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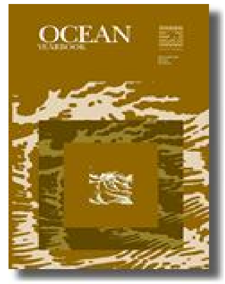

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Functioning of the Grijalva-Usumacinta River Delta, Mexico: Challenges for Coastal Management*

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INTRODUCTION

The Grijalva-Usumacinta River Delta is a tropical coastal ecosystem in the southern Gulf of Mexico. It is very important ecologically, socially, and economically, but urban development, agriculture, coastal development, and oil and gas activities have led to environmental impacts on the largest lowland tidal wetland ecosystem in Mesoamerica. The delta has the second highest river discharge in the Gulf of Mexico after the Mississippi River. At present there seems to be an increase in freshwater discharge of the Grijalva and Usumacinta Rivers, probably because of climate change and increased rainfall in the upper basin. Over the past half century, there has been an apparent increase in discharge. During the 1950s, the average total discharge was about 2,000 m^3/second. Mean discharged water increased to about 2,500 m^3/second in the 1970s, 3,000 m^3/second in the 1980s, and 3,500 m^3/second by the middle of the 1990s. Mean discharge was 3,400 m^3/second in 1990, 4,402 m^3/second in 2002, and 4,700 m^3/second in 2005. Peak river discharge at the mouth occurs in October, one month later than the highest rainfall in southern Mexico and northern Guatemala. The

*This research was supported by the following projects: INECOL 902-19-752, PEMEX-Centla 91-41, and GIWA GEF/UNEP Sub Region 2 Gulf of Mexico.

lowest discharge occurs in April and May. Sediment discharge from the drainage basin to the continental shelf has been estimated in 126 million tons/year.[1] Geologic subsidence has been estimated at ~2 mm/year. The highest river discharges of the Grijalva-Usumacinta River from 1950 to the present were in October 1999, after the El Niño of 1998 (followed by La Niña of 1999), the most severe El Niño event of the last 60 years with an estimated total freshwater discharge ~7,500 m^3/second,[2] and during October 2007 after Hurricanes Felix and Dean with an estimated total freshwater discharge near 9,000 m^3/second.

The Centla Wetlands (the largest coastal lowland wetland in Mesoamerica), and Terminos Lagoon (the largest lagoon-estuarine system in Mexico) were declared as natural protected areas (NPA) (Biosphere Reserve, and Special Area for Wildlife Protection, respectively) by the National Institute of Ecology, Department of Environment and Natural Resources in Mexico. The major problems for these NPAs are: 1) a comprehensive understanding of ecosystem functioning in terms of the coupling of physical and biological processes, which is a key concern of ecosystem-based management, 2) loss of mangrove and marsh wetlands, 3) surface water pollution, and 4) the role of oil and gas industries in the NPA beginning a half century ago. Thus, the challenge for development of ecological planning for the NPA will be the integration of social, economic, ecological, political, and juridical elements, in order to establish up-to-date criteria for ecosystem-based management of the river delta. Moreover, sea-level rise, subsidence, and altered hydrology are additional key factors inducing uncertainty for integrated coastal management of these NPAs, which is magnified by the construction of levees along the main river channels. Strategic ecological planning should be based on the geography of the delta, geomorphology, hydrology, coastal vegetation, habitat fragility, water quality, and predominant environmental problems. Because of this, it is implicit in this article that only management that is based on the functioning of the river delta is sustainable.

1. A. Yáñez-Arancibia and J.W. Day, ''Hydrology, Water Budget, and Residence Time in the Terminos Lagoon Estuarine System, Southern Gulf of Mexico,'' in *Coastal Hydrology and Processes*, eds. V.P. Singh and Y.J. Xu (Highlands, Colorado: Water Resources Publications LLC, 2006), pp. 423–435.

2. A. Yáñez-Arancibia, J.W. Day, A.L. Lara-Domínguez, P. Sánchez-Gil, G.J. Villalobos and J.A. Herrera-Silveira, ''Ecosystem Functioning: The Basis for Sustainable Management of Terminos Lagoon, Campeche Mexico,'' in *The Gulf of Mexico: Ecosystem-Based Management*, eds. J.W. Day and A. Yáñez-Arancibia (College Station, Texas: Harte Research Institute for Gulf of Mexico Studies, Texas A&M University Press, 2008), chap. 9.

THE GULF OF MEXICO WATERSHED

The Gulf of Mexico is fed by rivers that drain a vast area. Five countries are in the watershed of the Gulf. Three of these, the United States, Mexico, and Cuba, directly border the Gulf. Guatemala and Canada are not adjacent to the Gulf but provide runoff via the Usumacinta-Grijalva and Mississippi rivers, respectively. The entire Gulf of Mexico watershed covers almost 5.2 million km^2; about 4.1 million $km^2$are in the United States and Canada, and about 828,000 $km^2$are in Mexico and Guatemala. Northwestern Cuba accounts for a small area of the Gulf's watershed. About two-thirds of the area of the continental United States and about half of the area of Mexico drain into the Gulf. Recently, Yáñez-Arancibia et al.[3] related river discharge to the Gulf from southern Mexico (~10,000 m^3/second) and the Mississippi delta (~20,000 m^3/second) to aquatic primary productivity. They showed that there was a region-wide productivity pulse for the entire Gulf of Mexico, with the highest discharge in April/May in the Mississippi delta, the highest aquatic primary productivity (APP) in July, the highest discharge in the southern Gulf in September/October and the highest APP in November. This represents a clear signature of coupling of physical and biological processes for understanding the global functioning of coastal ecosystems in the entire Gulf.

In Mexico, the following rivers have significant freshwater discharge to the Gulf of Mexico with mean values for the last 30 years: Rio Bravo (Rio Grande) 480 m^3/second, Tamesi and Panuco Rivers 629 m^3/second, Cazones 43 m^3/second, Nautla 54 m^3/second, Tuxpan 80 m^3/second, Tecolutla 188 m^3/second, Actopan 15 m^3/second, Antigua 60 m^3/second, Jamapa 20 m^3/second, Coatzacoalcos 450 m^3/second, Blanco-Papaloapan River 1,360 m^3/second, Grijalva-Usumacinta Delta 4,402 m^3/second, San Pedro y San Pablo 400 m^3/second, Palizada 394 m^3/second, Chumpan 50 m^3/second, Candelaria and Mamantel Rivers 72 m^3/second. The Grijalva-Usumacinta Rivers has a mean combined annual discharge in a range of 3,000 to 4,700 m^3/second.

3. A. Yáñez-Arancibia, A.L. Lara-Domínguez, P. Sánchez-Gil and J.W. Day, ''Interacciones ecológicas estuario-mar: Marco conceptual para el manejo ambiental costero,'' in *Diagnóstico Ambiental del Golfo de México,* eds. M. Caso-Chávez, I. Pisanty and E. Ezcurra (México D.F., INE-SEMARNAT Press, 2004), pp. 431–490, hereinafter ''*Interacciones*''; A. Yáñez-Arancibia, A.L. Lara-Domínguez, D. Zárate Lomelí, P. Sánchez-Gil, S. Jiménez Hernández, A. Sánchez Martínez, E. Rivera, A. Flores Nava, M.A. Ortiz Pérez, C. Muñoz Piña, M. Becerra, J.W. Day, G.L. Powell, C.J. Madden, E. Reyes and C. Barrientos, *Sub-region 2 Gulf of Mexico: Scaling, Scoping and Detailed Assessment* (Kalmar Sweden: Global International Water Assessment GIWA Report, GEF-UNEP, 2003), pp. 1–396, hereinafter ''*Sub-region 2.*''

THE STUDY AREA

Within the Global International Water Assessment (GIWA, a UNEP-GEF initiative), sub-region 2 Gulf of Mexico, the Grijalva-Usumacinta River Basin and Delta is one of the priority geographic-hydrologic ecosystem units for developing strategic ecological planning leading to coastal management in the Gulf of Mexico as a Large Marine Ecosystem.[4] In this context, hydrological units are geographic units with a significant river basin draining through an important portion of the continent and extensive coastal plain, having high fresh-water discharge into the coastal zone, and having an important international approach both for USA and Mexico.

The Usumacinta River's total length is ~1,100 km, and the Grijalva River's total length is ~640 km. The delta complex is comprised of the Mescalapa, Grijalva, and Usumacinta Rivers, and together they constitute a large delta with more than 21,000 km^2, including the Centla Wetlands (RAMSAR Biosphere Reserve) and Terminos Lagoon (RAMSAR Natural Protected Area for Wildlife). Both of these areas constitute major portions of the Grijalva-Usumacinta River Delta system.[5]

Even though there is a major effort for natural protected area management in the Gulf of Mexico,[6] the lack of a comprehensive understanding of ecosystem functioning of the southern Gulf of Mexico in terms of the coupling of physical and biological processes, which is a key concern of ecosystem-based management, leads to a weak impact of management efforts.

4. A. Yáñez-Arancibia and J.W. Day, ''Environmental Sub-Regions in the Gulf of Mexico Coastal Zone: The Ecosystem Approach as an Integrated Management Tool,'' *Ocean and Coastal Management* 47, no. 11-12 (2004): 727–757, hereinafter ''Environment Sub-Regions''; A. Yáñez-Arancibia and J.W. Day, ''The Gulf of Mexico: Towards an Integration of Coastal Management with Large Marine Ecosystem Management,'' *Ocean and Coastal Management* 47, no. 11-12 (2004): 537–564, hereinafter ''The Gulf of Mexico.''

5. Yáñez-Arancibia et al., *Ecosystem Functioning,* n. 2 above.

6. *Id.*; Yáñez-Arancibia et al., ''Environmental Sub-Regions,'' n. 4 above; A. Yáñez-Arancibia A.L. Lara-Domínguez, J.L. Rojas, D. Zárate Lomelí, G.J. Villalobos and P. Sánchez-Gil, ''Integrating Science and Management on Coastal Marine Protected Areas in the Southern Gulf of Mexico,'' *Ocean and Coastal Management* 42, no. 2-4 (1999): 319–344, hereinafter ''Integrating Science and Management;'' J.E. Bezaury, ''Protected Areas and Coastal and Ocean Management in Mexico,'' *Ocean and Coastal Management* 48, no. 11-12 (2005): 1016–1046; A.L. Lara-Dominguez, E. Reyes, M.A. Ortiz, P. Mendez Linares, P. Sánchez-Gil, D. Zárate Lomeli, J.W. Day, A. Yáñez-Arancibia and E. Sáinz Hernandez, ''Ecosystem-Based Management of the Centla Wetlands Biosphere Reserve Based on Environmental Units: A Critical Review for Protecting Its Future,'' in *The Gulf of Mexico Ecosystem-Based Management* eds. J.W. Day and A. Yáñez-Arancibia (College Station, Texas: Harte Research Institute for Gulf of Mexico Studies, Texas A&M University Press, 2008), chap. 11.

THE ECOSYSTEM OF THE GRIJALVA-USUMACINTA RIVER BASIN AND DELTA

The watershed of the Grijalva and Usumacinta Rivers encompassesa watershed of 7,141,536 ha (corresponding 2,900,265 ha to Mexico and 4,241,271 ha to Guatemala), and the delta extends for an area more than 21,000 km^2fltextcolorred. The main physical factors for affecting the extensive wetlands are: a) rains, b) floods, and c) the extensive coastal plain of Tabasco and Campeche. An area of a broad continental shelf, Campeche Sound, is offshore of the delta system. Because of high river input, extensive wetlands, and the semi-enclosed nature of the shallow shelf, this area has very high primary and fisheries productivity.

The Usumacinta River of Mexico and Guatemala is the largest river in Mesoamerica and among the most significant shared water resources in the Western Hemisphere.[7] The delta comprises a main river, and the Usumacinta, and a major tributary, the Grijalva River. The watershed drains one of the largest areas of contiguous tropical forest in the region, including 177,987 ha in Campeche, 724,547 ha in Tabasco, 2,175,718 ha in Chiapas (all of three states in Mexico), and 4,241,271 ha in Guatemala, and it is extremely rich in natural and cultural resources.[8]

The Grijalva-Usumacinta River system headwaters are in a tropical forest that is little affected by humans. The lithographic and geomorphologic nature of the area, dominated by karsts, leads to high levels of sediment transport.[9] The Usumacinta River is formed by the Pasion River, which starts

7. Yáñez-Arancibia et al., ''Environmental Sub-Regions,'' n. 4 above; I.J. March and J.C. Fernández, ''La gran cuenca del Río Usumacinta: Una contradicción nacional,'' in *Agua, Medio Ambiente y Desarrollo en México,* ed. P. Ávila García (Memoria XX Coloquio Antropología e Historia Regionales, El Colegio de Michoacán A.C., Morelia, 1998), pp. 314–336; B. Bestermeyer and L.E. Alonso eds., *A Biological Assessment of Laguna del Tigre National Park, Higher Usumacinta Basin, Peten Guatemala* (Washington, D.C.: RAP Bulletin of Biological Assessment 16, Conservation International, 2000), pp. 1–220.

8. Day et al., ''*Sub-Region 2,*'' n. 2 above. J.W. Day, A. Yáñez-Arancibia, W.J. Mitsch, A.L. Lara-Domínguez, J.N. Day, J.Y. Ko, R. Lane, J. Lindsey and D. Zárate-Lomelí, ''Using Ecotechnology to Address Water Quality and Wetlands Habitat Loss Problems in the Mississippi Basin (and Grijalva-Usumacinta basin): A Hierarchical Approach,'' *Biotechnology Advances* 22, no. 1-2 (2003): 135–159, hereinafter ''Using Ecotechnology.''

9. M.A. Ortiz Pérez and J.A. Benítez, ''Elementos teóricos para el entendimiento de los problemas de impacto ambiental en planicies deltáicas: La región de Tabasco y Campeche,'' in *Golfo de México Contaminación e Impacto Ambiental: Diagnóstico y Tendencias,* eds. A.V. Botello, J.L. Rojas, J.A. Benítez and D. Zárate Lomelí (EPOMEX Serie Científica 6, Universidad de Campeche, México, 1996), pp. 483–503; M.A. Ortiz Pérez, C. Valverde and N.P. Psuty, ''The Impacts of Sea-Level Rise and Economic Development on the Low-Lands of the Mexican Gulf of Mexico,'' in *Golfo de México Contaminación e Impacto Ambiental: Diagnóstico y Tendencias,*

in the Sierra de Santa Cruz, Guatemala, and the Salinas River, also known as the Chixoy and the Negro, which descend from the Sierra Madre de Guatemala. The Usumacinta flows northwestward, meeting with the Lacantun River and forming part of the border between Mexico and Guatemala. Below the Maya ruins of Piedras Negras, located in Guatemala, the river begins a meandering course through the swampy low lands to the Bay of Campeche in the Southern Gulf of Mexico. The main channel joins the Grijalva River before emptying into the Bay of Campeche below the town of Frontera. The central channel, the San Pedro and San Pablo River, flows into the Gulf at the town of San Pedro and the eastern channel, the Palizada River, empties into Terminos Lagoon in the State of Campeche.[10] The total length of the main channel, including the Chixoy, is ~1,100 km, navigable for 480 km inland.

The Grijalva River is located in southeastern Mexico. In the watershed of the Grijalva and Usumacinta rivers, 36 percent of the watershed has been converted from forest to other uses, mainly agriculture but also to petroleum related activities such as pipelines, pumping stations, and drilling sites. The largest tributary is the Chilapa River, which begins in the Sierra Madre of Guatemala and the Sierra de Soconusco of Mexico. The Grijalva flows generally northwestward through the state of Chiapas, Mexico, where it is known as the Rio Grande de Chiapas, Rio Chilapa, or Rio de la Sierra. After leaving the reservoir created by the Malpaso Dam, it turns northward and eastward, roughly paralleling the Chiapas-Tabasco State border. Flowing northward again at Villa Hermosa, the capital city of Tabasco, it joins the Usumacinta River and empties into the Gulf of Mexico at the Bay of Campeche, 10 km north of Frontera. The river is navigable by shallow-draft vessels for ~95 km upstream from the Gulf, and for several stretches along its middle and upper course. The Grijalva's total length is ~640 km. The delta plains are assemblages of the Mescalapa, Grijalva, Chilapa, and Usumacinta Rivers, and together they form a large delta of more than 21,000 km^2.[11]

The shared drainage basin is located in a tropical region where the climate changes gradually from the river mouth to the upper parts of the basin. There are two types of climate, humid near the coast, and sub-humid

eds. A.V. Botello, J.L. Rojas, J.A. Benítez and D. Zárate Lomelí (EPOMEX Serie Científica 6, Universidad A. de Campeche, México, 1996), pp. 459–470.

10. A. Yáñez-Arancibia and J.W. Day eds., *Ecology of Coastal Ecosystems in the Southern Gulf of Mexico: The Terminos Lagoon Region* (Instituto de Ciencias del Mar y Limnología UNAM, Coastal Ecology Institute LSU, Organization of American States, OAS Washington D.C.: UNAM Press Mexico, 1988), pp. 1–518, hereinafter "*Ecology of Coastal Ecosystems.*"

11. Yáñez-Arancibia et al., *Ecosystem Functioning,* n. 2 above; Yáñez-Arancibia et al., *Interacciones,* n. 3 above.

in inland areas. Both are hot with abundant rainfall in summer (June to October). Mean annual temperature is greater than 26°C. Precipitation over the drainage basin is from 1,200 to more than 3,000 mm/year. There are two quite distinct coastal wind systems. During the ''nortes'' season, winds are from the northwest associated with cold fronts with mean wind speed slightly higher than 8 to 10 m/second. For most of the rest of the year there is a sea breeze system, with predominantly easterly winds with an average velocity of 4 to 6 m/second. The easterly orientation of the sea breeze reflects the regional influence of the trade winds. There are essentially no winds from the southwest. There are three ecological ''seasons.'' From June to October is the rainy season with almost daily afternoon and evening showers. From October into March is the season of ''nortes'' or winter storms; these storms are generally strongest and associated with some rains during November to January. Each ''norte'' lasts for 1 to 5 days and it is common to have 3 to 5 ''nortes'' per month. February to May is the dry season. Torrential rains during summer time are associated with cyclones (hurricanes). The Gulf of Mexico is a favorable area for tropical cyclones, which are accompanied by floods and storm tides.[12] Almost 35 to 40 percent of the cyclones originating in the Caribbean Sea affect the Mexican coast in the Gulf of Mexico.

The combined discharge of the Grijalva and Usumacinta is 3,000 to 4,700 m^3/second or 120,000 million m^3/year. Most of this occurs via the Usumacinta (52 percent) and Mescalapa (23 percent), with lowest values for the Chilapa (11 percent), De la Sierra (6 percent), and Tonala (5 percent) rivers. Recently, the Comision Nacional del Agua (CONAGUA Mexico) reported a combined discharge of 4,402 m^3/second, and Yáñez-Arancibia and Day reported 4,700 m^3/second, and an extreme combined river discharge of 7,500 m^3/second (October 1999) after El Niño 1998 and La Niña 1999. The increase in discharge coincides with the first maximum in precipitation over the basin in the beginning of summer. The highest discharge occurs from September to November when high discharge from all tributaries reaches the delta.[13] Discharge is lowest in April. Total combined discharge is about 30 million m^3/year. The mean annual peak

12. M.A. Ortiz-Pérez, A.P. Méndez-Linares and J.R. Hernández-Santana, ''Sea-Level Rise and Vulnerability of Coastal Low-Land in the Mexican Area of the Gulf of Mexico and the Caribbean Sea,'' in *The Gulf of Mexico Ecosystem-Based Management,* eds. J.W. Day and A. Yáñez-Arancibia (College Station, Texas: Harte Research Institute for Gulf of Mexico Studies, Texas A&M University Press, 2008), chap. 15, hereinafter ''Sea-Level Rise''; A. Yáñez-Arancibia and J.W. Day, ''Ecosistemas vulnerables, riesgo ecológico y el record 2005 de huracanes en el Golfo de México y Mar Caribe,'' available online: <http://www.ine.gob.mx/download/huracanes2005.pdf>, hereinafter ''Ecosistemas.''

13. Day et al., ''*Sub-Region 2,*'' n. 2 above; Yáñez-Arancibia and Day, n. 4 above.

discharge is in October registered in Boca del Cerro, Usumacinta, with 9,581,551 m^3/month.

The habitats of the ecosystem of Grijalva-Usumacinta River basin and delta are presented in Table 1, based on vegetation distribution and the regional identification plan as suggested in Day et al.[14] This scheme is based on vegetation and soil types of the deltaic plain. Future management should include using the energies and resources of the river to restore and maintain wetlands for both enhance accretion and to improve water quality.

GENERAL CONCEPTUAL MODEL OF THE FUNCTIONING OF THE GRIJALVA-USUMACINTA RIVER DELTA

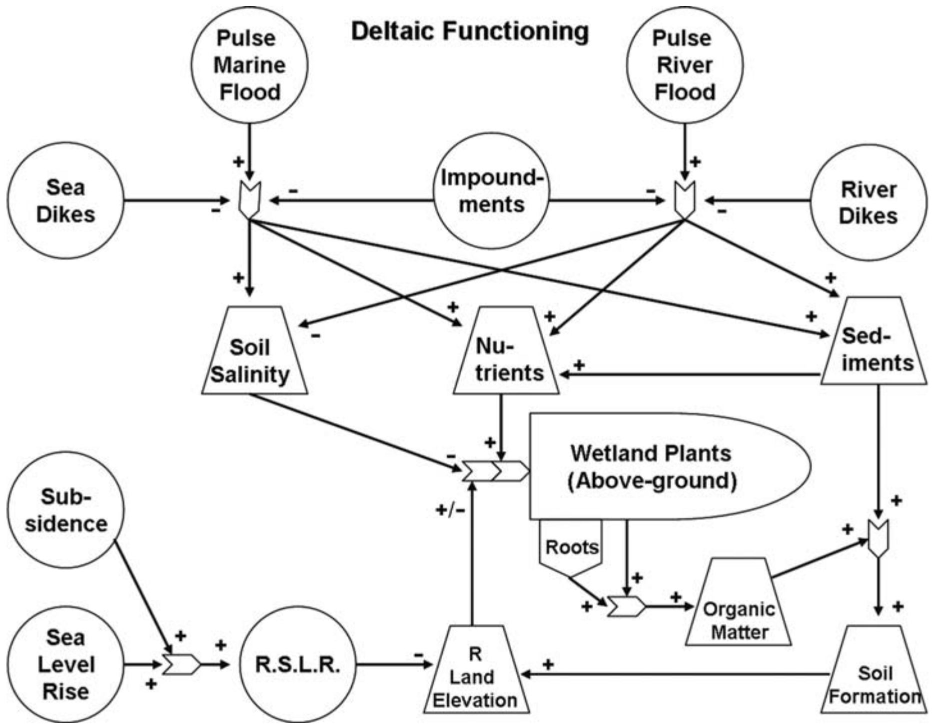
A generalized model of the ecological functioning of typical deltas in a natural state is presented in Figure 1. This approach was proposed by Day et al.[15] and one of the purposes of this model is to diagrammatically present the hypothesis of the relationship between overall deltaic functioning and energetic inputs. The model is focused around the annual cycle of riverine flooding, but includes shorter and longer term processes. In the natural state, the Grijalva-Usumacinta River Delta has broad areas of near-sea-level wetlands interlaced with channels through which fresh water and sea water mix. Each year, the river flood supplies a pulse of freshwater with suspended sediments, inorganic nutrients, and organic materials. These stimulate primary and secondary production. Increased plant production leads to higher rates of food production for consumers and to increased organic soil formation. Sediments and nutrients fertilize wetlands plants. Freshwater input also maintains a salinity gradient from fresh to saline that creates estuarine conditions and supports a high diversity of wetland and aquatic habitats that are optimal for estuarine species (Table 1). The increased area and productivity of wetlands resulting from riverine input lead to higher secondary production of fisheries and wildlife. Wetlands also assimilate and process nutrients. This leads to higher wetland productivity and lessens water quality problems. The relationship between riverine input and productivity of estuaries has been demonstrated by a number of authors.[16]

14. Day et al., ''Using Ecotechnology,'' n. 8 above.

15. J.W. Day, J.F. Martin, L. Cardoch and P.H. Templet, ''System Functioning as a Basis for Sustainable Management of Deltaic Ecosystems,'' *Coastal Management* 25, no. 2 (1997): 115–153, hereinafter ''System Functioning.''

16. Day et al., ''System Functioning,'' n. 15 above; J.C. Boynton, W.M. Kemp and C.W. Keefe, ''A Comparative Analysis of Nutrient and Other Factors Influencing Estuarine Phytoplankton Production,'' in *Estuarine Comparisons*, ed. V.S. Kennedy (New York: Academic Press Inc., 1982), pp. 69–90; J.W. Day, C.S. Hopkinson and W.H. Conner, ''An Analysis of Environmental Factors Regulating Community Metabolism and Fisheries Production in a Louisiana Estuary,'' in *Estuarine Comparisons*, ed. V.S. Kennedy (New York: Academic Press Inc., 1982), pp. 121–136; J.W.

FIG. 1.—Conceptual model of the functioning of the Grijalva-Usumacinta River Delta. The model shows how natural pulses of freshwater, nutrients, and sediments enhance productivity and soil formation, and buffer against relative sea-level rise (RSLR). Soil formation is broken down into inorganic and organic components. Organic matter production depends on relative land elevation (RLE), a balance between RSLR and soil formation. The symbols (+) and (-) indicate whether interactions are positive or negative.



Over the long term, rising water levels due to a combination of subsidence and eustatic sea-level rise poses particular problems for the Grijalva-Usumacinta River delta,[17] which will be discussed later.

Day, D. Pont, P. Hensel and C. Ibáñez, ''Impacts of Sea-Level Rise on Deltas in the Gulf of Mexico and the Mediterranean: The Importance of Pulsing Events to Sustainability,'' *Estuaries* 18 (1995): 636–647, hereinafter ''Impacts of Sea-Level Rise;'' S.W. Nixon and B.A. Buckley, ''A Strikingly Rich Zone: Nutrient Enrichment and Secondary Production in Coastal Marine Ecosystems,'' *Estuaries* 25, no. 4b (2002): 782–796.

17. J.W. Day, R.R. Christian, D.M. Boesch, A. Yáñez-Arancibia, J.T. Morris, R.R. Twilley, L. Naylor, L. Schaffner and J.C. Stevenson, ''Consequences of Climate Change on Eco-Geomorphology of Estuarine Wetlands,'' *Estuaries* (2008), in press.

Table 1.—Description of habitats in the Grijalva-Usumacinta River Delta system in the states of Tabasco and Campeche in the southern Gulf of Mexico.

Habitats	Freshwater influence	Marine influence
Minimally flooded	The soil is heavy to medium texture and well drained. High coastal plain. The natural vegetation is rain forest or medium height evergreen forest, most of which have been converted to agricultural fields.	*Semi-exposed*. Sandy soils are poorly developed. Soils contain low levels of inorganic salts. There is salt infiltration to the groundwater and aerial dispersion of aerosols. Relatively high areas on littoral ridges. The majority of these lands have been cleared for agricultural and livestock grazing.
Semi-flooded	Soil has medium texture, saturated for long periods during the growing season, and without stagnant water. Low coastal plain. Gallery evergreen forest with influence of annual agricultural crops and pasture.	
Seasonally flooded	Soil has a fine texture and are poorly drained, flooded for long periods during the growing season, and without superficial water during the dry season (Feb-May). Low coastal plain that borders fresh water lagoons and swamps. Gallery forest, low inundated forest, palm thickets and flood plain marshes with *tular, popal*, and *carrizal*	
Regularly flooded		*Semi-exposed*. Sandy soils with a high content of inorganic salts; exposed to the tidal action during the winter storm ''nortes''. Lower portions of littoral ridges affected by subsidence. Mangrove forests dominated by *Rhizophora mangle* and *Avicennia germinans*
Permanently flooded	Soil has very fine texture with high organic matter content, and saturated for most of the year. Freshwater lagoons, channels with slow flow, pools and swamps. Hydrophyte communities are rooted floating and submerged vegetation and floating with marshes of *tular, popal*, and *carrizal*.	*Exposed*. Shallow water bodies parallel to the shoreline. They frequently are at the mouth of rivers and influenced by tides. Alluvial soils with great content of inorganic salts and organic matter. Riverine and basin mangroves with *Rhizophora mangle, Avicennia germinans, Laguncularia racemosa* and *Conocarpus erectus*.

This river delta ecosystem undergoes succession changes in physiography,[18] biology,[19] and salinity,[20] which are partially determined by land building or land loss that occurs (Figure 1). The delta passes through consecutive sub aqueous (underwater), sub-aerial (emergent), and deterioration phases.[21] In Psuty,[22] it can be seen that the San Pedro y San Pablo river is in the declining phase of the delta cycle, typified by deteriorating wetlands, retreat of the coast line, increasing land-water interface, increasing salinity, and high aquatic productivity. Gagliano and VanBeek[23] and Madden and Day[24] proposed that biological productivity in deltaic environments is greatest during the initial stages of breakup. We feel that the additional nutrient load associated with riverine flow at the site of a new delta also stimulates primary production very early in the life cycle of the delta and this production is in turn used by coastal nekton.[25]

In deltaic systems, phytoplankton production in the water column[26] is controlled by a set of factors different from those controlling the productivity of wetland vegetation,[27] or coastal nekton utilizing the estuarine plume.[28] The relationship between delta succession and primary production is complex. There is high plankton production in the dynamic

18. Day et al., ''Impacts of Sea-Level Rise,'' n. 17 above.

19. A.L. Lara-Domínguez, A. Yáñez-Arancibia and J.W. Day, ''Sustainable Management of Mangroves in the Southern Mexico and Central America,'' in *Managing Forest Ecosystems for Sustainable Livelihoods* (The Hague, The Netherlands, The Global Biodiversity Forum, 2002),

20. Day et al., ''*Sub-region 2,*'' n. 2 above.

21. C.J. Madden and J.W. Day, ''Freshwater and Marine Coupling in Estuaries of the Mississippi River Deltaic Plain,'' *Limnology and Oceanography* 33, 4 part no. 2 (1988): 982–1004.

22. N.P. Psuty, ''Beach-Ridge Development in Tabasco, Mexico,'' *Annals of the Association of American Geographers* 55 (1965): 112–124.

23. S.G. Gagliano and J.L. VanBeek, ''An Approach to Multiuse Management in the Mississippi Delta System,'' in *Deltas, Models for Explorations*, ed. M. L. Broussard (Houston, Texas: Houston Geological Society, 1975), pp. 223–238.

24. Madden and Day, n. 22 above.

25. A. Yáñez-Arancibia, L. Lara-Domínguez, P. Sánchez-Gil, I. Vargas, M.C. García Abad, H. Álvarez Guillen, M. Tapia García, D. Flores and F. Amezcua, ''Ecology and Evaluation of Fish Community in Coastal Ecosystems: Estuary-Shelf Interrelationships in the Southern Gulf of Mexico,'' in *Fish Community Ecology in Estuaries and Coastal Lagoons: Towards an Ecosystem Integration*, ed. A. Yáñez-Arancibia (Mexico D.F.: UNAM Press, 1985), pp. 475–498.

26. Madden and Day, n. 22 above.

27. Day et al., ''Impacts of Sea-Level rise,'' n. 17 above.

28. D.M. Baltz and A. Yáñez-Arancibia, ''Ecosystem-Based Management of Coastal Fisheries in the Gulf of Mexico Environmental and Anthropogenic Impacts and Essential Habitat Protection,'' in *The Gulf of Mexico Ecosystem-Based Management,* eds. J.W. Day and A. Yáñez-Arancibia (College Station, Texas: Harte Research Institute for Gulf of Mexico Studies, Texas A&M University Press, 2008), chap. 19.

frontal mixing zone typical of the Grijalva-Usumacinta estuarine plume. The limitation of productivity in the area subjected to high turbidity is compensated by the high nutrient load that stimulates aquatic primary productivity in the zone where fresh and salt water mix. Furthermore, the shallowness of the low land tidal wetlands in the upper part of the deltaic system seems optimal for coupling benthic nutrient storage and regeneration processes to the water column; this may be a critical link between the pulse of nutrients in the rainy season and their maximum use by consumers during the ''nortes'' season.[29] A significant amount of the organic production in the river delta system is exported to the near shore zone of the southern Gulf of Mexico, probably increasing offshore metabolism (Figure 2). Day[30] calculated that 318 gCm^2/year was exported from saline marsh in the lower estuary of a similar system in the northern Gulf of Mexico, such as Barataria Basin, Louisiana, which through tidal action, much of this surplus is flushed out of the river delta system into the near shore coastal zone, and Yáñez-Arancibia et al.[31] supports high aquatic primary productivity (220 to 333 $mgC/m^3/hr$) in the near shore Gulf adjacent to the Grijalva-Usumacinta delta. We speculate that this out-welled energy is an important subsidy to the near shore coastal zone making it directly (consumption of organic matter) and indirectly (stimulation of aquatic primary productivity) ''wetland-dependent.'' Thus, there is a net export of materials to the southern Gulf of Mexico. As discussed by Baltz and Yanez,[32] coastal fishery productivity seems to be stimulated by high land-water interface, probably because such shallow and protected areas seem to satisfy the four major requirements outlined by Baltz and Yáñez-Arancibia,[33] for a nursery area: physiological suitability, habitat and water quality, food supply, and protection. Such areas support a much higher standing crop of nekton than upper fresh water areas, or offshore open marine areas.[34] The

29. Yáñez-Arancibia, ''*Ecology of Coastal Ecosystems*,'' n. 10 above.

30. J.W. Day, W.G. Smith, P.R. Wagner and W. Stowe, *Community Structure and Carbon Budget of a Salt Marsh and Shallow Bay Estuarine System in Louisiana* (Louisiana State University, Center for Wetland Resources, Publication LSU-SG-72-04, 1973), pp. 1–79.

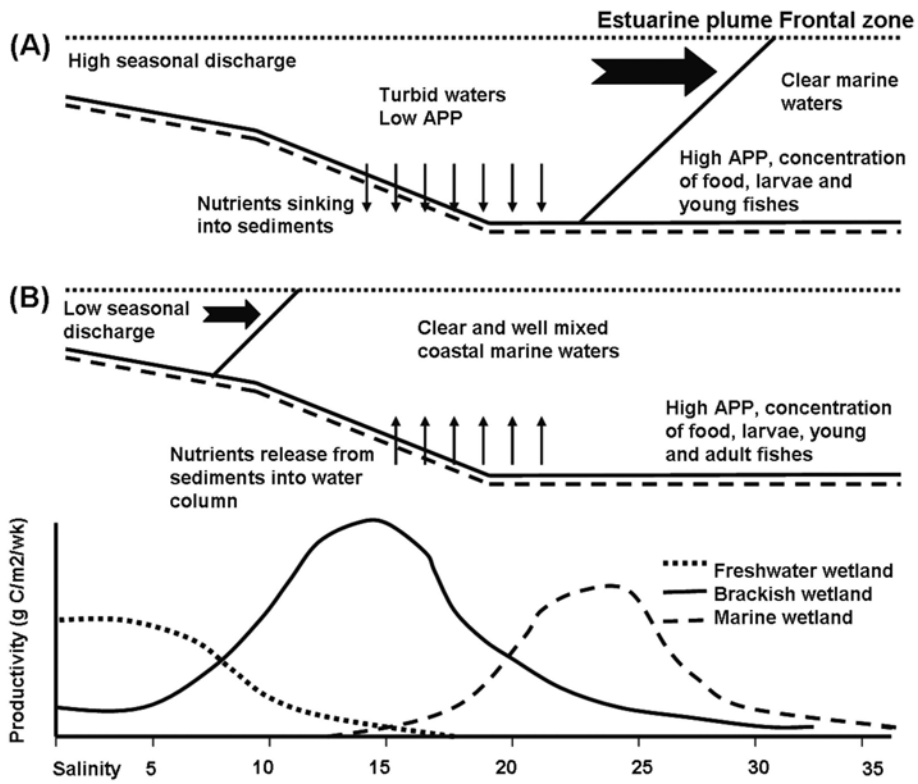
31. Yáñez-Arancibia et al., *Interacciones*, n. 3 above.

32. Baltz and Yáñez-Arancibia, n. 29 above; D.M. Baltz, J.W. Fleeger, C.F. Rakocinski and J.N. McCall, ''Food, Density, and Microhabitat: Factors Affecting Growth and Recruitment Potential of Juvenile Salt Marsh Fishes,'' *Environmental Biology of Fishes* 53 (1998): 89–103; G.P. Jenkins and M.J. Wheatley, ''The Influence of Habitat Structure on a Nearshore Fish Assemblage in a Southern Australia Embayment: Comparisons of Shallow Seagrass, Reef-Algal and Unvegetated Sand Habitats, with Emphasis on Their Importance to Recruitment,'' *Journal of Experimental Marine Biology and Ecology* 221 (1998): 147–172.

33. Baltz and Yáñez-Arancibia, n. 28 above.

34. Nixon and Buckley, n. 17 above.

Fig. 2.—(A): Conceptual model of seasonal functioning of the Grijalva-Usumacinta delta to changes in river discharge. At high river discharge, productivity is highest at the edge of the river plume. At low discharge, productivity is high throughout the estuarine gradient supported by regenerated nutrients. Fish larvae, juveniles and adults, and macro invertebrates as well, use the open water system and the gradient of the frontal zone in the estuarine plume as essential habitat, before and after migration between inshore estuarine and wetland habitats and the nearshore Gulf of Mexico. (B): The physical, chemical, and biological pulsing and gradients modulate the deltaic functioning and productivity. Different habitats have productivity optima, but overall high productivity is maintained by habitat replacement along the estuarine salinity gradient.



continuum gradient from the river through the delta to the estuarine plume is the key region for nekton biomass production and this part of the coastal ecosystem depends on the ecological integrity of the Grijalva-Usumacinta river-delta-wetland system and its water and habitat quality.

THE ECONOMIC IMPORTANCE OF THE RIVER DELTA INFLUENCE AREA

The Mexican coastal zone in the Gulf and Caribbean region forms a highly productive ecosystem that constitutes nearly 30 percent of the national total in Mexico. The Gulf and Caribbean coastal area contains more than 65 percent of the coastal plain forest reserves, more than 75 percent of the national total of coastal wetlands, and nearly 50 percent of the total shrimp fisheries in Mexico. The 5 most important industrial ports of the country are located in this region, which is comprised of, Altamira, Veracruz, Coatzacoalcos, Dos Bocas, and Ciudad Del Carmen. Agriculture is very important in the region. The cultivated area in the six coastal states of the region in 2000 was 217,250 km^{2}with an annual production of 4,227,923 tons, mainly corn, beans, wheat, rice, soybean, cotton, and sorghum. Over the last 10 years, the volume of fishery harvest has varied between 200,000 and 350,000 tons per year with a dockside value of US$240 million, almost 26 percent of the national total. Veracruz contributed 43.6 percent, Tabasco 14.7 percent, and Campeche 13.5 percent of the national total catch.[35] Tourism in the Gulf and Caribbean coastal area is an important source of foreign currency with 25 percent of the total national tourist infrastructure and a value of US$600 million per year. Another very important economic activity in the Mexican portion of the Gulf of Mexico is oil and gas production. The highest production is located in the states of Tabasco and Campeche. This production is among the most important in the Western Hemisphere and represents 80 percent of the crude petroleum and 90 percent of the natural gas production of Mexico. Oil production in the year 2003 was greater than 2 million barrels per day with export valued at US$16.8 million.[36] But since the middle of the 2000s, total oil production has declined dramatically in the Southern Gulf of Mexico.[37]

The proportion of the Gross Domestic Product (GDP) of the Gulf and Caribbean region was 13 percent of the national total in 2000.[38] The north-

35. A. Yáñez-Arancibia, J.J. Ramírez Gordillo, J.W. Day and D. Yoskowitz, ''Environmental Sustainability of Economic Trends in the Gulf of Mexico: What Is the Limit for the Mexican Coastal Development?,'' in *The Changing Ocean and Coastal Economy of the Gulf of Mexico*, ed. J.C. Cato (College Station, Texas: Harte Research Institute for Gulf of Mexico Studies, Texas A&M University Press, 2008), chap. 5, hereinafter ''Environmental Sustainability.''

36. PEMEX-PEP, *Informe de Indicadores Petroleros* (2004), available online: <http://www.pemex.com/index.cfm/action/contents/sectionID/1/catID/237/index.cfm?action=contents&sectionID=1&catID=237>.

37. *Id.*

38. *Id.*; P. Sánchez-Gil, A. Yáñez-Arancibia, J. Ramírez-Gordillo, J.W. Day and P.H. Templet, ''Some Socio-Economic Indicators in the Mexican States of the Gulf of Mexico,'' *Ocean and Coastal Management* 47, no. 11-12 (2004): 581–597.

central portion of the region (Tamaulipas and Veracruz) contributed more than 50 percent of the GDP of the region. The state of Veracruz has the largest economy of the region contributing about 4.5 to 5.5 percent of the national total GDP in the country. In 2000, Tamaulipas was 3.2 percent, Veracruz 4.5 percent, Tabasco 1.4 percent, Campeche 1.2 percent, Yucatán 1.3 percent, and Quintana Roo 1.3 percent. The low level of GDP of the region and even the decree in some productive economic activities is likely related to the decree of ecosystem integrity, particularly the dramatic rate of land-use change and pollution. Thus, the diminished environmental quality is likely contributing to the lack of sustainability of economic activities in the Mexican portion of the Gulf of Mexico. This is especially the case for the ecological integrity the Grijalva-Usumacinta River Delta.

HABITAT DEGRADATION, ECONOMIC DEVELOPMENT AND ENVIRONMENTAL SUSTAINABILITY

Numerous conflicts exist among the interests of development and local economies based on coastal resources in the Mexican coast of the southern Gulf of Mexico.[39] The intensity of exploitation of these resources is causing serious environmental and habitat deterioration. From Yáñez-Arancibia,[40] the link between economic activities and habitat degradation is clear, and it is exacerbated by the lack of strategic environmental planning.[41]

Pollution patterns reflect the major economic trends in each of the Mexican states in the Gulf. This is a result of a combination of forces

39. Day et al., ''Using Ecotechnology,'' n. 8 above; D. Zárate Lomelí, T. Saavedra, J.L. Rojas, A. Yáñez-Arancibia and E. Rivera, ''Terms of Reference Towards an Integrated Management Policy in the Coastal Zone of the Gulf of Mexico and the Caribbean,'' *Ocean and Coastal Management* 42, no. 1-2 (1999): 345–368; D. Zárate Lomelí, A. Yáñez-Arancibia, J.W. Day, M. Ortiz Pérez, A.L. Lara-Domínguez, C. Ojeda de la Fuente, L.J. Morales Arjona, and S. Guevara, ''Lineamientos para el programa regional de manejo integrado de la zona costera del Golfo de México y el Caribe,'' in *Diagnóstico Ambiental del Golfo de México*, eds. M. Caso-Chávez, I. Pisanty and E. Ezcurra (México D.F.: INE-SEMARNAT Press, 2004), pp. 899–935, hereinafter ''Lineamientos;'' D. Zárate Lomeli, A. Yáñez-Arancibia, J.W. Day, P. Sánchez-Gil, H. Alafita Vázquez, J.J. Ramirez Gordillo, ''Towards a Regional Programme for ICZM in the Mexican Area of the Gulf of Mexico and the Caribbean: Analysis Revisiting Two Decades of Publications,'' in *The Gulf of Mexico: Ecosystem-Based Management*, ed. J.W. Day and A. Yáñez-Arancibia (College Station, Texas, Harte Research Institute for Gulf of Mexico Studies, Texas A&M University Press, 2008), chap. 21, hereinafter ''Towards a Regional Programme.''

40. Yáñez-Arancibia, ''Environmental Sustainability,'' n. 36 above.

41. Zárate Lomelí, et al., ''Lineamientos,'' n. 40 above; Zárate Lomelí, et al., ''Lineamientos,'' n. 40 above; Zárate Lomeli et al., ''Towards a regional programme,'' n. 40 above.

including cultural process, natural changes in ecosystems, and also the expansion of industrial activities, dramatic land-use changes, and habitat alteration and destruction. For instance, the state of Tamaulipas receives considerable freshwater discharge from rivers draining from both the U.S. (i.e., Rio Grande/Rio Bravo) and Mexico (i.e., the Tamesi/Panuco River) with a total discharge of about 480 m^3per second for the period 1973–2000. Pesticides and heavy metals have been reported for all the rivers in Tamaulipas. The environment in the state of Veracruz has been degraded by port activities, hydrocarbons and petrochemical industries, agriculture, and cattle ranching. Veracruz has the highest land-use change in the region, at 87 percent, and there is significant organic matter contamination due to runoff from urban development, cattle ranches, and sugar cane fields and mills. In addition to the Grijalva-Usumacinta, there is significant river discharge in the southern Gulf of Mexico as we quoted earlier in the Gulf of Mexico watershed section.

The Usumacinta and Grijalva rivers drain a large area in southern Mexico and Guatemala, much of which is used for tropical agriculture and cattle ranching. This undoubtedly contributes to organic matter, pesticide, and nutrient pollution in the coastal zone. Campeche has the highest oil and gas production region and this is reflected in the highest hydrocarbon pollution in the coastal zone of the region. Agricultural activities occupy 787,000 ha in the state of Yucatan, which is 83 percent of the area of the state. There is also hydrocarbon pollution associated with Ports such as Progresso. Finally, Quintana Roo supports the major tourism activities in the region, with the highest rate of growth but the lowest land-use change because tourism is located mainly in the coastal area. There is hydrocarbon pollution associated with ports and maritime transport.

The loss of wetlands and other habitats of the coastal region are problems that generally characterize the coastal region of the Grijalva-Usumacinta River Delta and adjacent areas in the southern Gulf of México, not only in Mexico,[42] but the same type of impacts also occurs in the northern Gulf of Mexico in the United States.[43] Because of this, there is a tremendous impact on coastal ecosystem integrity.[44] As a result, the main

42. Yáñez-Arancibia, ''Environmental Sustainability,'' n. 36 above.

43. Day et al., ''Using Ecotechnology,'' n. 8 above; J.W. Day, J.Y. Ko, J. Rybczyk, D. Sabins, R. Bean, G. Berthelot, C. Brantley, L. Cardoch, W. Conner, J.N. Day, A.J. Englande, S. Feagly, E. Hyfield, R. Lane, J. Lindsey, W.J. Mitsch, E. Reyes and R. Twilley, ''The Use of Wetlands in the Mississippi Delta for Wastewater Assimilation: A Review,'' *Ocean and Coastal Management* 47, no. 11-12 (2004): 671–692, hereinafter ''A Review of Ecological Impacts.''

44. Yáñez-Arancibia et al., ''Interacciones,'' n. 3 above; N.N. Rabalais, R.E. Turner and W.J. Wiseman, ''Hypoxia in the Northern Gulf of Mexico: Linkage with the Mississippi River,'' in *The Gulf of Mexico Large Marine Ecosystem: Assessment, Sustainability and Management,* eds. H. Kumpf, K. Steidinger and K. Sherman (Malden, Massachusetts: Blackwell Science, 1999), pp. 297–322. N.N. Rabalais, R.E.

affected sectors of the economy are the primary ones. The predominant productive activities are agriculture, cattle ranching, forest exploitation, and fishing.[45] These rural and traditional activities often suffer with the development of modern high-technology industries, such as oil and gas exploitation, and petrochemical activities.

For example, over the past two decades, the deltaic region of Tabasco-Campeche, and the coastal plain of the state of Veracruz have undergone a remarkable economic transition.[46] The area has transformed from an isolated, mostly rural region to one characterized by large-scale commercial cattle ranching, the establishment of tropical monoculture plantations, the exploration, exploitation, transport, and refining of oil, the development of petrochemical industries, and urban expansion due both to industrial activities and tourism development. These changes have altered the landscape of the coastal area dramatically. The oil and gas industry in the southeastern portion of the Mexican Gulf coast has had a dramatic impact in the coastal zone.[47] There is pesticide,[48] heavy metal,[49] nutrient and

Turner and D. Scavia, ''Beyond Science into Policy: Gulf of Mexico Hypoxia and the Mississippi River,'' *BioScience* 52 (2002): 129–142; W.J. Mitsch, J.W. Day, J. Gilliam, P. Groffman, D. Hey, G. Randall and N. Wong, ''Reducing Nitrogen Loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to Counter a Persistent Problem,'' *BioScience* 51, no. 5 (2001): 373–388; M. Caso-Chávez, I. Pisanty and E. Ezcurra, eds., *Diagnóstico Ambiental del Golfo de México* (México D.F.: INE-SEMARNAT Press, 2004), pp. 1108.

45. Yáñez-Arancibia, ''Environmental Sustainability,'' n. 36 above; Sánchez-Gil et al., n. 39 above; Zárate Lomelí, et al., n. 40 above; Zárate Lomelí et al., ''Lineamientos,'' n. 40 above; Zárate Lomeli et al., ''Towards a Regional Programme,'' n. 40 above.

46. Yáñez-Arancibia, ''Environmental Sustainability,'' n. 36 above; Sánchez-Gil et al., n. 39 above; C. León and H. Rodríguez, ''Ambivalencias y asimetrías en el proceso de urbanización en el Golfo de México: Presión ambiental y concentración demográfica,'' in *Diagnóstico Ambiental del Golfo de México*, eds. M. Caso-Chávez, I. Pisanty and E. Ezcurra (México D.F.: INE-SEMARNAT Press, 2004), pp. 1043–1082.

47. Ko et al., ''A Review of Ecological Impacts,'' n. 40 above; J.W. Day, P.H. Templet, J.Y. Ko, W.J. Mitsch, G.P. Kemp, J. Johnston, G. Steyer, J. Barras, D. Justic, E. Clairain and R. Theriot, ''El delta del Mississippi: Funcionamiento del sistema, impactos ambientales, y desarrollo sustentable,'' in *Diagnóstico Ambiental del Golfo de México*, eds. M. Caso-Chávez, I. Pisanty and E. Ezcurra (México D.F.: INE-SEMARNAT Press, 2004), pp. 851–882; E. Reyes, J.W. Day, A.L. Lara-Domínguez, P. Sánchez-Gil, D. Zárate Lomelí and A. Yáñez-Arancibia, ''Assessing Coastal Management Plans Using Watershed Spatial Model for the Mississippi Delta, USA, and the Usumacinta-Grijalva delta, Mexico,'' *Ocean and Coastal Management* 47, no. 11-12 (2004): 693–708.

48. A.V. Botello, J.L. Rojas Galavíz, J.A. Benítez and D. Zárate Lomelí, eds., *Golfo de México Contaminación e Impacto Ambiental: Diagnóstico y Tendencias* (EPOMEX Serie Científica 6, Universidad A. de Campeche, México, 1996), 650 pp.

49. A.V. Botello, S. Villanueva and L. Rosales Hoz, ''Distribución y contaminación de metales en el Golfo de México,'' in *Diagnóstico Ambiental del Golfo de México*,

organic matter pollution.[50] The exploration, exploitation, and transport of hydrocarbons have led to water, air, and soil contamination, and loss of wetlands.[51]

The adoption of preventive measures seems to be the best alternative for prevention of environmental problems. Solutions to these problems will be more effective when there are studies of economic valuation of natural resources and environmental impacts. These need to be routinely incorporated into analyses of sustainable development in the coastal zone of the Grijalva-Usumacinta River Delta region. At present, the economic development pressure in the southern Gulf of Mexico coastal zone seems to be approaching a threshold beyond which environmental sustainability could collapse.[52] Sánchez-Gil[53] clearly pointed out that most natural resources under exploitation in the coastal zone are ''Gulf-dependent.'' Most economic and social issues are geographic in nature, associated with the coastal zone from the coastal plain to the inner sea shelf. Since many economic activities are dependent on the use of water resources from low river basins to the estuarine plume, they are also water-dependent.[54] In other words, economic development in the southern Gulf of Mexico coastal zone is ecosystem-dependent and based on ecological integrity of deltaic and wetland systems. The ecological integrity of the region is at risk because of land-use changes, pollution, urban and industrial expansion, but also because of global climatic change. The latter is an environmental variable often ignored or sub-valued in Mexican coastal development actions.

Global climate change will strongly impact the coastal zone of the southern Gulf of Mexico. Climate impacts will include more variable rainfall, increased temperature, increased frequency and strength of

eds. M. Caso-Chávez, I. Pisanty and E. Ezcurra (INE-SEMARNAT Press, México D.F., 2004), pp. 683–712.

50. J. Herrera-Silveira, A. Silva, A. G. J. Villalobos, I. Medina, J. Espinal, A. Zaldivar, J. Trejo, M. González. A. Cu and J. Ramirez, *Análisis de la Calidad Ambiental Usando Indicadores Hidrobiológicos y Modelo Hidrodinámico Actualizado de Laguna de Términos, Campeche* (Informe Técnico CINVESTAV-Mérida, EPOMEX-Campeche, UNAM-Mexico DF., 2002), pp. 187, hereinafter ''*Analisis*.''; J.A. Herrera-Silveira, N.A. Cirerol, L. Trocoli Ghinaglia, F.A. Comin and C.J. Madden, ''Eutrofización costera en la Península de Yucatán,'' in *Diagnóstico Ambiental del Golfo de Méxic*o, eds. M. Caso-Chávez, I. Pisanty and E. Ezcurra (México D.F.: INE-SEMARNAT Press, 2004), pp. 823–850.

51. Day et al., ''Using Ecotechnology,'' n. 8 above; J.W. Day, J. Barras, E. Clairain, J. Johnston, D. Justic, P. Kemp, J. Y. Ko, R.R. Lane, W.J. Mitsch, G. Steyer, P.H. Templet and A. Yáñez-Arancibia, ''Implications of Global Climatic Change and Energy Cost and Availability for the Restoration of the Mississippi Delta,'' *Ecological Engineering* 24, no. 4 (2005): 253–265, ''Implications of Global Climate Change.''

52. Yáñez-Arancibia, ''Environmental Sustainability,'' n. 36 above.

53. Sánchez-Gil et al., n. 39 above.

54. *Id.*

hurricanes, and sea-level rise.[55] These impacts are similar to those predicted for the northern Gulf of Mexico.[56] These effects will likely have tremendous human, economic, and ecological impacts in coming decades in the Grijalva-Usumacinta delta region. There is a broad consensus in the scientific community that human activity is affecting global climate.[57] Global warming will lead to accelerated eustatic sea-level rise that the Intergovernmental Panel on Climate Change (IPCC) predicts will rise by about 40 cm by the end of the 21st century. However, there is evidence that eustatic sea-level rise will be much more, perhaps one meter.[58] This increase in sea level must be added to subsidence to obtain the relative sea-level rise that coastal wetlands in the Usumacinta/Grijalva delta will be subject to over the 21st century (Figure 3). Thus, relative sea-level rise in the delta will likely be in excess of 1.5 m in this century, a 30 to 70 percent increase,[59] Accelerated sea-level rise, frequency of tropical storms and hurricanes, and higher river discharge will likely lead to a significant increase in flooding in the southern Gulf of Mexico. For instance, it was shown byZarate et al.[60]that sea level in the southern Gulf of Mexico is highest from September to November associated with the highest tidal variation, high wave energy, and the ''*nortes*'' storm period. This is significant because the Grijalva-Usumacinta River has the highest water discharge during the same period. Thus, the combined impact of high river discharge and high Gulf level will lead to greater flooding in the coastal zone. Figure 3 shows the city areas under

55. Ortiz-Pérez, ''Sea-level rise,'' n. 12 above; Yáñez-Arancibia, ''Ecosistemas,'' n. 12 above.

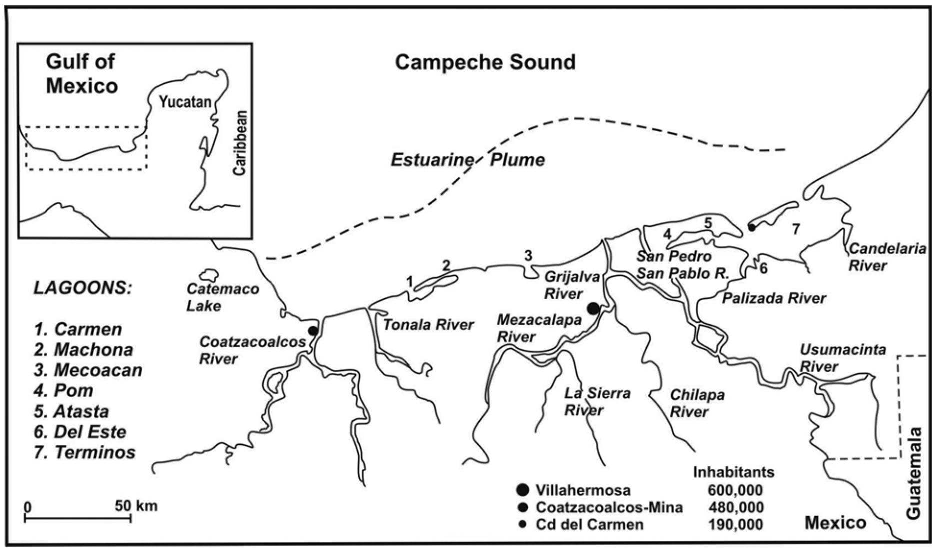
56. Day et al., ''Implications on Global Climate Change,'' n. 52 above; J.W. Day and P.H. Templet, ''Consequences of Sea-Level Rise: Implications from the Mississippi Delta,'' *Coastal Management* 17 (1989): 241–257; R.R. Twilley, E.J. Barron, H.L. Gholz, M.A. Harwell, R.L. Miller, D.J. Reed, J.B. Rose, E.H. Siemann, R.G. Wetzel, and R.J. Zimmerman, eds., *Confronting Climate Change in the Gulf Coast Region: Prospects for Sustaining Our Ecological Heritage* (Cambridge, Massachusetts: Union of Concerned Scientist, and Washington D.C.: Ecological Society of America, 2001), p. 82; N. LeRoy Poff, M.M. Brinson and J.W. Day, eds., *Aquatic Ecosystems & Global Climate Change: Potential Impacts on Inland Freshwater and Coastal Wetlands Ecosystems in the United States* (Arlington, Virginia: Pew Center on Global Climate Change, 2002), p. 44; Z.H. Ning, R.E. Turner, T. Doyle and K. Abdollahi, eds., *Integrated Assessment of the Climate Change Impacts on the Gulf Coast Region* (Baton Rouge, Louisiana: United States Environmental Protection Agency and United States Geological Services, 2003), p. 236; D. Scavia, J.C. Field, D.F. Boesch, R.W. Buddemeier, V. Burkett, D.R. Cayan, M. Fogarty, M.A. Harwell, R.W. Howarth, C. Mason, D.J. Reed, T.C. Royer, A.H. Sallenger and J.G. Titus, ''Climate Change Impacts on U.S. Coastal and Marine Ecosystems,'' *Estuaries* 25, no. 2 (2002): 149–164.

57. Scavia, et al., n. 57 above.

58. S. Rahmstorf, ''A Semi-Empirical Approach to Predicting Sea-Level Rise,'' *Science* (2007): 315 at 368–370.

59. Ortiz-Pérez, ''Sea-Level Rise,'' n. 12 above; Day, et al., ''Implications on Global Climate Change,'' n. 52 above.

FIG. 3.—The physiographic map for the coastal plain of Southern Gulf of Mexico: Veracruz State (Catemaco Lake, Coatzacoalcos River, Tonala River), Tabasco State (Mescalapa River, Grijalva River, Carmen, Machona, and Mecoacan Lagoons), Chiapas State (La Sierra River, Chilapa River), Campeche State (Usumacinta River, San Pedro San Pablo River, Palizada River, Candelaria River, Pom, Atasta, Del Este, and Carmen Lagoons); and the international border between Mexico and Guatemala is shown. Over 1,200,000 inhabitants in three main cities (Villahermosa, Tabasco; Coatzacoalcos, Veracruz; and Ciudad del Carmen, Campeche) are under severe risk because they are located in the deltaic plain one meter or less from the sea-level rise.



severe risk because of sea-level rise in the Grijalva-Usumacinta River delta considering two scenarios of sea-level rise (e.g., 1 and 2 meters rise) after Zarate et al.[60] Unless wetlands can accrete vertically at the same rate as water level rise, coastal vegetation will become progressively more stressed and ultimately die. Proper functioning of the delta is critical if coastal wetlands are to survive sea-level rise. But, human impacts in the delta decrease the likelihood of wetland survival. These impacts include hydrological alteration levee construction and canal dredging, salt water intrusion, habitat fragmentation, and pollution. Thus, the combined effects of human impacts and climate change on the delta system will be greater than either impact operating separately.[61]

60. Zárate Lomelí et al., ''Lineamientos,'' n. 40 above.

61. Yáñez-Arancibia, ''Environmental Sustainability,'' n. 36 above; Zárate Lomelí et al., ''Lineamientos,'' n. 40 above.

EXISTING ENVIRONMENTAL MANAGEMENT SYSTEM

A key management challenge is poor water quality. Excess nutrients in the rivers are caused by a variety of diffuse and point sources, including agrochemicals, animal waste, and untreated wastewater. There is insufficient treatment of wastewater discharged into the river and water taken from rivers for potable water contributes to health problems among those who do not have sufficient resources to purchase bottled water for personal consumption.

Formed in 2000, the Usumacinta Watershed Council (*Consejo de Cuenca de los Ríos Grijalva y Usumacinta*) unites representatives from CNA (*Comisión Nacional del Agua,* now CONAGUA), state governments, and five different sectors: ranching, agriculture, industry, hydropower, and potable water networks. The CNA is represented by its Director General, while state governments are represented by their governors. The Director General named a chairperson to coordinate the council. The sector representatives were elected among stakeholders that attend water user assemblies convened by CNA of the holders of water rights within each sector. These representatives became members of the Council for a term of three years in which they were to attend meetings, represent the interests of their sector, and inform water users of the Council's actions. There was also a Citizens' Forum (*Consejo Ciudadano del Agua*) that was intended to represent the interests of the general public. This forum perceived itself as a watchdog, monitoring government actions, yet CNA saw the forum as merely a vehicle for raising public awareness of water issues.

The Usumacinta Watershed Council was supported by a number of working groups and committees. The most important was a monitoring and evaluation (M&E) group (*grupo de seguimiento y evaluación*), which basically replicated the Watershed Council structure, yet included substitutes for the governmental representatives, such as the state governors. The M&E group was the operational group of the Watershed Council, while the Council was a symbolic connection to the higher levels of the government authority. The M&E group formed working groups (*grupos de trabajo especializado*) in Tabasco to address particular aspects of water management, while catchments committees (*comités de cuenca*) were formed in Chiapas to tackle multiple issues inside smaller-scale drainage basins nested within the larger watershed.

In theory, the Usumacinta Watershed Council facilitated integrated water resources management by bringing high-ranking government officials to the table together with sector representatives that resided within the watershed. Yet the reality was less than ideal, water users were generally unaware of the Council's existence; federal and state authorities conflict over jurisdiction, and the council tended to marginalize municipal authorities, NGOs, and academics. The water user assemblies convened by CNA were more or less defunct and did not meet during the three years following the election of sector representatives. These assemblies relied on the initiative of their representatives to consult with users and gather feedback for the Council, yet no such consultation occurred in practice due to lack of interest, time, or resources. The Council was supposed to coordinate the actions of multiple stakeholders towards a common goal, yet there was no collective vision for IWRM. Instead, different roles were advocated for the Council, including coordinating government agencies, building new infrastructure, promoting economic development, and fostering water conservation and awareness of a watershed perspective.

CNA representatives saw the Council as a vehicle for transferring responsibilities for water management from the federal government to local governments and the water users themselves; yet, this vision faced serious obstacles in the form of limited legal, technical, and financial capacity among water users, states, and municipalities. Stakeholders joined the Council in order to voice their concerns, connect their efforts with a wider process, and potentially access new government funding. Instead of fostering open dialogue and joint planning, Council meetings primarily focused on presentations about water programming within different government agencies. Stakeholders were frustrated by a lack of continuity between meetings and felt that CNA needed to provide more access to biophysical and other information required to better understand the issues the Council was to engage.

Economic and political interests both dominated and undermined the council; nonetheless, there was evidence of mutual learning among stakeholders. While each of the sector representatives was supposed to have had an equal voice within the council, three sectors (i.e., industry, potable water networks, and hydropower) tend to dominate the agenda and discussion. Representatives of these influential sectors interacted with CNA officials and affected water policy outside the council, which served to undermine the Council's power and relevance in water management. Despite these weaknesses, the scope of the discussion slowly moved beyond first order scarcity of mere water quantity and quality, to consider second order scarcity related to the socio-economic value of water use. Some participants also expressed an interest in expanding the Council's geographic boundaries beyond the Mexican border in order to include Guatemala and tackle transboundary water issues.

The barriers to participation can be overcome if the water user assemblies were reconvened and CNA acted as the Council's facilitator rather than convener. The sectors represented on the Council include a diversity of water users, both small and large, thus no single person could adequately represent the sector without the support of water users. On the one hand, an active water user assembly is required to inform each sector representative, which otherwise is left to act in the interests of their particular organization, rather than those of the sector as a whole. In order for the Council to work, water users have to be informed about the Council's actions, ensure their interests are represented, and pressure their representatives for results. On the other hand, CNA representatives described their role in terms of logistics: arranging travel, calculating per diems, and booking meeting space. CNA expected that the water users assemblies and the Watershed Council would be self-sustaining once it had convened the representatives; yet meaningful participation requires skills to facilitate and sustain dialogue among these stakeholders. While CNA provided biophysical information on the watershed's resources, representatives also required capacity building and training in how to conduct analysis, make proposals, and negotiate with others.

Although this discussion has focused on the Centla area, the same general findings hold true for the Terminos Lagoon area. The discovery of large oil deposits in Campeche Sound in the 1970s brought significant economic and demographic changes to the Terminos Lagoon region, as Carmen Island became an important administrative and logistics hub for oil platforms in the Gulf of Mexico. Concerned that oil development would expand inshore, a number of NGOs sought the support of the state government and local universities to establish a protected area. This initiative resulted in a federal government decree that established the region as a wildlife protection area (*Área de Protección para la Flora y Fauna Silvestre y Acuática*), a conservation category that allows for the multiple use of the region's resources.[62]

Existing land tenure was unaltered by the decree, and the region remained a mixture of public, private, and communal property. Conservation policies thus cannot be imposed from the top-down, but instead must accommodate various interests and rely on voluntary actions by landowners. Responsibility for the national protected area system lies with the federal environmental department, SEMARNAT (*Secretaria de Medio Ambiente y Recursos Naturales*). SEMARNAT coordinated its activities with the state and municipal governments through a small administrative office (*Dirección*) that housed a government-appointed protected area director, a modest budget, and a few conservation scientists.

Despite these humble beginnings, events over the next three years gathered national attention, as Terminos Lagoon became an experiment in participation. A public consultation process began in 1994 with the purpose

62. B. Currie-Alder, ''The Role of Participation in Ecosystem-Based Management: Insights from the Usumacinta Watershed River and Terminos Lagoon, Mexico,'' in *The Gulf of Mexico: Ecosystem-Based Management*, eds. J.W. Day and A. Yáñez-Arancibia (College Station, Texas: Harte Research Institute for Gulf of Mexico Studies, Texas A&M University Press, 2008), chap. 10.

of developing a protected area management plan.[63] This public consultation, which included open meetings throughout the region, created a precedent as local organizations began to expect a role in managing the protected area. In March 1996, the federal environmental protection agency approved an impact assessment to drill two oil wells within the protected area. Local NGOs, fishing cooperatives, and farmers associations felt the federal government had betrayed them, and that the new wells undermined public consultation. They distributed white flags to symbolize opposition to further oil development, petitioned the national oil company, PEMEX (*Petroleos Mexicanos*), to cancel the project, and organized street protests that ultimately resulted in the temporary occupation of Carmen municipal offices. SEMARNAT finally intervened to negotiate a solution where local organizations would halt the protests and permit the new oil drilling in return for a moratorium on oil development throughout the protected area and the inclusion of a land-use suitability assessment in the management plan. PEMEX also promised to fund conservation activities within the protected area, and federal and state governments agreed to establish a collaborative management body for the protected area, the Terminos Lagoon Consultative Council (*Consejo Consultivo para la Laguna de Términos*).

In 1997, the management plan was finally published and the Consultative Council began to meet in Ciudad del Carmen.[64] The council's mandate was to promote dialogue among stakeholders and to implement the management plan. This meant advising the protected area director and assessing different proposals for how to spend the funding donated by PEMEX. Membership in the Council was open to all stakeholders that had participated in the public consultation process. As such, the council began with over 45 representatives, including the three levels of government, PEMEX, and locals, including environment NGOs, fishing cooperatives, and farmer associations. The protected area director called meetings and set the agenda, while stakeholders debated proposals and made decisions by consensus or by simple majority in open votes.

The council operated with moderate success from 1997 to 1999—in part due to the availability or lack of funding for the protected area—yet there were two competing interpretations of the scope of the Council's mandate and powers. Funding provided by PEMEX gave the council the means to implement the management plan through research projects, monitoring, and other actions. Equally, government agencies leveraged their limited funds by working through the Council to recruit locals to participate in an informal network to monitor poaching. Locals who had lobbied for the protected area status and participated in the protests against

63. *Id.*
64. *Id.*

oil development saw the Council as an embodiment of citizen power—a collegial body of equals intended to decide on and coordinate those activities that would be permitted within the protected area. Yet government viewed the Council as merely an institutionalized form of consultation without any real power, and a mechanism that prevented protests by allowing stakeholders to voice their opinions. The tension between these two visions went beyond whether the Council was an advisory board or a decision-making forum, however, as it concerned which stakeholders held the power to decide the fate of the region's ecosystems.

By 1999, the Consultative Council was in crisis as it was accused of supporting unrelated projects and the protected area director was accused of misdirecting funds intended for the Council. Fearing local stakeholders had captured the Council, government representatives began to ignore it, believing that only they could ultimately act in the public interest. PEMEX reacted by bypassing the Council and recruiting an NGO based in Mexico City to allocate the funding the company donated for conservation activities. Consequently, both the Council and protected area director were required to submit proposals to this outside organization in order to receive PEMEX funding. Eventually, the Council stopped meeting on a regular basis after a new protected area director was appointed in 2000.

After 2000, stakeholders on both sides continued to press different visions for reframing the Council. SEMARNAT officials saw the Council as a rogue forum captured by special interests. They point out that the Council lacked enabling legislation and called for a modified council that conforms to the model of an Advisory Committee (*Comité Técnico Asesor*) described in the protected area regulation. Yet, locals argue that the council predates the Advisory Committee and need not conform to this legislation. Despite these differences, government policies increasingly emulate local concerns. Locals are motivated to control oil development in order to protect the environmental and human health of the region, however, achieving this goal requires more than merely establishing the protected area. It requires a more sustainable model of development that safeguards the region's environment, society, and economy. While SEMARNAT initially pursued a narrow conservationist agenda, Mexican policies increasingly incorporate the discourse of sustainable development. Such a policy shift represents a convergence between local and official visions and offers new opportunities for dialogue on the Council's future.

CONCLUDING REMARKS: HUMAN ACTIVITY AND ECOSYSTEM BASED-MANAGEMENT IMPLICATIONS

There are a number of significant impacts on wetlands and other ecosystems of the Grijalva-Usumacinta Delta region. These include: a) urban expansion and social development, b) the development of oil, gas, and petrochemical industries, c) expansion of agricultural and cattle ranching, d) expansion of tourism and road infrastructure, and e) the uncertainty of the compatibility of economic development and environmental sustainability.

In order to achieve environmental sustainability with economic trends in the Grijalva-Usumacinta Delta system, it is important that planning be incorporated into the development process. Sustainability for social and economic development must be based on the functioning of the river basin and delta, integrating natural resource exploitation with natural ecosystem dynamics, and assuring that as social and economic development takes place, ecosystem integrity is preserved.[65] The contrasting relationships currently among abundant natural resources, dramatic habitat degradation, high levels of pollution, and low contribution to the Gross Domestic Product reflect the lack of strategic environmental strategic planning in the southern Gulf of Mexico. Climate change effects will make the situation worse.[66] Any project initiated today, which is expected to last for more than a decade, will be affected by both the absence of strategic environmental strategic planning and climate change.

In this coastal, deltaic setting with strong river input, the ecosystem is developed and maintained by a series of energetic pulses that occur on different temporal and spatial scales. These include switching of river channels every few hundred years, large storms, such as hurricanes, and great river floods, annual river floods, frontal systems, and tides. The maintenance of these pulses is critical to maintaining healthy ecosystems in an area with a high level of development.[67] This approach can be used to integrate environmental functions with economic and ecological processes. This allows better environmental and development decisions to be made and leads to more sustainable development. Another important criterion to consider is the intrinsic economic value of coastal resources. These resources represent a ''natural capital'' that supports the economic health of society. The natural capital of deltaic ecosystems is among the highest on earth. The goods and services provided by natural capital represent the ''interest'' generated by human investment in natural ecosystems.[68] This is the reason that healthy ecosystems support a healthy economy in the southern Gulf of Mexico.

65. Yáñez-Arancibia et al., *Interacciones*, n. 3 above; Day et al., ''System Functioning,'' n. 15 above; Yáñez-Arancibia, ''Environmental Sustainability,'' n. 36 above; Day et al., ''Implications on Global Climate Change,'' n. 52 above.

66. Ortiz-Pérez, ''Sea-level rise,'' n. 12 above; Day et al., ''Implications on Global Climate Change,'' n. 52 above; Twilley et al., n. 57 above; LeRoy Poff et al., n. 57 above; Ning et al., n. 37 above; Scavia et al., n. 57 above.

67. Rahmstorf, n. 59 above.

68. Yáñez-Arancibia, ''Environmental Sustainability,'' n. 36 above.

Anthropogenic impacts interact with climate forcing leading to impacts that are often more severe than either impact acting alone. Isolation of the delta from the river with levees and pervasive hydrologic alteration (e.g., oil and gas activities) have caused a high rate of coastal wetland loss,[69] which could reach more than 20 percent of the delta area in the next 10 years. These changes have also made the delta more vulnerable to an acceleration of sea-level rise and reduced freshwater input due to climate change. Hydrological alterations and diversion of freshwater flows for agriculture, human consumption, industries, and flood control have reduced freshwater input into the lower delta. In addition, runoff from the agricultural area inland of Chiapas, Tabasco, and Campeche states has caused nutrient enrichment over the last twenty years,[70] resulting in replacement of native vegetation such as in Laguna El Vapor of the Palizada inner delta in the Terminos Lagoon area.

It is important to maintain a healthy Grijalva-Usumacinta felt ecosystem because it will be able to better cope with climate change. This should involve careful management of freshwater, sediment, and nutrient resources, and working with natural systems to adjust to climate change. As noted earlier, diversions of freshwater can enhance the ability of coastal wetlands to survive sea-level rise and increases in salinity. However, care must be taken to minimize the potential for eutrophication. Where possible, wetlands should be allowed to migrate inland as sea-level rises. Increasing temperature is already having impacts on coastal ecosystems. Hurricanes have been a regular, if episodic, occurrence in the southern Gulf of Mexico for thousands of years and they bring positive benefits to coastal ecosystems. They are more likely to be a deleterious impact when coastal ecosystems are degraded and when humans put themselves in harm's way. If hurricanes become more frequent and stronger, it is possible that the structure of coastal ecosystems, that is, barrier islands, mangroves, marshes, and swamps, will be diminished. The best defense against hurricanes seems to be healthy coastal wetland ecosystems.

Unfortunately, the plans for economic growth do not generally take into consideration either the value of ecosystem services or climate change. Economic development pressure in the Grijalva-Usumacinta region may be approaching a threshold where environmental sustainability will likely be threatened in a near future.[71] In order to achieve sustainable development, we need to develop and apply methods of analysis of environmental and economic information and to integrate this information into economic and

69. Reyes et al., n. 48 above.

70. Yáñez-Arancibia et al., *Ecosystem Functioning,* n. 2 above; Herrera-Silveira et al., ‘‘*Analisis,*’’ n. 51 above.

71. Currie-Alder, n. 63 above.

ecological plans for each one of the coastal states of the Gulf and Caribbean region in Mexico. If not, economic development will be limited by threats to the ecological integrity of ecosystems. Humans need to understand that there are can limits that ecosystem integrity can be diminished. A clear priority is to measure environmental sustainability quantitatively so that socio-economic development of the coastal region influenced by the Grijalva-Usumacinta River Delta can take place in an environmentally friendly manner.

The Usumacinta Watershed Council was a government initiative that intended to bring high-ranking government officials together with representatives that resided within the watershed. Yet, in practice, the council was limited by power imbalances among representatives, weak downward accountability to water users, and weak legal, technical, and financial capacity among these users. Strengthening the Usumacinta Watershed Council depends on CNA adopting a more active facilitation role, rather than merely convening the Council's meetings, and reinvigorating the water user assemblies. In comparison, the Terminos Lagoon Consultative Council was a civil society initiative that tried to include a more numerous membership. Government was initially forced to accept the council in order to avoid further social protests in the region, yet over time, the council became polarized between local stakeholders who aspired to a model of participatory governance, and government agencies that saw the council merely as an advisory board.

These initiatives offer two sets of insights into the potential for ecosystem-based management for the Gulf of Mexico as a whole. First, ecosystem-based management is as much about the arts of power and politics as it is about the sciences of hydrology and oceanography. Despite its weaknesses, the Consultative Council can be interpreted as having been a more democratic forum and less vulnerable to resource capture than the Watershed Council. Beyond mere matters of legislation and policies, ecosystem-based management must engage the complexities of power and politics that enable or restrict how people relate to ecosystems, in particular how women and men participate differently in ecosystem-based management. Second, ecosystem-based management means going to scale, either scaling up by expanding geographic and institutional boundaries outwards or by creating cross-scale linkages that enable management to tackle issues at different levels. Over time, the Usumacinta Watershed Council expanded the scope of dialogue to consider the socio-economic value of water use and interest grew in expanding to include the Guatemalan portion of the basin. Meanwhile, the Terminos Lagoon Consultative Council faced pressures to consider the impacts of offshore oil platforms and declines in fishery productivity in the open waters of Campeche Sound, beyond the protected area's boundaries. Thus, in considering the potential for ecosystem-based management across the Gulf of Mexico, it is necessary to assess how to expand the geographic and institutional boundaries of existing management practices to encompass higher-level processes.

The future of ecosystem-based management in the Gulf of Mexico lies in strengthening institutional arrangements among linking existing organizations at different levels to work together in novel ways. Initiatives such as the Usumacinta Watershed Council and Terminos Lagoon Consultative Council both offer building blocks that can potentially contribute to a larger-scale mosaic of ecosystem-based management, as well as more general insights into how to scale up the participatory governance of ecosystems more widely. Clearly, the Gulf of Mexico is not a blank slate and already counts on a rich legacy of experimentation in watershed and coastal approaches to managing ecosystems. Rather than building a system for ecosystem-based management from scratch, more research is needed to understand what initiatives already exist and how they can inform policy towards implementing a new generation of efforts to steward the Gulf of Mexico as a whole.