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Management Approaches to Address Water Quality and Habitat Loss Problems in Coastal Ecosystems and Their Watersheds: Ecotechnology and Ecological Engineering*

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INTRODUCTION

In this article we address ecological approaches to solving water quality and habitat deterioration in coastal ecosystems and their watersheds. We focus on the Mississippi delta and basin, and similar basins in Latin America. Human impacts are occurring from local to global scales. This is especially important in large river basins where there has been large-scale loss of habitat degradation, especially wetlands and riparian areas, and water quality deterioration. We use the Mississippi basin and delta, with a mean

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river discharge of approximately 18,000 m^3/second, as a model for both environmental impact and holistic management. Many wetland and riparian ecosystems have been isolated from rivers and streams and there has been wide spread loss of wetlands, both in the Mississippi basin and elsewhere. Wetland loss is due both to reclamation, mainly for agriculture and urban development, and isolation of rivers by levees from their floodplains and deltas. Water quality has deteriorated throughout the basin due to several factors including heavy use of fertilizers, efficient drainage, wetland loss, and reduced diversity of crops. Habitat loss and poor water quality are a result of the cumulative impacts of actions throughout the basin. Thus, the solutions must address these impacts over the entire basin. Because of the high expense of conventional approaches to environmental restoration, new approaches that work with the natural system are needed. Ecotechnology and ecological engineering offer such approaches that are both ecologically based and economical. Wetlands improve water quality in a number of ways. Both phosphorus and nitrogen can be assimilated via plant uptake and burial, and nitrate can be lost to the atmosphere via denitrification. At the level of the drainage basin, changes in farming practices and use of wetlands for nutrient assimilation can reduce nutrients in rivers. Mitsch et al. discussed how wetlands could be used to reduce fertilizer runoff to streams and showed that a return to more traditional farming practices, what they called multifunctional agriculture, would also promote lower fertilizer runoff from farm fields.[1] Restoration of wetland and riparian ecosystems also results in improved flood control, reduction in public health threats such as blue baby syndrome, and more habitats for wildlife and fisheries. Reconnection of the river to the floodplain and delta is an integral part of restoration of river basins.[2] The use of river diversions in the Mississippi delta can address both problems of coastal land loss and water quality deterioration: nitrate levels in river water can be removed in wetlands by the process of denitrification; and, wetlands are being used throughout the Mississippi basin to assimilate nutrients in municipal wastewater and

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[1] P. Vitousek, H. Mooney, J. Lubchenko and J. Melillo, "Human Domination of Earth's Ecosystems," *Science* 277 (1997): 494–499; W.J. Mitsch, J.W. Day, J.W. Gilliam, P.M. Groffman, D.L. Hey, G.W. Randall, "Reducing Nitrogen Loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to Counter a Persistent Ecological Problem," *BioScience* 51 (2001): 373–388.

[2] Vitousek et al., n. 1 above; Mitsch et al., n. 1 above; S.L. Postel, G.C. Daily and P.R. Ehrlich, "Human Appropriation of Renewable Fresh Water," *Science* 271 (1996): 785–788; W.J. Mitsch and J.W. Day, "Restoration of Wetlands in the Mississippi-Ohio-Missouri (MOM) River Basin: Experience and Needed Research," *Ecological Engineering* 26, no. 1 (2006): 55–69.

agricultural runoff. This approach is cost-effective and results in improved water quality, enhanced wetland productivity, and increased accretion.[3]

The "Mississippi basin lesson" is an appropriate term of reference for projecting the ecosystem-approach to similar deltaic systems in Latin America, where there is a strong need for economical solutions to ecological problems. In this paper, we address problems of loss of wetland habitat and declining water quality in the Mississippi basin and delta, and show how ecotechnological methods can be used in a restoration ecology approach to addressing these problems. The problems are a result of cumulative impacts of many activities that have taken place at different times and in different places in many parts of the basin. We then apply lessons learned from the Mississippi basin to these finding to similar systems in Latin America where the need for local, cost-effective solutions is great.

ENVIRONMENTAL DETERIORATION OF THE 20TH CENTURY

The problems described above for the Mississippi basin occur unfortunately throughout the world. During the 20th century, the effects of human activities affected ecological and biogeochemical processes at the global level,[4] and these changes mirror what has happened in the Mississippi basin. For example, humans directly or indirectly use about 40 percent of net terrestria' primary productivity,[5] and about 30 percent of the accessible renewable fresh water runoff.[6] In the upper Mississippi basin, up to 90 percent of natural habitat has been converted to other uses, mostly agriculture.[7] About 55 percent of tropical forests have been cut with strong impacts on biodiversity.[8] Even greater losses have occurred in the vast bottomland forests of the lower Mississippi floodplain. There is widespread land degradation due to soil erosion, salination, and desertification.[9]

Human activity has affected the global nitrogen cycle, and nutrient levels are increasing in many of the world's rivers.[10] As a result, hypoxia is a

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3. Postel et al., n. 2 above; Mitsch et al., n. 2 above.

4. United Nations Environment Program, Millennium Ecosystem Assessment (2006), available online: <http://www.millenniumassessment.org>.

5. Vitousek et al., n. 1 above; Mitsch et al., n. 1 above.

6. Postel et al., n. 2 above; Mitsch et al., n. 2 above.

7. Vitousek et al., n. 1 above; Mitsch et al., n. 1 above; Postel et al., n. 2 above; Mitsch et al., n. 2 above.

8. R. Goodland and H. Daly, "Environmental Sustainability: Universal and Non-Negotiable," *Ecological Applications* 6 (1996): 1002–1017.

9. D. Pimentel, C. Harvey, P. Rososudarmo, K. Sinclair, D. Kurz and M. McNair, "Environmental and Economic Cost of Soil Erosion and Conservation Benefits," *Science* 267 (1995): 1117–1123.

10. R. Howarth, R.G. Billen, D. Swaney, A. Townsend, N. Jaworski and K Lajtha, "Regional Nitrogen Budgets and Riverine N and P Fluxes for the Drainages to the

common phenomenon in many shallow continental shelf areas that receive significant fresh water input, such as the Mississippi and Grijalva-Usumacinta deltas. Solving the problem of hypoxia demands a basin wide approach using ecotechnology and ecological engineering approaches.[11]

Global climate and the availability and cost of energy will make coastal and drainage basin restoration much more challenging.[12] Climate change is leading to increased temperature, sea-level rise, and changes in rainfall patterns.[13] Three climate change drivers are already affecting coastal areas, and their impact will grow more severe during the 21st century. Eustatic sea-level rise was about 15 cm (1.5 mm/year) during the 20th century. The Intergovernmental Panel on Climate Change (IPCC) predicts a rise of about 40 in the 21st century, but recent satellite measurements indicate that it is already about 3 mm/year. Information from the Arctic on decreasing sea ice and snow cover, decreasing albedo, and more rapid melting of the Greenland ice mass has suggested to some climate scientists that sea-level rise will be higher, perhaps a meter.[14] Thus, relative sea-level rise in deltaic areas with high levels of subsidence will be considerably higher than a meter in this century. Recent evidence also suggests that there is a trend toward

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North Atlantic Ocean: Natural and Human Influences," *Biogeochemistry* 35 (1995): 1995–2004; S.W. Nixon, J.W. Ammerman, L.P. Atkinson, V.M. Berounsky, G. Billen and W.C. Boicourt, "The Fate of Nitrogen and Phosphorous at the Land-Sea Margin of the North Atlantic Ocean," *Biogeochemistry* 35 (1996): 141–180; J.A. Downing, M. McClain, R.R. Twilley, J.M. Melack, J. Elser, N.N. Rabalais, W.M. Lewis, R.E. Turner, J. Corredor, D. Soto, A. Yáñez-Arancibia, J.A. Kopaska and R.W. Howarth, "The Impact of Accelerating Land-Use Change on the N-Cycle of Tropical Aquatic Ecosystems: Current Conditions and Projected Changes," *Biogeochemistry* 46 (1999): 109–148.

[11] W.J. Mitsch and J. W. Day, "Restoration of Wetlands in the Mississippi-Ohio-Missouri (MOM) River Basin: Experience and Needed Research," *Ecological Engineering* 26, no. 1 (2006): 55–69; J.W. Day, A. Yáñez-Arancibia, W.J. Mitsch, A.L. Lara-Dominguez, J.N. Day, J.Y. Ko, R. Lane, J. Lindsey and D. Zárate Lomeli, "Using Ecotechnology to Address Water Quality and Wetland Habitat Loss Problems in the Mississippi Basin (and Grijalva-Usumacinta basin): A Hierarchical Approach," *Biotechnology Advances* 22, no. 1-2 (2003): 135–159.

[12] 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.

[13] T. Wigley and S. Raper, "Implications for Climate and Sea Level of Revised IPCC Emissions Scenarios," *Nature* 357 (1992): 293–300; IPCC, *Climate Change 2007: The Physical Science Basis, Summary for Policymakers* (Report Working Group 1 to the Fourth Assessment Report, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge UK, 2007), p. 18; S. Rahmstorf, "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," *Science* 315 (19 January 2007): 368–370.

[14] Wigley et al., n. 13 above; IPCC, n. 13 above; Rahmstorf, n. 13 above.

stronger, more frequent hurricanes. This is controversial and other scientists suggest that this is part of a decades long cycle of hurricane activity. Whoever is correct, we will almost certainly have more activity in the next 2–3 decades. Finally, there will probably be more frequent droughts in the outer tropics and lower temperate zone.

Energy scarcity will likely become an important factor affecting delta management. Recent analyses suggest that world oil production will soon peak, implying that demand will consistently be greater than supply, and that the cost of energy will increase significantly in coming decades.[15] Some argue that the peak is occurring now, while others argue it is two to three decades away. But the planning horizon for coastal and basin protection and restoration is 50 to 100 years, so energy scarcity will certainly affect how we manage the coast. Both protection and restoration are very energy intensive. Levees, barrier island restoration, and pumping of sediments are energy intensive both in construction and maintenance. River diversions and wetlands for water quality improvement have relatively low long-term maintenance costs.

TOWARD A GREEN, SUSTAINABLE FUTURE: ECOTECHNOLOGY AND ECOLOGICAL ENGINNERING

It is clear that in the coming decades, society will be faced with restoring valuable ecosystems in a time of climate change and energy scarcity. This restoration will be necessary for the services they provide, because in a time of declining energy, services from ecosystems will become relatively more important in supporting the human economy; and, productive ecosystems like river deltas and flood plains will become extremely important. In order to be able to carry out ecological restoration in a time of energy scarcity, energy efficient ecotechnologies will be necessary.

This kind of ecotechnology is ecological engineering,[16] and the concepts and tools for dealing with such as problems are explained by Yáñez-Arancibia et al.[17]

Ecological engineering is defined as: "the design of sustainable ecosystems that integrate human society with its natural environment for the

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[15] See for example, K.S. Deffeyes, *Hubbert's Peak—The Impending World Oil Shortage* (Princeton, N.J.: Princeton University Press, 2001): 208.

[16] Mitsch et al., n. 11 above.

[17] A.J. Yáñez-Arancibia, J.W. Day, R.R. Twilley and W.J. Mitsch, "Enfoque de ecosistema para restaurar humedales costeros ante los cambios globales," *Ambientico* 165 (2007): 35–39; D.F. Boesch, "Scientific Requirements for Ecosystem-Based Management in the Restoration of Chesapeake Bay and Coastal Louisiana," *Ecological Engineering* 26, no. 1 (2006): 6–26.

benefit of both."[18] Ecological engineering involves creating and restoring sustainable ecosystems that have value to both humans and nature by combining basic and applied science for the restoration, design, and construction of aquatic and terrestrial ecosystems. Ecological engineering uses mainly the energies of nature with human energy used in design and control of key processes. This will become extremely important in a time of energy scarcity. The goals of ecological engineering are: 1) The restoration of ecosystems that have been substantially disturbed by human activities such as environmental pollution or land disturbance, and 2) The development of new sustainable ecosystems that have both human and ecological value. Ecological engineering involves the design of the natural environment using quantitative approaches grounded in the basic science of ecology. The primary components of ecological engineering are self-designing ecosystems with their biological species and biogeochemical processes. Ecological engineering often involves ecological restoration and rehabilitation. Restoration ecology and the restoration fields (e.g., terrestrial, aquatic, and wetlands) have many features in common with ecological engineering. Ecosystem restoration is "ecological engineering of the best kind" because we are putting back ecosystems that used to exist.[19]

Self-design and the related concepts of self-organization are important properties of ecosystems in the context of their creation and restoration.[20] In fact, these two concepts are central to ecological engineering. Self-organization is the property of systems to reorganize themselves, given an unstable and non-homogeneous environment. Self-organization applies well to ecosystems where species are continually introduced and deleted, that is, species interactions such as predation and mutualism change in dominance and the environment itself changes. All of these activities go on to some extent continuously. Self-organization is a characteristic of the system itself. The species that succeed in an ecosystem are those that reinforce other species through nutrient cycles, aids to reproduction, control of spatial diversity, population regulation, and other means."[21]

All systems have some level of organization, but Pahl-Wostl argues that there are ways systems can be organized by rigid top-down control or

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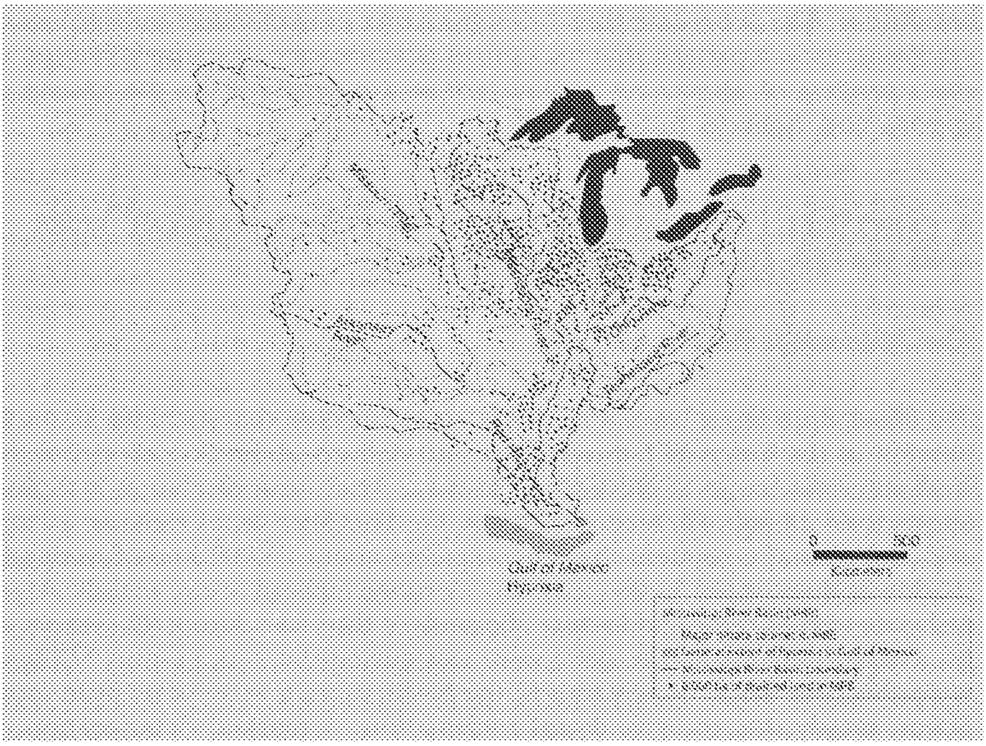
[18] W.J. Mitsch, "Ecological Engineering: The Seven-Year Itch," *Ecological Engineering* 10, no. 2 (1998): 119–128; W.J. Mitsch and S.E. Jorgensen, *Ecological Engineering and Ecosystem Restoration* (New York: Wiley Interscience, 2003).

[19] A. Bradshaw, "Restoration of Mined Lands: Using Natural Processes," *Ecological Engineering* 8 (1997): 255–269.

[20] Mitsch and Jorgensen, n. 18 above.

[21] H.T. Odum, "Ecological Engineering and Self-Organization," in *Ecological Engineering: An Introduction to Ecotechnology*, eds. W.J. Mitsch and S.E. Jorgensen (New York: Wiley Interscience, 1989), pp. 79–101.

Fig. 1.—**Mississippi-Ohio-Missouri River Basin, showing location and general extent of Gulf of Mexico hypoxia, the area in the Midwest that is an important source of nitrogen, and the extent of drainage in the basin. After Mitsch et al. 2005. Used by permission.**



external influence (imposed organization) or by self-organization.[22] Imposed organization, as in many conventional engineering approaches, results in rigid structures and has little potential for adapting to change. This is desirable for engineering design where predictability of safe and reliable structures is necessary, such as for bridges, airplanes, and industrial machines. Self-organization, by contrast, develops flexible networks with a higher potential for adaptation to new situations. Thus, self-design is desirable for solving many ecological problems, particularly in coastal river basin wetlands. When biological systems are involved, the ability for the ecosystems to change, adapts, and grow is very important.

Self-design is defined by Mitch and Jorgensen[23] as: "the application of self-organization in the design of ecosystems." Self-design is an ecosystem function in a way where the chance introduction of species is analogous to

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[22] C. Pahl-Wostl, *The Dynamic Nature of Ecosystems: Chaos and Order Entwined* (New York: Wiley Interscience, 1995): 267.

[23] Mitsch and Jorgensen, n. 18 above.

chance mutations in evolution. In the concept of ecosystem development, self-design means that if an ecosystem is open to allow "seeding" of enough species, the system itself will optimize its design by selecting for the assemblage of species and processes that is best adapted for existing conditions. The ecosystem then "designs a mix of man-made and ecological components in a pattern that maximizes performance, because it reinforces the strongest of alternative pathways that are provided by the variety of species and humans initiatives."[24]

A CONTINENTAL SCALE PROBLEM: WETLAND HABITAT LOSS AND WATER QUALITY DETERIORATION

The Mississippi Basin and Delta

The Mississippi basin has a 3.2-million km^2 watershed that includes about 40 percent of the lower 48 United States and delivers about 90 percent of the freshwater discharge to the Gulf of Mexico. The mean discharge is slightly larger than 18,000 m^3/second (Figure 1). The Mississippi delta is a large regional coastal ecosystem that encompasses about 25,000 km^2 of wetlands, shallow inshore water bodies and low elevation upland areas, mainly ridges associate with current and former channels of the river. About 25 percent of the coastal wetlands of the delta were lost during the 20th century.[25] There were also large losses of wetlands in the basin, as high as 90 percent in some States, mostly due to agricultural reclamation. A marked deterioration of water quality occurred at the same time as the wetland loss. One of the most well known water quality problems is the large zone of low oxygen in the nearshore Gulf of Mexico, adjacent to the Mississippi delta. But water quality has declined throughout the basin due mainly to agricultural runoff. The decline in water quality is due to a number of cumulative impacts including loss of wetlands, efficient drainage of the landscape, heavy fertilizer use, and a reduction of agricultural diversity to that dominated by corn and soybeans.[26] It is ironic that the wetlands which could have buffered agricultural runoff, and thus minimized water quality deterioration, are now largely replaced by agricultural fields. Seven States in the upper Mississippi River basin, namely Indiana, Illinois, Iowa, Minnesota, Missouri, Ohio, and Wisconsin, have collectively had about 18.6 million ha (46 million acres) of land drained,[27] much of which was wetland. The landscape has lost much its

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[24] Odum, n. 21 above.

[25] Day et al., 2007, n. 31 below.

[26] Mitsch et al., n. 1 above.

[27] Day et al., n. 11 above; Mitsch et al., n. 1 above.

ability to maintain a biogeochemical balance, and the streams are no longer buffered from agricultural areas. The environmental services associated with these wetlands have also been lost.

In the Mississippi delta, 25 percent of wetlands present at the beginning of the 20th century are gone with rates of loss as high as 100 km^2/year,[28] and a total loss of about 3,900 km^2 of coastal wetlands has been lost.[29] An understanding of the causes of this land loss is important, not only for a scientific understanding of the mechanisms involved, but also so that effective management plans can be developed to recover these losses.

Coastal wetland loss is the result of several interacting impacts, including: a) elimination of riverine input to most of the coastal zone due to construction of flood control levees along the Mississippi River, b) reduction of the suspended sediment in the Mississippi River, c) alteration of the internal hydrology of the delta, mostly due to canal construction, d) saltwater intrusion resulting from lower freshwater input and canals, e) wave erosion of marsh shorelines, and f) high relative sea-level rise (RSLR) resulting from geologic subsidence.[30] Thus, wetland loss is a complex interaction of different factors acting at different spatial and temporal scales, but the loss of riverine input to most of the delta is probably the most important factor.[31]

Water quality deterioration in the delta is a result of point (e.g., inadequately treated sewage) and non-point (e.g., agricultural and urban runoff) pollutants. High nutrient input and altered hydrology both contribute to poor water quality. Most upland runoff used to flow through wetlands before reaching water bodies, leading to a reduction of nutrients. Now, runoff more often flows directly to water bodies. The use of wetlands to improve water quality is an economical and environmental friendly

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28. J.W. Day, W.G. Shaffer, L. Britsch, D. Reed, S. Hawes, D. Cahoon, ''Pattern and Process of Land Loss in the Mississippi Delta: A Spatial and Temporal Analysis of Wetland Habitat Change,'' *Estuaries* 23 (2000): 425–438.

29. Boesch, n. 17 above; J.A. Barras, P.E. Burgeois and L.R. Handley, *Land Loss in Coastal Louisiana, 1956–1990* (National Biological Survey, National Wetlands Research Center Open File Report 94-01, 1994): 104, 10 color prints.

30. R. Costanza, W.J. Mitsch and J.W. Day, ''Creating a Sustainable and Desirable New Orleans,'' *Ecological Engineering* 26 (2006): 317–320; R. Costanza, W.J. Mitsch and J.W. Day, ''A New Vision for New Orleans and the Mississippi Delta: Applying Ecological Economics and Ecological Engineering,'' *Frontiers in Ecology* 4, no. 9 (2006): 465–472.

31. J.W. Day, D.F. Boesch, E.J. Clairain, G.P. Kemp, S.B. Laska, W.J. Mitsch, K. Orth, H. Mashriqui, D.J. Reed, L. Shabman, C.A. Simenstad, B.J. Streever, R.R. Twilley, C.C. Watson, J.T. Wells and D.F. Whigham, ''Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita,'' *Science* 315 (23 March 2007): 1679–1684.

approach to improving water quality.[32] Hypoxia conditions (low dissolved oxygen conditions in bottom waters, generally <2 mg/l) on the continental shelf of the northern Gulf of Mexico[33] is related to land use changes and high fertilizer use in the Mississippi basin.[34] A reduction of nutrients in the Mississippi River can help reduce the problem of hypoxia.

Perspectives for Some Latin American River Deltaic Systems

We believe that the problems and potential solutions of water quality deterioration and habitat loss in the Mississippi basin serve as a model for drainage basins in Latin American. The kinds of problems identified for the Mississippi basin are common throughout Central and South America, and the application of ecotechnology offers an ecologically sound and cost-effective method to their solution. Two major environmental problems currently affecting the coastal zone of Latin America are loss of lowland and coastal wetlands, and surface water pollution by agriculture, land-use change, urban discharge, and industrial activities. There are important lessons from the Gulf of Mexico that can be applied to large altered watersheds in Latin America such as Grijalva-Usumacinta, Mexico, 4,700 m^3/second; Rio Dulce, Guatemala, 1,200 m^3/second; Magdalena, Colombia, 7,800 m^3/second; San Fernando, Brazil, 2,850 m^3/second; Bio-Bio, Chile, 1,100 m^3/second, and Guayas, Ecuador, 1,860m^3/second;, as well as to relatively natural ones such as Orinoco, Venezuela, 35,000 m^3/second; Amazon, Brazil, 200,000 m^3/second, and La Plata, Argentina-Uruguay, 25,000 m^3/second).

The benefits of restoring wetland habitat include improved water quality, increased accretion rates to balance sea-level rise in coastal wetlands affected by sea-level rise, improved plant production and habitat quality, and decreased cost compared to conventional approaches. Wetland assimilation can be designed and operated to restore deteriorating wetlands and maintain existing wetlands. Wetlands are appropriate for receiving munici-

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[32] Mitsch et al., n. 1 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. Feagley, E. Hyfield, R. Lane, J. Lindsey, J. Mistich, E. Reyes and R.R. Twilley, "The Use of Wetlands in the Mississippi Delta for Wastewater Assimilation: A Review," *Ocean and Coastal Management* 47, no. 11-12 (2004): 671–691.

[33] N.N. Rabalais and R.E. Turner, eds. *Coastal Hypoxia: Consequences for Living Resources and Ecosystems,* Coastal and Estuarine Studies 58 (Washington, D.C.: American Geophysical Union, 2001); N.N. Rabalais, R.E. Turner and D. Scavia, "Beyond Science into Policy: Gulf of Mexico Hypoxia and the Mississippi River," *BioScience* 52 (2002): 129–142.

[34] E.R. Turner and N.N. Rabalais, "Linking Landscape and Water Quality in the Mississippi River Basin for 200 Years," *BioScience* 53, no. 6 (2003): 563–572.

pal and some types of industrial (e.g., non-toxic effluent such as for fish processing plants) effluents. Both constructed and natural wetlands have been used for assimilation. Sea-level rise is projected to increase from 1 and 2 mm/year of the 20th century to perhaps more than a meter.[35] In many coastal deltaic wetlands, geologic subsidence results in a rate of relative sea-level rise that is more than eustatic sea-level rise.[36] It is also likely that tropical storms will significantly increase in intensity in the coming decades.[37] Fresh water in effluent can help offset salinity intrusion due to storms. The use of wetlands to assimilate nutrients should be incorporated into comprehensive management plans designed to increase sediment and nutrient input into coastal wetlands. This general approach could be very well applied to a number of deltaic systems in Latin America.

THE USE OF WETLANDS FOR WATER QUALITY IMPROVEMENT

Numerous studies have shown that both natural and constructed wetlands can be effective tertiary processors of wastewater effluent and agricultural runoff.[38] Wetlands are efficient at removing excess nutrients and pollutants by physical settling and filtration, chemical precipitation and adsorption, and biological metabolic process that result in burial, storage in vegetation, and denitrification. These wetland functions can be especially critical for coastal regions affected by degraded water quality. It is important that the size of the wetland be matched with the amount of effluent or agricultural runoff entering the wetland so that significant nutrient reduction can take place (Figure 2). It is also important to note that wetlands should not be used to treat raw sewage. Sewage should be treated to a certain extent before discharge to wetlands.[39] Wastewater effluent may also serve as a restoration tool in flood plain systems and in coastal wetlands impacted by high rates of relative sea-level rise (RSLR). Coastal wetlands have been shown to persist in the face of RSLR when vertical accretion and elevationfl

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[35] S. Rahmstorf, "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," *Science* 315 (19 January 2007): 368–370.

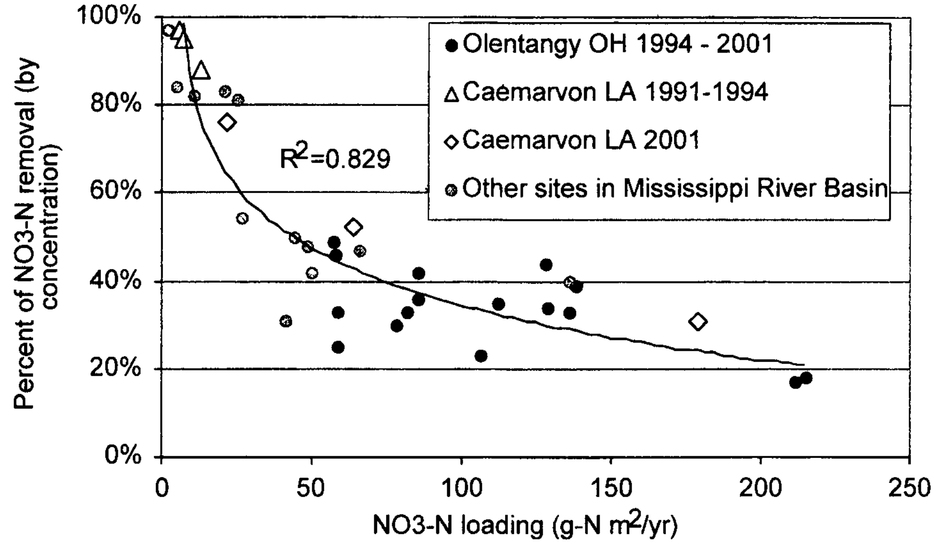
[36] J.W. Day and L. Giosan, "Geomorphology: Survive or Subside?," *Nature Geoscience* 1 (March 2008): 1–2.

[37] C.D. Hoyos, P.A. Agudelo and J.A. Curry, "Deconvolution of the Factors Contributing to the Increase in Global Hurricane Intensity," *Science* 313 (7 April 2007): 94–97.

[38] Day et al., n. 32 above; R.H. Kadlec and R.L. Knight, *Treatment Wetlands* (New York: Lewis Publishers Inc., 1996); C.J. Richardson and D.S. Davis, "Natural and Artificial Wetland Ecosystems: Ecological Opportunities and Limitations," in *Aquatic Plants for Water Treatment and Resource Recovery*, eds. K.R. Reddy and W.H. Smith (Orlando: Magnolia Publishing Inc., 1987): 819–854.

[39] Day et al., n. 32 above.

FIG. 2.—Decrease in nitrate-nitrogen versus nitrate loading rate for created and managed wetlands in Mississippi River Basin. Nitrate reduction is shown as percent removal by mass and by concentration. Each data point represents data for a complete year for a wetland. After Mitsch et al. 2005. Used by permission.



gain equals or exceed the rate of water level rise.[40] Historically, seasonal over bank flooding from rivers such as the Mississippi River deposited sediments and nutrients into wetlands of delta plains.[41] Not only did floods provide an allocthonous source of material or mineral sediments, which contributed directly to vertical accretion, but the nutrients associated with these sediments promoted vertical accretion through organic matter production as well as deposition. This sediment and nutrient source to coastal wetlands has been largely lost in the Mississippi delta and many other

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[40] R.D. Delaune, R.H. Baumann and J.G. Gosselink, "Relationship Among Vertical Accretion Coastal Submergence, and Erosion in a Louisiana Gulf Coastal Marsh," *Journal of Sedimentary Petrology* 53 (1983): 147–157; D. Cahoon, D. Reed and J.W. Day, "Estimating Shallow Subsidence in Micro Tidal Salt Marshes of the Southeastern United States," *Marine Geology* 130 (1995): 1–9.

[41] H.H. Roberts, "Dynamics changes of the Holocene Mississippi River Delta Plain: The Delta Cycle," *Journal of Coastal Research* 13 (1997): 605–627; J.W. Day, L. Cardoch and P.H. Templet, "System Functioning as a Basis for Sustainable Management of Deltaic Ecosystems," *Coastal Management* 25, no. 2 (1997): 115–154; J.W. Day, N.P. Psuty and B.C. Perez, "The Role of Pulsing Events in the Functioning of Coastal Barriers and Wetlands: Implications for Human Impact, Management and the Response to Sea-Level Rise," in *Concepts and Controversies in Tidal Marsh Ecology*, eds. M.P. Weinstein and D.A. Kreeger (Dordrecht, The Netherlands: Kluwer Academic Publishers, 2000): 633–650.

coastal systems[42] resulting in wetland loss.[43] In such stressed wetland systems, there are several benefits derived from the discharge of treated effluent: 1) improved water quality, 2) increased accretion rates, 3) increased productivity of vegetation, and 4) financial and energy savings.[44] Figure 3 shows how increased vegetation productivity results in greater root production leading to organic soil formation that can enhance accretion necessary to offset the subsidence that is contributing to wetland loss.

CONCLUSION

Results from numerous studies of wetland assimilation systems indicate that they are achieving the ecological goals of enhancing water quality, stimulating accretion, and increasing productivity. At low loading rates, nutrient reductions are high, often greater than 80 percent, due to plant uptake, denitrification, and burial. There are substantial economic and energy saving for communities and non-toxic industrial processors, and wetland assimilation offers an ecologically sensitive way to deal with agricultural runoff. Properly designed regulatory review and permit processes ensure that projects comply with State and Federal clean water laws. As water quality regulations become more stringent, it will be increasingly difficult for small communities to meet water quality standards using conventional treatment methods. Wetland wastewater treatment can provide an economically viable, effective, and sustainable alternative to expensive conventional tertiary treatment. In combination with improved agronomic practices, wetland assimilation also offers a practicable way of dealing with agricultural runoff. Finally, we believe that the management approach using ecotechnology and ecological engineering in watershed and coastal regions represents a clear "green window" for solving ecosystem problems in a sustainable way for many areas of North, Central, and South America.

[42] Day et al., 1997, n. 41 above.

[43] W.H. Conner and J.W. Day, "Rising Water Levels in Coastal Louisiana: Implications for two Coastal Forested Wetland Areas in Louisiana," *Journal of Coastal Research* 4, no. 4 (1988): 589–596; J.W. Day, G. Shaffer, L. Britsch, D. Reed, S. Hawes and D. Cahoon, "Patterns and Process of Land Loss in the Mississippi Delta: A Spatial and Temporal Analysis of Wetland Habitat Change," *Estuaries* 23 (2000): 425–438.

[44] A.M. Breaux and J.W. Day, "Policy Considerations for Wetland Wastewater Treatment in the Coastal Zone: A Case Study for Louisiana," *Coastal Management* 22 (1994): 285–307; J.Y. Ko, J.W. Day, R. Lane and J.N. Day, "A Comparative Evaluation of Cost-Benefit Analysis and Embodies Energy Analysis of Terrestrial Municipal Wastewater Treatment Using Forested Wetlands in Louisiana," *Ecological Engineering* 49 (2004): 331–347.

FIG. 3.—A conceptual model of wastewater assimilation by wetlands showing the three main pathways of permanent nutrient uptake (e.g., vegetative uptake, denitrification, and burial). The global positive "feedback" on the effects of effluent application to wetland is shown in a flow from effluent, to primary producers, to accretion (elevation). N = Nitrogen, P = Phosphorous, TSS = Total Suspended Sediments. Modified from Day et al. 2004.