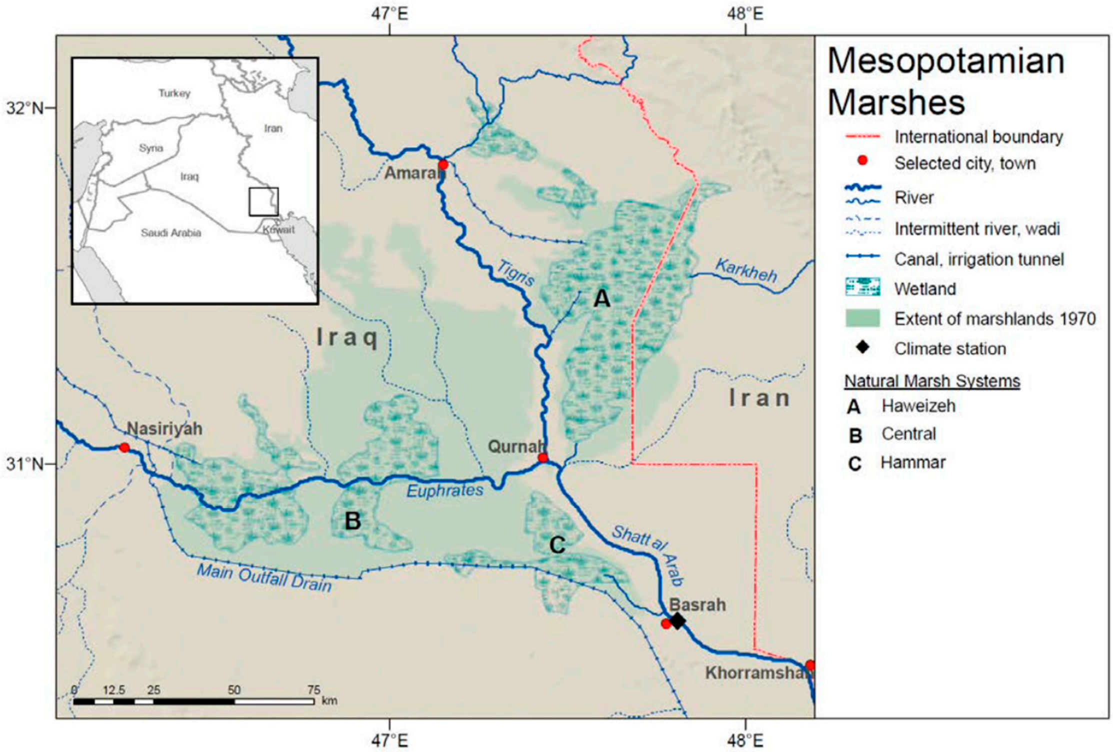

Figure 7. Location of the Mesopatamian marshes in the Tigres-Euphrates-Kuran Delta showing the decrease in wetland area since 1979 (Modified from [76]).

The ecological impacts of upstream damming and downstream drainage have been enormous. The interconnected lakes and marshes in southern Iraq and southwestern Iran are home to several endemic or near-endemic species of birds, fish, reptiles and mammals. At one time, the region was home to the largest wetland ecosystem in southwest Asia, roughly twice the size of Florida's Everglades [77]. Because these permanent wetlands are relatively recent in the geographical record, they mark a biological hotspot where endemic speciation and subspeciation reflect radical evolutionary processes on account of a unique ecosystem [78]. Their location also serves as a wintering and resting area for migratory birds, and they fall within the largest flyway in the Middle East [79]. Wetland decline has interfered with the breeding grounds of migratory waterbirds, which also served as a nursery and destination for spawning migrations of coastal fish populations from the Gulf [80,81]. Finally, the marshlands, once a natural sponge and filter for waste and other pollutants from upstream sources, are no longer shielding the Gulf from their effluent [77].

4.2. Water Rights and Allocation

The Tigris and Euphrates rivers distribute water across a transboundary basin. 46 percent of this distribution falls within Iraq, 22 percent in Turkey, 19 percent in Iran, 11 percent in Syria, 1.9 percent in Saudi Arabia and 0.03 percent in Jordan. The Karun river distributes water across two countries, where its drops down from the Iranian uplands to join the Shatt al-Arab in Iraq before entering the Gulf. While the Tigris and Euphrates' headwaters lie largely in Turkey, the Karun's are entirely within Iran, resulting in a geopolitically fraught regime with Turkey and Iran strategically well placed against their downstream neighbors, despite the centrality of the rivers and their combined deltas to the regional economy.

The middle of the 20th century ushered in a zero-sum game of hydroelectric engineering projects between the rivers' three largest stakeholders, namely Turkey, Syria, and Iraq [82]. Construction of large dams, such as the Keban in Turkey (1975), the Tabqa in Syria (1975), and the Haditha in Iraq (1984), increasingly led to uncoordinated water management between and within countries. By the turn of the millennium, 20 largescale dams throughout the Delta's catchment served a range of intrastate goals, from hydropower production and irrigation to flood protection [83]. Their impacts on end-users, particularly in southern Iraq, have been devasting. In 1966, the wetlands of the inner Mesopotamian Delta spanned some 7970 km^2; by 1984, engineering projects upstream reduced them by a third [84]. Saddam Hussein's forced drainage of the Iraqi and Iranian marshes in the early 1990s took away the little that was left [85], and, in 2000, only 15 percent of their mid-century extent remained [11].

Despite their slow, but steady restoration, following regime change, water entering the marshes of the inner delta remain degraded from return flow irrigation and urban pollution. Furthermore, the region still lacks adequate infrastructure for wastewater remediation [86]. Pesticides, nitrate and other nutrients, and spent munitions threaten wetland ecology, soils, and human populations in the basin's southern reaches [87].

Political relations amongst the riparians have waxed and waned over the years. Bilateral agreements for river management have recently increased but continued civil strife throughout the Middle East, coupled with disagreements over the basin's basic hydrography (e.g., do the Tigris and Euphrates constitute separate rivers or single system?), have stymied the institutionalization of transboundary water usage and regulation [88]. Taken together, climate change, volatile geopolitics, and population increase call for basin countries to enter trilateral and bilateral agreements to avoid future conflict and protect the delta as a natural resource.

4.3. Salinity

More than five millennia of villages, cities, and states have depended on the silt and salt content of the Tigris, Euphrates, and Karun rivers to create and nourish their floodplain [89]. Today, at peak flow, the Euphrates carries 1000–4000 ppm of sediment, the Tigris some 25,000 ppm [90]. In 1950, Cressey [91] stated that the Tigris moved some 40,000,000 cubic meters of sediment below Baghdad per year, most of it deposited in the upper and middle floodplain before its waters reached the southern marshes. In fact, both the Tigris and Euphrates empty more than 90% of their content into the inner fluviatile delta above Basra, while the Karun River deposits its entire load into the Shatt al-Arab estuary and marine external delta.

The chemical content (including salt, lime, and gypsum) of the Euphrates and Tigris rivers averages 445 ppm and 250 ppm, respectively. So much water is withdrawn for irrigation purposes and lost from evaporation that their combined tributary, the Shatt al-Arab river, averages 746 ppm—this despite the latter's greatly reduced volume [92]. As evaporation losses on the irrigated lands of Iraq exceed 30 cubic kilometers of water annually, the 22,000,000 metric tons of dissolved chemicals are added to the irrigated areas yearly, so [91] estimated a total accumulation of soluble salts at over a billion tons. Several dams were built in the Karun river basin between 1963 and 2010, reducing sediment fluxes and further increasing salinity in the Shatt al-Arab. Several prominent historians and anthropologists have postulated that soil salinization in the inner delta triggered the collapse of Mesopotamia's great societies [93].

4.4. The Mesopotamian Delta through Time

The Delta lies in present day southern Iraq, extending to the Khuzestan plain in Iran. The climate is arid to semi-arid, with mean yearly rainfall approaching 139 mm but ranging from 72 to 316 mm. Temperatures vary from 0 to 50 degrees C. Semi-permanent, low-pressure zones form over the Gulf during summer months to direct hot, dry winds across the floodplain, leading to severe dust storms. The poor timing and overall scarcity of rainfall (predominantly between November and April) requires intense irrigation agriculture along the rivers before they converge into marsh and estuary near al-Qurna in southern Iraq.

The Tigris river begins at Lake Hazar in the Taurus Mountains, where a small number of tributaries drain a wide area of eastern Turkey and contribute one-third to half of the Tigris's total annual water discharge (between 8 and 34 km^3 out of ~50 km^3). After flowing beneath large basalt walls that partly encircle Diyarbakir, it enters Iraq south of Cizre, and receives input from the Khabur River in Iraqi Kurdistan. Other left bank tributaries include the Greater Zab, sourced from southeastern Turkey, as well as the Lesser Zab, the Adhaim, and Diyala, sourced from the Zagros Mountains in Iran. Its total length is 1850 km.

At 2800 km, the Euphrates is the largest river in Southwest Asia. Its headwaters originate from the Karasu and Murat rivers in the Armenian Highland of northeastern Turkey, situated at 3290 and 3520 m a.s.l., respectively. They join at Keban to form the Euphrates, which drops from the Taurus Mountains onto southeastern Turkey's high plain and through the Karakaya and Atatürk dams. 88% to 98% of Euphrates water and sediment, respectively, derive from Turkey. The Euphrates then flows southwest, starting 160 km from the Mediterranean Sea, before bending south and southeast to reach Syria's Ṭabaqah Dam. The Euphrates's reduced flow is then supplemented by the Balīkh and the Khābūr rivers before winding its way to the Syria/Iraq border at Abū Kamāl and thence to the Ḥadīthah Dam north of Hīt. During particularly rainy seasons, small, seasonal wadis from the western desert contribute water to the Euphrates south of this position.

The head of the inner delta begins at the line of Ramadi and Samarra in Iraq, each city located about 100 kms from Baghdad. It is here that the delta plain takes its wedge shape, a tectonic depression formed when the Arabian Plate collided with and plunged below the Eurasian Plate during the Cenozoic. This created a zone of subduction between the Zagros Mountains to the east and the desert escarpment to the west, resulting in a low and flat floodplain with a weak longitudinal slope. From the point the Euphrates enters this basin it builds levees and flows above the plain, splitting into two rivers downstream of the Hindiyya Dam (the Al-Ḥillah and Al-Hindiyyah braches) before rejoining as a single course at Samawah. Once south of Nasiriyah, the Euphrates reaches the Al-Hammar marshes, where it deposits its remaining sediment load and marks the mouth of the inland delta. The Tigris, on the other hand, does not rise above the plain until it reaches Al-Kūt, some 320 km downstream from Baghdad, where a barrage diverts the river into the Shatt Al-Gharrāf. This channel also empties into the marshes south of Nasiriyah, depositing most of its sediment before outflow of the Tigris and Euphrates from the marshes meet at Al-Qurnah to form the head of Shatt Al-Arab.

The Karun River, having the highest discharge of all rivers in Iran, travels a tortuous course of 829 km from source to sink. It begins in the Bakhtīārī Mountains where its headwaters represent 75% of its catchment, before dividing into three parts, first, from its headwaters to Gatvand, where the river exits the mountains, second, from Gatvand to where the river is joined by the Dez tributary at Band Qīr, and third, from Band Qīr through Ahvāz, and thence, to the Shatt Al-Arab, where it joins the Tigris and Euphrates and accounts for the majority of the river's sediment after Khorramshah.

Finally, the Shatt Al-Arab terminates in an estuarine delta as it fills a shallow and narrow part of the Gulf with sediment [94]. Slow tectonic subsidence counterbalances progradation and strong tidal action maintains the estuary, resulting in an outer, tide-dominated delta [95].

Earlier in the Holocene, the Mesopotamian delta formed a more typical, estuarine delta. During the last glacial period, lowered sea levels left the Gulf dry except for a deeply incised river (a precursor to today's Shatt Al-Arab) that directly emptied into the Gulf of Oman (Figure 8A) [96]. As the continental icecaps melted, sea level rose by fits and starts, bringing about a punctuated marine transgression. Scholars have long argued over the precise timing and spatial conformation of the transgression in Mesopotamia, especially its effect on settlement and the world's first cities, such as Ur and Eridu (see [97] for a review). While an incursion of some 150 to 200 km is likely to have taken place between 6000 and 4000 BP [98], conclusive evidence remains scarce, and even less is known about the geomorphodynamics of what was surely, then, an estuarine delta, other than the belief that the Tigris and Euphrates emptied directly into the sea as separate entities [67].

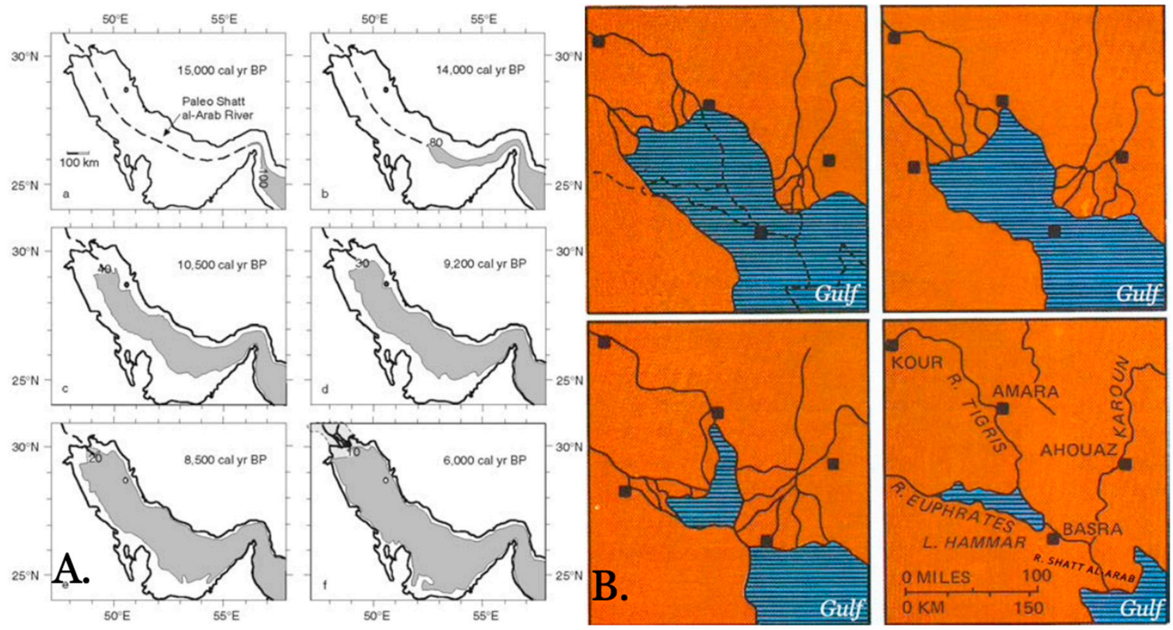

Figure 8. (**A**) Progression of marine water into the Gulf basin from the Pleistocene to the early Holocene, including the position of a precursor to the Shatt al-Arab that once emptied directly into today's Gulf of Oman (modified from [59]). For scale, see Figure 7. (**B**) From left to right and top to bottom, hypothetical geomorphodynamics of the formation of the modern deltaic complex during the Middle-Late Holocene: 5000 BP, 4000 BP, 3000 BP, and 2000 BP (modified from [101]).

Though we do not know the exact timing, the interior delta did not exist until millennia later (see Figure 8B). Around 6000 BP, the unified Tigris and Euphrates rivers continued to run down the spine of an elongated delta fan; by 4000 BP, the two rivers split into separate channels, displaced outward from the central axis by continued fan development. Later, the two main watercourses were further displaced to the margins of the floodplain before being forced back together by the constricting effect of the Pleistocene-aged Wadi Batin fan and the rapidly growing Karun fan, impounding the Tigris and Euphrates's outflow behind a berm that created marshes and eventually an inland delta (Figure 9) [99]. The Karun, with reduced inputs from the Tigris and Euphrates, flows through what is now Basra and builds out the present head of the Gulf through a complex interaction among progradation, subsidence, continued eustacy, and tidal action [69,100]. The particulars of this process remain poorly understood and invite a targeted geological research program.

Similar to the other deltas discussed in this paper, the sustainability of Tigris-Euphates delta system is in question due to a combination of global climate change, human impacts, and geopolitical confrontations.

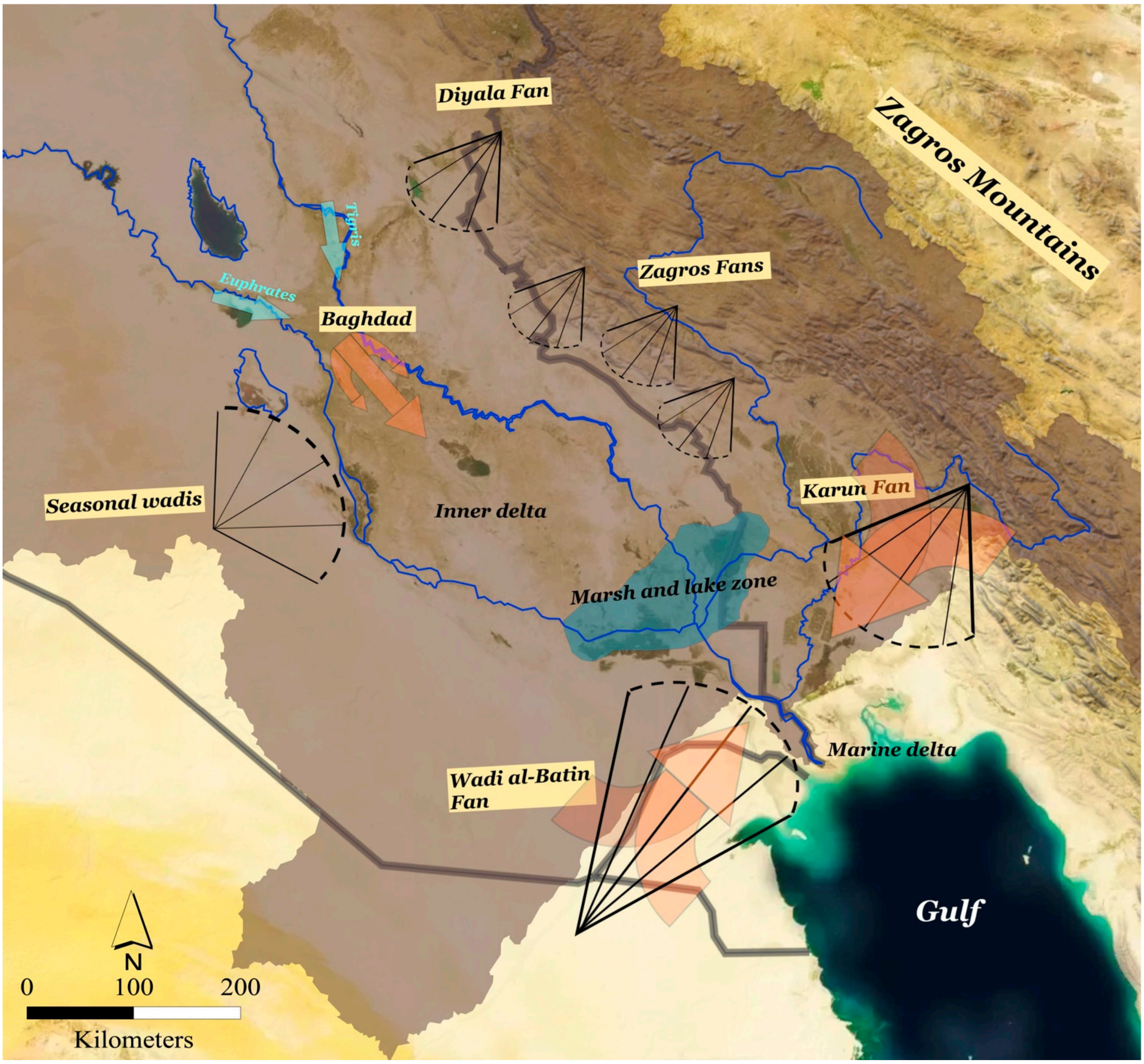

Figure 9. Features of the Tigris-Euphrates-Karun Delta. Black shading represents Tigris-Euphrates-Karun river catchment. Orange arrows represent directional influence of alluvial fan systems on the Mesopotamian Delta's hydrography. Modified from [63,99].

5. The Indus Delta

The expansive arid delta of the River Indus (Figure 10) is the result of a special set of past extreme conditions that affect its current sustainability in conflicting ways. Built by vast amounts of sediment accumulated at the coast during a distant wetter past, the delta is now deprived of fluvial input from its remote headwaters. This water and sediment starvation is not only due to a secular aridification trend combined with climatically-controlled loss of sediment toward its long alluvial plain but also by a vast array of irrigation works, primarily for agriculture, built to tackle such aridity. The delta, now severed most of the year from the river, has become a relict landscape remodeled by tides, waves, and humans. Perhaps more than for other large deltas, the future geomorphic, ecological, and economic sustainability of the Indus delta depends on how interests in the drainage basin are reconciled with the natural and human needs in the delta.

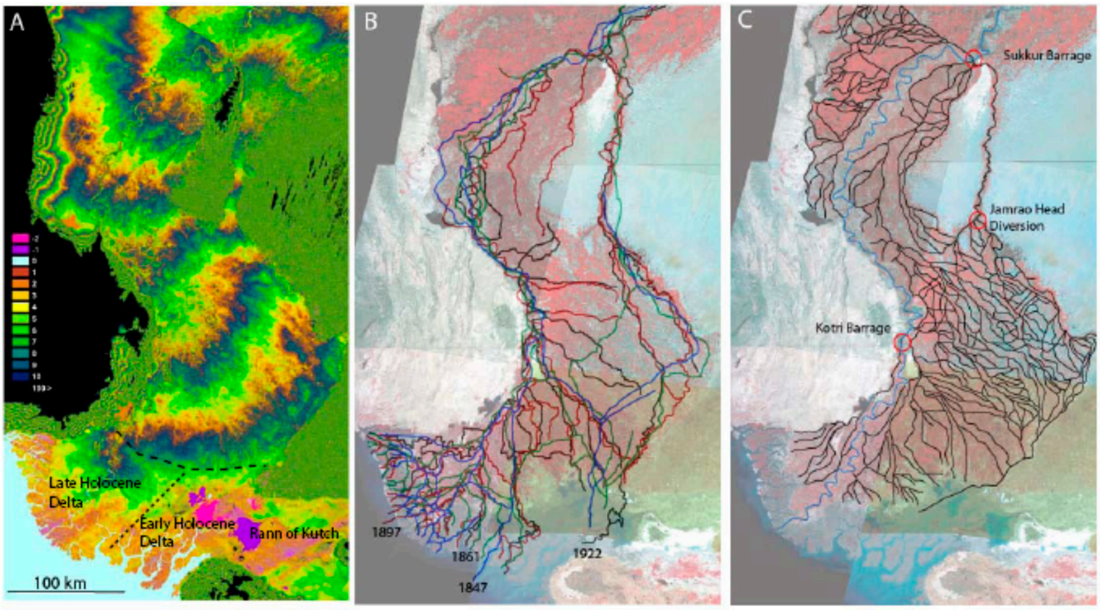

Figure 10. (**A**) Morphology of the Indus alluvial mega-ridge and delta (after [6,9,102]) displayed with SRTM altimetry, binned at 1 m vertical intervals, starting at sea level (light blue), then 1 color per 1 m interval, with colors cycled every 10 m, to a height of 100 m, then black. Topography below mean sea level is in shades of pink. Extent of the Indus delta is indicated by long dashed black line and its early Holocene vs. late Holocene sectors are separated by short-dashed line. (**B**) Historical location of distributary channels and (**C**) Irrigation channel system with main water distribution stations.

The Indus River has had a naturally large sediment load (i.e., 5th largest of all rivers with at least 250 Mt/year reaching its delta) in comparison to its relatively low water discharge (i.e., 20th largest in the world with ~90 km^3/year). These conditions, prevalent before dams were built on the river [9,103], were the combined result of regional aridity and, consequently, a poorly vegetated drainage basin, coupled with strong erosion of the high-relief tectonic units of the western Tibetan Plateau, Karakoram and the Himalayas [102,104–106]. Before ca. 4 to 3 thousand years ago sediment productivity was significantly higher due to enhanced seasonal precipitation from the South Asian monsoon and mid latitude Westerlies [107]. During this sediment-rich past, the Indus delta built as the extensive subaerial marine edge of a long continuum of fluvial sediment bodies accumulated along the river [102].

South of the confluence with its large Himalayan tributaries (i.e., Jhelum, Chenab, Ravi, Beas and Sutlej) the Indus alluvial plain is a fluvial mega-ridge (Figure 10a), a uniquely long distributive-type fluvial system showing maximum aggradation near the modern channel belt and tapering out toward the plain edges (Figure 10a,b). Before damming for irrigation, and especially during the wet early Holocene, the flood-prone, monsoon-controlled Indus river lost about half of its sediment load all along this ridge before reaching the coast [105] either through avulsion or via spillover channels (Figure 10b; see [9] and references therein). Although the secular trend of aridification over the late Holocene led to a decrease in sediment leakage before reaching the delta [6], avulsions and crevassing remained frequent enough to maintain multiple deltaic distributaries at the coast [9].

The large pre-engineering sediment load of the Indus led to the construction of a large subaerial and submarine delta [104,105] in an arid sub-tropical climate. The avulsion dynamics of the river, controlled by intense sediment deposition, resulted in a migration of the active delta from the eastern region near the mudflats of the Rann of Kutch in the early Holocene to the west in the last ca. 4000 years (Figure 10a). Historically, multiple distributary channels were active at the same time in the delta [9] with the modern coastline now dissected by numerous tidally-reworked former river channels. The tidal creek network is most extensive and mature in the older eastern part of the delta towards Kutch where wide channels penetrate deep inland with floods, affecting wide areas during the summer monsoon [6]. However, the delta shoreline has been relatively straight under an energetic wave climate typical for the northern Arabian Sea.

Since the late 19th century, the Indus River came gradually under human control, with the systematic construction of continuous levees and the world's largest irrigation system sustained by mainstem dams (Figure 10c). The Indus Basin Irrigation System (IBIS) consists of 43 major canals with a total length of 57,000 km and ca. 89,000 associated watercourses with a total length of 1.65 million km [103]. According to the Indus Treaty on water redistribution [108], water is also extracted in India, from the Indus tributaries, to irrigate fields in Punjab. The cumulative effect of engineering the river has been the cessation of fluvial water and sediment contributions to the delta for most of the year with a reduction in the number of distributaries to a single channel. Development of a dense tidal creek networks has been the response to this distributary simplification with infilling of older channels as a subordinate phenomenon [9]. A dominant coastal erosion regime of the deltaic shoreline has been established over the last decades, although some progradation occurs locally, due to nearshore sediment transfer processes under tidal currents and waves. Tectonic subsidence and uplift, associated with intra-continental seismicity in the Kutch region, also affects the delta.

Current global warming conditions are expected to lead to heterogeneous glacier retreat in the headwaters [109], and an increase in summer monsoon precipitation (e.g., [110]), which would make Indus water flow more extreme, leading to an increase in sediment production. However, given the importance of upstream water extraction for irrigation in Pakistan and India, it is not likely that augmented fluvial inputs to the Indus delta would be re-established soon. Geomorphic sustainability of the Indus delta is dependent on the drastic deficit of new fluvial sediment, but long-term persistence of the eastern half of the delta, that was slowly being abandoned over the last millennia with minimal fluvial input in historical times [9], illustrates a high degree of geomorphic resilience of the deltaic landscape. Similar to other tidally influenced deltas [111], erosion and subsidence is compensated, in part, by local channel infilling via tidal import of offshore sediment. In addition, typical of abandoned deltas [112], sediment transferred by waves from erosional sectors of the coast supports local progradation elsewhere [6]. In contrast to this geomorphic resilience, the freshwater deficit to the delta has strongly affected its ecological and economic sustainability, as well as human habitability [2].

Water logging, soil degradation, sea water intrusion, water table lowering, and salinization, as a result of upstream water use, have already destroyed the once fertile, richly vegetated delta [103,113,114]. All these problems, as well as direct exploitation of biological resources in the delta, have combined to cause a rapid decline of the deltaic mangroves and fisheries linked to mangrove creeks. The largest contiguous mangrove ecosystem in the world, developed around the tidal creek network of Indus delta (see [115] and references therein), is now reduced by more than 60%. Reductions in freshwater inflows have had strong impacts on mangrove ecology and on the fish populations that rely on them for breeding and habitat. The rural population of the delta depends, directly or indirectly, on fishing as their main source of income, and most of Pakistan's commercial marine fishery operates in and around the mangrove creeks on the delta coast. Declines in the catch offshore of the delta have been attributed to the decline in the integrity of the deltaic mangrove ecosystem. A rapid degradation of the deltaic agricultural system has also taken place, affecting cultivation of red rice, production of exotic fruit, and the raising of livestock [103].

Studies commissioned for the region (e.g., [116]) recommended reestablishment of a modicum of monthly water flow to the delta to maintain the river channel, to fight seawater intrusion and ameliorate fisheries and environmental sustainability. Additional flow, combined with sediment bypassing dams, was recommended to be restored to compensate for delta erosion and mangrove loss. However, climate warming is expected to drive up water demands, in addition to demand increases from population and economic growth. In this context, the future of the Indus delta looks bleak as its importance is small compared to the advantages provided by the irrigation to food production.

6. Summary-Diminishing Sustainability of Deltas in Arid Environments

Arid deltas, which often have arid drainage basins as well as delta plains, are among the most threatened deltas globally, with many already in an advanced state of deterioration. For the Colorado, Indus, Nile, and Tigris-Euphrates rivers, as is the case for arid region deltas, little freshwater regularly enters the sea. Even though the upper Nile basin is wet, the lower basin is hyper-arid, and little water reaches the Mediterranean due to the Aswan High Dam. For the Colorado and Indus deltas, hypersaline conditions, due to freshwater reductions, have led to widespread wetland death [2–9,47]. Background rates of geologic subsidence is often increased by groundwater withdrawals as well as drainage of wetlands. In the Nile delta, almost all river water is diverted into the delta to support agriculture that occupies most of the delta plain. Much of this agriculture is threatened due to subsidence, increasing salinization, and sea-level rise [5]. The GERD dam in Ethiopia will further reduce freshwater delivery to the delta and nearshore coastal area. In the Tigris-Euphrates delta, river water was used as a political weapon when the Iraq government diverted water away from the delta to punish marsh Arabs [10]. Freshwater has now been reintroduced to some areas, and marshes are recovering [11]. Based on our analysis of the four deltas, we draw the following conclusions that are applicable to most deltas in arid regions. In arid drainage basins, there is a great demand for water for human use, and climate change will lead to further drying in most of these areas. The growing freshwater demand in drainage basins and trapping of sediment behind dams, combined with climate impacts, makes the sustainability of deltas in arid regions unlikely in terms of hyper-salinity and reduced basin inputs. More efficient water use for agricultural, industrial, and domestic use could increase water discharge to the coast. Sediment bypassing dams can supply more sediments to offset subsidence in deltas. Judicious use of available freshwater and sediment resources can restore, at least, parts of arid deltas. Wetland restoration can also increase accretion via organic soil formation. Delta restoration will also enhance fisheries.

Author Contributions: Conceptualization, J.D.; writing—original draft preparation, J.D., R.G., Z.C., R.H., L.G., Y.W.; writing—review and editing, J.D., R.G., Z.C., R.H., L.G., Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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