

# **Response of Salinity in Barataria Basin to Alternative 3 Freshwater Diversions**

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# CONTENTS

- 1 INTRODUCTION ..... 3
- 2 METHODS ..... 3
- 3 RESULTS ..... 12
  - 3.1 Base Case ..... 14
  - 3.2 Alt 3 ..... 16
  - 3.3 Alt 3A..... 18
  - 3.4 Alt 3B..... 20
  - 3.5 Alt 3C..... 22
  - 3.6 Alt 3D..... 24
- 4 DISCUSSION ..... 26
- 5 REFERENCES ..... 27
- APPENDIX – BARATARIA BOX MODEL CALCULATIONS ..... 28

# 1 INTRODUCTION

Louisiana's Comprehensive Master Plan for a Sustainable Coast calls for diverting a large portion of the water and sediment carried by the Mississippi and Atchafalaya Rivers to rebuild and sustain the wetlands along the Louisiana coast (CPRA 2007). Large-scale diversions are one element in an integrated plan that addresses the need to restore coastal ecosystems while also protecting coastal communities from hurricanes. Controlled diversions will deliver the sediment needed to reverse land loss and the nutrients needed to sustain rebuilt wetlands. The overall goal for coastal restoration in the master plan is to restore sustainability to the ecosystems that support the valuable natural resources of the Louisiana coast.

The successful application of controlled diversions for coastal restoration depends on managers striking a balance between providing the river sediment needed to build and sustain wetlands and the competing objective to maximize the diversity of habitats within a basin. Land building by deposition of river-born sediment is a freshwater process. Diversions on the scale envisioned in the Master Plan will alter radically the freshwater budgets in coastal wetland basins, replacing mesohaline habitat with euhaline conditions typical of a prograding delta mouth. Such a drastic change will undoubtedly affect the commercial and sport fisheries that depend on the diverse estuarine habitats that are currently found along the Louisiana coast.

Pulsed operation of controlled diversions offer a possible strategy for maintaining a wide range of salinity conditions while at the same time delivering river sediments into a wetland basin. For example, if diversions are operated alternating between periods of full discharge and zero discharge, then one might expect surface water salinity in the basin to fluctuate between less saline and more saline conditions, depending on the residence time of water in the basin and the frequency with which the diversion discharge is pulsed. Day et al. (2003) document the ecological response to pulsed operation in the wetlands downstream of the Caernarvon diversion. The results from Caernarvon are promising, but it is open to question whether similar ecological benefits can be achieved from pulsed operations of the much larger river diversions proposed in the Master Plan.

This study investigates factors to be considered in developing a pulsing regime that maintains estuarine conditions while delivering river sediments into a wetland basin. In particular, we examine the effect of different pulsing regimes on surface water salinity in the Barataria Basin. The results suggest that pulsed operation of large-scale diversions is a viable strategy for maximizing habitat diversity. However, the frequency of pulsing must be chosen carefully to achieve the desired results.

# 2 METHODS

We simulate salinity conditions in the Barataria basin (Louisiana) under different strategies for managing controlled diversions of water and sediment into the basin from the Mississippi River. Simulated salinity values are calculated with the salinity desktop model, i.e. box model, developed for Barataria basin by the CLEAR program (Justic et al. 2006). The location and rates of discharge for the river diversions are those described for Alternative 3 in a preliminary draft (December 2006) of the Master Plan. Alternative 3 (Alt3 in Table 1) prescribes a hydrograph of monthly average flow rates that vary seasonally and from year-to-year based on fluctuations in

Mississippi River discharge. Using Alt3 as the base, we prescribe three pulsed discharge strategies and one phased discharge strategy for investigation, Table 1; discharge rates are adjusted so that all scenarios deliver the same discharge into the basin over the long term. The simulated salinity values obtained for these diversion scenarios are compared with each other and with a Base Case that represents present hydrologic and salinity conditions in the Barataria basin.

**Table 1: Scenarios used to investigate the effects of pulsing and phasing river discharge into Barataria basin**

	<b>Management Regime</b>
Alt 3	Seasonal variation only, no pulsing or phasing of inflow
Alt 3A	Pulsed two months on, two months off
Alt 3B	Pulsed one year on, one year off
Alt 3C	Pulsed three years on, three years off
Alt 3D	Phased alternating years upper and lower basin diversions

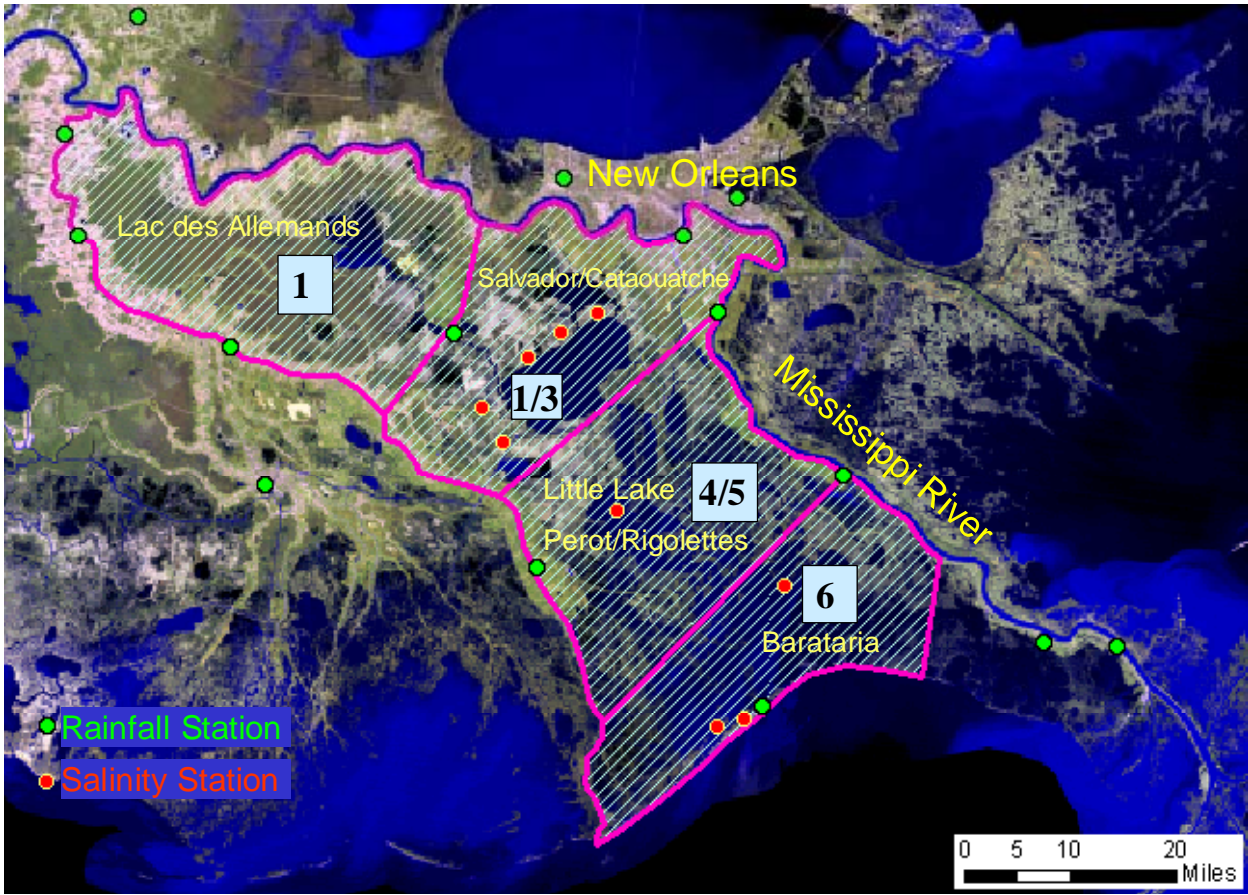
The salinity desktop model calculates changes in salinity by keeping track of the amounts of salt and water in each of four sub-basins in the Barataria basin, Figure 1. The current model formulation includes a total of six parameters that can be determined through calibration against reference sub-basin salinities. These parameters include five flux exchange parameters, which control the fluxes of salt carried by exchange flows between any two connected sub-basins. In addition, an evaporation coefficient parameter is used to estimate actual evapotranspiration rates over wetland and land areas from specified potential evaporation rates. A detailed description of the model, its formulation and the calibration to estimate values for the six model parameters is given by Justic et al. (2006) and summarized in the Appendix.

Processes driving changes in salinity include the variations in the net supply of fresh water and advection and exchange among the sub-basins and between the entire estuarine basin and the coastal gulf. The balance between rainfall, evaporation and surface water inflows determines the net supply of fresh water to each sub-basin. The fresh water balance and changes in mean sea level determine the net discharge (or inflow) from each sub-basin, and this advects salt out of (or into) the sub-basin. Exchange fluxes are the result of dispersion and mixing by sub-monthly high frequency water movements driven by wind and tides.

Salinity model calculations make use of monthly time series of sub-basin average rainfall, evapotranspiration rates, boundary salinity at the mouth of Barataria Bay, and monthly volumes of freshwater diversions into each sub-basin. Simulations cover a period of 11 years (1994-2005) for all the scenarios.

**Rainfall** - The monthly time-step model applies the monthly depth of rainfall measured at New Orleans airport, Figure 2.2, uniformly across the entire Barataria basin. Average annual rainfall for the period 1994 through 2004 is 154 cm.

**Figure 1: Sub-basin areas and sources of calibration data used in the desktop salinity model for Barataria basin**



**Evapotranspiration** - The monthly time-step model calculates monthly evaporation and evapotranspiration based on a basin-wide potential evaporation rate. The basin-wide potential evaporation rate varies from month to month following a sinusoidal curve fitted to evaporation estimated by Baumann et al. (1984), Figure 2. Average annual potential evaporation is 113 cm.

**Boundary Salinity** - Changes in the flow of the Mississippi River exert a large influence on salinity values in the near shore region along the entire Louisiana coast, including at the mouth of Barataria Bay. In order to be able to represent this influence in the calculations with the monthly time-step model, we used the sampled salinity data for the mouth of Barataria Bay to derive an empirical relationship for salinity at the mouth in terms of monthly discharge estimated at the Tarbert Landing river gauge (Justic 2006).

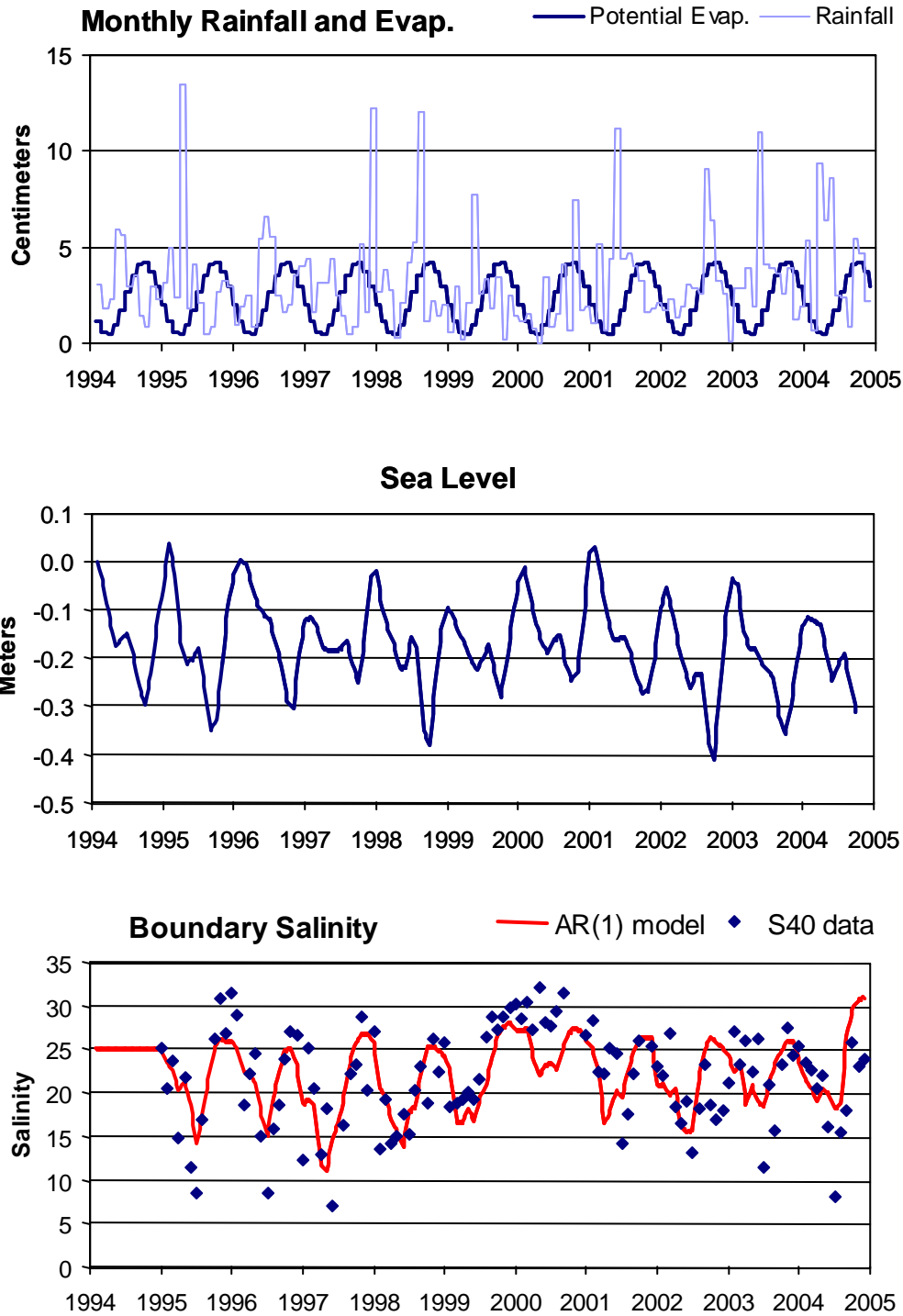
Salinity calculations for the Base Case represent current characteristics of the distribution and variation of salinity in the Barataria basin. The Base Case simulations use the rainfall, evapotranspiration and boundary salinity data just described, Figure 2, and hydrographs of monthly average discharge for the existing diversions at Davis Pond, Naomi, and La Hache, Figure 3.

Salinity calculations for the Alternative 3 scenarios represent characteristics of salinity in the Barataria basin anticipated with implementation of the projects described in the Master Plan (CPRA 2007). The Alternative 3 scenarios explore the effect of different operating strategies for the diversions; all use the rainfall, evapotranspiration and boundary salinity data just described, Figure 2, and average discharge for new diversions planned for the Barataria basin, Figure 4. Boundary salinity values for are calculated based on discharge to the Birdfoot delta reduced by the total diversion withdrawals upstream of Empire, Figure 5; this results in a modest increase in salinity in the coastal waters at the mouth of Barataria Bay compared to the Base Case.

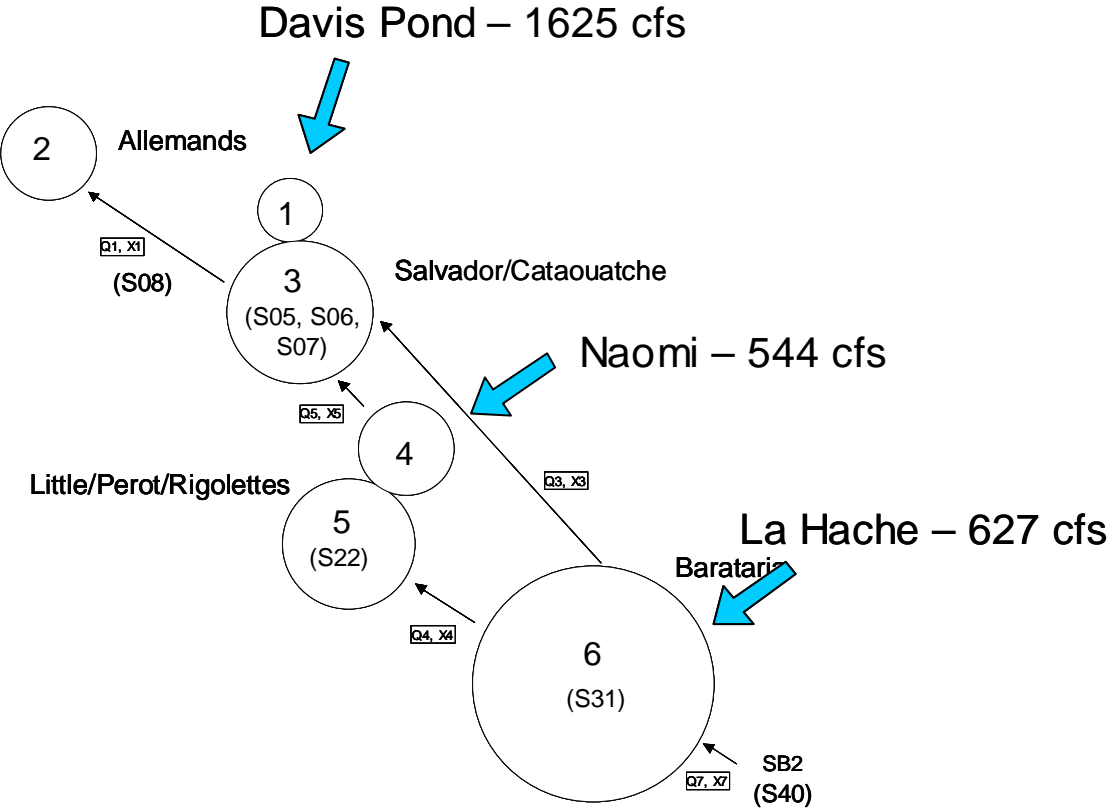
The diversion of Mississippi River water into the Barataria basin on the scale contemplated in the Master Plan alters the water budget for the basin. Conditions shift from the present, rainfall-driven conditions to conditions where the diversions drive fluctuations in the freshwater supply, Figure 6.

The pulsed scenarios (Alt 3A, Alt 3B, and Alt 3C) alternate between periods of flow at twice the long-term discharge and equal periods with zero discharge in the diversions, Table 1. The phased scenario (Alt 3D) alternates periods with the upstream diversions (sub-basins 2 and 1/3) discharging at twice the average rate and the downstream diversions (sub-basins 4/5 and 6) off with periods with upstream diversions off and downstream diversions discharging.

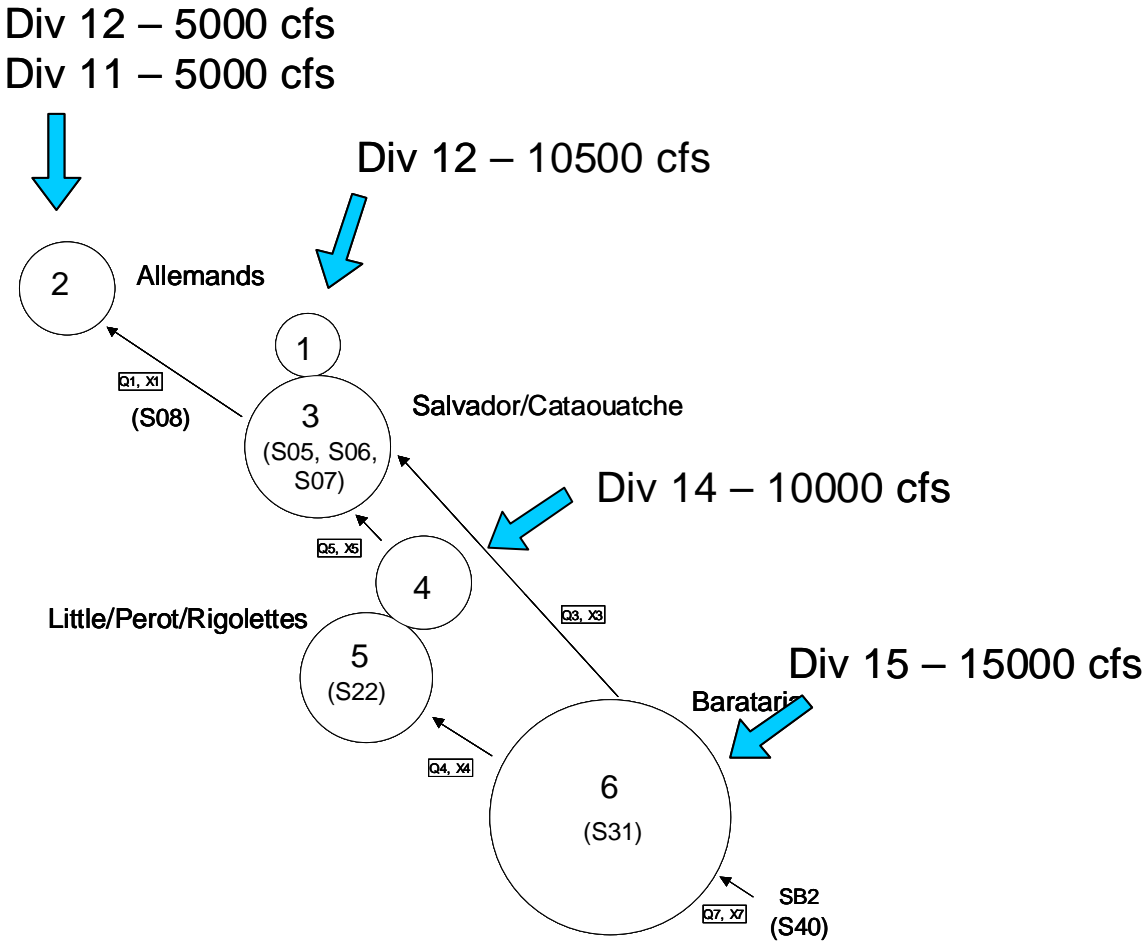
**Figure 2: Historical data for period 1994 through 2004 used as input for all scenarios. Boundary salinity is represented as a function of Mississippi River discharge (solid line).**



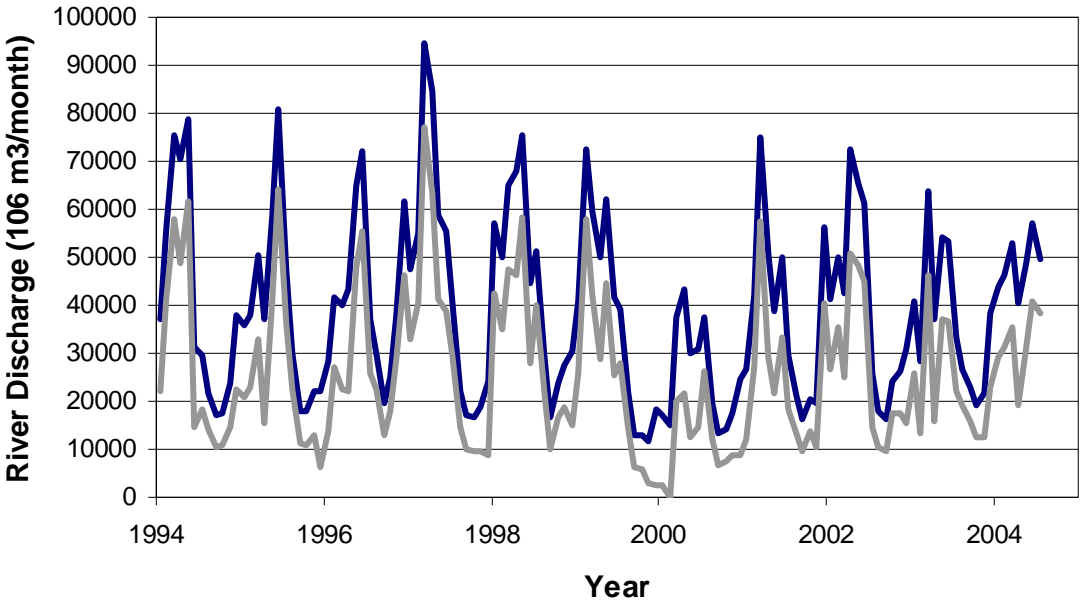
**Figure 3: Schematic representation of Barataria desktop salinity model showing model parameters (X1, X3, X4, X5, and X7) and the location and average discharge of existing river diversions in the Base Case scenario.**



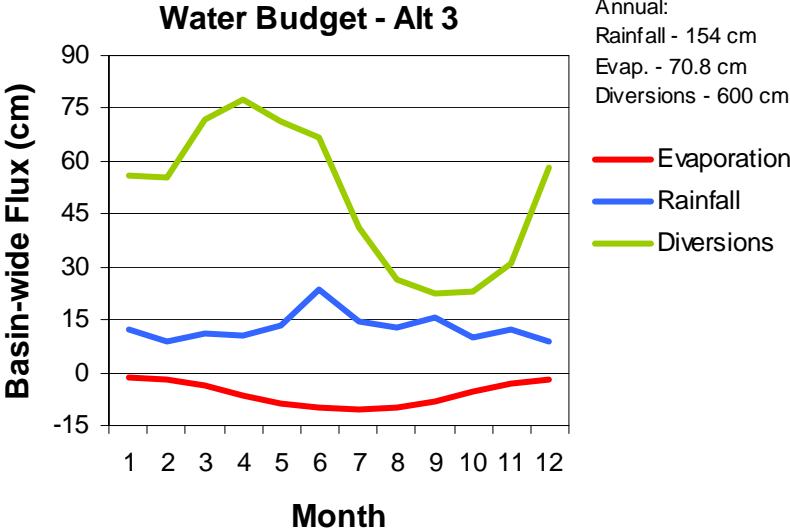
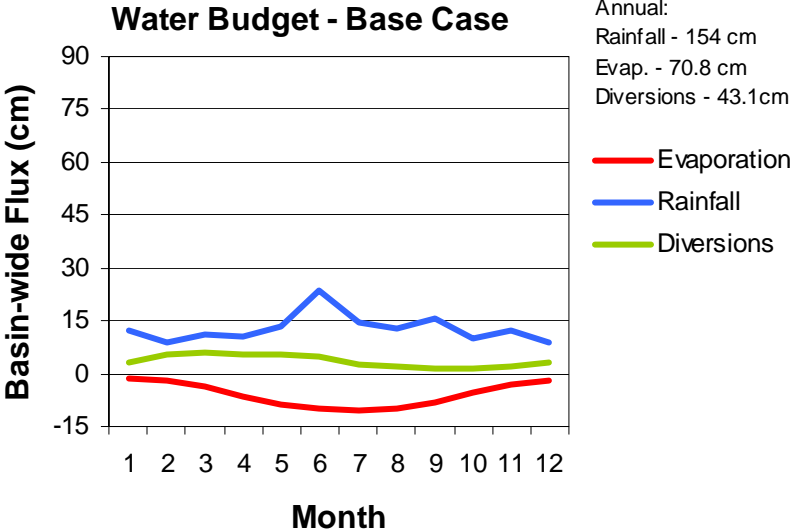
**Figure 4: Schematic representation of Barataria desktop model showing the locations and average discharge of the diversions used for all Alternative 3 scenarios.**



**Figure 5: Historical Mississippi River discharge to the Birdfoot Delta for Base Case and discharge reduced by approximately 35% by upstream diversions in Alternative 3.**



**Figure 6: Barataria basin water budgets showing the shift from rainfall-dominated conditions (Base Case) to diversion-dominated conditions with the addition of the Alternative 3 diversions.**



### 3 RESULTS

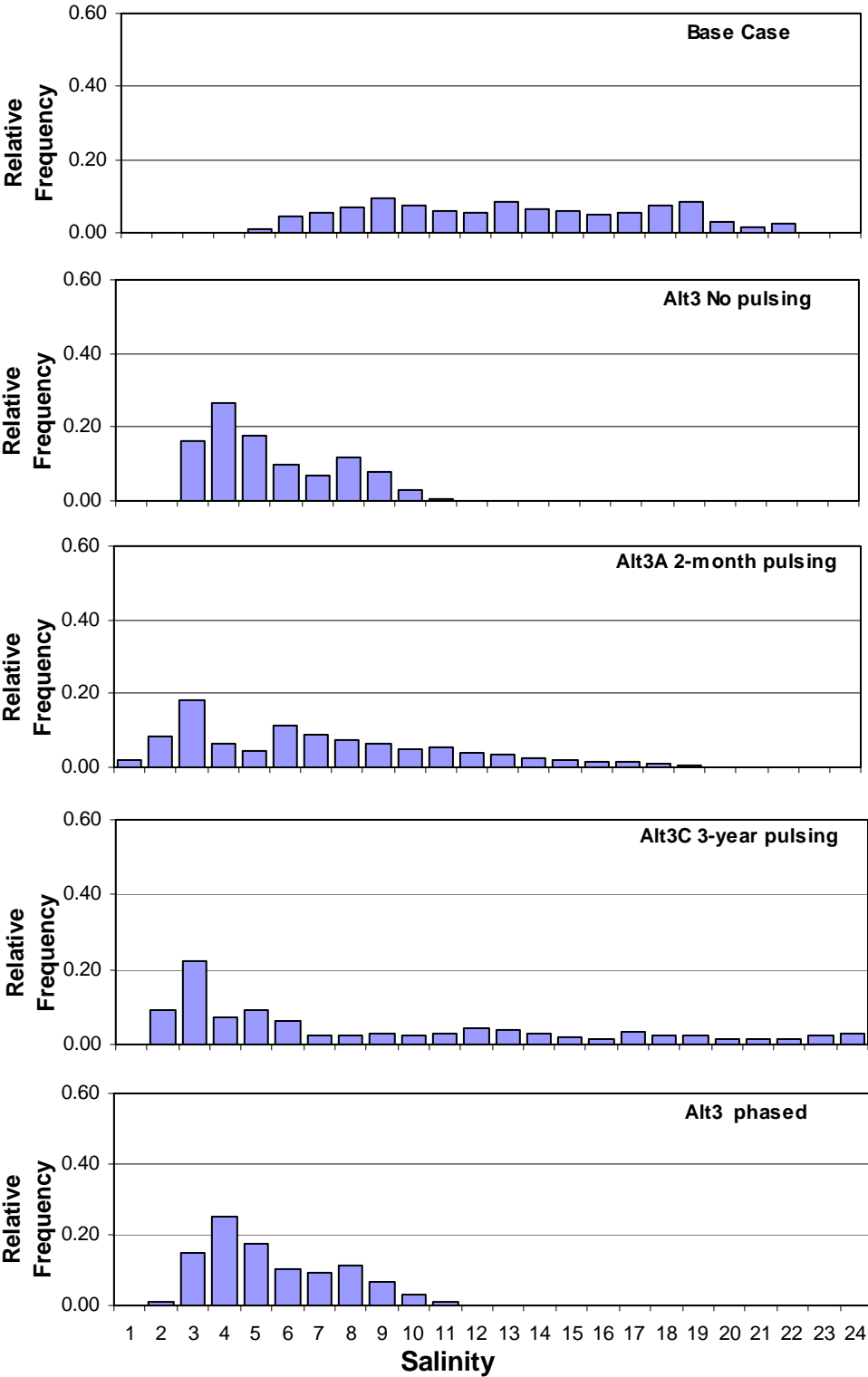
The simulated salinity values demonstrate sensitivity to the range of strategies investigated for the management of the controlled diversions into Barataria basin proposed in the Master Plan. Introduction of Mississippi River water as contemplated in the Master Plan will alter salinity values dramatically from current conditions, Table 8. Introducing temporal variation into the diversion flows by pulsed operation will restore the range of variation in salinity in to what is observed under present conditions, Figure 7. This can be expected based the dominant role that the proposed diversions will assume in the basin water budget. The pulsed operations have the additional, unexpected effect of increasing the average salinity values relative to the Alt 3, non-pulsed operations. The effect of pulsed operations on the range of salinity variation and on average salinity increases with the length of the pulses. Phased operation of the upstream and downstream diversions has little effect on salinity values compared to the Alt 3 strategy.

**Table 8: Summary of simulated monthly salinity values**

Scenario	Basin 2		Basin 1/3		Basin 4/5		Basin 6	
	Average	Range	Average	Range	Average	Range	Average	Range
Base Case	0.5	2.6	0.5	2.8	3.2	7.5	13	18
Alt 3	0.0	0.6	0.0	0.4	0.2	2.5	4.9	11
Alt 3A	0.1	1.4	0.1	2.0	0.5	3.0	7.2	19
Alt 3B	0.5	5.2	0.5	6.0	1.3	9.5	8.3	23
Alt 3C	0.5	5.2	0.5	5.6	1.8	10	8.5	23
Alt 3D	0.2	1.4	0.2	1.6	0.2	4.0	2.2	11

The following sections provide a summary of detailed results obtained for each scenario.

Figure 7: Comparison of salinity distributions for Barataria Bay (sub-basin 6)

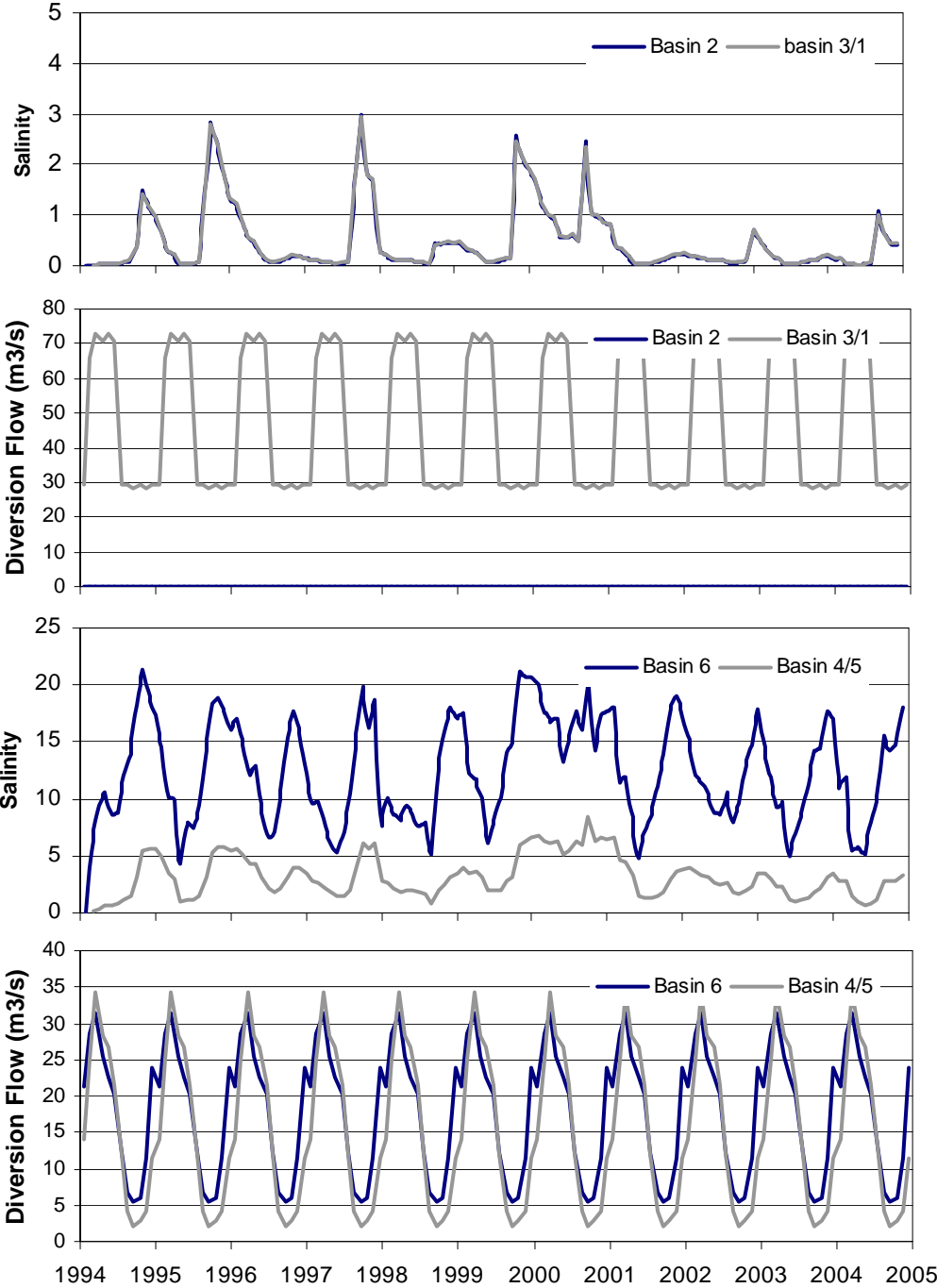


### 3.1 Base Case

**Table 2: Summary of monthly mean salinity values calculated for the Base Case**

Salinity					
month	basin 2	basin 3/1	basin 4/5	basin 6	boundary
1	0.6	0.6	4.4	14.8	22.8
2	0.4	0.4	3.4	11.5	21.7
3	0.3	0.3	3.0	10.3	19.2
4	0.2	0.2	2.6	9.5	19.0
5	0.1	0.1	1.9	7.5	18.5
6	0.1	0.1	1.9	8.3	18.5
7	0.1	0.1	2.0	10.3	20.7
8	0.5	0.4	2.5	12.3	23.9
9	0.9	0.9	3.6	15.7	26.1
10	1.0	1.0	4.1	16.9	26.5
11	0.8	0.9	4.5	17.9	26.3
12	0.7	0.7	4.5	16.1	24.1
mean	0.5	0.5	3.2	12.6	22.3
s.d.	0.3	0.3	1.0	3.5	3.1

Figure 8: Diversion flows and calculated salinity values for the Base Case

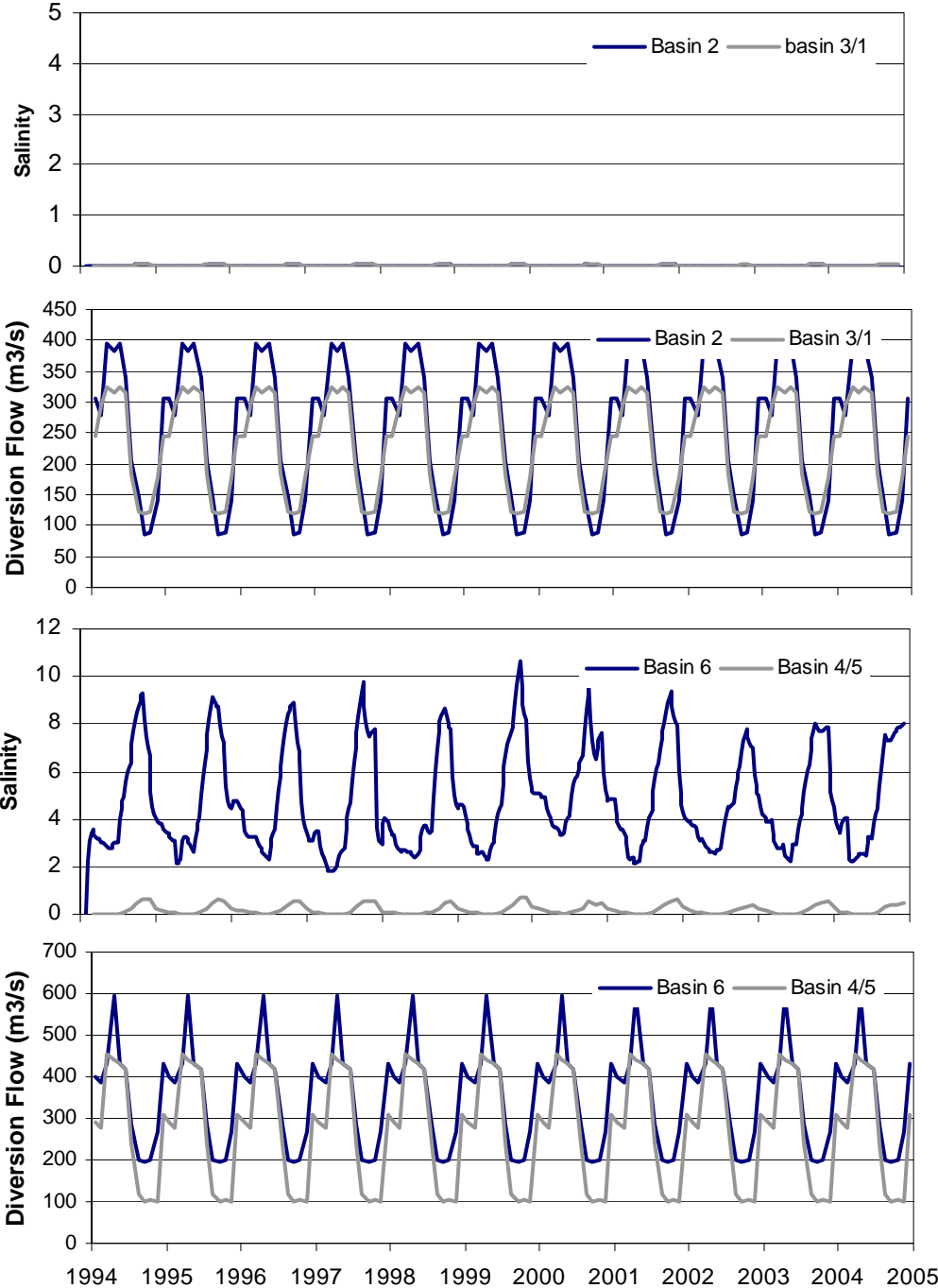


### 3.2 Alt 3

**Table 3: Summary of monthly mean salinity values calculated for the Alt 3 scenario**

Salinity					
month	basin 2	basin 3/1	basin 4/5	basin 6	boundary
1	0.0	0.0	0.1	4.1	26.1
2	0.0	0.0	0.1	3.8	24.9
3	0.0	0.0	0.0	2.9	22.8
4	0.0	0.0	0.0	2.7	23.4
5	0.0	0.0	0.0	2.6	22.6
6	0.0	0.0	0.0	3.0	22.3
7	0.0	0.0	0.1	4.5	23.7
8	0.0	0.0	0.2	6.3	26.0
9	0.0	0.0	0.4	8.3	27.7
10	0.0	0.0	0.5	8.4	28.0
11	0.0	0.0	0.6	7.5	28.0
12	0.0	0.0	0.3	4.3	27.0
mean	0.0	0.0	0.2	4.9	25.2
s.d.	0.0	0.0	0.2	2.2	2.2

Figure 9: Diversion flows and calculated salinity values for the Alt 3 scenario

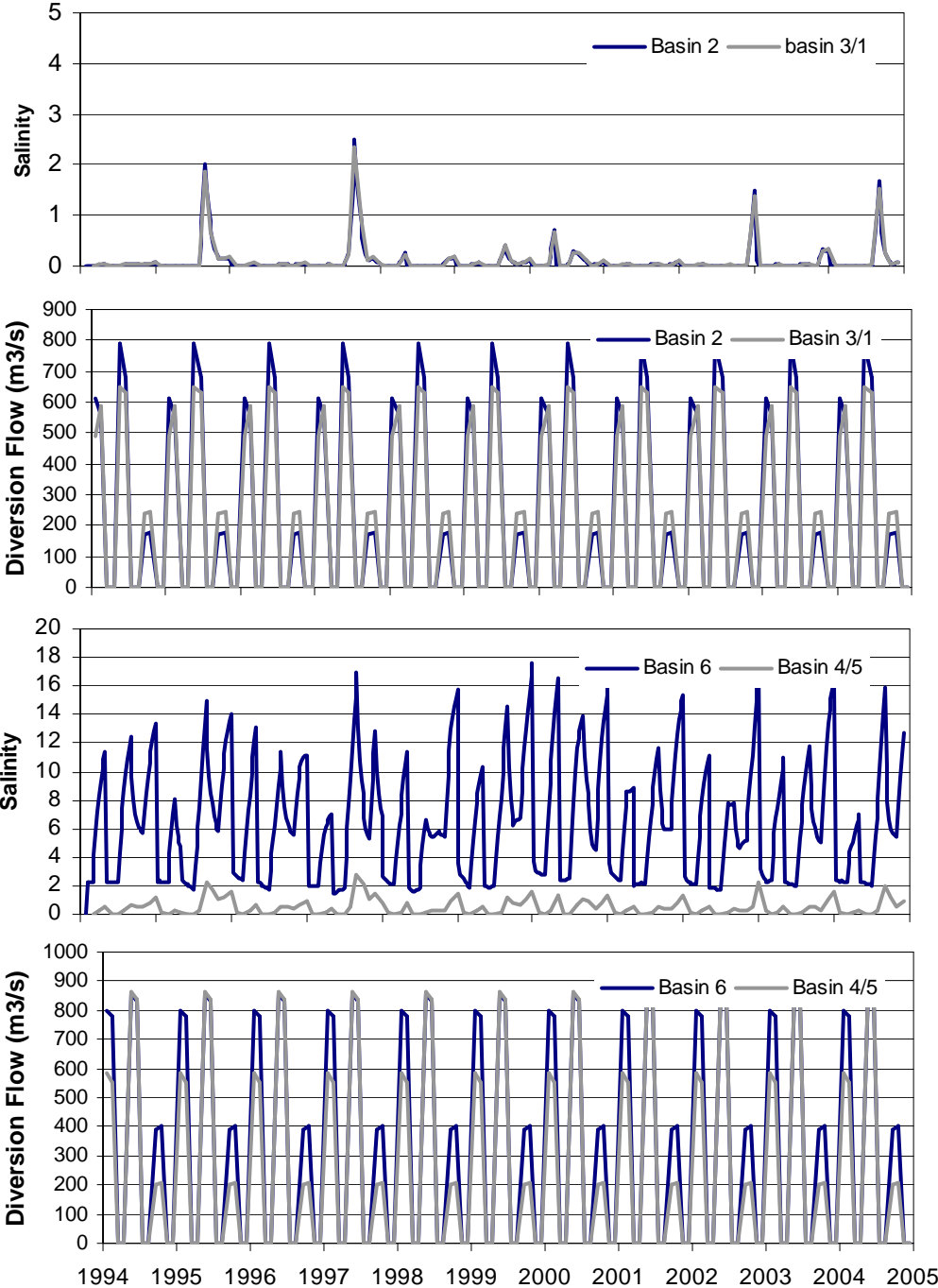


### 3.3 Alt 3A

**Table 4: Summary of monthly mean salinity values calculated for the Alt 3A scenario**

Salinity					
month	basin 2	basin 3/1	basin 4/5	basin 6	boundary
1	0.0	0.0	0.1	2.4	26.1
2	0.0	0.0	0.0	2.2	24.9
3	0.0	0.0	0.2	7.8	22.8
4	0.1	0.1	0.6	10.2	23.4
5	0.0	0.0	0.0	2.0	22.6
6	0.0	0.0	0.0	2.0	22.3
7	0.1	0.1	0.3	8.1	23.7
8	0.6	0.6	1.1	12.5	26.0
9	0.2	0.2	0.8	6.5	27.7
10	0.0	0.0	0.5	5.5	28.0
11	0.1	0.1	0.9	12.1	28.0
12	0.3	0.3	1.4	14.4	27.0
mean	0.1	0.1	0.5	7.2	25.2
s.d.	0.2	0.2	0.5	4.5	2.2

Figure 10: Diversion flows and calculated salinity values for the Alt 3A scenario

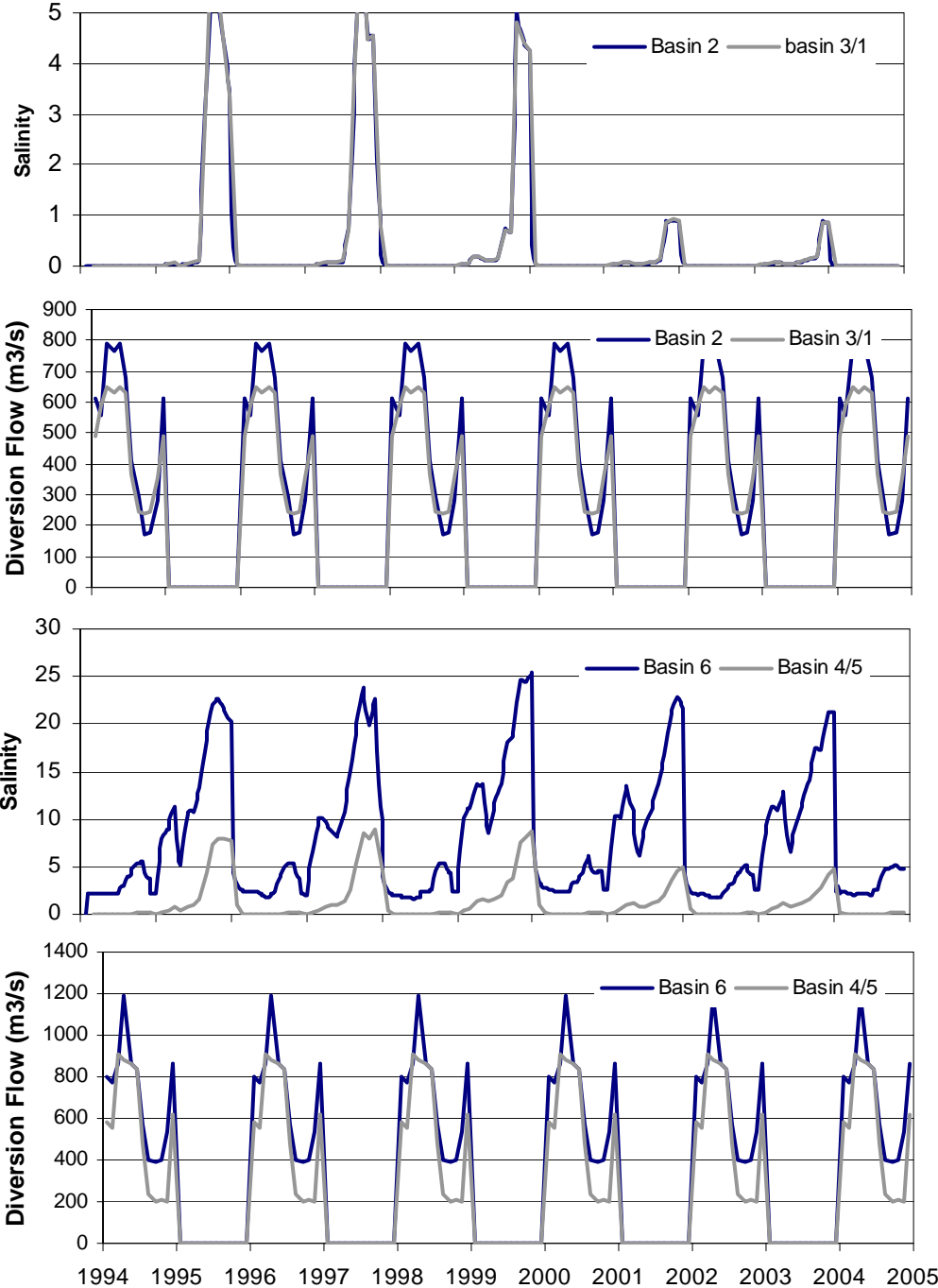


### 3.4 Alt 3B

**Table 5: Summary of monthly mean salinity values calculated for the Alt 3B scenario**

Salinity					
month	basin 2	basin 3/1	basin 4/5	basin 6	boundary
1	0.0	0.0	0.4	5.7	26.1
2	0.0	0.0	0.3	5.9	24.9
3	0.0	0.0	0.4	6.6	22.8
4	0.0	0.0	0.5	5.8	23.4
5	0.0	0.0	0.4	4.8	22.6
6	0.0	0.0	0.5	5.8	22.3
7	0.1	0.1	0.8	7.4	23.7
8	0.7	0.7	1.5	9.8	26.0
9	1.3	1.3	2.3	11.9	27.7
10	1.5	1.4	2.8	12.4	28.0
11	1.4	1.4	3.1	12.5	28.0
12	1.0	1.0	3.1	11.0	27.0
mean	0.5	0.5	1.3	8.3	25.2
s.d.	0.6	0.6	1.2	3.0	2.2

Figure 11: Diversion flows and calculated salinity values for the Alt 3B scenario

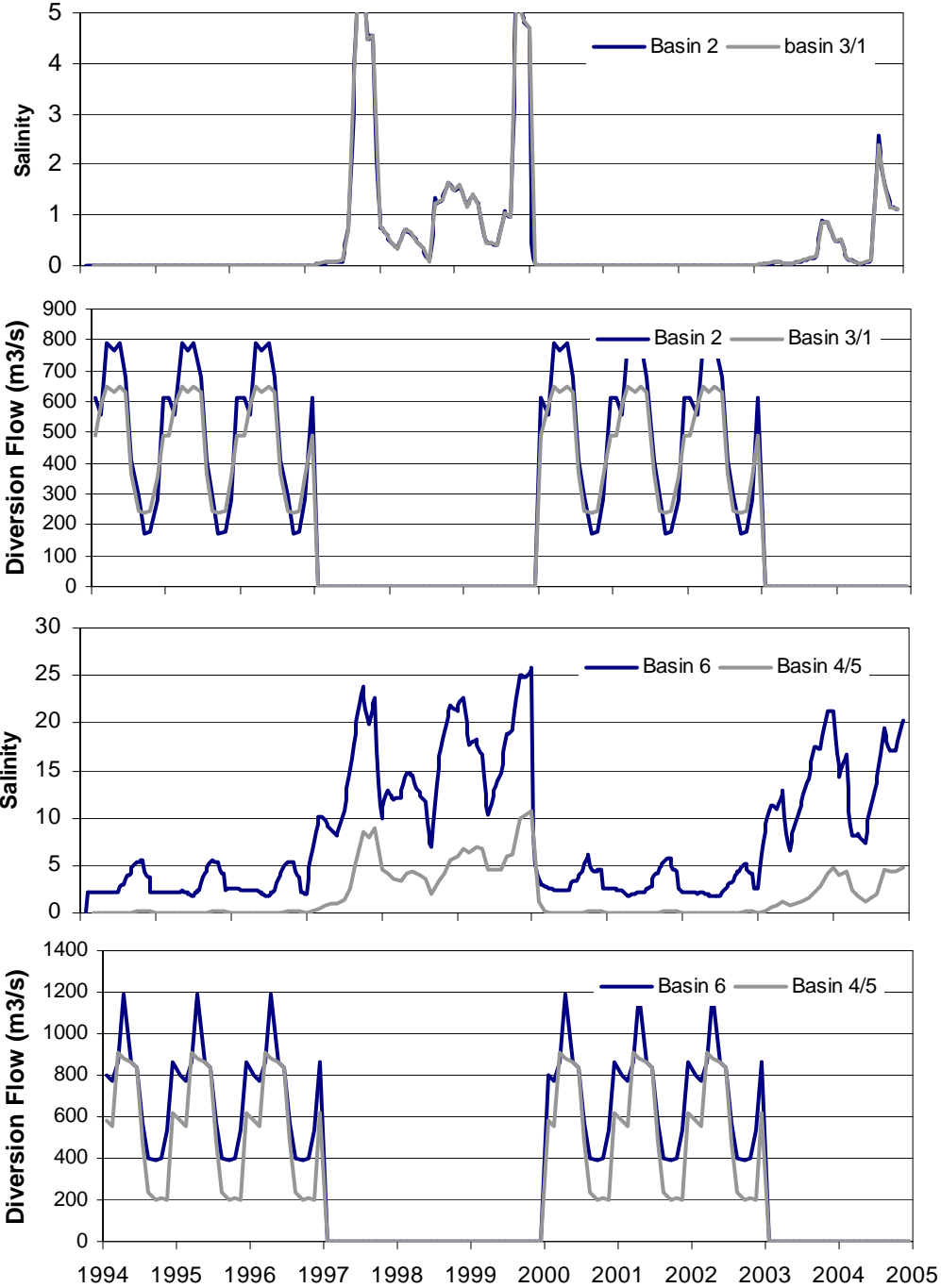


### 3.5 Alt 3C

**Table 6: Summary of monthly mean salinity values calculated for the Alt 3C scenario**

Salinity					
month	basin 2	basin 3/1	basin 4/5	basin 6	boundary
1	0.3	0.3	1.7	7.8	26.1
2	0.2	0.2	1.4	7.4	24.9
3	0.2	0.2	1.3	6.6	22.8
4	0.2	0.2	1.4	6.8	23.4
5	0.1	0.1	1.1	5.4	22.6
6	0.1	0.1	1.1	6.3	22.3
7	0.2	0.2	1.3	7.6	23.7
8	0.7	0.7	1.8	9.4	26.0
9	1.0	1.0	2.3	11.4	27.7
10	1.2	1.1	2.7	11.8	28.0
11	1.2	1.2	3.1	12.3	28.0
12	0.8	0.8	2.6	9.2	27.0
mean	0.5	0.5	1.8	8.5	25.2
s.d.	0.4	0.4	0.7	2.3	2.2

Figure 12: Diversion flows and calculated salinity values for the Alt 3C scenario

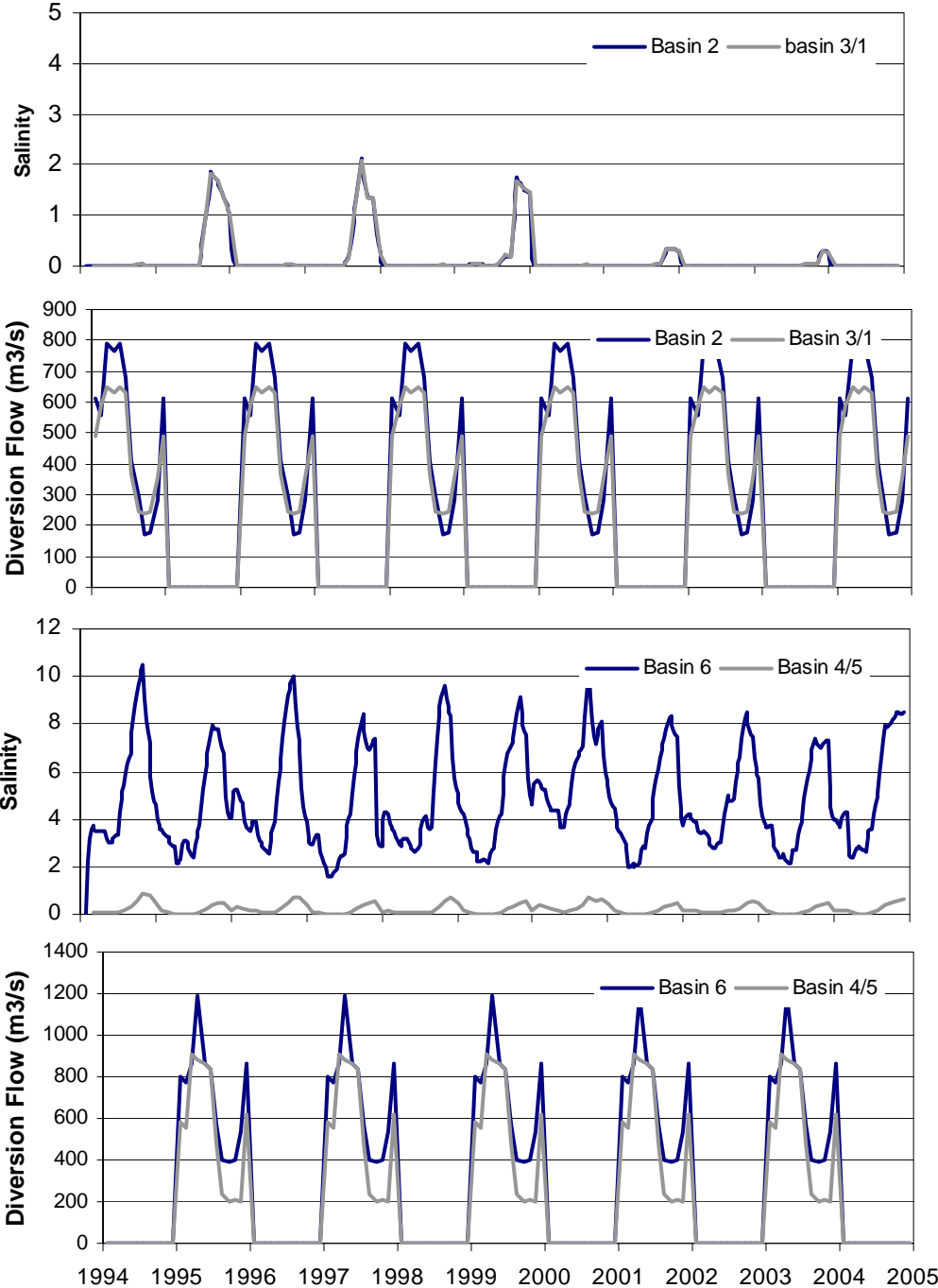


### 3.6 Alt 3D

**Table 7: Summary of monthly mean salinity values calculated for the Alt 3D scenario**

Salinity					
month	basin 2	basin 3/1	basin 4/5	basin 6	boundary
1	0.0	0.0	0.2	4.2	26.1
2	0.0	0.0	0.1	3.8	24.9
3	0.0	0.0	0.1	3.0	22.8
4	0.0	0.0	0.1	2.9	23.4
5	0.0	0.0	0.0	2.6	22.6
6	0.0	0.0	0.1	3.0	22.3
7	0.0	0.0	0.1	4.6	23.7
8	0.2	0.2	0.2	6.3	26.0
9	0.4	0.4	0.4	8.2	27.7
10	0.5	0.5	0.5	8.5	28.0
11	0.4	0.4	0.6	7.5	28.0
12	0.3	0.3	0.3	4.4	27.0
mean	0.2	0.2	0.2	4.9	25.2
s.d.	0.2	0.2	0.2	2.2	2.2

Figure 13: Diversion flows and calculated salinity values for the Alt 3D scenario



## **4 DISCUSSION**

Based on the results obtained in this study, it appears that pulsed operation of river diversions offers a viable strategy for maintaining the range of salinity values typical of estuarine conditions in the Barataria basin while at the same time obtaining the benefits from the large-scale introduction of river-born sediments. By contrast with pulsing, phased operation of diversions in the basin will have a relatively minor effect on salinity values, at least for diversions on the scale contemplated in the Master Plan. The diversions proposed for the Barataria basin will shift the water budget from a rainfall-dominated budget to a diversion-dominated budget. Under these conditions, it is the total inflow of the diversions into the basin, rather than the spatial distribution of freshwater inflows, that most influences salinity values basin-wide.

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## APPENDIX – BARATARIA BOX MODEL CALCULATIONS

In implementing the mass-balance model, the Barataria basin was divided into a series of four sub-basins, Figure (2). The surface area of each sub-basin ( $A_t$ ) was partitioned into two parts: water surface area ( $A_w$ ) and wetland and land surface area ( $A_l$ ). The following is a description of each component of the water and salt balance and how it is calculated by the model:

### Volumes of sub-basins (V)

Volume of water in each sub-basin  $j$ , and for each month  $i$ , is calculated according to monthly changes in the relative sea level SL:

$$V_j^i = V_j^{i-1} + (SL^i - SL^{i-1})A_{w,j} \quad \text{A-1}$$

### Net supply of fresh water ( $Q_R$ )

The monthly net supply of fresh water to each sub-basin is calculated as follows:

$$Q_{R,j}^i = R_j^i A_t - E_j^i A_w + E_c E_j^i A_l + Q_{D,j}^i \quad \text{A-2}$$

Where  $R_j^i$ ,  $E_j^i$ , and  $Q_{D,j}^i$  represent rainfall, potential evaporation, and river diversion, respectively, for sub-basin  $j$  and month  $i$ . The model calculates losses from water bodies at the potential rate of evaporation, while losses from wetland and land areas are calculated as a fraction of the potential rate of evaporation. The fraction,  $E_c$ , is one of the model parameters to be determined through calibration.

### Mean flows among sub-basins ( $Q_o$ )

The excess of water volume (N) in each sub-basin is calculated first:

$$N_j^i = (V_j^i - V_j^{i-1}) - Q_{R,j}^i \quad \text{A-3}$$

Water excesses are used to calculate mean flow advection fluxes ( $Q_o$ ) between each connected pair of sub-basins. According to the schematic shown in Figure (2), the following fluxes need to be calculated:  $Q_{o,1-2}$  between sub-basins 1 and 2,  $Q_{o,2-3}$  between sub-basins 2 and 3,  $Q_{o,3-4}$  between sub-basins 3 and 4, and  $Q_{o,4-G}$  between sub-basin 4 and the Gulf of Mexico. In addition, hydraulic connections in the Barataria basin indicated that water can flow between sub-basins 2 and 4, which is represented by  $Q_{o,2-4}$ . The following set of equations is used to solve for each  $Q_o$ :

$$\begin{aligned} Q_{o,1-2}^i &= N_1^i, \\ Q_{o,2-3}^i &= N_2^i + Q_{o,1-2}^i - Q_{o,2-4}^i, \\ Q_{o,3-4}^i &= N_3^i + Q_{o,2-3}^i, \\ Q_{o,4-G}^i &= N_4^i + Q_{o,2-4}^i + Q_{o,3-4}^i \end{aligned} \quad \text{A-4}$$

### Water exchange fluxes (X)

Exchange fluxes among the different sub-basins occur as a result of dispersion and wind and tidal mixing. To understand the exchange flux, consider that at any time during a certain month, the discharge of water between the estuarine basin and the gulf can be represented as a sum of a time varying component and the (constant) mean discharge for that month  $Q_o$ . The exchange flux  $X$  (same units of  $Q_o$ ) represents the average magnitude of the time varying component of discharge. In the current model formulation, the exchange flux  $X$  for each pair of sub-basins is a represented as a parameter to be estimated by calibration. Similar to  $Q_o$ , there are five of these exchange fluxes (parameters):  $X_{1-2}$ ,  $X_{2-3}$ ,  $X_{2-4}$ ,  $X_{3-4}$ , and  $X_{4-G}$ . While the mean discharge  $Q_o$  varies

from month to month in response to changes in sea level and in the net supply of freshwater, the model uses the same value of each exchange flux  $X$  in its calculation of salinity through the entire period of simulation.

It should be noted that while equation (A-4) includes five unknown  $Q_o$  fluxes, only four relationships are available. This arises from the additional flux term,  $Q_{2-4}$ , that was added to represent the connection between sub-basins 2 and 4. This is resolved by assuming that where mean discharge fluxes ( $Q_o$ ) are arranged in parallel, their relative magnitudes are in proportion to the corresponding set of exchange fluxes,  $X$ . Both the mean discharge and the exchange flux arise from an underlying hydraulic connection. Therefore it is reasonable to assume that the pathway with the larger exchange flux would also support the larger mean discharge. This results in an additional relationship between  $Q_{2-4}$  and  $Q_{2-3}$ :

$$Q_{o,2-4}^i = Q_{o,2-3}^i X_{2-4} / X_{2-3} \quad \text{A-5}$$

#### **Advective fluxes of salt (SQ)**

For each time step, the advective salt fluxes associated with the mean fluxes of water are calculated as the product of  $Q_o$  between each two connected sub-basins and the salinity  $S$  of the “upstream” sub-basin. For example,  $SQ_{1-2}$  is calculated as  $SQ_{1-2}^i = Q_{o,1-2}^i S_1^i$  if the flow direction is from sub-basin 1 to sub-basin 2, or as  $SQ_{1-2}^i = Q_{o,1-2}^i S_2^i$  if the flow is in the opposite direction.

Similar calculations are applied for the other advective fluxes  $SQ_{1-2}$ ,  $SQ_{2-3}$ ,  $SQ_{3-4}$ , and  $SQ_{2-4}$ . The flux between the gulf and sub-basin 4,  $SQ_{4-G}$ , is similarly calculated using either  $S_4$  or the boundary salinity  $S_B$ .

#### **Exchange fluxes of salt (SX)**

Following the flow directions assumed in Figure (2), fluxes of salt carried by exchange flows are calculated as the product of  $X$  between each two connected sub-basins and the difference in their salinities. For example,  $SX_{1-2}$  is calculated as  $SX_{1-2}^i = X_{1-2} (S_2^i - S_1^i)$ . Similar calculations are used for the other flux terms  $SX_{1-2}$ ,  $SX_{2-3}$ ,  $SX_{3-4}$ ,  $SX_{2-4}$ , and  $SX_{4-G}$ .

#### **Sub-basin salinity (S)**

Finally, the monthly average salinity in each sub-basin is calculated by dividing the salt content by the volume of water in the sub-basin. For example, salinity in sub-basin 1 is calculated as:

$$S_1^{j+1} = \frac{S_1^j V_1^j + SQ_{1-2}^j + SX_{1-2}^j}{V_1^{j+1}} \quad \text{A-6}$$

Similar calculations are performed to estimate monthly salinities in the other three sub-basins.