CHAPTER C.5
HYDRODYNAMIC MODELS OF SUBPROVINCE 3

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5.1 Introduction

Restoration targets for changing the historic rate of land change to open water in each subprovince were developed as part of the activities of LCA project delivery team. Three progressively more ambitious targets were identified: (1) *Reduce*; (2) *Maintain*; and (3) *Enhance* (Twilley 2003). A menu of specific restoration targets (in km^2 yr^{-1}) for subprovince 3 included the following scenarios: (1) *Future Without* with a loss of 11.50; (2) *Reduce* with a net loss of 5.75; (3) *Maintain* with net 0 losses or a gain of 11.50; and (4) *Enhance* with a gain of 17.25. Examples of the activities needed to achieve these targets might be a river diversion of a given size at a particular location to be operated on a specific discharge schedule. The LCA team combined measures into draft "alternatives" that were qualitatively matched to one of the *Reduce*, *Maintain* or *Enhance* targets. The evaluation of these measures, alternatives and targets required the use of hydrodynamic and ecological models.

Deterministic numerical landscape models have been introduced and improved for various basins of coastal Louisiana over the past two decades (Sklar *et al.* 1985; Costanza *et al.* 1987; Costanza *et al.* 1989; Costanza *et al* 1990; Reyes *et al.* 1998; Martin *et al.* 2002; Reyes *et al.* 2003). The Coastal Ecological Landscape Spatial Simulation (CELSS) model (Sklar *et al.* 1985; Costanza *et al.* 1987; Costanza *et al.* 1989) was the initial model to be applied to a portion of the Terrebonne watershed. The latest versions of this type of approach are capable of simulating decades of change, while still resolving tidal and wind forcing of hydrodynamics (Martin *et al.* 2002; Reyes *et al.* 2003).

The CELSS-type models evolve the landscape composition according to explicit rules and formulae similar to those applied by the desktop models, but are calibrated against the record of past landscape change and forced by a continuous hydrodynamic simulation (Martin *et al.* 2000; Reyes *et al.* 2003). They incorporate a range of observed environmental conditions, such as river flow, climate, and relative sea level rise. CELSS-type models couple the hydrology and the three-dimensional geometry of the system as it changes over time.

The Acadiana Basin Model (ABM) version of CELSS was calibrated and historical validations have been run for a portion of subprovince 3 (Figure C.5-1). It has been used by the USACE to run 70-year simulations for the Lower Atchafalaya Basin Reevaluation Study (Martin

et al. 2002). ABM includes routines for subaqueous deposition, resuspension and consolidation of sediments, as well as for colonization of emergent land by plants. ABM incorporates a soil-building module similar to that of Callaway *et al.* (1996) that simulates marsh adaptation to relative sea level rise.

Figure C.5-1 Location of Subprovince 3 with Superimposed Acadiana Basin Model Domain

The central part of the Louisiana coast known as the Acadiana Bays has experienced active deltaic growth associated with maturation of the Atchafalaya River as a Mississippi River distributary. Detailed surveys have been conducted repeatedly by the USACE to document the near-field pace of delta development resulting from Atchafalaya River discharge and sedimentation. This information has been summarized by Mashriqui *et al.* (1997), and by Fitzgerald (1998).

The following sections provide a summary of the modeling work performed for the evaluation of subprovince 3. A description of the mechanics of the hydrodynamic module part of the ABM code (Martin *et al.* 2000) used in the Acadiana Bays is presented, as well as a comprehensive review of the sediment deposited by the different alternatives. A brief discussion of the ecological module of the same ABM code (Martin *et al.* 2002; Reyes *et al.* 2003) and the overall assumptions and limitations of using this simulation to examine the LCA alternatives of reduce, maintain and enhance land coverage in the Acadiana watershed. In addition, a

discussion of how the Acadiana Bays portion of subprovince 3 was used to cross-calibrate desktop and numerical methods to predict the 50-year effects of proposed restoration measures is discussed, as is the assessment of the preliminary match between targets and the alternatives recommended to achieve them.

5.2 Methods

5.2.1 Hydrodynamic Module

The hydrodynamic model used by the ABM (Acadiana Basin Model) is a two-dimensional, depth-integrated model that uses a finite difference solution for water and constituent transport. The model can be further classified based on its numerical computational scheme as an implicit direct method that allows for greater time steps, as the calculations are not limited by a restricted Courant stability criterion, only by accuracy considerations. The advantage of using greater time steps is that it translated into reduced total computation time and long-term simulations.

Finite difference numerical models can calculate moving boundaries (or wet and dry conditions, which was the case for this analysis) by using fractional steps. The vertically integrated shallow water equations are split into three steps, which are advection, diffusion and propagation. A different numerical scheme is used for each step. The dry land was assumed to remain covered with a thin layer of water, and the flow was assumed to be governed by bottom friction. The actual movement of the boundary was also assumed to take place during the propagation step, which is represented by a resistance equation. The ABM hydrodynamic model accounts for wet and dry conditions using a semi-implicit finite difference algorithm to discretize the governing equations.

The ABM was calibrated using this information, as well as habitat classifications developed by the U.S. Geological Survey (USGS) for two intervals between 1956 and 1988 and aggregated to the 1 km^2 cell size (Martin 2000). This landscape model was then run for the 70-year interval between 1988 and 2058 to predict land building and loss within the Acadiana Bays model domain. That domain included 833 $mile^2$ (2,157 km^2) of wetlands in 1988, extending from western Terrebonne on the east to Freshwater Bayou on the west (Outlined in Figure C.5-1).

Suspended sediment inputs used in the ABM are derived from measurements made at Simmesport, at the northern end of the Atchafalaya Basin. Subsidence for the 70-year period was held constant in these runs at 0.5 cm y^{--1} for the entire model domain. Martin (2000) simulated river discharge scenarios set at 50, 100 and 200 percent of those observed between 1956 and 1995. Results were then used to estimate the influence of different sediment and water input rates on landscape evolution and provide three points from which intermediate effects can be interpolated.

The deltaic area included the emerging Wax Lake Outlet (WLO) and Lower Atchafalaya River (LAR) deltas, as well as upstream wetlands adjacent to the main channels (Figure C.5-2). Any changes predicted in this area can be considered near-field effects. “Point au Fer Island” and “Marsh Island” are located approximately 19 and 31 miles (30 and 50 km), respectively from the centroid of this area, midway between the mouths of the LAR and the WLO. Changes in these areas would be considered far-field effects, associated with nourishment of subsiding marshes.

The areas of "Vermillion Bay" and "Freshwater Bayou" have historically experienced far less land loss than marshes to the east, as they belong to the more stable Chenier plain.

Visser *et al.* (2003) developed a spatial hind-casting methodology to estimate river influence based on detailed analysis of land loss in areas somewhat distant from the locus of Atchafalaya River discharge. The area used for this analysis is located in the western Terrebonne basin, and is largely included within the domain of the ABM. To compare hind-cast observations of river influence on land loss with model predictions, it was necessary to shift this origin 6.2 miles (10 km) west to the delta zone (Martin 2000).

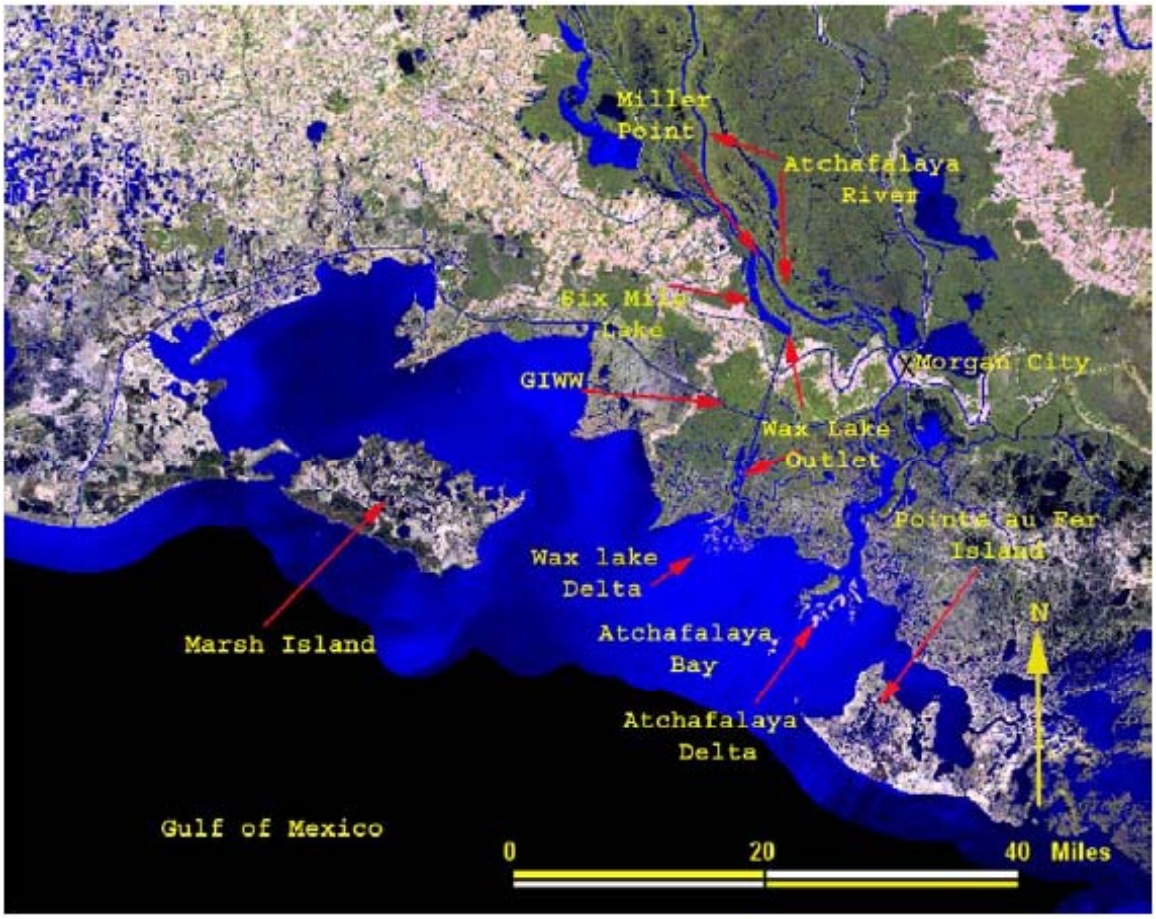

Figure C.5-2 Detailed View of the Acadiana Basin Locations and Other Geographical Features of Interest

5.3 Results

5.3.1 Hydrodynamic Module

The effect of the discharge from the two mouths of the Atchafalaya on observed delta building and landscape response was separated into near- and far-field components. Near-field effects are confined to deltaic processes involving primarily the coarser fraction of the sediment discharge. Far-field effects are a more complex result of the interplay between wetland soil

building and the nourishment associated with the availability of freshwater, sediments and nutrients. The sediments involved in this nourishment are almost exclusively the clay fraction.

5.3.2 Near-Field Deltaic Land Building

Most of the mass of the LAR and WLO deltas occurs below the bottom of the inter-tidal zone (–0.6 m NGVD). Fitzgerald (1998) classified deposition above this point as delta lobe or land, and the remainder as delta flank development. According to this data, the WLO delta grew 1.27 mi^2-y^{-1} (3.3 km^2-y^{-1}) between 1981 and 1994, reaching 24mi^2 (63 km^2) above -2 ft (–0.6 m) in 1994. The LAR delta grew at a rate of 1.04 mi^2-y^{-1} (2.7 km^2-y^{-1}) in the same period, reaching 40 mi^2 (102 km^2) in 1994. Suspended sediment retention within this footprint was estimated at 13 and 15 percent, respectively, for the LAR and WLO, showing an increase between the intervals for the LAR and a decrease for the WLO (Table C.5-1).

Table C.5-1 Annual Sediment Supply and Percent Retention in the WLO and LAR Deltas

	Sediment Flux	Volume Change >-0.6 m NGVD	Retention >-0.6 m NGVD	Land Gain >-0.6 m NGVD	Retention >0 m NGVD	Land Gain >0 m NGVD
	(m^3-y^{-1})	(10^6 m^3-y^{-1})	(%)	km^2-y^{-1}	(%)	km^2-y^{-1}
Wax Lake						
1981-89	24,276,142	4.5	19.0	3.5	10.0	2.8
1989-94	17,255,592	1.2	7.0	3.0	2.6	0.0
Mean	21,579,305	3.6	15.0	3.3	7.0	1.5
Lower Atchafalaya						
1981-89	36,493,429	4.0	11.0	2.2	6.1	1.3
1989-94	38,288,539	6.3	16.0	3.2	16.0	3.4
Mean	37,183,856	4.8	13.0	2.7	9.9	2.1

Land growth rate estimates are dependent on the time interval selected, and are not simply linked to sediment supply. Growth estimates are also unique to the elevation selected to separate land from water. Because of the low profile, the total area in the two deltas above 0.0 (NGVD) in 1994 was only 35.14mi^2 (91 km^2), 55 percent of the area above -2 ft (–0.6 m). The 0.0 m elevation was used in the ABM to initiate colonization of land, and was the lower bound for rooted vegetation. Using this definition, the area of the WLO delta in 1994 dropped from 24 to 9 mi^2 (63 to 23 km^2), which is somewhat lower than the 12 ft^2 (30 km^2) value used by Visser *et al.* (2003). WLO delta growth above 0 m NGVD is reduced to .6 ft^2-y^1 (1.5 km^2-y^{-1}). Estimated sediment retention rates for the WLO lobe defined in this way dropped to 7 percent.

The LAR delta growth, in contrast to that of the WLO, has been profoundly influenced by nearly annual dredging to maintain a large navigation channel that bisects the deltaic mass. Material mined from this channel has been placed following protocols that have changed over the years from minimizing to maximizing the resulting wetland footprint.

The LAR delta had an area above 0.0 m NGVD in 1994 of 26 mi^2 (68 km^2) and retained an estimated 10 percent of suspended sediment supplied between 1981 and 1994 (Table C.5-1). Sediment retention within the delta lobe increased substantially between 1981-89 and 1989-94 intervals. Sediment retention was the same, 16 percent, in the 1989-94 interval for both the

0 and -2ft (0 and – 0.6 m) lobe. This shows the effect of a new management protocol calling for placement of all sediment dredged from the navigation channel at an elevation above 0 m NGVD. In the more natural WLO, sediment retention actually decreased for this interval as deltaic channels became more efficient at transporting sediments to the delta flank (Fitzgerald 1998).

The ABM predicted 68 mi^2 (175 km^2) of deltaic land growth over the 70-year period from 1988 to 2058, at a rate of 0.9 mi^2-y^{-1} (2.5 km^2-y^{-1}) (Table C.5-2). This figure is 70% of the observed growth above 0.0 m NGVD of both deltas, over the 1981 to 1994 period (Table C.5-2). However, most land building actually took place in the model during the first 50 years. After model year 2038, the deltas lost land as quickly as they gained it, once an apparent equilibrium was established between discharge and subsidence (Martin 2000). Delta building for the first 50 years is consistent with the observed growth rate.

The effects of changing discharge were also informative. The ABM predicted that the relationship should be linear between land building and mean annual discharge for a river with the sediment transport characteristics of the Atchafalaya:

$$Y = X * 10^{-5} + 0.1865$$

where X is mean annual discharge in cubic feet per second (cfs) and Y is the land building rate in km^2-y^{-1}.

5.3.3 Far-field Effects on Marsh Nourishment

The ABM distributes river sediment to adjacent marshes if it passes through the deltas, does not settle permanently in the bay bottoms or escape to the Gulf. This mineral material stimulates plant soil development if elevation, salinity and flooding conditions are suitable. The distance of each sub-area of the ABM domain was measured from the deltas zone, a point between the mouths of the WLO and LAR Figure C.5-2. The deltas zone was assumed to be the 0 distance, though it actually included some areas near the LAR channel that Visser *et al.* (2003) discuss as being 3 to 6 miles (3.1 mi (5 km) to 6.2 mi (10 km)) from the river. When the hind cast (observed) and ABM predictions were brought together (Table C.5-3), two patterns were apparent. First, the model predicted lower deltaic land building in the future than has been observed in the past. Second, the model predicted that land loss rates in marshes at some distance from the river will not be as high as observed in the past, if the characteristics of Atchafalaya discharge and sediment flux do not change. In fact, the model predicted that past land loss rates within the model domain would recur only if Atchafalaya discharge were halved.

Table C.5-2 Land Change Results of 70-Year ABM Runs

Q	Q_{sed}	End Yr.	Zone	Distance	Open Water	All Land	Chg 1988	Diff No Act	Total area	% change	Annual %
1.0	1.0	1988	Deltas	0	415	242	0	-175	657	0.00	0.00
2.0	1.0	2058	Deltas	0	108	549	307	132	657	126.86	1.81
1.0	1.0	2058	Deltas	0	240	417	175	0	657	72.31	1.03
0.5	1.0	2058	Deltas	0	316	341	99	-76	657	40.91	0.58
1.0	1.0	1988	Pt. au Fer	30	469	246	0	29	715	0.00	0.00
2.0	1.0	2058	Pt. au Fer	30	436	279	33	62	715	13.41	0.19
1.0	1.0	2058	Pt. au Fer	30	498	217	-29	0	715	-11.79	-0.17
0.5	1.0	2058	Pt. au Fer	30	515	200	-46	-17	715	-18.70	-0.27
1.0	1.0	1988	Marsh Island	50	278	223	0	28	501	0.00	0.00
2.0	1.0	2058	Marsh Island	50	274	227	4	32	501	1.79	0.03
1.0	1.0	2058	Marsh Island	50	306	195	-28	0	501	-12.56	-0.18
0.5	1.0	2058	Marsh Island	50	359	142	-81	-53	501	-36.32	-0.52
1.0	1.0	1988	Vermilion Bay	65	287	445	0	-7	732	0.00	0.00
2.0	1.0	2058	Vermilion Bay	65	279	453	8	1	732	1.80	0.03
1.0	1.0	2058	Vermilion Bay	65	280	452	7	0	732	1.57	0.02
0.5	1.0	2058	Vermilion Bay	65	285	447	2	-5	732	0.45	0.01
1.0	1.0	1988	Freshwater Bayou	80	250	193	0	2	443	0.00	0.00
2.0	1.0	2058	Freshwater Bayou	80	250	193	0	2	443	0.00	0.00
1.0	1.0	2058	Freshwater Bayou	80	252	191	-2	0	443	-1.04	-0.01
0.5	1.0	2058	Freshwater Bayou	80	261	182	-11	-9	443	-5.70	-0.08
1.0	1.0	1988	Model Domain		6465	2157	0	-228	8622	0.00	0.00
2.0	1.0	2058	Model Domain		5942	2680	523	295	8622	24.25	0.35
1.0	1.0	2058	Model Domain		6237	2385	228	0	8622	10.57	0.15
0.5	1.0	2058	Model Domain		6454	2168	11	-217	8622	0.51	0.01

5.4 Assumptions and Limitations

5.4.1 Data Vigor

The accuracy of model functioning and predictions could be improved with better input and validation data. For example, elevation is one of the most sensitive parameters affecting marsh survival. However, accurate elevation data exists for only a few locations. Extensive monitoring of salinity and water level would also allow much better calibration and validation of the model.

The results suggested that the current Atchafalaya discharge affects marsh sustainability within a radius of 19 to 31 miles (30 to 50 km), depending on the intervening topography. The ABM predicted that Marsh Island, separated by 50 km of bay from the source, would lose land at a rate of - 0.5 percent per year if river discharge was halved (Table C.5-3). This is similar to the loss rate that prevailed for the 1956-90 hind cast period for western Terrebonne marshes more than 22 mi (35 km) from the deltas (-0.4 to -0.6% per year). These were presumed to lie outside the influence of the river. Marshes at greater distances to the west on the eastern margin of the chenier plain experience far lower historical loss rates, so the effect of the river is more difficult to detect.

Loss rate diminishes as river influence grows, whether this is due to an increase in discharge or a decrease in distance from the source, but not all areas within the ABM domain were equally susceptible to loss. Averaging predicted loss rates from all sub-areas outside of the deltas permitted extrapolation to a base rate, without the river, of - 0.285 percent per year 2.36 ft^2 $-y^{-1}$ (6.11 km^2 y^{-1}). Deviation from this base, then, was used to scale the effects of the river over the ABM domain (Table C.5-4).

Table C.5-3 Observed and Predicted Effects of Discharge on Annualized Land Change Rates (%-y^{-1})

Distance from deltas	Deltaic Development 1981-94	Atchafalaya Discharge Martin (2000) (mean cfs-y^{-1})			Hind Cast Marsh Loss 1956-90
(km)	Fitzgerald (1998)	438,000	219,000	110,000	Visser *et al.* (2003)
0	2.560	*1.812*	*1.033*	*0.584*	
25		*0.137*	*0.073*	*-0.240*	-0.200
30		*0.192*	*-0.168*	*-0.267*	-0.320
35					-0.500
40					-0.600
45					-0.460
50		*0.026*	*-0.179*	*-0.519*	-0.420
65		*0.026*	*0.022*	*0.006*	
80		*0.000*	*-0.014*	*-0.081*	

ABM predictions in italics

The ecological module simulated plant growth conditions that were represented as a series of habitat maps for the ABM area. The 1978 habitat map from USFWS was used to initialize the ABM along with a data series from 1978 to 1988 to simulate 10 years of habitat change as part of the calibration exercise. The resulting 1988 habitat map was compared to the 1988 USFWS habitat map. The agreement between the two maps was assessed with a goodness-of-fit spatial statistics routine that compares the spatial pattern of habitat cells at multiple resolutions (Costanza 1989), which returned a value of 94.9 out of a possible 100 (Martin 2000). The multiple resolution approach allowed a more complete analysis of the way in which the spatial patterns matched (Turner 1997; Day *et al.* 2000; Turner 2001). All six habitat types of the ABM were accounted for in the calibration and validation procedures. The BTELSS returned values of 89.3 and 74.4 for calibration and validation simulations, respectively (Reyes *et al.* 1998, Reyes *et al.* 2000). Further calibration and validation of the models included comparing predicted habitat trends with historic rates of change and comparing recorded and predicted salinity and suspended sediment concentrations at specific locations (Martin *et al.* 2002; Reyes *et al.* 2003).

5.4.2 Scientific Uncertainty

The ecological and habitat switching modules of the ABM focused on those factors that directly and predictably influence land elevation and habitat type. Among the most important factors for vegetation production is nutrient availability. The influence of river-borne nutrients can not be distinguished from the effects of freshwater and sediment when examined in a landscape context. This lack of watershed nutrient information made it difficult to predict availability, rates of transformations within the estuary, or exchange with the atmosphere, much less the response of plant communities to all of these factors. While nutrient influences affect land elevation, inclusion of nutrients would have required an extensive and comprehensive field monitoring effort perhaps at a prohibitively cost. The productivity module of the ABM should include nutrient influences to make the model a more realistic tool in predicting eutrophication and wetland nutrient cycling.

5.5 Discussion

The domain of the ABM falls into subprovince 3, although that planning area extends east far beyond the model boundary to include the entire Terrebonne basin Figure C.5-2). Other portions of subprovince 3 were modeled using desktop techniques. The *Reduce* target for subprovince 3 was to decrease land-loss by 2.22 mi^2-y^{-1} (5.75 km^2 yr^{-1}). The *Maintain* target was to offset the 4.44 mi^2-y^{-1} (11.5 km^2 yr^{-1}) expected to be lost under no action. The *Enhance* target sought to offset loss entirely and increase land area by 2.22 mi^2-y^{-1} (5.75 km^2 yr^{-1}).

Table C.5-4 ABM Prediction of the Influence of River Discharge on Land Gain and Loss Within the Model Domain (km^2 yr^{-1})

		Atchafalaya Discharge	
	Half	Current	Twice
Land Gain Caused by River	0.16	3.26	7.47
Land Loss Prevented by River	6.11	6.11	6.11
Total River Effect	6.31	9.40	13.62

If Atchafalaya River influence on land loss diminishes with distance as indicated by Visser *et al.* (2003), then most of the ameliorative effects should be confined to the ABM domain, rather than extending farther to the east into the remainder of Subprovince 3. If the ABM is assumed to completely capture the influence, then the 6.3 mi^2-y^{-1} (9.4 km^2 yr^{-1}) of land retained or added as a result of the current discharge provides a scale for assessing what additional discharges will be required to reach targets for the whole of Subprovince 3.

The ABM predicted that just under half the current discharge of the Atchafalaya is required to maintain the simulated wetlands coverage at 1988 levels. The 1.25 mi^2-y^{-1} (3.25 km^2 yr^{-1}) of land gain predicted within the ABM domain if current discharge continues must be factored into meeting the Subprovince 3 targets, where it would have to offset the very rapid land loss occurring to the east (Table C.5-2).

To decrease land loss in subprovince 3 by the *Reduce* target of 2.22 mi^2-y^{-1} (5.75 km^2 yr^{-1}), additional diversions must be constructed with the combined land building and nourishment capacity of just over half the current average discharge of the Atchafalaya River. This magnitude can be described as a 0.6 Atchafalaya Equivalent (*0.6AE*). Such a diversion would produce an average annual flow of 130,000 cfs from the lower Mississippi River into Terrebonne Parish. This is comparable to the "Third Delta," with an average discharge of 120,000 cfs, which was a measure included in some alternatives to reach the *Enhanced* target in subprovince 3.

To stop land loss entirely by 2050 would necessitate adding *1.2AE* (260,000 cfs), or other measures that would double the effect of the proposed "Third Delta" discharge. Increasing the land area of subprovince 3 by 1,421 acres per year could require adding more than *2.5AE*, or an average of 548,000 cfs. This is slightly greater than the mean flow of the Mississippi River (534,000 cfs). The LCA team mentions the possibility of modifying the division of flow between the Mississippi and Atchafalaya Rivers, now nominally set at 70:30 on a percentage basis, but does not propose new discharges into Terrebonne greater than *0.5AE* for any alternative.

With respect to near-field land building in a deltaic setting, the Atchafalaya prototype suggested that natural sediment retention may be somewhat less than assumed in Visser *et al.* (2003), but this depends on what elevation is selected to define land. Both the ABM and Fitzgerald (1999) produced similar rates of deltaic land building, comparable to Wells *et al.* (1982) if land is assumed higher than 0.0 m NGVD.

The ABM prediction of far-field nourishment of more distant marshes appeared to agree reasonably well with the hind casts developed by Visser *et al.* (2003), though it projected lower base land loss rates in areas on the margins of river influence. The ABM provided a calibrated projection of landscape evolution that can be used to assess the land change potential of diversions proposed in other deltaic basins