CULTURAL RESOURCES

ISLAND ATTRIBUTE	DATA SOURCE and NOTES
Known prehistoric sites	U.S Bureau of Reclamation. 1996. Cultural resources of the Sacramento-San Joaquin Delta, CALFED Bay-Delta Program. Draft. Sacramento, CA. The information on prehistoric and historic resources in the Delta depends on whether an area has been surveyed and results have been reported. Therefore, the lack of an occurrence on an island does not preclude the presence of prehistoric and historic resources.
Potential historic sites	U.S Bureau of Reclamation. 1996. Cultural resources of the Sacramento-San Joaquin Delta, CALFED Bay-Delta Program. Draft. Sacramento, CA. See above note.

		Cultural Resources	
ISLAND	Reclamation District	Known Prehistoric Sites	Potential Historic Sites
Bacon Island	2028		13
Bethel Island	-	4	
Bishop Tract	2042	1	
Boggs (Moss Tract)	404	1	
Bouldin Island	756		6
Brack Tract	2033		
Bradford Island	2059		
Brannan/Andrus Island	-		
Andrus	317		
Andrus, Isleton	407		
Andrus, Upper	556	1	
Brannan	2067		
Byron Tract	800	5	1
Canal Ranch	2086		
Coney Island	2117		
Dead Horse Island	2111		
Empire Tract	2029		
Fabian Tract	773	3	2
Fay	2113		
Glanville Tract	1002	2	
Grand Island	3		
Hastings Tract	2060		
Holland Tract	2025	4	2
Holt Station	2116		
Hotchkiss Tract	799	8	
Jersey Island	830	1	
Jones Tract	-		
Jones, Lower	2038		
Jones, Upper	2039		
King Island	2044		
Little Mandeville	2118		
Mandeville Island	2027		
McCormack Williamson Tr.	2110		
McDonald Island	2030	1	
Medford Island	2041		
Merritt Island	150	2	
Mildred Island	2021		
Naglee Burke	1007		
New Hope Tract	348	24	2
Orwood Island	2024		
Palm Tract	2036	1	
Pescadero	2058	2	1
Pierson District	551	3	
Prospect Island	1667		
Quimby Island	2090		
Rindge Tract	2037		
Rio Blanco Tract	2114		
Roberts Island	-	-	
Roberts, Lower	684		
Roberts, Middle	524	1	
Roberts, Upper	544		
Rough and Ready Island	-		
Ryer Island	501		
Sargent Barnhart Tract	2074	1	1
Sherman Island	341		
Shima Tract	2115		
Shin Kee Tract	-		
Smith	1614		
Stark	2089		
Staten Island	38		1
Stewart Tract	2062		
Sutter Island	349		
Terminous	548	1	
Twitchell	1601		
Tyler Island	563	4	
Walnut Grove	554	-	
Union Island	1,2	1	
Van Sickle Island	1607		
Veale Tract	2065	2	
Venice Island	2023		
Victoria Island	2040		
Webb Tract	2026		2
Weber	828	1	
Winter Island	2122		
Woodward Island	2072		1
Wright-Elmwood Tract	2119		
-	307	5	1
-	369	4	
-	536		
-	765		
-	813	4	
-	900		
-	999	5	
-	1608		
-	2084		
-	2093		
-	2095	1	
-	2098		
-	2121		

INFRASTRUCTURE OF LOCAL CONCERN

ISLAND ATTRIBUTE	DATA SOURCE and NOTES
County roads	DWR Delta atlas. The team selected "present/absent" as the appropriate unit to report over "miles of roadway" because if any portion of a road is damaged or inundated during a levee breach or flood event, circulation patterns would need to be re-routed.
Commercial lands	DWR Land use mapping data.
Industrial lands	DWR Land use mapping data.
Acreage protected per levee mile	DWR Delta atlas and DWR Land use mapping data. Acreage protected per levee mile was computed by dividing each island's acreage by the corresponding number of levee miles.

ISLAND	Reclamation District	Infrastructure of Local Concern: County Roads	Commercial Lands (Acres)	Industrial Lands (Acres)	Acreage Protected per Levee Mile (Acres/Mile)
Bacon Island	2028	present	0.0	13.8	393
Bethel Island	-	present	0.0	0.0	304
Bishop Tract	2042	present	0.0	0.0	374
Boggs (Moss Tract)	404	absent	31.5	42.0	817
Bouldin Island	756	absent	0.0	45.3	334
Brack Tract	2033	present	0.0	0.0	451
Bradford Island	2059	absent	0.0	0.0	277
Brannan/Andrus Islan	-	-	-	-	376
Andrus	317	present	0.0	5.3	-
Andrus, Isleton	407	present	3.8	48.7	-
Andrus, Upper	556	present	0.0	1.8	-
Brannan	2067	present	2.4	9.8	-
Byron Tract	800	present	0.0	0.0	715
Canal Ranch	2086	absent	0.0	0.0	399
Coney Island	2117	absent	0.0	0.0	173
Dead Horse Island	2111	absent	0.0	0.0	81
Empire Tract	2029	present	0.0	0.0	327
Fabian Tract	773	present	0.0	0.0	347
Fay	2113	absent	0.0	0.0	63
Glanville Tract	1002	present	0.0	0.0	538
Grand Island	3	present	5.8	5.3	587
Hastings Tract	2060	absent	0.0	0.0	447
Holland Tract	2025	present	0.0	0.0	372
Holt Station	2116	present	0.0	0.0	490
Hotchkiss Tract	799	present	17.3	9.9	492
Jersey Island	830	present	0.0	0.0	223
Jones Tract	-	-	-	-	-
Jones, Lower	2038	present	0.0	0.0	670
Jones, Upper	2039	present	0.0	0.0	673
King Island	2044	present	0.0	0.0	362
Little Mandeville	2118	absent	0.0	0.0	80
Mandeville Island	2027	absent	0.0	0.0	371
McCormack Williamso	2110	absent	0.0	3.0	188
McDonald Island	2030	absent	0.0	84.0	449
Medford Island	2041	absent	0.0	0.0	207
Merritt Island	150	present	0.0	3.3	262
Mildred Island	2021	absent	0.0	0.0	137
Naglee Burke	1007	present	0.0	0.0	734
New Hope Tract	348	present	18.8	26.0	500
Orwood Island	2024	present	0.0	0.0	380
Palm Tract	2036	absent	0.0	0.0	325
Pescadero	2058	present	3.1	138.4	955
Pierson District	551	present	0.0	16.4	612
Prospect Island	1667	absent	0.0	0.0	123
Quimby Island	2090	absent	0.0	0.0	110
Rindge Tract	2037	absent	0.0	0.0	435
Rio Blanco Tract	2114	absent	0.0	0.0	176
Roberts Island	-	-	-	-	-
Roberts, Lower	684	present	5.5	53.5	676
Roberts, Middle	524	present	0.0	672.2	1310
Roberts, Upper	544	present	0.0	0.0	550
Rough and Ready Isla	-	absent	0.0	835.7	218
Ryer Island	501	present	0.0	0.0	577
Sargent Barnhart Trac	2074	present	0.0	0.0	282
Sherman Island	341	present	7.1	0.0	510
Shima Tract	2115	absent	0.0	0.0	363
Shin Kee Tract	-	absent	0.0	0.0	246
Smith	1614	present	0.0	0.0	248
Stark	2089	absent	0.0	0.0	210
Staten Island	38	present	0.0	9.4	361
Stewart Tract	2062	present	0.0	0.0	318
Sutter Island	349	present	0.0	0.0	210
Terminous	548	present	0.0	0.0	650
Twitchell	1601	present	0.0	10.1	298
Tyler Island	563	present	0.0	3.0	375
Walnut Grove	554	present	0.0	25.3	208
Union Island	1,2	present	10.1	0.0	735
Van Sickle Island	1607	absent	0.0	0.0	278
Veale Tract	2065	present	0.0	4.0	228
Venice Island	2023	absent	0.0	0.0	262
Victoria Island	2040	absent	0.0	0.0	480
Webb Tract	2026	absent	0.0	0.0	429
Weber	828	absent	0.0	0.0	958
Winter Island	2122	absent	0.0	0.0	100
Woodward Island	2072	absent	0.0	0.0	207
Wright-Elmwood Tract	2119	present	0.0	0.0	312
-	307	present	0.0	1.7	463
-	369	present	0.0	0.0	313
-	536	present	0.0	0.0	456
-	765	present	0.0	0.0	237
-	813	present	0.0	0.0	317
-	900	present	0.0	0.0	614
-	999	present	0.0	105.2	786
-	1608	absent	0.0	39.8	302
-	2084	present	0.0	51.1	453
-	2093	absent	0.0	0.0	245
-	2095	present	147.8	56.8	1368
-	2098	absent	0.0	0.0	326
-	2121	present	0.0	0.0	229

Infrastructure of Statewide Concern

ISLAND ATTRIBUTE	DATA SOURCE and NOTES
Federal and state highways	DWR Delta atlas. See note for "County Roads" above.
Water supply conveyance	DWR Delta atlas.
Railroad mainlines	DWR Delta atlas.
Natural gas pipelines	Warner, Chris. Supervisor of mapping. Pacific Gas and Electric, Central Area, Walnut Creek, CA. November 25 and December 7, 1996; January 2,3 and 17, 1997 - telephone conversations and facsimile. (PG&E natural gas facilities data) Gas distribution line mileages are approximate.
Natural gas fields and storage	DWR Delta atlas and PG&E natural gas facilities data.
Power transmission lines	DWR Delta atlas.

		Statewide Infrastructure					
ISLAND	Reclamation District	Federal and State Highways	Water Supply Conveyance (Miles)	Railroad Mainlines (Miles)	Natural Gas Fields and Storage	Natural Gas Pipelines (Miles)	Power Transmission Lines (Miles)
Bacon Island	2028	absent	0	0	Absent	4.32	0
Bethel Island	-	absent	0	0	Production	1.29	0
Bishop Tract	2042	present	0	0	Absent	0	2
Boggs (Moss Tract)	404	present	0	3	Production	na	1
Bouldin Island	756	present	0	0	Absent	0	0
Brack Tract	2033	absent	0	0	Absent	10.03	0
Bradford Island	2059	absent	0	0	Production	5.43	0
Brannan/Andrus Island	-		-	-	-	-	-
Andrus	317	present	0	0	Production	15.34	0
Andrus, Isleton	407	present	0	0	Production	na	0
Andrus, Upper	556	absent	0	0	Production	na	0
Brannan	2067	present	0	0	Production	49.28	6
Byron Tract	800	present	0	1	Absent	1.85	2
Canal Ranch	2086	absent	0	0	Absent	0.89	0
Coney Island	2117	absent	0	0	Absent	0	0
Dead Horse Island	2111	absent	0	0	Absent	0	0
Empire Tract	2029	absent	0	0	Absent	0	0
Fabian Tract	773	absent	0	0	Absent	0	0
Fay	2113	absent	0	0	Absent	0	0
Glanville Tract	1002	present	0	0	Absent	0	0
Grand Island	3	present	0	0	Production	6.06	9
Hastings Tract	2060	absent	3.4	0	Production	3.91	2
Holland Tract	2025	absent	0	0	Absent	0	0
Holt Station	2116	present	0.2	0	Absent	na	0
Hotchkiss Tract	799	absent	1.7	0	Production	9.2	3
Jersey Island	830	absent	0	0	Production	4.89	3
Jones Tract	-	-	-	-	-	-	-
Jones, Lower	2038	absent	5.5	5	Absent	0	0
Jones, Upper	2039	present	5.5	0	Absent	0	4
King Island	2044	absent	0	0	Production	0.61	0
Little Mandeville	2118	absent	0	0	Absent	na	0
Mandeville Island	2027	absent	0	0	Absent	0	0
McCormack Williamson Tr	2110	absent	0	0	Present	na	0
McDonald Island	2030	absent	0	0	STORAGE	9.27	0
Medford Island	2041	absent	0	0	Absent	0	0
Merritt Island	150	absent	0	0	Production	0	0
Mildred Island	2021	absent	0	0	Absent	2.53	0
Naglee Burke	1007	absent	0	0	Absent	na	3
New Hope Tract	348	present	0	2	Production	16.46	0
Orwood Island	2024	absent	2.6	0	Absent	1.15	0
Palm Tract	2036	absent	0	2	Absent	5.24	0
Pescadero	2058	present	0	4	Absent	0	0
Pierson District	551	present	0.8	0	Production	0.05	4
Prospect Island	1667	absent	0	0	Absent	0	0
Quimby Island	2090	absent	0	0	Absent	0	0
Rindge Tract	2037	absent	0	0	Absent	0	0
Rio Blanco Tract	2114	absent	0	0	Production	0	1
Roberts Island	-	-	-	-	-	15.34	-
Roberts, Lower	684	absent	3	5	Production	-	3
Roberts, Middle	524	present	0	0	Production	-	1
Roberts, Upper	544	absent	0	0	Production	-	4
Rough and Ready Island	-	absent	0	0	Absent	0	0
Ryer Island	501	present	0	0	Absent	0	0
Sargent Barnhart Tract	2074	absent	1.5	0	Absent	0	0
Sherman Island	341	present	0	0	Production	40.72	13
Shima Tract	2115	absent	0	0	Absent	0	1
Shin Kee Tract	-	present	0	0	Absent	0.97	1
Smith	1614	present	0	0	Absent	na	0
Stark	2089	absent	0	0	Absent	0	1
Staten Island	38	absent	0	0	Production	4.15	0
Stewart Tract	2062	present	0	3	Absent	0	1
Sutter Island	349	absent	0	0	Absent	0	0
Terminous	548	present	0	0	Production	7.56	3
Twitchell	1601	absent	0	0	Production	6.89	0
Tyler Island	563	absent	0.8	0	Production	19.09	0
Walnut Grove	554	absent	0.7	0	Production	-	-
Union Island	1,2	absent	0	0	Production	12.53	6
Van Sickle Island	1607	absent	0	0	Absent	0	0
Veale Tract	2065	absent	0	0	Absent	1.02	1
Venice Island	2023	absent	0	0	Absent	0	0
Victoria Island	2040	present	0	0	Absent	0	0
Webb Tract	2026	absent	0	0	Production	0.02	0
Weber	828	present	0	0	Production	N/D	0
Winter Island	2122	absent	0	0	Absent	N/D	0
Woodward Island	2072	absent	1.5	0	Absent	0	0
Wright-Elmwood Tract	2119	absent	0	0	Absent	0	2
-	307	absent	0	0	N/D	N/D	3
-	389	absent	0	0	Production	N/D	0
-	536	absent	0	0	Production	N/D	2
-	765	present	0	0	N/D	N/D	0
-	813	present	0	0	Absent	N/D	2
-	900	present	0	0	N/D	N/D	0
-	999	present	0	0	Absent	N/D	1
-	1608	present	0	0	Absent	N/D	0
-	2084	absent	0	0	Production	N/D	0
-	2093	absent	0	0	Production	N/D	0
-	2095	present	0	2.7	Absent	N/D	3
-	2096	absent	0	0	Production	N/D	3
-	2121	absent	0	1	Absent	N/D	0
			3.5	5 3		49.26	12 9

ADJACENT ISLAND RESOURCES

ISLAND ATTRIBUTE	DATA SOURCE and NOTES
Adjacent levees at risk	**
Adjacent acreage at risk	**
Seepage risk	**

Adjacent island resources are an important element to the Delta levee system integrity program. This objective has been included in the Special Projects prioritization process to recognize the relationships between a breached island and adjacent islands. The main factors that the team wants to capture in the information matrix include wind and wave erosion and seepage. Waterside levee slopes are subject to varying erosional effects of channel flows, tidal action, wind-generated waves, and boat wakes. A levee breach can result in increased wave action over time because the wind fetch across open water results in bigger waves which can affect erosion of an adjacent island's exterior levee slopes. Seepage of water from waterways or adjacent islands is a major concern of Delta land users. Seepage from these sources can affect levee erosion problems or instability and create drainage problems for landowners. The amount of seepage that occurs is controlled by the permeability of soils, length of the seepage path, and height of the hydraulic head (i.e., the pressure created by water within a given volume). A flooded island would result in potential increases in seepage to adjacent islands.

In discussing how to capture these issues, the team recommended using the attributes listed above. However, detailed assumptions needed to characterize these attributes have not yet been worked out. For example, what is an appropriate distance between levees to define "adjacent"? How can the seepage risk attribute capture differences in soil and current seepage conditions throughout the Delta? and How should the seepage risk attribute be characterized (e.g., a qualitative or quantitative scale). Additional investigation and discussion is needed to fully develop the "Adjacent Island Resources" attributes. Therefore, data will be presented in a future version of the information matrix.

		Adjacent Islands		
ISLAND	Reclamation District	Adjacent Levees At Risk (Miles)	Adjacent Acreage At Risk (Acres)	Seepage Risk
Bacon Island	2028		19512	
Bethel Island	-		10631	
Bishop Tract	2042		13193	
Boggs (Moss Tract)	404			
Bouldin Island	756		50326	
Brack Tract	2033		22639	
Bradford Island	2059		22414	
Brannan/Andrus Island	-		50542	
Andrus	317		-	
Andrus, Isleton	407		-	
Andrus, Upper	556		-	
Brannan	2067		-	
Byron Tract	800		13210	
Canal Ranch	2086		23346	
Coney Island	2117		29452	
Dead Horse Island	2111		28710	
Empire Tract	2029		29790	
Fabian Tract	773		36972	
Fay	2113		8061	
Glanville Tract	1002		10634	
Grand Island	3		38930	
Hastings Tract	2060		0	
Holland Tract	2025		16726	
Holt Station	2116			
Hotchkiss Tract	799		12329	
Jersey Island	830		18588	
Jones Tract	-		-	
Jones, Lower	2038		52398	
Jones, Upper	2039		41619	
King Island	2044		24624	
Little Mandeville	2118			
Mandeville Island	2027		22468	
McCormack Williamson Tr	2110		34684	
McDonald Island	2030		51794	
Medford Island	2041		18095	
Merritt Island	150		11600	
Mildred Island	2021			
Naglee Burke	1007		15210	
New Hope Tract	348		13823	
Orwood Island	2024		11191	
Palm Tract	2036		15121	
Pescadero	2058		12590	
Pierson District	551		31370	
Prospect Island	1667		11880	
Quimby Island	2090		9360	
Rindge Tract	2037		52066	
Rio Blanco Tract	2114		6445	
Roberts Island	-		56009	
Roberts, Lower	684		-	
Roberts, Middle	524		-	
Roberts, Upper	544		-	
Rough and Ready Island	-		33761	
Ryer Island	501		20858	
Sargent Barnhart Tract	2074		36098	
Sherman Island	341		25116	
Shima Tract	2115		11124	
Shin Kee Tract	-		14435	
Smith	1614			
Stark	2089		34792	
Staten Island	38		42439	
Stewart Tract	2062		84163	
Sutter Island	349		42610	
Terminous	548		27758	
Twitchell	1601		32928	
Tyler Island	563		58484	
Walnut Grove	554		-	
Union Island	1,2		51908	
Van Sickle Island	1607			
Veale Tract	2065		9598	
Venice Island	2023		21445	
Victoria Island	2040		38151	
Webb Tract	2026		35543	
Weber	828			
Winter Island	2122			
Woodward Island	2072		36099	
Wright-Elmwood Tract	2119		42989	
-	307			
-	369			
-	536			
-	765			
-	813			
-	900			
-	999			
-	1608			
-	2084			
-	2093			
-	2095			
-	2098			
-	2121			

ECOSYSTEM

ISLAND ATTRIBUTE	DATA SOURCE and NOTES
Native vegetation	DWR Land use mapping data. 1993.
Wetlands	U.S. Fish and Wildlife Service. 1995. National Wetland Inventory based on 1985 aerial photographs mapped at 1:124,000 scale. (NWI mapping data)
Riparian habitats	NWI mapping data
Agricultural waterfowl habitats	DWR Land use mapping data. 1993. Agricultural land classifications considered potential waterfowl habitat are grain and hay crops (barley, wheat, oats, miscellaneous and mixed hay and grain); field crops (safflower, flax, hops, sugar beets, corn [field or sweet], grain sorghum); and rice.
Known special-status plant occurrences	Natural Diversity Database. 1996. Records search for the Bay-Delta study area. California Department of Fish and Game. Sacramento, CA. (NDDB) California Department of Fish and Game. 1995. SB 34 Delta Levees Master Environmental Assessment. Sacramento, CA. (SB 34 MEA) Data for the "Habitat and Special-Status Species Interior to Levee Systems" category was compiled from the Natural Diversity Database and California Department of Fish and Game's SB 34 Delta Levees Master Environmental Assessment. Species locations were reconciled (cross-referenced) in order to eliminate duplicative data. The information on special-status plant and wildlife occurrences in the Delta depends on whether an area has been surveyed and results have been reported. Therefore, the lack of an occurrence on an island does not preclude the presence of special-status plants and wildlife.
Known special-status wildlife occurrences	NDDB and SB 34 MEA See above notes.

Ecosystem attribute data (acreages and species occurrences) have been presented in three ways: totals for each island, resources interior to the levee system, and resources on the exterior (water side) of the island levees. The attribute data are divided this way to distinguish those resources that are protected by the existing levee system (interior to the levee system) and those resources exterior to the system. This distinction was used in ranking the islands for the Special Projects prioritization exercise.

		Island Total							
						Known Special-Status Plant Occurrences (by 1995)		Known Special-Status Wildlife Occurrences (by 1995)	
ISLAND	Reclamation District	Native Vegetation (Acres)	Wetlands (Acres)	Riparian Habitats (Acres)	Agricultural Waterfowl Habitats (Acres)	# species	# occurences	# species	# occurences
Bacon Island	2028	360.3	0.0	7.2	1112.7	4	48	3	9
Bethel Island	-	344.7	2.4	90.9	0	4	19	1	1
Bishop Tract	2042	103.1	7.8	1.7	817.5	1	1	1	1
Boggs (Moss Tract)	404	183.5	3.4	62.5	0.0				
Bouldin Island	756	217.4	0.3	5.3	5348.9	5	46	4	5
Brack Tract	2033	196.0	8.3	0.0	1263.7	2	7	3	15
Bradford Island	2059	171.1	0.0	14.8	0.0	2	5		
Brannan/Andrus Island	-	-	-	-	-	6	48	3	7
Andrus	317	138.0	7.7	5.6	2723.4	-	-	-	-
Andrus, Isleton	407	138.6	24.1	0.0	947.7	-	-	-	-
Andrus, Upper	556	157.1	0.0	1.7	873.3	-	-	-	-
Brannan	2067	475.5	26.5	15.6	4691.5	-	-	-	-
Byron Tract	800	874.3	54.9	0.6	1280.8	7	17	2	5
Canal Ranch	2086	179.4	18.5	0.0	2255.8	4	9	2	8
Coney Island	2117	84.4	2.5	1.6	658.1	2	8	1	3
Dead Horse Island	2111	28.8	0.0	0.0	0.0	1	5	1	1
Empire Tract	2029	178.6	16.2	14.7	2159.9	4	15	2	2
Fabian Tract	773	339.6	13.0	38.6	1003.8	2	9	3	10
Fay	2113	31.4	0.0	2.7	63.9	2	5	1	1
Glanville Tract	1002	298.5	100.9	39.8	1212.1	4	9	3	3
Grand Island	3	666.6	37.3	28.8	7901.0		...	1	2
Hastings Tract	2060	385.0	82.2	0.0	503.3	2	3		
Holland Tract	2025	384.0	15.8	31.0	2923.7	4	39	2	2
Holt Station	2116	2.9	0.9	0.0	113.6				
Hotchkiss Tract	799	746.5	4.7	44.5	185.4	2	11	2	2
Jersey Island	830	697.5	16.8	58.3	0.0				
Jones Tract	-	-	-	-	-	-	-	-	-
Jones, Lower	2038	167.6	0.0	1.1	2458.4	4	14	2	3
Jones, Upper	2039	406.1	5.5	0.0	2447.7	4	15	3	4
King Island	2044	115.0	0.0	0.0	2819.3				
Little Mandeville	2118	50.3	0.0	7.6	269.2				
Mandeville Island	2027	336.1	85.7	41.9	501.6	3	20	1	1
McCormack Williamson Tr	2110	66.7	0.0	8.5	180.7	4	18	1	5
McDonald Island	2030	395.2	76.8	14.2	1537.6	4	16	2	2
Medford Island	2041	64.7	3.2	17.4	328.8	2	4	3	3
Merritt Island	150	238.5	0.0	1.0	1007.5			1	2
Mildred Island	2021	151.9	0.0	0.0	-	1	1		
Naglee Burke	1007	0.0	0.0	0.0	-			1	1
New Hope Tract	348	303.0	54.5	4.7	3905.7	1	12	4	17
Orwood Island	2024	212.3	0.0	4.7	596.2	2	4		
Palm Tract	2036	205.6	0.6	0.0	1882.4	3	17	2	5
Pescadero	2058	304.9	10.5	24.2	873.4			2	6
Pierson District	551	277.7	64.4	24.7	2012.2	2	6	3	5
Prospect Island	1667	418.4	3.3	3.4	389.0	2	3		
Quimby Island	2090	139.4	0.0	14.2	303.2	4	7		
Rindge Tract	2037	347.3	0.0	0.6	3075.4	3	26	1	1
Rio Blanco Tract	2114	94.5	17.1	14.4	422.4			1	1
Roberts Island	-	-	-	-	-	3	9	4	23
Roberts, Lower	684	303.8	26.7	10.0	4947.3	-	-	-	-
Roberts, Middle	524	177.3	8.8	24.8	4589.8	-	-	-	-
Roberts, Upper	544	207.1	9.9	7.4	3141.5	-	-	-	-
Rough and Ready Island	-	233.9	64.6	118.7	358.0	1	2		
Ryer Island	501	317.8	6.0	12.3	6178.8				
Sargent Barnhart Tract	2074	41.6	4.3	9.3	155.1	1	1		
Sherman Island	341	381.9	40.6	2.4	1772.4	5	65	5	6
Shima Tract	2115	103.1	0.0	0.0	442.0	2	3	1	2
Shin Kee Tract	-	26.7	0.2	0.0	605.2	1	1	2	2
Smith	1614	24.3	0.0	38.3	0.0				
Stark	2089	85.9	9.4	8.8	339.5	1	2	2	4
Staten Island	38	250.1	0.0	2.4	8397.9	7	26	3	11
Stewart Tract	2062	233.9	42.9	17.2	1115.9				
Sutter Island	349	223.5	0.0	0.0	494.1				
Terminous	548	648.0	181.5	4.4	7859.6	5	19	4	8
Twitchell	1601	236.7	0.0	4.6	832.1	4	5		
Tyler Island	563	403.6	10.2	1.4	5599.8	3	4	3	5
Walnut Grove	554	23.8	0.0	0.0	137.8	-	-	-	-
Union Island	1,2	645.0	8.9	46.7	8391.0	4	29	4	11
Van Sickle Island	1607	0.0	0.0	0.0	0.0	4	14	1	1
Veale Tract	2065	161.1	5.2	0.0	926.2				
Venice Island	2023	295.0	3.2	68.9	1311.9	3	7	1	1
Victoria Island	2040	265.6	1.7	0.0	2097.6	4	34	1	3
Webb Tract	2026	400.6	76.7	92.9	1332.8	5	33		
Weber	828	0.0	0.0	3.9	898.1				
Winter Island	2122	N/D	N/D	N/D	0.0				
Woodward Island	2072	143.0	0.1	0.0	0.0	2	22	3	4
Wright-Elmwood Tract	2119	122.9	0.1	7.7	0.0	1	1		
-	307	199.7	10.9	6.0	1264.7				
-	369	73.9	156.8	139.5	0.0				
-	536	1179.4	78.9	0.3	807.6				
-	765	96.2	4.8	11.2	426.6				
-	813	90.9	9.3	1.7	405.9				
-	900	687.7	70.7	21.8	1740.2				
-	999	652.6	33.6	23.3	8779.4				
-	1608	0.0	0.1	0.0	0.0				
-	2084	205.4	1.1	5.7	1005.6				
-	2093	240.8	39.6	12.5	3087.3				
-	2095	226.9	69.7	74.9	1111.8				
-	2098	1265.8	857.0	5.8	1350.4				
-	2121	10.3	45.6	0.4	261.9				

		Interior to Levee						
					Known Special-Status Plant Occurrences (by 1995)		Known Special-Status Wildlife Occurrences (by 1995)	
ISLAND	Reclamation District	Native Vegetation (Acres)	Wetlands (Acres)	Riparian Habitats (Acres)	# species	# occurences	# species	# occurences
Bacon Island	2028	280.5	0.0	6.8	1	1	1	1
Bethel Island	-	326.7	2.4	90.7			1	1
Bishop Tract	2042	70.2	6.7	1.1			1	1
Boggs (Moss Tract)	404	158.2	3.4	61.9				
Bouldin Island	756	144.2	0.0	5.3				
Brack Tract	2033	106.3	8.3	0.0	1	2	2	8
Bradford Island	2059	121.9	0.0	14.8				
Brannan/Andrus Island	-	-	-	-	3	6	2	2
Andrus	317	67.5	6.2	2.2	-	-	-	-
Andrus, Isleton	407	44.2	23.9	0.0	-	-	-	-
Andrus, Upper	556	8.6	0.0	0.0	-	-	-	-
Brannan	2067	124.9	21.6	5.7	-	-	-	-
Byron Tract	800	836.5	54.7	0.3	6	7	1	3
Canal Ranch	2086	132.1	18.5	0.0			2	6
Coney Island	2117	35.4	1.6	1.4				
Dead Horse Island	2111	10.1	0.0	0.0				
Empire Tract	2029	106.2	18.2	14.6				
Fabian Tract	773	124.4	10.9	10.0				
Fay	2113	18.4	0.0	2.7				
Glanville Tract	1002	239.0	55.7	11.3				
Grand Island	3	256.7	37.3	13.2	2	3	1	1
Hastings Tract	2060	266.8	80.3	0.0				
Holland Tract	2025	310.9	15.7	31.0			1	1
Holt Station	2116	2.2	0.8	0.0				
Hotchkiss Tract	799	723.5	4.3	44.5				
Jersey Island	830	574.6	16.3	51.6				
Jones Tract	-	-	-	-	-	-	-	-
Jones, Lower	2038	95.6	0.0	1.1			1	1
Jones, Upper	2039	312.7	2.4	0.0				
King Island	2044	51.2	0.0	0.0				
Little Mandeville	2118	33.4	0.0	5.8				
Mandeville Island	2027	291.3	85.6	13.7				
McCormack Williamson Tr	2110	34.1	0.0	6.6				
McDonald Island	2030	223.1	76.8	10.9				
Medford Island	2041	67.9	2.3	16.2			1	1
Merritt Island	150	117.1	0.0	0.0				
Mildred Island	2021	100.2	0.0	0.0				
Naglee Burke	1007	0.0	0.0	0.0				
New Hope Tract	348	236.1	52.9	4.2			1	1
Orwood Island	2024	158.7	0.0	3.3				
Palm Tract	2036	148.9	0.0	0.0				
Pescadero	2058	164.6	8.7	8.4			2	4
Pierson District	551	124.6	25.8	3.6				
Prospect Island	1667	368.4	2.6	0.2	1	1		
Quimby Island	2090	120.6	0.0	13.6				
Rindge Tract	2037	232.8	0.0	0.5				
Rio Blanco Tract	2114	76.7	16.6	4.7				
Roberts Island	-	-	-	-			2	6
Roberts, Lower	684	173.5	21.4	4.7	-	-	-	-
Roberts, Middle	524	99.6	8.8	1.3	-	-	-	-
Roberts, Upper	544	47.8	0.7	4.2	-	-	-	-
Rough and Ready Island	-	201.2	80.7	113.0				
Ryer Island	501	66.7	4.5	0.4				
Sargent Barnhart Tract	2074	19.4	1.2	8.3				
Sherman Island	341	167.4	0.0	2.0			2	2
Shima Tract	2115	64.7	0.0	0.0				
Shin Kee Tract	-	3.7	.0.1	0.0	1	1		
Smith	1614	12.1	0.0	1.9				
Stark	2089	47.7	8.3	0.4				
Staten Island	38	138.5	0.0	0.9	2	2	1	6
Stewart Tract	2062	105.9	2.6	3.6	2	2	2	2
Sutter Island	349	104.7	0.0	0.0				
Terminous	548	517.3	174.9	4.4			1	1
Twitchell	1601	141.6	0.0	4.5				
Tyler Island	563	50.7	9.9	0.5			1	1
Walnut Grove	554	11.9	0.0	0.0	-	-	-	-
Union Island	1,2	398.2	7.0	42.8	2	2	3	5
Van Sickle Island	1607	0.0	0.0	0.0				
Veale Tract	2065	125.6	4.4	0.0				
Venice Island	2023	218.0	3.2	66.5				
Victoria Island	2040	140.6	0.0	0.0				
Webb Tract	2026	337.9	78.7	84.3				
Weber	828	0.0	0.0	3.9				
Winter Island	2122	n/d	n/d	n/d				
Woodward Island	2072	79.8	0.0	0.0				
Wright-Elmwood Tract	2119	67.4	0.0	7.5				
-	307	153.5	10.9	1.2				
-	369	63.6	15.6	16.3				
-	536	1154.5	78.9	0.0				
-	765	85.4	4.8	0.0				
-	813	57.3	9.1	0.0				
-	900	531.2	66.5	17.6				
-	999	420.2	28.4	18.6				
-	1608	0.0	0.0	0.0				
-	2084	161.6	1.1	5.7				
-	2093	140.3	21.9	2.8				
-	2095	191.5	60.3	63.2				
-	2098	1229.0	644.8	0.0				
-	2121	10.2	43.7	0.0				

		Exterior to Levee						
					Known Special-Status Plant Occurrences (by 1995)		Known Special-Status Wildlife Occurrences (by 1995)	
ISLAND	Reclamation District	Native Vegetation (Acres)	Wetlands (Acres)	Riparian Habitats (Acres)	# species	# occurences	# species	# occurences
Bacon Island	2028	99.7	0.0	0.4	4	47	2	8
Bethel Island	-	18.0	0.0	0.2	4	19		
Bishop Tract	2042	32.9	0.9	0.5	1	1		
Boggs (Moss Tract)	404	35.3	0.0	0.7				
Bouldin Island	756	73.2	0.3	0.0	5	46	4	5
Brack Tract	2033	89.6	0.0	0.0	2	5	2	7
Bradford Island	2059	49.2	0.0	0.0	2	5		
Brannan/Andrus Island	-	-	-	-	6	40	3	5
Andrus	317	68.5	1.5	3.3	-	-	-	-
Andrus, Isleton	407	94.5	0.2	0.0	-	-	-	-
Andrus, Upper	556	148.5	0.0	1.7	-	-	-	-
Brannan	2067	350.6	10.0	2067	-	-	-	-
Byron Tract	800	37.8	0.2	0.3	3	10	1	2
Canal Ranch	2086	47.3	0.0	0.0	4	9	1	2
Coney Island	2117	49.0	0.7	0.2	2	8	1	3
Dead Horse Island	2111	18.7	0.0	0.0	1	5	1	1
Empire Tract	2029	70.4	0.0	0.1	4	15	2	2
Fabian Tract	773	215.1	2.1	28.6	2	9	3	10
Fay	2113	13.1	0.0	0.0	2	5	1	1
Glanville Tract	1002	59.5	45.3	28.3	4	9	3	3
Grand Island	3	410.0	0.0	15.6			1	1
Hastings Tract	2060	118.2	1.9	0.0	2	3		
Holland Tract	2025	73.1	0.1	0.0	4	39	1	1
Holt Station	2116	0.7	0.2	0.0				
Hotchkiss Tract	799	23.1	0.4	0.0	2	11	2	2
Jersey Island	830	122.9	0.5	6.6				
Jones Tract	-	-	-	-	-	-	-	-
Jones, Lower	2038	72.0	0.0	0.0	4	14	1	2
Jones, Upper	2039	93.3	31.4	0.0	4	15	3	4
King Island	2044	63.8	0.0	0.0				
Little Mandeville	2118	17.0	0.0	1.8				
Mandeville Island	2027	44.8	0.1	28.2	3	20	1	1
McCormack Williamson Tr	2110	32.6	0.0	1.9	4	18	1	6
McDonald Island	2030	172.1	0.0	3.3	4	16	2	2
Medford Island	2041	16.8	0.9	1.1	2	4	2	2
Merritt Island	150	121.4	0.0	1.0			1	2
Mildred Island	2021	51.7	0.0	0.0	1	1		
Naglee Burke	1007	0.0	0.0	0.0			1	1
New Hope Tract	348	66.9	1.6	0.5	1	12	4	16
Orwood Island	2024	53.6	0.0	1.3	2	4		
Palm Tract	2036	56.7	0.6	0.0	3	17	2	5
Pescadero	2058	140.3	1.8	17.8			1	2
Pierson District	551	153.0	38.6	21.1	2	6	3	5
Prospect Island	1667	50.0	0.7	3.2	2	2		
Quimby Island	2090	18.8	0.0	0.8	4	7		
Rindge Tract	2037	114.6	0.0	0.1	3	26	1	1
Rio Blanco Tract	2114	17.8	0.5	9.7			1	1
Roberts Island	-	-	-	-	3	9	4	17
Roberts, Lower	684	130.2	5.3	5.2	-	-	-	-
Roberts, Middle	524	77.7	0.1	23.5	-	-	-	-
Roberts, Upper	544	159.3	9.2	3.2	-	-	-	-
Rough and Ready Island	-	32.7	3.9	5.7	1	2		
Ryer Island	501	251.1	1.5	11.9				
Sargent Barnhart Tract	2074	22.2	3.1	0.9	1	1		
Sherman Island	341	214.5	40.6	0.4	5	65	3	4
Shima Tract	2115	38.4	0.0	0.0	2	3	1	2
Shin Kee Tract	-	23.0	0.1	0.0			2	2
Smith	1614	12.2	0.0	36.3				
Stark	2089	38.2	1.1	8.4	1	2	2	4
Staten Island	38	111.7	0.0	1.5	7	24	3	5
Stewart Tract	2062	127.9	40.4	13.6				
Sutter Island	349	118.6	0.0	0.0				
Terminous	548	130.7	6.6	0.0	5	19	4	7
Twitchell	1601	95.1	0.0	0.0	4	5		
Tyler Island	563	353.0	0.3	0.9	3	4	2	4
Walnut Grove	554	11.9	0.0	0.0	-	-	-	-
Union Island	1,2	246.8	1.9	3.9	4	27	2	6
Van Sickle Island	1607	0.0	0.0	0.0	4	14	1	1
Veale Tract	2065	35.5	0.8	0.0				
Venice Island	2023	49.0	0.0	0.3	3	7	1	1
Victoria Island	2040	125.0	1.7	0.0	4	34	1	3
Webb Tract	2026	62.7	0.0	8.6	5	33		
Weber	828	0.0	0.0	0.0				
Winter Island	2122	n/d	n/d	n/d				
Woodward Island	2072	83.2	0.1	0.0	2	22	3	4
Wright-Elmwood Tract	2119	55.6	0.1	0.1	1	1		
-	307	46.2	0.0	4.8				
-	369	10.3	141.2	121.2				
-	536	24.9	0.0	0.3				
-	765	10.8	0.0	11.2				
-	813	33.6	0.2	1.7				
-	900	156.5	4.2	4.2				
-	999	432.3	5.1	4.7				
-	1608	0.0	0.1	0.0				
-	2084	43.8	0.0	0.1				
-	2093	100.5	17.7	9.7				
-	2095	37.4	9.4	11.7				
-	2098	36.8	12.2	5.8				
-	2121	0.1	1.8	0.4				
		432 2915	141.1941	121.199				

ISLAND		Swainson's Hawk	Giant Garter Snake	Western Pond Turtle	Burrowing Owl	San Joaquin Pocket Mouse	California Black Rail	Greater Sandhill Crane	Valley Elderberry Longhorn Beetle	San Joaquin Kit Fox	Lange's Metalmark Butterfly	Tri-colored Blackbird	Great Blue Heron	Salt Marsh Harvest Mouse	Sacramento Anthicid Beetle	California Least Tern	Antioch Dunes Anthicid Beetle	White-tailed Kite	Double Crested Cormorant
		Known Special-Status Wildlife Occurrences Interior to Levee Systems (by 1995)																	
Bacon Island					1														
Bethel Island					1														
Bishop Tract		1																	
Bouldin Island																			
Brack Tract					1			7											
Bradford Island																			
Brannan Island		1													1				
Byron Tract					3														
Canal Ranch		1						5											
Coney Island																			
Dead Horse Island																			
Decker Island																			
Empire Tract																			
Fabian Tract																			
Fay																			
Glanville Tract																			
Grand Island		1																	
Hastings Tract																			
Holland Tract												1							
Hotchkiss Tract																			
Jersey Island																			
Jones, Lower					1														
Jones, Upper																			
King Island																			
Mandeville Island																			
McCormack Williamson Tract																			
McDonald Island																			
Medford Island		1																	
Merritt Island																			
Mildred Island																			
Naglee Burke																			
New Hope Tract		1																	
Orwood Island																			
Palm Tract																			
Pescadero		3										1							
Pierson District																			
Prospect Island																			
Quimby Island																			
Rindge Tract																			
Rio Blanco Tract																			
Roberts Island	f	5			1														
Rough and Ready Island																			
Ryer Island																			
Sargent Barnhart Tract																			
Sherman Island								1											1
Shima Tract																			
Shin Kee Tract																			
Stark																			
Staten Island								6											
Stewart Tract		1										1							
Sutter Island																			
Terminous			1																
Twitchell																			
Tyler Island								1											
Union Island	g	3				1			1										
Van Sickle Island																			
Veale Tract																			
Venice Island																			
Victoria Island																			
Webb Tract																			
Woodward Island																			
Wright-Elmwood Tract																			

Known Special-Status Plant Occurrences Interior to Levee Systems (by 1995)

ISLAND	Mason's Lilaeopsis	Delta Tule Pea	California Hibiscus	Elderberry Bush	Suisun Marsh Aster	Delta Button Celery	Caper Fruited Tropidocarpum	Recurved Larkspur	Delta Mudwort	Sanford's Arrowhead	Antioch Dunes Evening Primrose	Carquinez Goldenbush	Brittlescale	San Joaquin Saltbush	Soft Bird's Beak	Slough Thistle	Marsh Skullcap
Bacon Island			1														
Bethel Island																	
Bishop Tract																	
Bouldin Island																	
Brack Tract			2														
Bradford Island																	
Brannan Island	2				2						2						
Byron Tract			1				2	1				1	1	1			
Canal Ranch																	
Coney Island																	
Dead Horse Island																	
Decker Island																	
Empire Tract																	
Fabian Tract																	
Fay																	
Glanville Tract																	
Grand Island	2	1															
Hastings Tract																	
Holland Tract																	
Hotchkiss Tract																	
Jersey Island																	
Jones, Lower																	
Jones, Upper																	
King Island																	
Mandeville Island																	
McCormack Williamson Tract																	
McDonald Island																	
Medford Island																	
Merritt Island																	
Mildred Island																	
Naglee Burke																	
New Hope Tract																	
Orwood Island																	
Palm Tract																	
Pescadero																	
Pierson District																	
Prospect Island		1															
Quimby Island																	
Rindge Tract																	
Rio Blanco Tract																	
Roberts Island																	
Rough and Ready Island																	
Ryer Island																	
Sargent Barnhart Tract																	
Sherman Island																	
Shima Tract																	
Shin Kee Tract			1														
Stark																	
Staten Island		1	1														
Stewart Tract						1										1	
Sutter Island																	
Terminous																	
Twitchell																	
Tyler Island																	
Union Island			1	1													
Van Sickle Island																	
Veale Tract																	
Venice Island																	
Victoria Island																	
Webb Tract																	
Woodward Island																	
Wright-Elmwood Tract																	

ISLAND		Mason's Lilaeopsis	Delta Tule Pea	California Hibiscus	Elderberry Bush	Suisun Marsh Aster	Delta Button Celery	Caper Fruited Tropidocarpum	Recurved Larkspur	Delta Mudwort	Sanford's Arrowhead	Antioch Dunes Evening Primrose	Carquinez Goldenbush	Brittlescale	San Joaquin Saltbush	Soft Bird's Beak	Marsh Skullcap
		Known Special-Status Plant Occurrences (by 1995)															
Bacon Island		22		16		8				2							
Bethel Island		7		2		4				6							
Bishop Tract				1													
Bouldin Island		10	9	6		18				3							
Brack Tract		4		3													
Bradford Island		3				2											
Brannan Island		10	11		6	12				2		5					
Byron Tract		4		5				4	1				1	1	1		
Canal Ranch		3	2	3						1							
Coney Island		5		3													
Dead Horse Island					5												
Decker Island																	
Empire Tract		3		5		6				1							
Fabian Tract		8			1												
Fay		4		1													
Glanville Tract		1	3	4	1												
Grand Island		2	1														
Hastings Tract		2				1											
Holland Tract		16		12		10											1
Hotchkiss Tract		8								3							
Jersey Island																	
Jones, Lower		6	1	6						1							
Jones, Upper		6	4	4													1
King Island																	
Mandeville Island		11		2		7											
McCormack Williamson Tract		1	5	1	11												
McDonald Island		2		6	2	6											
Medford Island		3				1											
Merritt Island																	
Mildred Island							1										
Naglee Burke																	
New Hope Tract					12												
Orwood Island		2		2													
Palm Tract		10		4		3											
Pescadero																	
Pierson District			2	4													
Prospect Island		1	2														
Quimby Island		3		2		1											1
Rindge Tract		7		8		11											
Rio Blanco Tract																	
Roberts Island	f		1	7		1											
Rough and Ready Island			2														
Ryer Island										1							
Sargent Barnhart Tract				1													
Sherman Island		35	2			25				2						1	
Shima Tract		2		1													
Shin Kee Tract				1													
Stark					2												
Staten Island		9	4	3	3	1				5							1
Stewart Tract							1										
Sutter Island																	
Terminous		3	2	3		9				2							
Twitchell		1	1			1						2					
Tyler Island		2	1								1						
Union Island	g	4		12	10		3										
Van Sickle Island		2	6			5				1							
Veale Tract																	
Venice Island		2		1		4											
Victoria Island		8	5	20													1
Webb Tract		9	2	5		13				4							
Woodward Island		10		12													
Wright-Elmwood Tract				1													

Known Special-Status Plant Occurrences Exterior to Levee Systems (by 1995)

ISLAND		Mason's Lilaeopsis	Delta Tule Pea	California Hibiscus	Elderberry Bush	Suisun Marsh Aster	Delta Button Celery	Caper Fruited Tropidocarpum	Recurved Larkspur	Delta Mudwort	Sanford's Arrowhead	Antioch Dunes Evening Primrose	Carquinez Goldenbush	Brittlescale	San Joaquin Saltbush	Soft Bird's Beak	Slough Thistle	Marsh Skullcap
Bacon Island		22		15		8				2								
Bethel Island		7		2		4				6								
Bishop Tract				1														
Bouldin Island		10	9	6		18				3								
Brack Tract		4		1														
Bradford Island		3				2												
Brannan Island		8	11		8	10				2		3						
Byron Tract		4		4				2										
Canal Ranch		3	2	3						1								
Coney Island		5		3														
Dead Horse Island					5													
Decker Island																		
Empire Tract		3		5		6				1								
Fabian Tract		8			1													
Fay		4		1														
Glanville Tract		1	3	4	1													
Grand Island																		
Hastings Tract		2				1												
Holland Tract		16		12		10												1
Hotchkiss Tract		8								3								
Jersey Island																		
Jones, Lower		6	1	6						1								
Jones, Upper		6	4	4														1
King Island																		
Mandeville Island		11		2		7												
McCormack Williamson Tract		1	5	1	11													
McDonald Island		2		6	2	6												
Medford Island		3				1												
Merritt Island																		
Mildred Island							1											
Naglee Burke																		
New Hope Tract					12													
Orwood Island		2		2														
Palm Tract		10		4		3												
Pescadero																		
Pierson District			2	4														
Prospect Island		1	1															
Quimby Island		3		2		1												1
Rindge Tract		7		8		11												
Rio Blanco Tract																		
Roberts Island	f		1	7		1												
Rough and Ready Island			2															
Ryer Island										1								
Sargent Barnhart Tract				1														
Sherman Island		35	2			25				2						1		
Shima Tract		2		1														
Shin Kee Tract																		
Stark					2													
Staten Island		9	3	2	3	1				5								1
Stewart Tract																		
Sutter Island																		
Terminous		3	2	3		9				2								
Twitchell		1	1			1						2						
Tyler Island		2	1								1							
Union Island	g	4		11	9		3											
Van Sickle Island		2	8			5				1								
Veale Tract																		
Venice Island		2		1		4												
Victoria Island		8	5	20														1
Webb Tract		9	2	5		13				4								
Woodward Island		10		12														
Wright-Elmwood Tract				1														

Known Special-Status Wildlife Occurrences Exterior to the Levee Systems (by 1995)

ISLAND		Swainson's Hawk	Giant Garter Snake	Western Pond Turtle	Burrowing Owl	San Joaquin Pocket Mouse	California Black Rail	Greater Sandhill Crane	Valley Elderberry Longhorn Beetle	San Joaquin Kit Fox	Lange's Metalmark Butterfly	Tri-colored Blackbird	Great Blue Heron	Salt Marsh Harvest Mouse	Sacramento Anthicid Beetle	California Least Tern	Antioch Dunes Anthicid Beetle	White-tailed Kite	Double Crested Cormorant
Bacon Island				2			6												
Bethel Island																			
Bishop Tract																			
Bouldin Island				1	1		2	1											
Brack Tract		1						6											
Bradford Island																			
Brannan Island		2													2		1		
Byron Tract				2															
Canal Ranch								2											
Coney Island		3																	
Dead Horse Island									1										
Decker Island																			
Empire Tract					1		1												
Fabian Tract		8	1	1															
Fay							1												
Glanville Tract		1			1				1										
Grand Island		1																	
Hastings Tract																			
Holland Tract							1												
Hotchkiss Tract					1					1									
Jersey Island																			
Jones, Lower							2												
Jones, Upper				1			2								1				
King Island																			
Mandeville Island							1												
McCormack Williamson Tract									5										
McDonald Island							1		1										
Medford Island							1		1										
Merritt Island		2																	
Mildred Island																			
Naglee Burke					1														
New Hope Tract		9	1				1		5										
Orwood Island																			
Palm Tract				1			4												
Pescadero		2																	
Pierson District		3	1															1	
Prospect Island																			
Quimby Island																			
Rindge Tract									1										
Rio Blanco Tract					1														
Roberts Island	f	8			1				5			3							
Rough and Ready Island																			
Ryer Island																			
Sargent Barnhart Tract																			
Sherman Island			1								2				1				
Shima Tract		2																	
Shin Kee Tract			1				1												
Stark		2		2															
Staten Island				2				2	1										
Stewart Tract																			
Sutter Island																			
Terminous			2		1		3	1											
Twitchell																			
Tyler Island		2							2										
Union Island	g	4	2																
Van Sickle Island				1															
Veale Tract																			
Venice Island													1						
Victoria Island				3															
Webb Tract																			
Woodward Island				1			2								1				
Wright-Elmwood Tract																			

ISLAND	Swainson's Hawk	Giant Garter Snake	Western Pond Turtle	Burrowing Owl	San Joaquin Pocket Mouse	California Black Rail	Greater Sandhill Crane	Valley Elderberry Longhorn Beetle	San Joaquin Kit Fox	Lance's Metalwork Butterfly	Tri-colored Blackbird	Great Blue Heron	Sacramento Anthicid Beetle	California Least Tern	Antioch Dunes Anthicid Beetle	White-tailed Kite	Double Crested Cormorant
Known Special-Status Widlife Occurrences (by 1995)																	
Bacon Island			2	1		6											
Bethel Island				1													
Bishop Tract	1																
Bouldin Island			1	1		2	1										
Brack Tract	1			1			13										
Bradford Island																	
Brannan Island	3												3		1		
Byron Tract			2	3													
Canal Ranch	1						7										
Coney Island	3																
Dead Horse Island								1									
Decker Island																	
Empire Tract				1		1											
Fabian Tract	6	1	1														
Fay						1											
Glanville Tract	1			1				1									
Grand Island	2																
Hastings Tract																	
Holland Tract						1					1						
Hotchkiss Tract				1					1								
Jersey Island																	
Jones, Lower				1		2											
Jones, Upper			1			2							1				
King Island																	
Mandeville Island						1											
McCormack Williamson Tract								5									
McDonald Island						1		1									
Medford Island	1					1		1									
Merritt Island	2																
Mildred Island																	
Naglee Burke				1													
New Hope Tract	10	1				1		5									
Orwood Island																	
Palm Tract			1			4											
Pescadero	5										1						
Pierson District	3	1														1	
Prospect Island																	
Quimby Island																	
Rindge Tract								1									
Rio Blanco Tract				1													
Roberts Island	13			2				5			3						
Rough and Ready Island																	
Ryer Island																	
Sargent Barnhart Tract																	
Sherman Island		1					1			2			1				1
Shima Tract	2																
Shin Kee Tract		1				1											
Stark	2		2														
Staten Island			2				8	1									
Stewart Tract	1										1						
Sutter Island																	
Terminous		3		1		3	1										
Twitchell																	
Tyler Island	2						1	2									
Union Island	7	2			1			1									
Van Sickle Island			1														
Veale Tract																	
Venice Island												1					
Victoria Island			3														
Webb Tract																	
Woodward Island			1			2							1				
Wright-Elmwood Tract																	

USGS 1

ISLAND	Reclamation District	USGS Quad
Bacon Island	2028	Bouldin Island, Woodward Island
Bethel Island	-	Bouldin Island, Jersey Island
Bishop Tract	2042	Terminous
Boggs (Moss Tract)	404	Stockton West
Bouldin Island	756	Bouldin Island, Isleton, Terminous
Brack Tract	2033	Thornton
Bradford Island	2059	Jersey Island
Brannan/Andrus Island	-	
Andrus	317	Bouldin Island, Isleton
Andrus, Isleton	407	Isleton
Andrus, Upper	556	Isleton
Brannan	2067	Rio Vista, Jersey Island
Byron Tract	800	Clifton Court Forebay, Woodward Island
Canal Ranch	2086	Thornton
Coney Island	2117	Clifton Court Forebay
Dead Horse Island	2111	Thornton
Empire Tract	2029	Terminous
Fabian Tract	773	Clifton Court Forebay, Union Island
Fay	2113	Woodward Island
Glanville Tract	1002	Bruceville
Grand Island	3	Rio Vista, Courtland, Isleton
Hastings Tract	2060	Dozier, Liberty Island
Holland Tract	2025	Bouldin Island, Woodward Island
Holt Station	2116	Holt
Hotchkiss Tract	799	Jersey Island
Jersey Island	830	Jersey Island
Jones Tract	-	
Jones, Lower	2038	Woodward Island, Holt
Jones, Upper	2039	Woodward Island, Holt
King Island	2044	Terminous
Little Mandeville	2118	Bouldin Island
Mandeville Island	2027	Bouldin Island
McCormack Williamson Tr	2110	Bruceville
McDonald Island	2030	Bouldin Island, Woodward Island, Holt, Terminous
Medford Island	2041	Bouldin Island
Merritt Island	150	Clarksburg, Courtland
Mildred Island	2021	Woodward Island
Naglee Burke	1007	Union Island
New Hope Tract	348	Bruceville, Thornton
Orwood Island	2024	Woodward Island
Palm Tract	2036	Woodward Island
Pescadero	2058	Lathrop, Union Island
Pierson District	551	Courtland
Prospect Island	1667	Rio Vista, Liberty Island
Quimby Island	2090	Bouldin Island
Rindge Tract	2037	Holt, Terminous

USGS 2

ISLAND	Reclamation District	USGS Quad
Rio Blanco Tract	2114	Terminous
Roberts Island	-	
Roberts, Lower	684	Holt
Roberts, Middle	524	Stockton West, Holt
Roberts, Upper	544	Lathrop, Union Island, Holt
Rough and Ready Island	-	Stockton West
Ryer Island	501	Rio Vista, Liberty Island, Courtland, Isleton
Sargent Barnhart Tract	2074	Stockton West
Sherman Island	341	Antioch North, Jersey Island
Shima Tract	2115	Lodi South, Terminous
Shin Kee Tract	-	Terminous
Smith	1614	Stockton West
Stark	2089	Union Island
Staten Island	38	Bouldin Island, Isleton, Thornton
Stewart Tract	2062	Stewart, Union Island
Sutter Island	349	Courtland
Terminous	548	Thornton, Terminous
Twitchell	1601	Jersey Island
Tyler Island	563	Isleton
Union Island	1, 2	Clifton Court Forebay, Woodward Island, Union Island, Holt
Van Sickle Island	1607	Honker Bay
Veale Tract	2065	Woodward Island
Venice Island	2023	Bouldin Island
Victoria Island	2040	Clifton Court Forebay, Woodward Island, Holt
Walnut Grove	554	Thornton, Isleton
Webb Tract	2026	Bouldin Island, Jersey Island
Weber	828	Stockton West
Winter Island	2122	Antioch North
Woodward Island	2072	Woodward Island
Wright-Elmwood Tract	2119	Stockton West, Lodi South, Holt, Terminous
-	307	Clarksburg
-	369	Thornton, Courtland
-	536	Rio Vista
-	765	Clarksburg
-	813	Courtland
-	900	Sacramento West
-	999	Clarksburg, Liberty Island, Courtland
-	1608	Lodi South, Stockton West
-	2084	Rio Vista
-	2093	Liberty Island
-	2095	Vernalis, Lathrop
-	2098	Liberty Island
-	2121	Woodward Island

APPENDIX E

SUBSIDENCE REPORTS

SUBSIDENCE AND LEVEE INTEGRITY IN THE SACRAMENTO-SAN JOAQUIN DELTA

By
The Subsidence Sub-Team
of the Levees and Channels Technical Team

DRAFT

December 16, 1998

Summary

Island subsidence has played a key role in bringing the Delta islands to where they are today; relatively tall levees (8 to 25 feet above sea level) protecting interiors (up to 22 feet) below sea-level. Island subsidence is an important issue in the Delta. The Subsidence Subteam, however, was tasked with addressing the relation of island subsidence to levee system integrity.

The risk to levee integrity from island subsidence has diminished because of improved levee maintenance practices and land management practices. Island subsidence rates have decreased, and levee construction techniques have improved. In addition, a zone of influence extending from the levee crest to some distance inland has been identified, beyond which interior island subsidence will not affect levee integrity. The levees lose ground elevation on their own due to the addition of levee material, but this is a very different process than island subsidence. This report addresses subsidence as it affects levee integrity within the zone of influence adjacent to levees.

Goal

The goals of the Subsidence element of the Levee Program are to reduce or eliminate the risk to levee integrity from subsidence, and assist in the coordination of subsidence-related linkages with the other CALFED programs.

Scope

The Long Term Levee Protection Plan focuses on subsidence that affects the levee system. This report describes Delta conditions, causes of subsidence, subsidence as it affects levee integrity, mitigation options related to levee integrity, and target areas for subsidence control based on the best available information. Subsidence issues, concerns, and solutions will also be addressed in the Ecosystem Restoration and Water Quality Programs.

Conditions In The Delta

Surface and subsurface materials. (References 5 through 12)

The present-day Delta deposits began to form during the end of the last glacial period, 7,000 to 11,000 years ago as sea level began to rise (Ref 4). As the Delta evolved, tributaries formed a series of channels, natural levees, berms, islands and sloughs. The major rivers and channels periodically incised, then were backfilled as the climate changed. Tules, reeds, and other fibrous aquatic plants growing at water level were preserved as peat beds when post glacial sea levels rose slowly and inundated the

Delta. Under natural conditions, the islands received fine- and coarse-grained sediments during river floods. As a result, the subsurface sedimentary profile generally contains inter-bedded layers of sand, silt, clay and peat of varying thickness. The complexity of subsurface conditions is reflected in the wide variety of surface soil types found throughout the delta. The surficial materials encountered in the Delta include mineral soils, mineral organic complexes, organic soils, and peat.

Ground surface elevations. (Reference 11, Delta Atlas)

Ground surface elevation varies throughout the Delta from the high ground along the levee crests to the low ground in the island interiors. Levee crest elevations generally range from about 8 to 25 feet above sea level. A significant portion of Delta land surface is below sea level. Lowest surface elevations are on the order of 22 feet below sea level. Refer to Figure 1 (based upon a 1974 survey) for an indication of the extent of land surface elevation below sea level. Updated ground surface elevation data is needed.

Island Subsidence and Levee Subsidence

Definition

Subsidence is a downward movement of the ground surface over time. For the purposes of this report, "Island subsidence" refers to the loss of interior Delta island ground surface elevation. The downward movement of the levee itself, generally due to an application of a load, is referred to as "levee subsidence." The causes and impacts of levee subsidence are much different than the causes and impacts of island subsidence, but the primary causes of both will be discussed here together because there is an overlap of contributing causes.

Causes of Island Subsidence and Levee Subsidence (References 1 through 12)

Island subsidence and levee subsidence in the Delta are mainly caused by near-surface processes including consolidation/settlement, shrinkage, and aerobic decomposition. Other near-surface causes of island and levee subsidence include anaerobic decomposition, wind erosion, and burning. Deep seated causes of subsidence include the withdrawal of oil, natural gas, and water, and tectonic activity. These causes were assumed to contribute little to present-day subsidence.

a) Consolidation/settlement: Consolidation/settlement occurs in response to an increase in load, such as when ground water is removed or when materials are deposited in an area by humans or nature. Consolidation due to levee building (increasing loads on foundation materials) is the primary cause of levee subsidence. Consolidation also occurs due to increased effective stress on underlying peat and decreased buoyant forces supporting peat as a result of incremental dewatering (Ref. 1).

b) Shrinkage: Shallow de-watering is considered a cause of island and levee subsidence because it leads directly to shrinkage and drying of soils above the water table, consolidation of soils just above the water table, and leads to aerobic decomposition of organic soils above the water table. The relative effect of each of these factors depends on the amount of organic matter in the soil, the depth of de-watering, and climate. With each incremental lowering of the water table, the contribution to island subsidence from shrinkage, consolidation, and oxidation are all high. With time, long-term island subsidence is sustained by oxidation. Shrinkage is governed by the initial moisture content and the organic matter content. Fine grained organic soils and peat can shrink 50% or more in volume.

c) Aerobic decomposition (microbial oxidation): Long-term island subsidence is sustained primarily by the microbial oxidation of soil organic carbon. The peat soils contain a complex mass of carbon. Microorganisms such as bacteria and fungi use it as an energy source resulting in peat decomposition and the release of carbon dioxide (CO_2) under drained, oxygen-rich conditions. Studies by the Department of Water Resources and the US Geological Survey (Deverel and Rojstaczer, 1996) demonstrate that the amount of oxidation is proportional to the soil temperature and moisture content.

Oxidation rates increase with temperature, higher pH, and higher organic matter content of the soil. There is an optimum moisture content for oxidation; oxidation decreases at very high and very low moisture contents. Drainage and tillage promote aerobic decomposition, but island subsidence is not substantially affected by crop type. Island subsidence due to oxidation will decrease with time as the organic matter content in the upper soil decreases and the relative percentage of mineral constituents increases. There does not appear to be a correlation between peat thickness and subsidence rates. There is a direct correlation between depth to the water table and the amount of subsidence due to microbial oxidation. The higher the water table, the less the island subsidence.

Levee Subsidence (Reference 4,12,13)

Most levee subsidence is caused by the weight of the levee fills compressing the foundation materials. The foundation materials underlying the levees vary throughout the Delta from various thicknesses of peat soils to mineral soils. Rate of levee building and foundation conditions govern levee subsidence rates and the total amount of subsidence. Geotechnical engineering fundamentals must be applied to safely and economically build new levees and rehabilitate existing levees founded on weak, compressible materials.

Regardless of load application to the levees, the levees settle with time. In the 1960's, a set of curves was developed for estimating crest settlement with respect to variables of peat thickness, height of levee, and age of levee. These curves were updated to incorporate recent data, and are included as Figures 8 and 9. These curves of predicted movement were compared with actual crest elevation measurements on selected islands, and results indicated that measured settlements were generally comparable to calculated values and ranged from 2 to 7 inches per year (Ref 5).

There is a great deal of information on the causes and effects of interior island subsidence, but interior island subsidence has never been directly linked in publications to levee subsidence. A recent Corps of Engineers geotechnical report stated that, "Independent of the island subsidence, the levees settle with time. This settlement is caused primarily as a result of consolidation and plastic flows of the underlying organic soils. Since island subsidence is independent of levee settlement, numerous levee geometries are produced (Ref. 5)." Although "independent," the Corps document recognizes that island subsidence may influence levee integrity. This document also presents the concept of a "zone of influence(ZOI)," beyond which interior island subsidence does not affect levee integrity.

The Corps developed curves for estimating settlement of fills placed on organic material (figures 6 and 7). Considerable judgement should be exercised in using these curves. As examples, settlements were calculated using these curves for a 4.5-foot-thick stabilizing berm and a 2-foot-thick subsidence control cap. Assuming a 45-foot-thick unconsolidated peat layer, the 4.5-foot thick fill causes approximately 13.8 feet of total settlement at an initial time-averaged rate of about 6 inches per year, and the 2.5-foot-thick soil cap causes approximately 6.0 feet of total settlement at an initial time-averaged rate of about 2 inches per year. Based on experience, the calculated settlements are too high and the initial settlement rates are too low. It is common in the Delta for new fill to settle rapidly and total settlement to be roughly equal to the applied fill layer thickness. When compared to interior island subsidence, levee subsidence (settlement) can be significantly greater than island subsidence and is probably the primary reason for performing a high level of levee maintenance.

Near-levee subsidence will effect levee stability. This subsidence is the result of de-watering and the associated consolidation, shrinkage and decomposition of high organic content materials near the levee. Engineering analysis indicates there is a discrete distance away from a levee, a zone of influence, beyond which subsidence no longer adversely affects levee integrity.

<u>Zone of Influence</u>

The zone of influence is an area from the crest of the levee to some distance inland where island subsidence may impact levee integrity. Beyond this zone of influence, island subsidence will not affect levee integrity. Although the ZOI for a reach of levee can only be determined using site-specific data, geotechnical engineering analysis and judgement can be applied to characterize its extent. The Subteam estimated the ZOI for planning purposes. Based upon available information and engineering judgement, the ZOI is estimated to range from 0 to 500 feet from the levee crest, depending on site-specific conditions. Since the ZOI is a site-specific characteristic, it could change with time as site conditions change. The following engineering analyses could contribute to the determination of the ZOI on a site-specific basis.

a) Static stability: geotechnical engineers use stability analysis to determine factors of safety and critical failure modes for earthen structures (Refer to Figure 2). Numerous Delta levee stability analyses indicate that there is a definable distance from the levee beyond which soil properties and changes do not affect levee stability. The limiting distance often turns out to be approximately 3- to 4-times the thickness of the peat layer beneath the levee. For example, the thickness of the deepest peat layer in the Delta is approximately 60 feet (Refer to Figure 3). Therefore, any island subsidence beyond 180-to 240 feet from the levee would probably not affect static levee stability. If the peat layer was less thick, which it is for most of the Delta, then the distance would be smaller for static stability.

b) Seepage: Subsidence of the land side ground surface adjacent to a levee may cause through-levee and foundation seepage changes. Changes in hydraulic gradients, seepage volume, water levels, and exit gradients may all result from subsidence. Site specific analysis will determine whether these changes impact levee integrity, however, we can use generalized flow net analysis to make some observations.

Flow net analyses indicate that critical exit gradients are most likely to be exceeded at or in close proximity to the levees. Critical gradients are less likely to be exceeded as the distance from the levee increases. In addition, flow net analyses indicate that drainage ditches located near the levees can have a detrimental effect on levee seepage (Refer to Figure 4). Interior island subsidence adjacent to levees could affect seepage by decreasing the seepage path. A shorter seepage path leads to increased seepage. Increased seepage may lead to piping and levee integrity problems.

Seepage analyses also indicate that there is a definable distance from a levee beyond which soil properties and changes in ground surface elevations do not affect seepage and levee integrity. Similar to the stability analyses, determining a precise zone of influence with respect to seepage is difficult, because seepage is dependent upon complex local subsurface conditions and levee and foundation geometry. What the seepage modeling and "flow nets" show, however, is that there are limits beyond which changes and affects are negligible. Thus we can deduce that there are boundaries beyond which changes will not affect seepage and levee integrity. This boundary can be determined through site-specific analysis, but from a practical standpoint, wherever an open seepage collection trench can be constructed without jeopardizing levee integrity, then interior island subsidence beyond that point is unlikely to be a levee concern.

c) Deformation: Deformation is the spreading movement of soft soils in a reaction to load. Deformation can also be the result of loss of support at the levee toe, i.e, subsidence, and excavation of a drainage ditch. The Sherman Island deformation analysis report (ref 13) provided analysis for an island that might be considered worst-case due to the thickness of the peat layer beneath the levee and the size (load) of the levee. Although the Sherman Island analysis did not consider the impact of future island subsidence on deformation, the information indicates that there is a distance beyond which deformations do not occur. For the computer deformation modeling, a boundary condition was set at approximately 300 feet from the crest of the levee, a distance beyond which deformation did not occur. Extreme future island subsidence may impact a levee, however, it is important to note that island subsidence occurs slowly, and that levees usually adjust to island subsidence as it occurs without detrimental effects on stability.

Clearly, the zone of influence will vary with site specific levee and foundation conditions and levee geometry. For example, the greater the height of the levee embankment above the island floor and the greater the thickness of weak and compressible layers, such as peat, the wider is the zone of influence. Monitoring and research will later define this zone.

Hydrostatic Pressure.

It has been commonly reported that subsidence of island interiors leads to increased hydrostatic pressure and levee instability. The implication that levees are now required to withstand a greater hydrostatic head of water than they were originally constructed is inaccurate in that the exterior water elevations remain the same. However, a decrease in the land mass resisting such hydraulic pressures may occur. Also, seepage forces and quantity will change due to increased hydraulic gradient. The decrease of island surface elevations is a contributing cause to the need for ongoing work to maintain the height and desired safety factor of the levees. Periodic levee improvements replace some of the land mass that was lost to subsidence.

Island Subsidence

Island Subsidence will be generally discussed here, because the focus of this report is subsidence as it impacts levee integrity. Island subsidence impacts levee integrity only when it occurs in proximity to a levee. Subsidence within the ZOI may decrease stability, increase seepage, increase the potential for piping, or increase the potential for levee deformation. At many locations, however, island subsidence is occurring too slowly or too far from the levee to be a threat to levee integrity. As long as the ZOI is protected from subsidence, levee integrity with respect to island subsidence should be assured. Although island subsidence outside of the ZOI does not impact levee integrity, it does impact the interior of Delta islands and their associated land uses.

Historically, time-averaged Delta-wide island subsidence rates have ranged from about 0.5 to 5.0 in/yr. Recent research indicates that island subsidence varied from about 0.2 in/yr to 1.2 in/yr for soils with organic contents varying between 20% and 50% (Reference 4, Rojstaczer and Deverel (1995).

Subsidence rates are slowing . Present day subsidence rates were measured continuously from 1990 to 1992 by Deverel and Rojstaczer (1996) on Sherman and Jersey Islands and Orwood Tract. These authors reported rates of 0.2, 0.24, and 0.32 inch per year on Sherman, Jersey, and Orwood, respectively.

Island subsidence rates are site specific. No single island subsidence rate, such as the commonly used 2.5 to 3 inches per year, is valid for an entire island. Total island subsidence rates vary greatly and average island subsidence rates at specific sites appear to be diminishing with time. Rates may be greater in areas subjected to new or deeper de-watering.

Remedial Action and Prevention

The approach to control of levee subsidence will be fundamentally different than the means and methods employed to control island subsidence because of the differences in the primary causes of subsidence.

Levees (References 4 through 13)

Potential levee subsidence mitigation actions that should be considered are:

1)Thorough application of geotechnical engineering principles and practices in conjunction with proven construction methods. Levee subsidence will continue as long as levee building and repair continue to add loads onto weak compressible foundations.

2)Seepage control, de-watering efforts, excavations, and land management activities in proximity to levees must be modified to minimize adverse impacts to levee integrity.

3)Stability and drainage berms can be strategically located and sequentially constructed to minimize or prevent levee deformation.

4)Land leveling and other ground surface modifications (e.g. ditching) should be restricted within the zone of influence. High ground water levels and vegetative growth could be tolerated in some areas to accommodate measures aimed at reducing island subsidence due to oxidation.

Island Interiors, Including the ZOI (References 1 through 10)

Currently the best approaches to managing island subsidence, include a) minimizing or preventing the lowering of the groundwater level, b) capping or covering susceptible surface deposits with mineral soil, and c) permanent shallow flooding. and d)reverse wetland flooding.

Delineation of Target Areas for Subsidence

Subsidence control and monitoring will be most important for the western and central Delta islands, where the depth of organic soils are the greatest and the organic content of the deposits are commonly high. Previous attempts at prioritizing areas and islands, based on depth of peat and organic matter content, provide a good starting point for the development of a subsidence control and prevention program. It appears from this initial prioritization effort that only some islands and in some cases only parts of islands are affected. Refer to Figures 5-1 through 5-8, Subsidence Target Areas, for examples of islands and levee reaches most likely to be affected by subsidence (Deverel 1997, References 1&2). The number of levee miles potentially affected by subsidence was calculated using Figure 5. About 60% of the levees in the central and western Delta, but less than 30% of all the levees in the legal Delta, are targeted for subsidence control.

The objective of the maps in Figures 5-1 through 5-8 is to target areas for subsidence monitoring and control in the Delta. The general approach was to enter recent available data for the Delta for island subsidence rates, depth of peat soils and soil characteristics into a geographic information system (GIS). The estimates for rates of island subsidence and peat thickness are an improvement relative to the previous efforts by the Department of Water Resources because 1) the error in the estimated island subsidence rate is lower, quantifiable and the result of uniform elevation change measurements, and 2) the estimates for peat thickness are based on more recent and comprehensive data.. Also, the data was entered into a GIS which facilitated the evaluation of the data for delineation of target areas in greater areal detail than entire islands such as is presented in Department of Water Resources (1980).

The areal distribution of island subsidence rates and peat thickness is used to delineate target areas for additional data gathering and monitoring. The maps in Figures 5-1 through 5-8 used the estimated ZOI boundary of 500 feet around the islands. Within this boundary, the target areas are those where the island subsidence rates are high and there is substantial peat remaining. The target areas have time-averaged island subsidence rates greater than 1.5 inches per year (island subsidence rates ranged from about 0.4 inches per year to 5 inches per year) and peat thickness greater than 10 feet within the 500 foot boundary.

The term "peat" has been defined in many different ways. For the maps in Figure 5, "peat" will refer to peat or peaty mud of tidal wetlands comprised of the organic deposits derived from decayed vegetation that formed as the result of sea level rise during the last 7,000 to 11,000 years. The peat thickness shown on the maps was calculated as the difference between the basal elevation of peat or peaty mud deposits of tidal wetlands as mapped by Atwater (1982) and the land-surface elevation from the USGS topographic maps(1976-1978). Atwater's delineation of peat and peaty mud include the organic soils mapped by Cosby (1941) and more recent soils surveys. The maps reflect borehole data collected as of 1980.

Monitoring

Subsidence monitoring should be tied to constructed base level projects because these areas provide the most economical opportunities for gathering more data in conjunction with construction explorations and monitoring. Subsidence monitoring should start with an evaluation of existing soils and their distribution and a determination of land surface elevation within Target Areas in the Delta. Efforts should be directed to areas on and adjacent to the levees, within the ZOI. From a new, continually updated database, a target list of levees and islands being impacted by subsidence can be maintained. Monitoring will allow subsidence control to be adaptively managed as levee rehabilitation goes forward. This monitoring efforts will be coordinated through CALFED's Comprehensive Monitoring, Assessment, and Research Program (CMARP).

Conclusions

Although subsidence has caused problems in the past, and will continue to be a problem for island interiors, the potential impact of island subsidence on levee integrity has diminished. Land management and levee maintenance practices have improved and island subsidence rates have decreased. As long as island subsidence is adequately managed within the ZOI, levee integrity should be unaffected. Although the ZOI for a reach of levee can only be determined using site-specific data, the Subteam has estimated the ZOI for planning purposes. Based upon available information and engineering judgement, the ZOI is estimated to range from 0 to 500 feet from the levee crest depending on site-specific conditions. The ZOI could change with time as site-specific conditions change.

Subsidence control and monitoring will be most important for the western and central Delta islands, where the depth of organic soils are the greatest and the organic content of the deposits are commonly high. Previous attempts at prioritizing areas and islands, based on depth of peat and organic matter content, provide a good starting point for the development of a subsidence monitoring, control, and prevention program.

The levees identified as being target areas for subsidence remedial action and prevention will require screening and integration with other issues affecting levees such as seismic stability requirements, ecosystem restoration, and Delta water operations. This integration will allow a better prioritization of future subsidence remediation of the Delta levees.

References: Subsidence in the Sacramento-San Joaquin Delta

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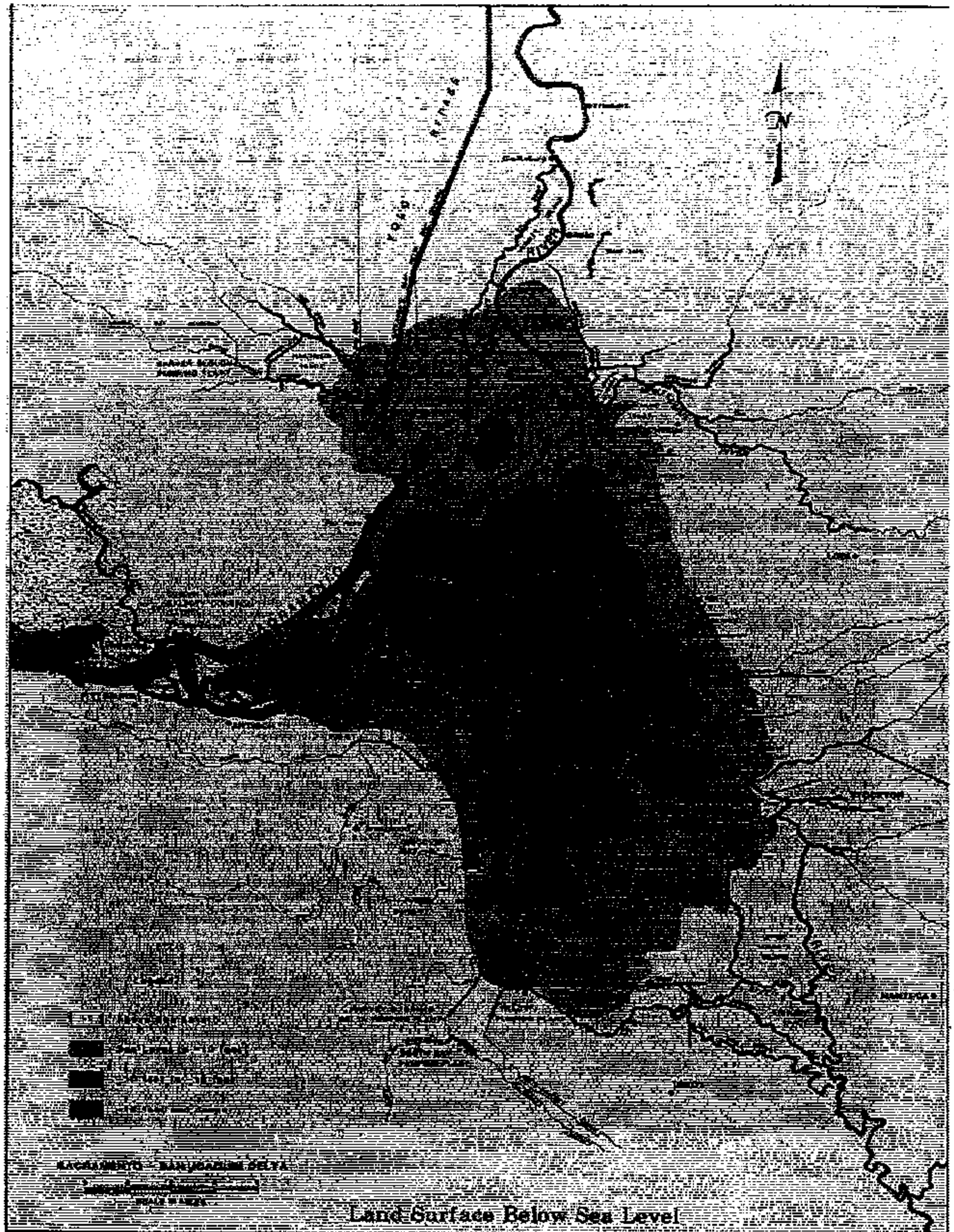
14. Foott, Sisson, and Bell (1992) ; Threatened Levees on Sherman Island. A reprint from Stability and Performance of Slopes and Embankments II Proceedings, GT Div/ASCE, Berkeley, CA, June 29-July 1, 1992.



Land Surface Below Sea Level

Sacramento–San Joaquin Delta Atlas *Department of Water Resources*

FIGURE 1

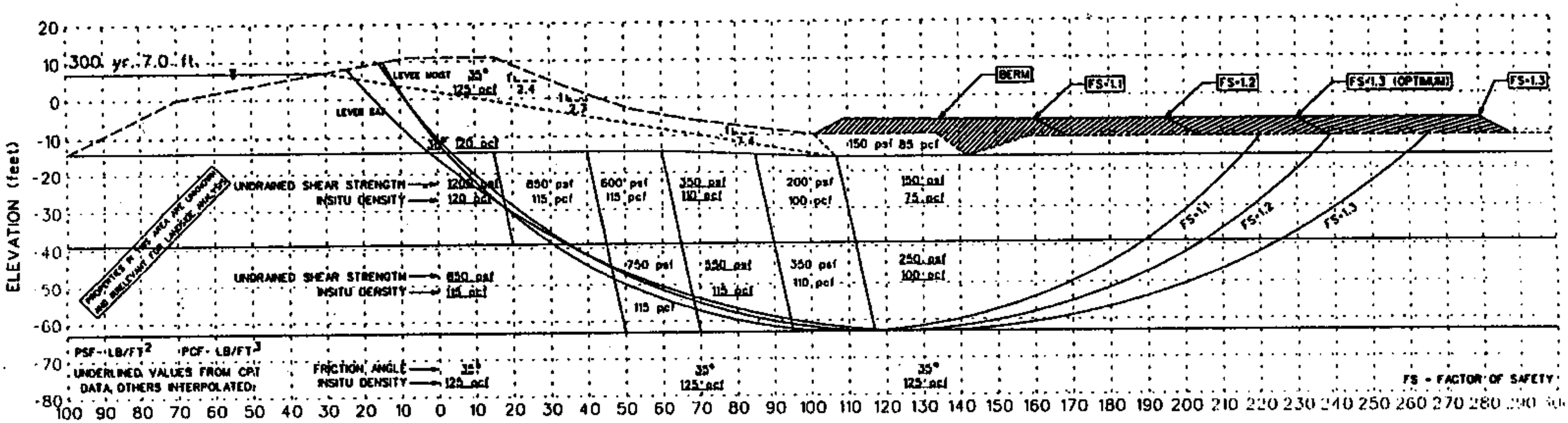


FIGURE 2 SLOPE STABILITY - OPTIMUM BERM SECTION (BERM FILL ONLY).

FIGURE 2

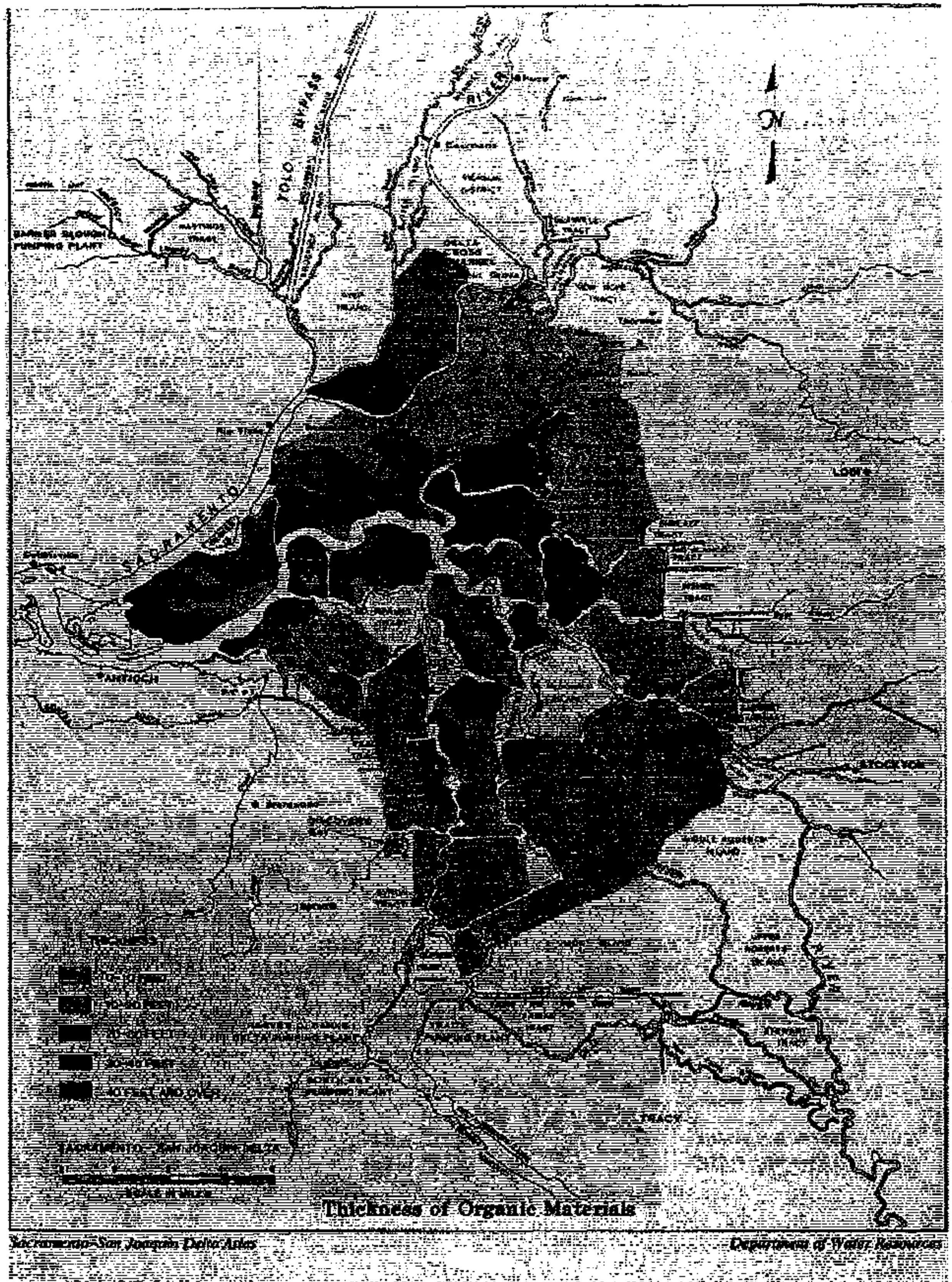
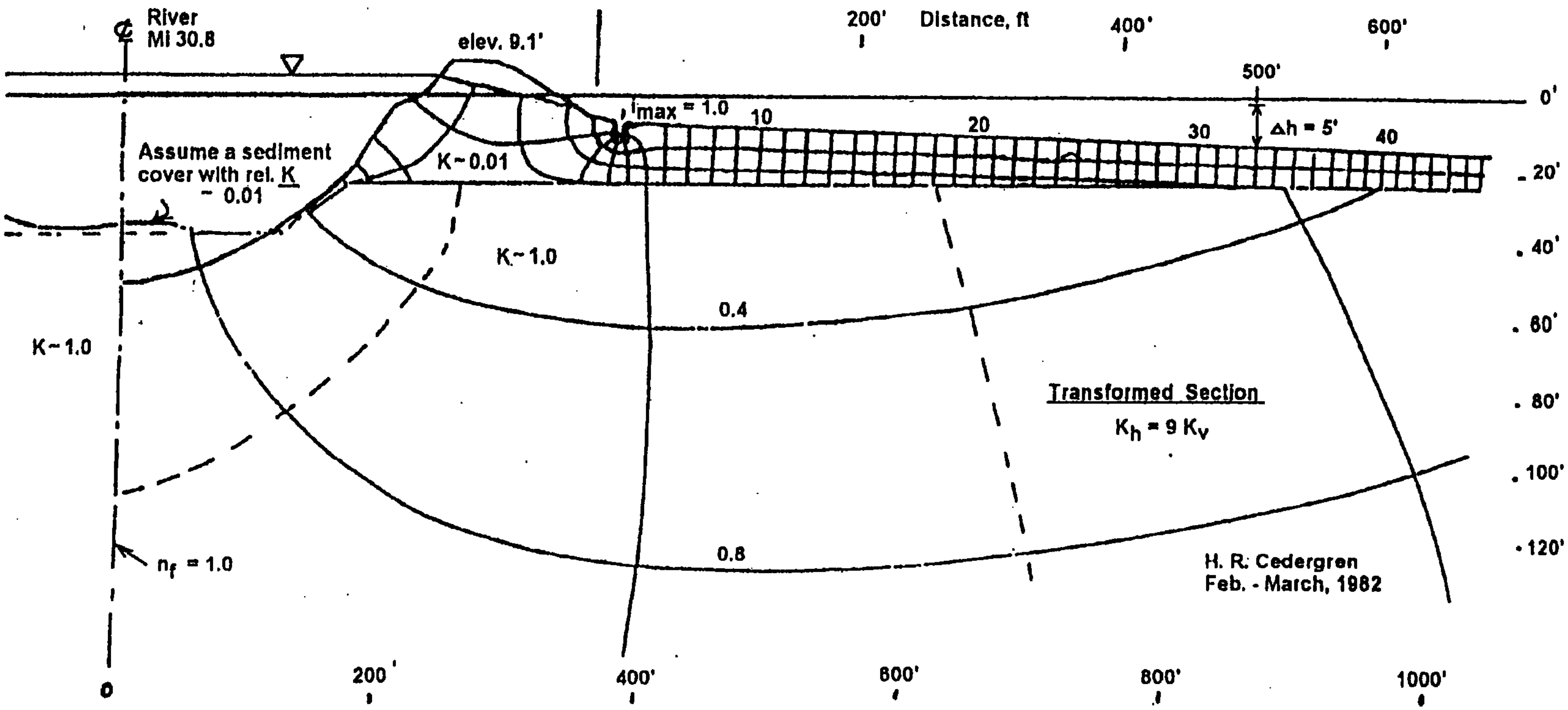

Thickness of Organic Materials
Sacramento-San Joaquin Delta Atlas
Department of Water Resources

FIGURE 3

RINGE TRACT



STOCKTON DEEP WATER CHANNEL
SEEPAGE STUDY
FLOW NET NO. 6 - NA

SACRAMENTO - SAN JOAQUIN DELTA
APPENDIX B
SPECIAL STUDY
JANUARY 1993

FIGURE 4

Figure 5-1

Brannan & Andrus Islands

Target Areas

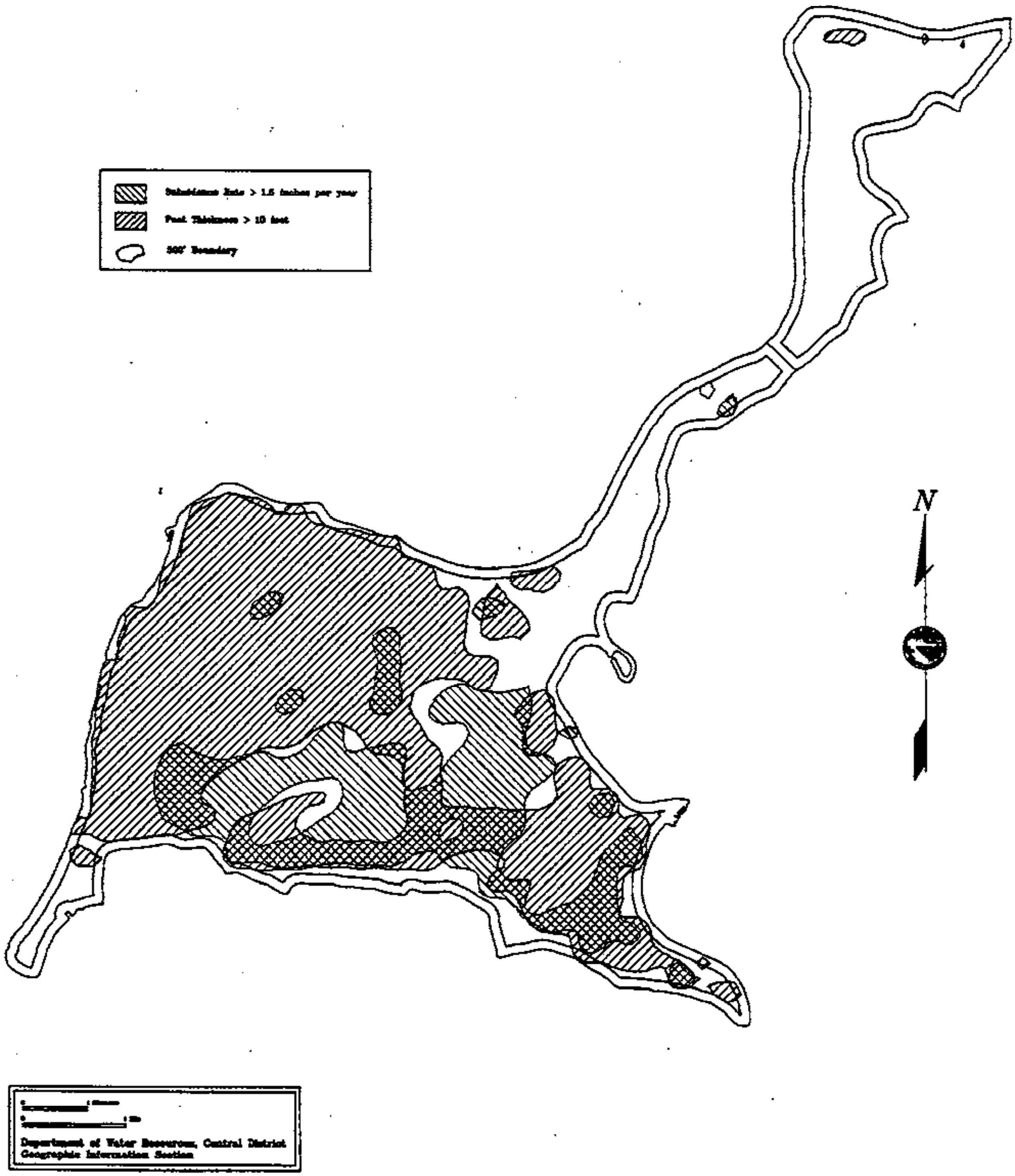


Figure 5-2

Staten & Tyler Islands

Target Areas

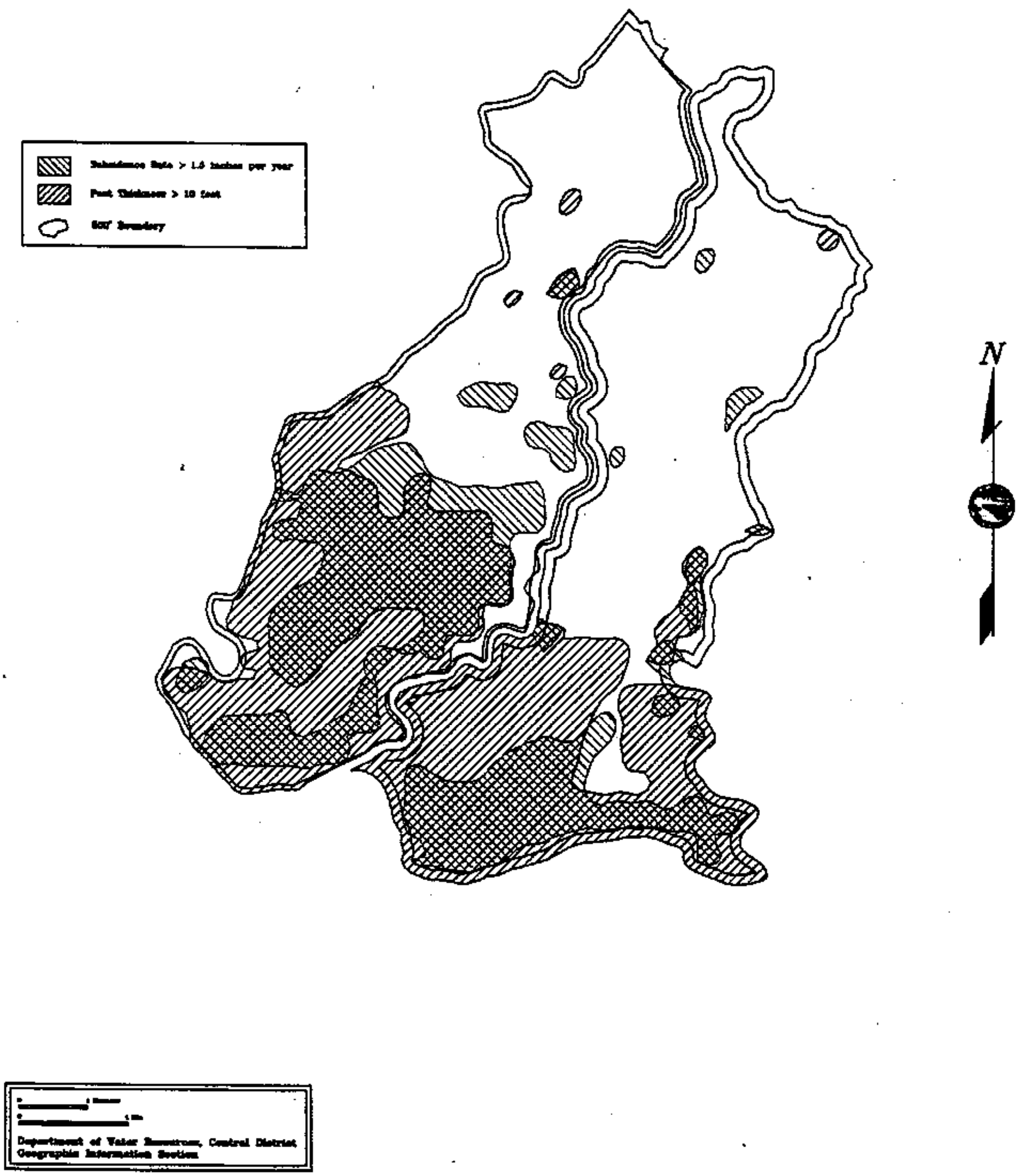


Figure 5-3

Bethel, Bradford, Jersey, Twichell & Webb

Target Areas

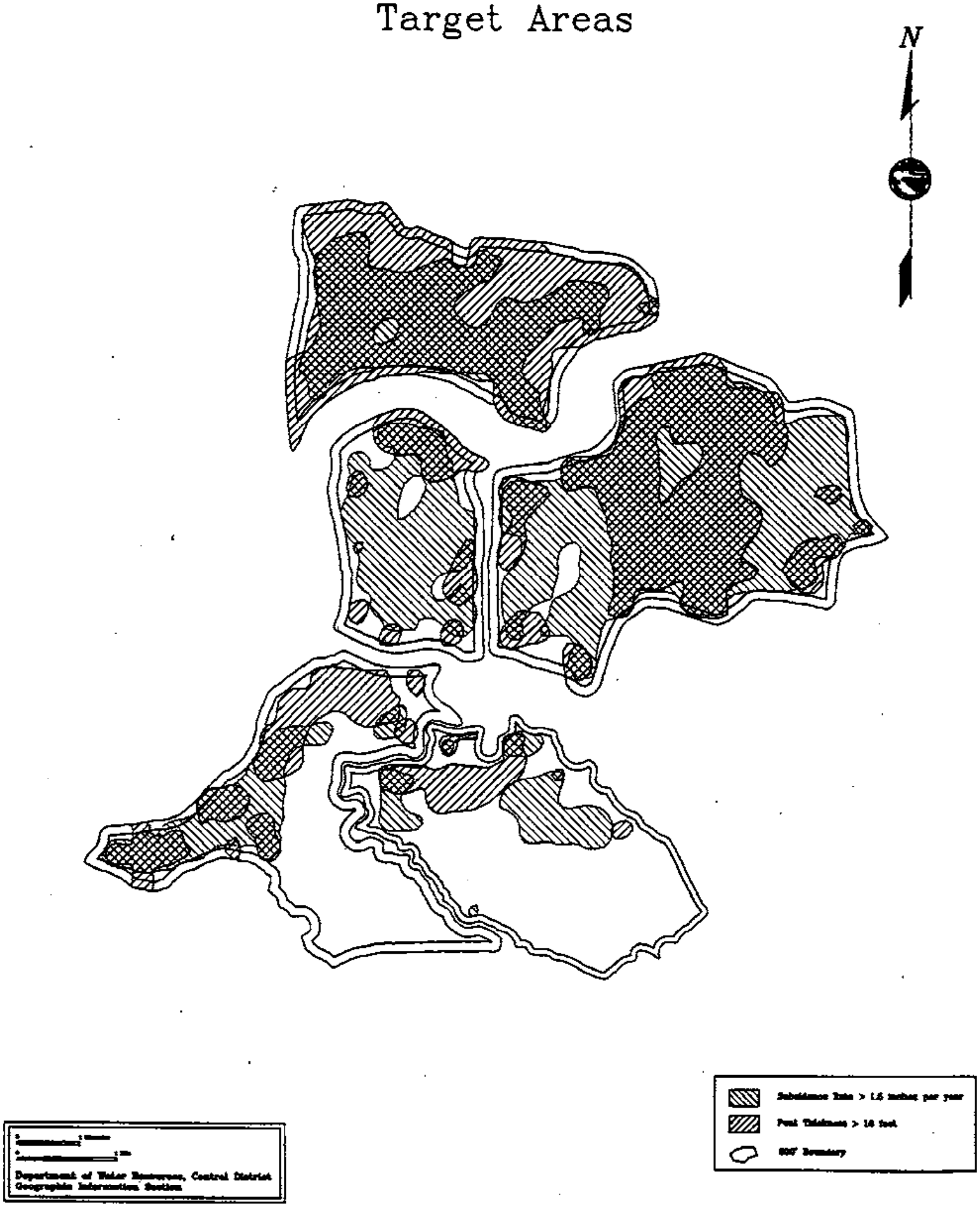


Figure 5–4

Sherman Island

Target Areas

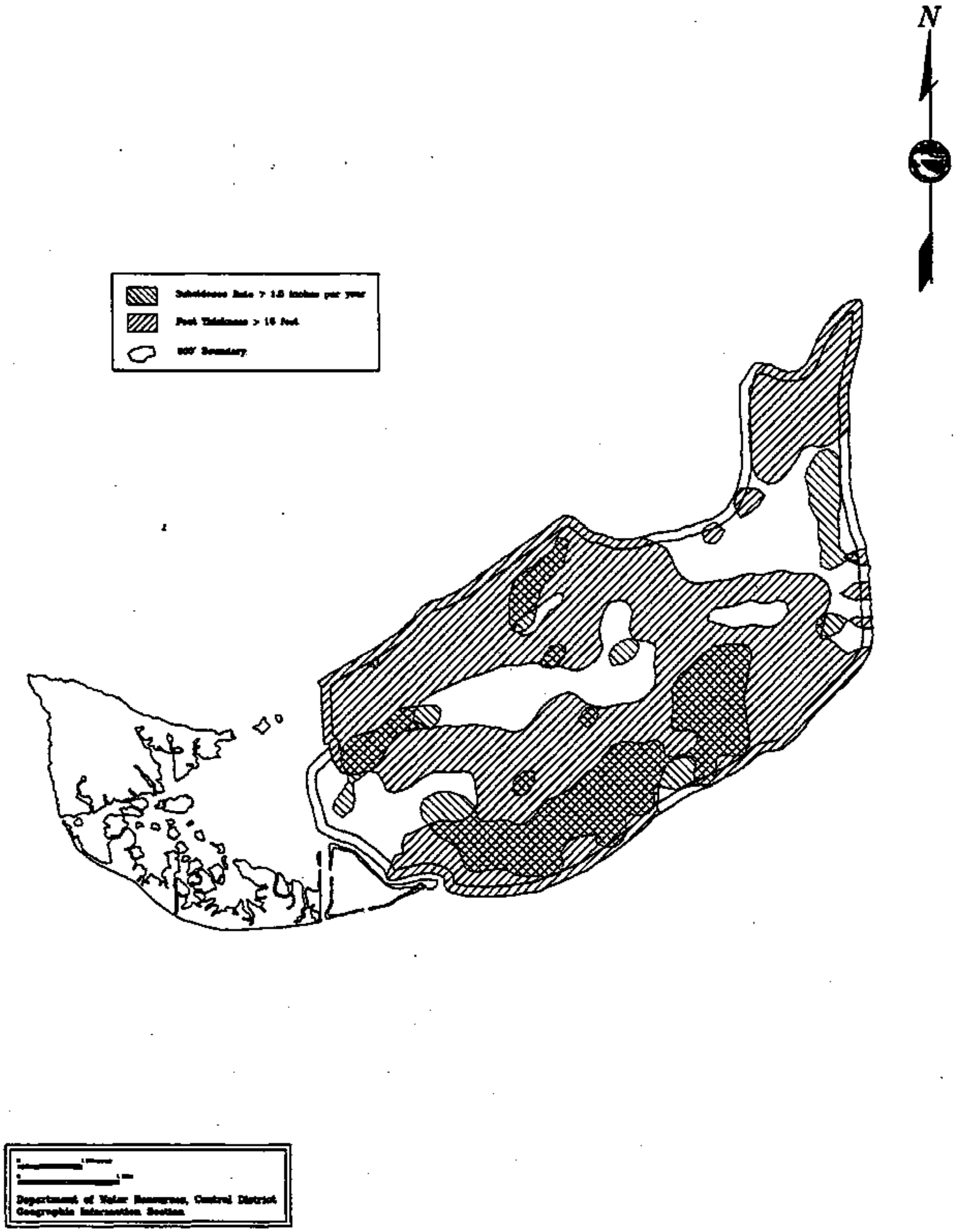


Figure 5-5

Bouldin, Empire, McDonald, Medford & Venice

Target Areas

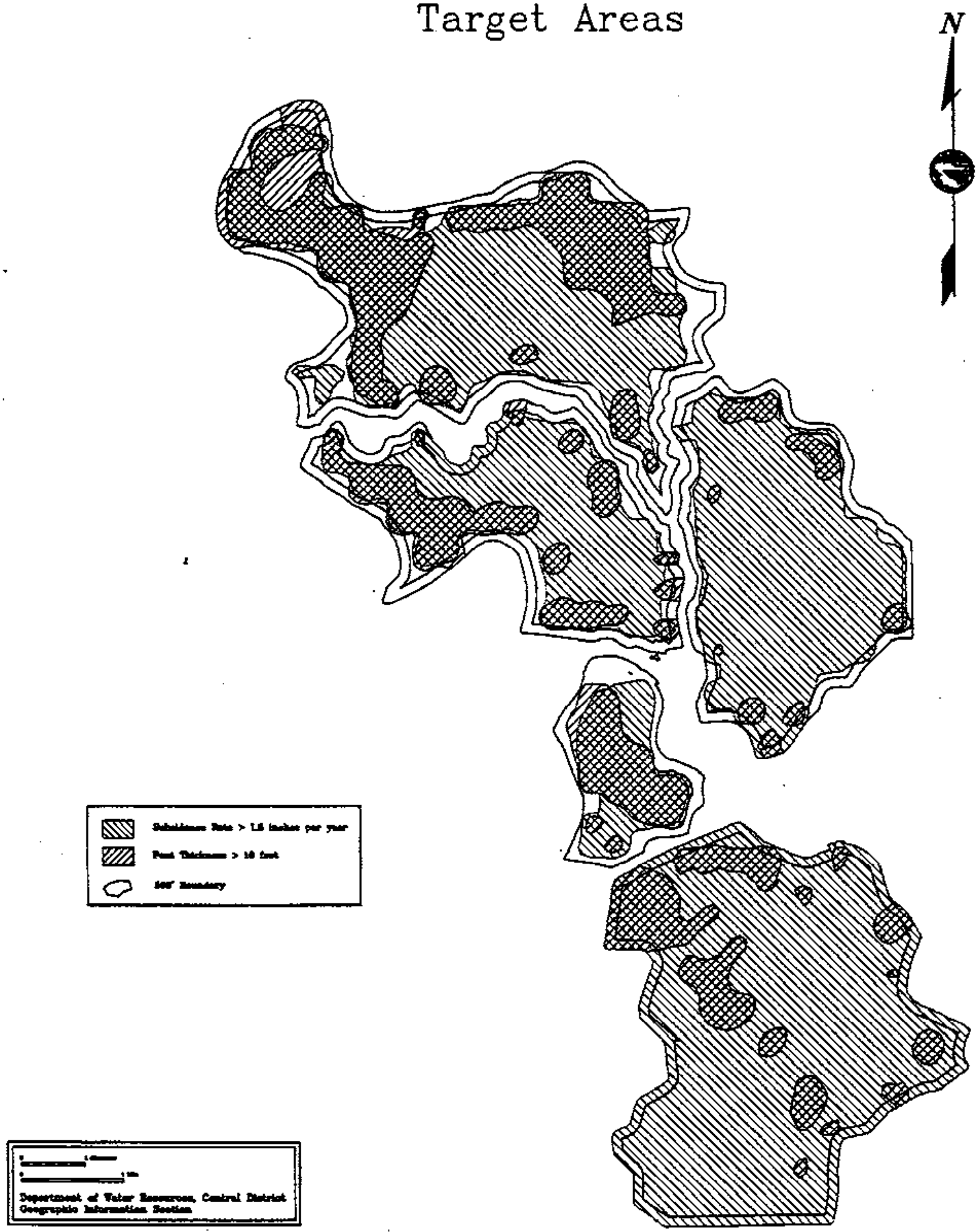


Figure 5-6

King & Ringe

Target Areas

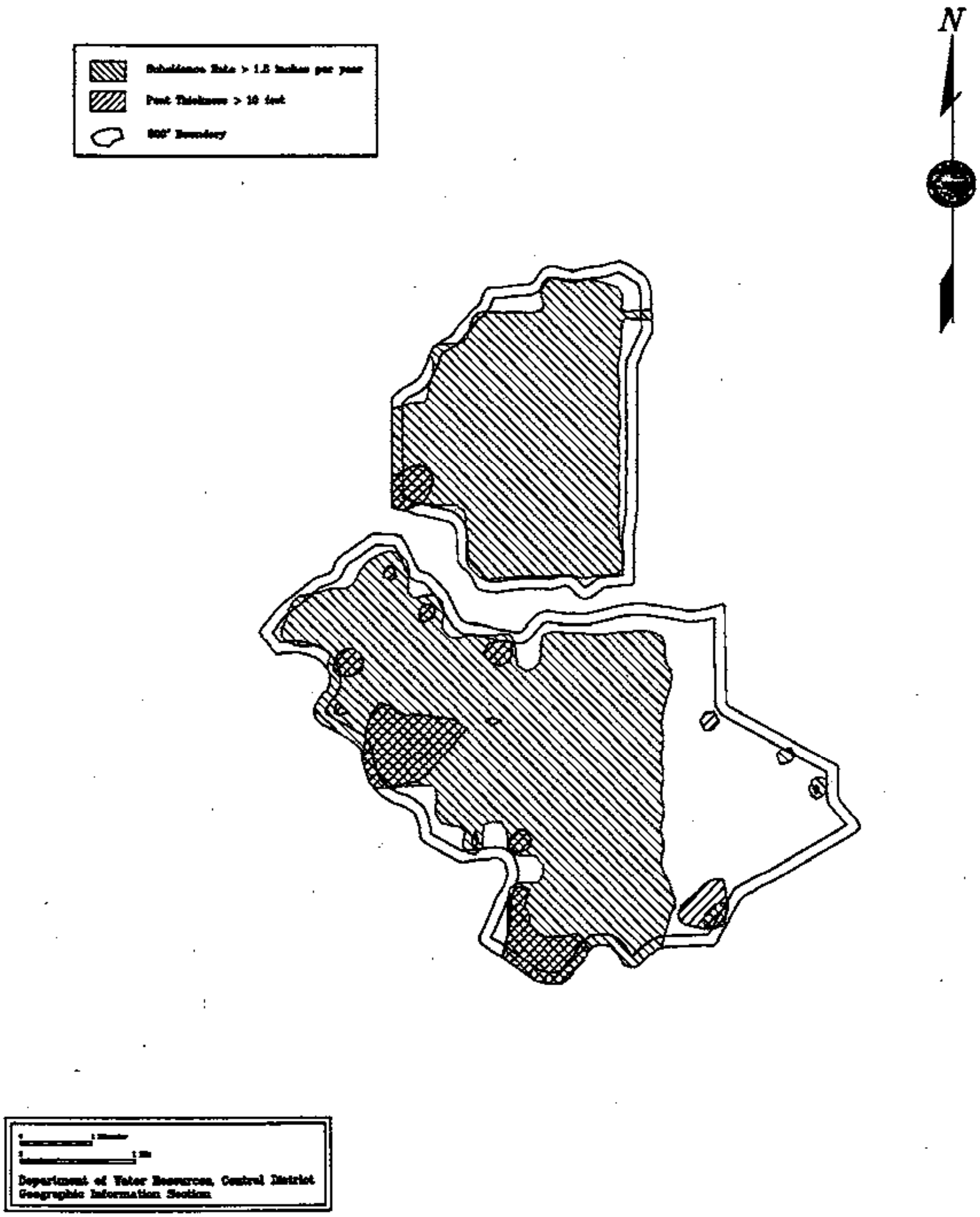


Figure 5-7

Bacon, Holland, Hotchkiss Palm, Quimby & Veale

Target Areas

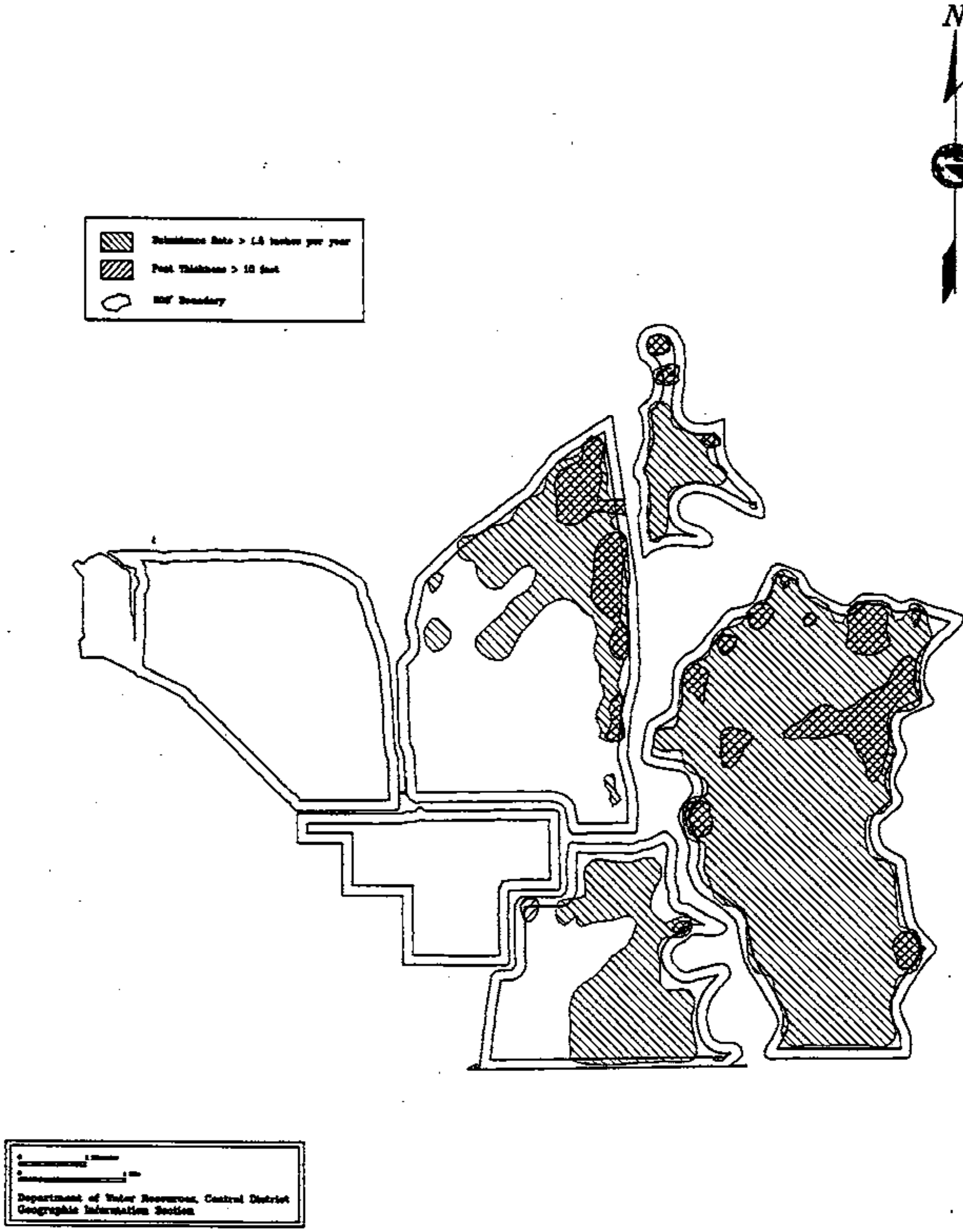
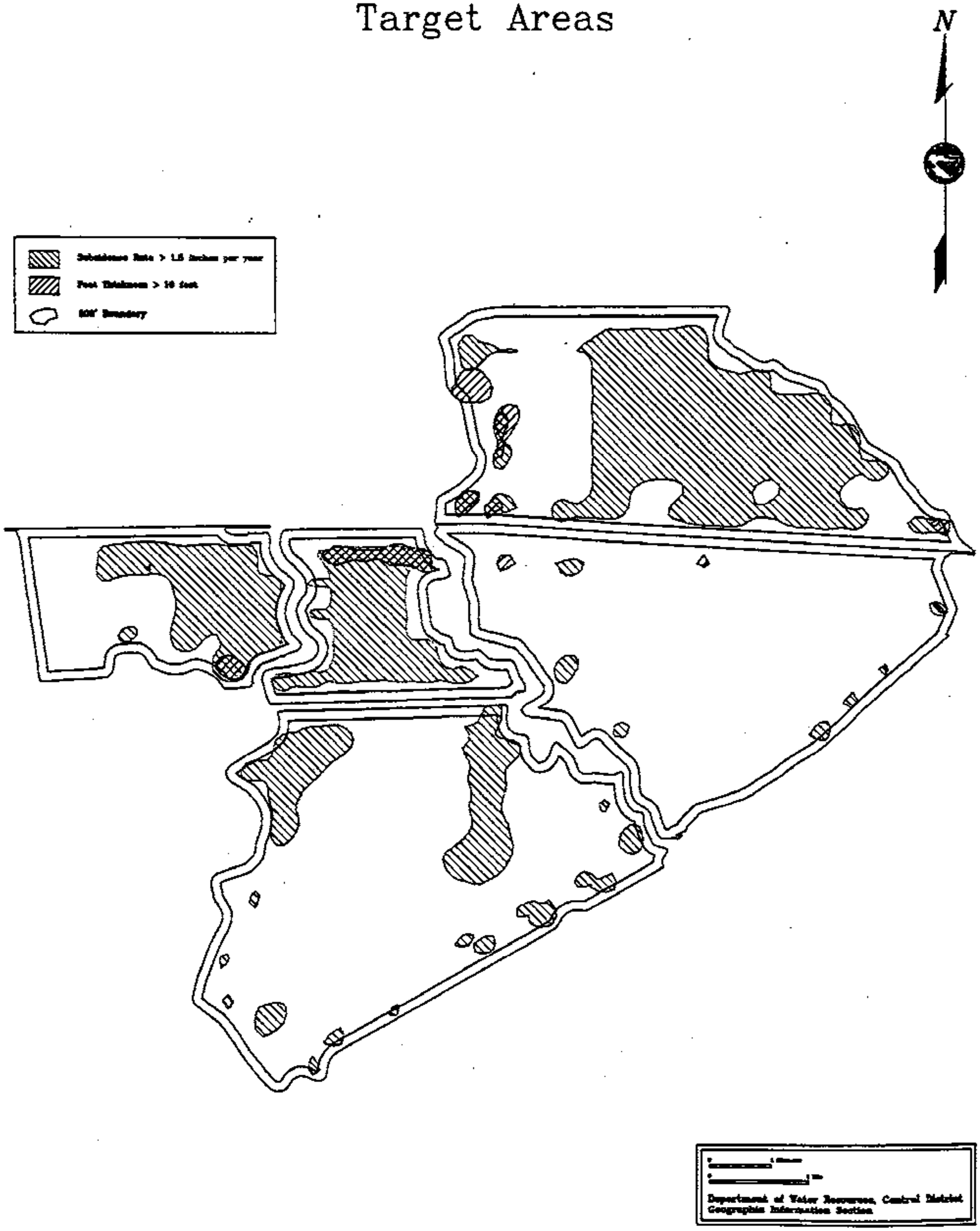
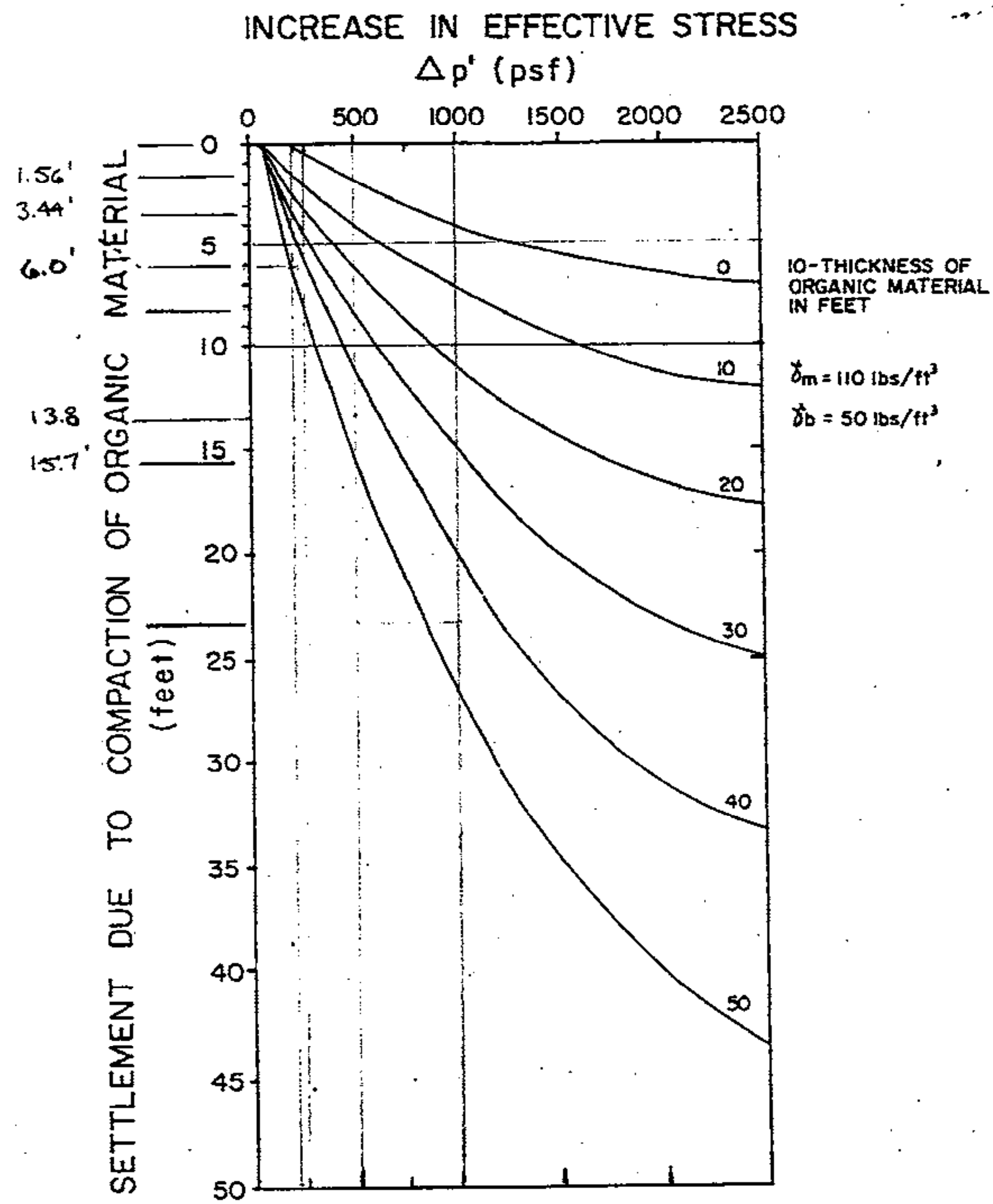


Figure 5-8

Upper & Lower Jones, Orwood Woodward & Victoria

Target Areas





SETTLEMENT OF FILLS
PLACED ON ORGANIC
MATERIAL

SACRAMENTO-SAN JOAQUIN DELTA

SPECIAL STUDY

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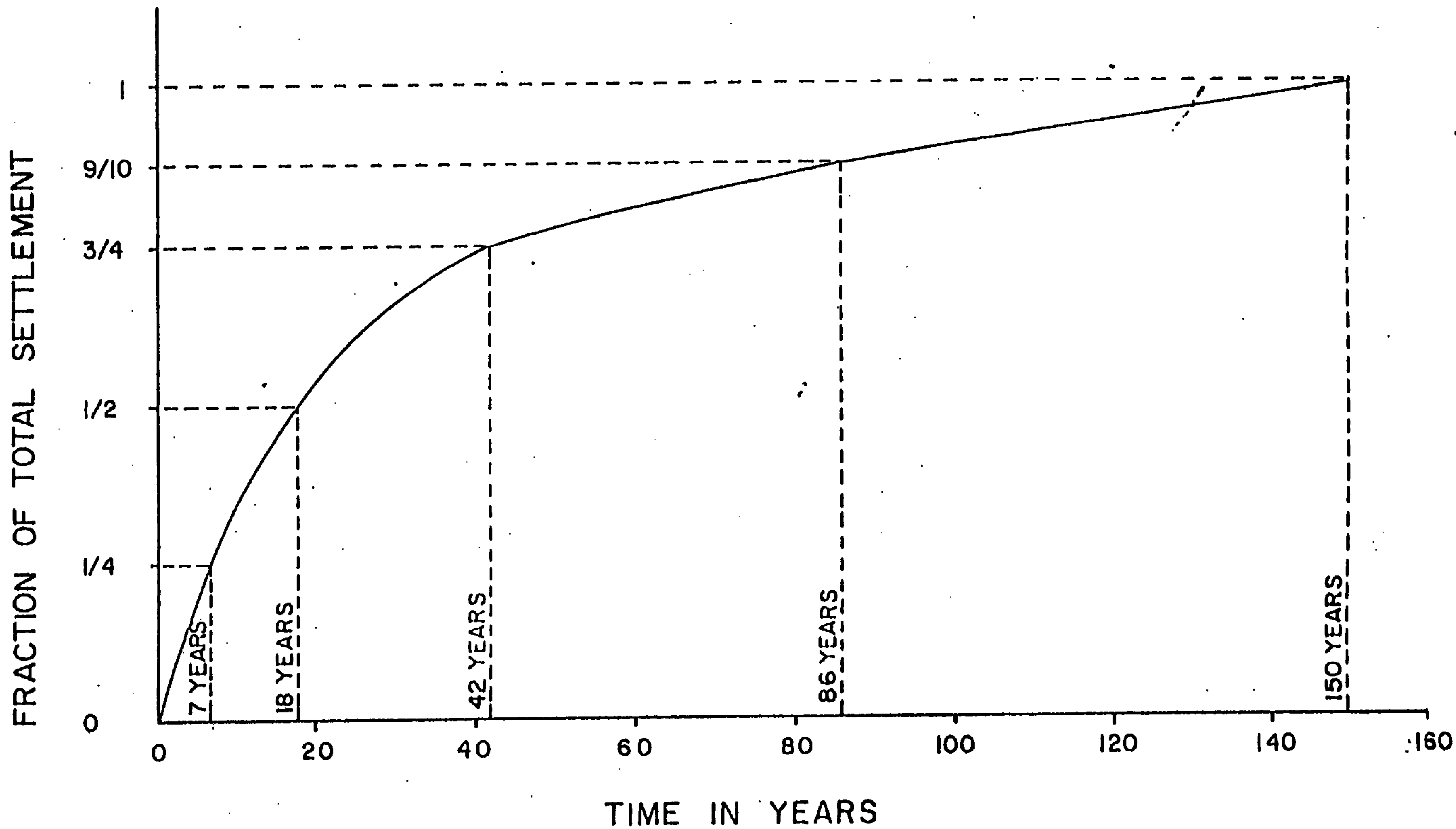
JANUARY 1993 Figure 4-

FIGURE 6



FRACTIONAL RATE OF SETTLEMENT

SACRAMENTO-SAN JOAQUIN DEL
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APPENDIX B 4-13
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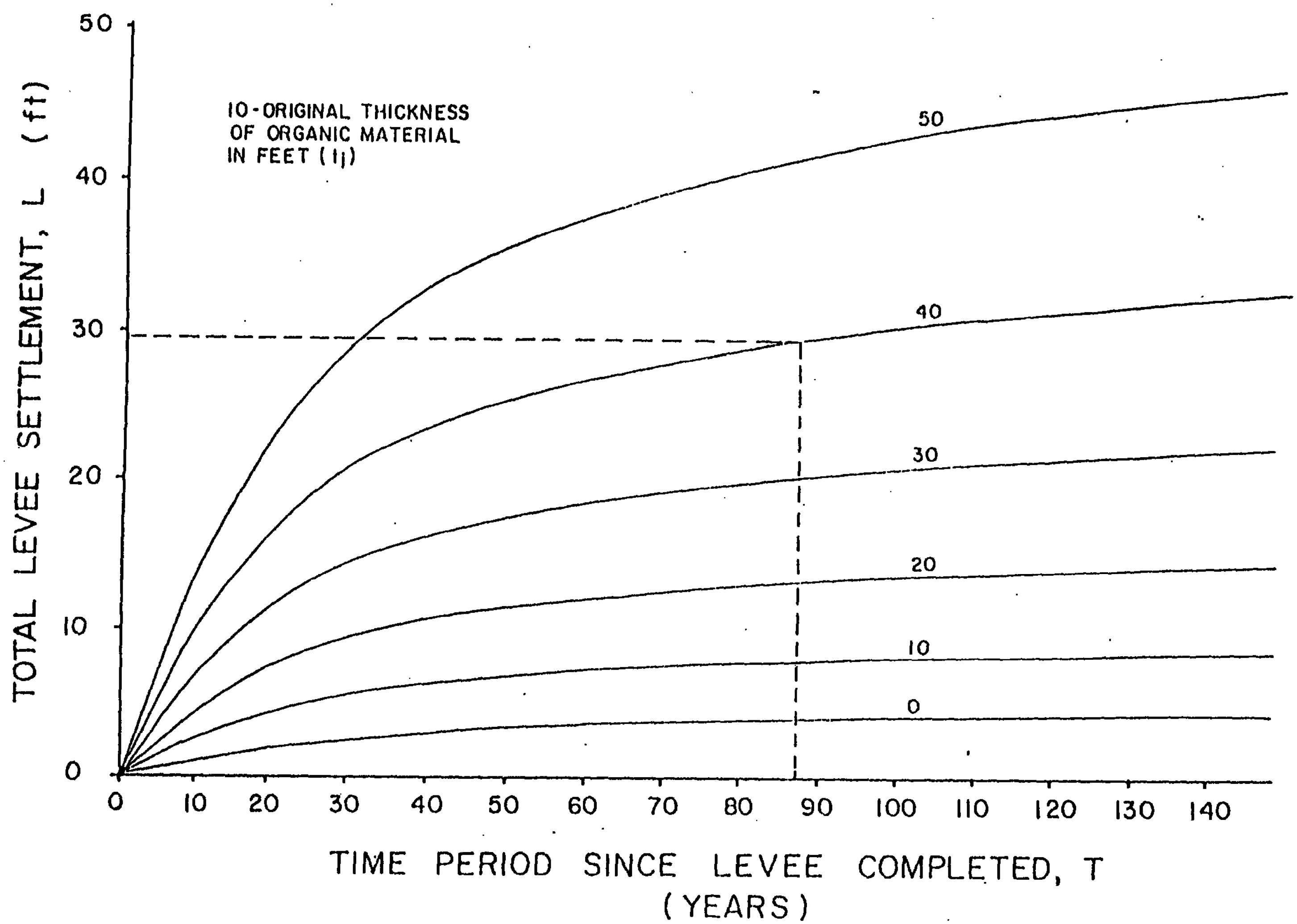
FIGURE 7



EXAMPLE: FIND TOTAL LEVEE SETTLEMENT ON BOULDIN ISLAND FROM RECLAMATIOI TO 1987.

FROM FIGURE 4-5, Ii = 40ft.

FROM TABLE 4-1, RECLAMATION 1910.
IN 1987 TIME PERIOD, T = 1987 - 1910 = 77yrs.

FROM BELOW
ENTER T = 77yrs
EXTEND LINE VERTICALLY TO I = 40ft,
EXTEND LINE HORIZON TALLY TO READ
L_s = 29ft

SACRAMENTO-SAN JOAQUIN DELTA

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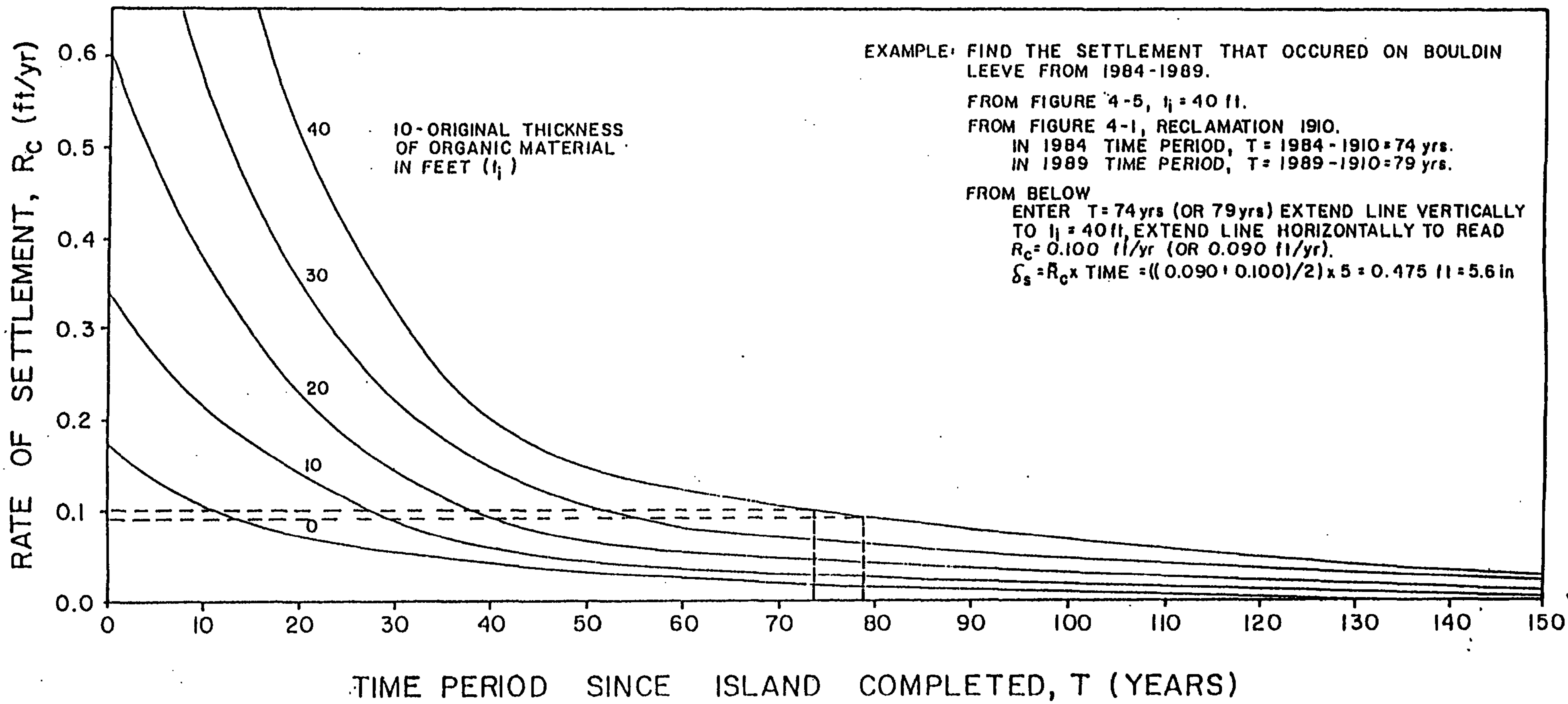
JANUARY 1993 Figure 4-9

FIGURE 8



SACRAMENTO - SAN JOAQUIN, DELTA

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JANUARY 1993 Figure 4-10

FIGURE 9

SUBSIDENCE MITIGATION IN THE SACRAMENTO-SAN JOAQUIN DELTA

Prepared for the CALFED Bay-Delta Program

by

Steven Deverel
Hydrofocus, Inc.
December 1, 1998

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FIGURES

TABLES

SUBSIDENCE MITIGATION IN THE SACRAMENTO-SAN JOAQUIN DELTA

Executive Summary

Subsidence on Delta islands crosses the boundaries of three of the CALFED common programs, Water Quality, Ecosystem Restoration and Levee System Integrity. Consistent with the CALFED values of integration, synergy and developing equitable solutions, subsidence mitigation needs to be addressed comprehensively. Island subsidence merits attention, future study and mitigation because of its relation to ecosystem restoration, Delta water quality, levee stability and seepage onto islands from Delta channels.

Subsidence of peat soils on Delta islands has caused the land-surface elevations to decrease since the islands were initially drained for agriculture in the late 1800's and early 1900's. The land-surface elevations of islands where peat was once present or where peat is present today range from 5 to over 20 feet below sea level. The peat soils have historically subsided at rates ranging from 0.5 to 4.5 inches per year but subsidence rates have decreased in recent years. The decreasing land-surface elevations have resulted in a decrease in the landmass resisting the hydraulic pressures on the levees and levees have been enlarged and strengthened over time. As the result of subsidence and other factors, levee failure and flooding of islands have occurred frequently since the early 1900's. A long-term approach to subsidence mitigation needs to consider a combination of non-structural and structural alternatives for managing and reversing the effects of subsidence and integrating these efforts with ecosystem restoration.

Management and reversal of the effects of subsidence in the Delta is necessary to achieve CALFED's ecosystem restoration objectives. Ecological connectivity is important for migratory fish species in the Delta, but the current lack of connectivity between Suisun Marsh west of the Delta and riparian riverine habitat east of the Delta may limit the restoration of these species. Steve Johnson of The Nature Conservancy in 1997 said: "From an ecological perspective, there needs to be tidal freshwater wetlands covering the full range of ecosystem gradients in the Delta, not just a few points here and there with the rest of the tidal wetlands hugging the shores of the eastern Delta. To achieve this range, elevations need to be restored on western Delta islands so that they can be brought back into tidal circulation." Long-term reversal of the effects of subsidence in the Delta combined with habitat restoration will be necessary to restore connectivity across the entire Delta.

Mitigation and reversal of the effects of interior-island subsidence is necessary to minimize the consequences of levee failure over the long term. Probabilistic analysis developed by the CALFED seismic hazard team suggest that levee failure is inevitable over the long-term regardless of plans to upgrade levees to PL-99 standards. The consequences and costs of levee failure and island flooding will be proportional to the depth of interior-island subsidence.

Water quality degradation in the Delta channel waters can result from levee failure in the western Delta during periods of low flow, as in the example of the flooding of Brannan and Andrus islands in 1972. This flooding required substantial operational changes in the State and Federal water projects to reestablish the hydraulic balance and compensate for salt-water intrusion. Continued subsidence on western Delta islands where there remains 10 to 60 feet of peat, will increase the volume of water that is drawn onto flooded islands thus increasing salt water intrusion and the need for dilution releases from the State and Federal water projects. For example, an average additional foot of subsidence on Sherman Island (at the rate of 0.5 inch per year this will occur in 24 years) would create about 9,900 acre feet of additional volume below sea level. This additional volume of water could be drawn from the west during flooding and could increase reclamation costs. Repairs and upgrades of Delta levees can cost from several tens of thousands of dollars to over 1 million dollars per mile.

Seepage onto Delta islands will increase as the difference in the water level in the channel and the groundwater level on the islands increases due to continued subsidence and deepening of drainage ditches. Increased seepage may require increased volumes of drainage to be pumped from Delta islands and increased pumping capacity and pumping costs. Increased drainage volumes may lead to increased loading of dissolved organic carbon to Delta channels. Increased seepage may also detrimentally affect levee stability.

The objectives of this report are to summarize the current knowledge of the causes, rates and effects of subsidence, to present the information about non-structural alternatives for stopping and reversing the effects of subsidence and to recommend directions for future research and data collection. The approach was to 1) review and summarize the available literature, 2) determine the relative magnitude of the different causes of subsidence using the available data, 3) use the areal distribution of historic subsidence rates and peat thickness to delineate priority areas for subsidence mitigation and future study and 4) determine and describe possible mitigation measures and future data collection efforts.

Consistent with the May, 1997 Governor's Flood Emergency Action Team Report that recommended that "proactive nonstructural floodplain management strategies…be implemented to reduce future flood loss and curtail the spiraling cost of State and Federal disaster assistance", this report describes non-structural options for subsidence mitigation. This report is a first step towards implementation of subsidence mitigation measures on Delta islands. The focus is the subsidence of peat soils on Delta islands. Levee subsidence that occurs primarily as the result of consolidation of organic materials underlying levees is described in another report that focuses on levee integrity.

The results of the analyses presented here indicate that present-day subsidence in the Sacramento-San Joaquin Delta is primarily the result of microbial oxidation of the peat soils. The peat soils contain a complex mass of carbon that microbes such as bacteria and fungi use as an energy source thus oxidizing the carbon to carbon dioxide gas. The available data indicate that historically, microbial oxidation caused 29 to 55 percent, consolidation and shrinkage caused 22 to 29 percent, wind erosion caused 3 to 34 percent and burning caused 9 to 24 percent of the total subsidence that occurred from the late

1800's through the 1970's. Consolidation continues to occur as the elevations of drainage ditches are lowered in response to subsidence due to microbial oxidation. Burning and wind erosion no longer appear to be significant causes of subsidence.

This report summarizes the data for changing land- and water-management practices for stopping and reversing the effects of subsidence of the peat soils. The results of research conducted by the USGS in cooperation with DWR on Twitchell Island indicate that seasonal wetlands in which the land is flooded during the fall and winter and drained in the spring and summer will not stop subsidence or reverse its effects. The primary cause of subsidence is carbon loss due to microbial oxidation of the peat. This oxidation is highest during the spring and summer. In general, land- and water management practices that result in drained and oxidized conditions during the spring and summer will result in a net carbon loss and continued subsidence. In contrast, permanent shallow flooding to a depth of about one foot resulted in a net accumulation of carbon which lead to the accumulation of biomass. The results of coring in the experimental flooded pond showed that about 3 to 6 inches of firm biomass accreted from 1993 to 1997 during 2 years of growth under full vegetative cover and 2 years of growth under partial vegetative cover. Capping of the peat with mineral material in the laboratory reduced carbon loss from the peat.

A Geographic Information System developed and housed at the Department of Water Resources Central District and available data for subsidence rates and peat thickness were used to delineate priority areas for subsidence mitigation. Figure 2 shows the location of the priority areas. There are about 23,000 acres in first priority area that includes lands where time-averaged subsidence rates from the early 1900's to the mid-1970's were 1.5 inch per year or greater and the peat is greater than 10 feet thick. There are about 36,000 acres in the priority 2 area that includes lands where time-averaged subsidence rates were greater than 1.5 inch per year and the peat is equal to or less than 10 feet thick. Lands in the priority 1 area are generally located in the central and central-western Delta where there is relatively deep peat and time-averaged subsidence rates have been generally high. Large tracts of land in the western Delta are also included in the priority 1 area. Most of the lands in the priority 2 area are in the central and central-eastern Delta where there have historically been high rates of subsidence but the peat thickness is generally less than 10 feet.

The error in the determination of areas in each priority varies depending on the magnitude of the time-averaged subsidence rate and the error in the peat thickness data. Where time-averaged subsidence rates were generally greater than 1.5 to 2 inches per year, the possible error in the delineation of the priority areas appears to be low. Where time-averaged subsidence rates are less than or equal to 1.5 inch per year, the error can be large. The peat thickness estimates can be in error due to lack of data for specific areas and because the data are based on land surface elevation data that are over 20 years old. The possible error in the delineation of priority areas for subsidence mitigation and slowing of subsidence rates in recent years points to the need for data collection to determine the present-day magnitude and areal distribution of subsidence rates.

The delineation of priority areas for subsidence mitigation is a first step towards implementation, designed to identify areas where future research and data collection efforts are needed. There is still much to be learned about subsidence, subsidence mitigation and the effects of subsidence. A comprehensive CALFED program is needed to effectively conduct and integrate future subsidence mitigation efforts. Additional data collection and research are required to:

- quantify and predict present-day and future subsidence rates,
- determine the present-day areal distribution of peat thickness,
- refine the delineation of priority areas for subsidence mitigation,
- temporally and spatially define the effects of subsidence on levee stability,
- determine the influence of future subsidence on levee foundation deformation and seepage through levees,
- determine the effects of continuing subsidence on future land use,
- determine the effects of future land subsidence on drainage water quality in Delta channels and seepage onto islands,
- develop land- and water-management practices for stopping and reversing the effects of subsidence and
- integrate subsidence mitigation into ecosystem restoration efforts.

This report resulted from a cooperative effort among the Department of Water Resources Central District (DWR), U.S. Geological Survey (USGS), the CALFED Bay-Delta Program and HydroFocus, Inc. DWR funded the majority of the data analysis and data collection described in this report related to the causes of subsidence, delineation of priority areas for subsidence mitigation and development of options for stopping and reversing the effects of subsidence. USGS provided partial funding for data collection and analysis related to the development of options for stopping and reversing the effects of subsidence and provided comments on this report. CALFED provided the majority of the funds for the writing of this report. Hydrofocus, Inc. donated time and materials for the writing of this report. The Natural Heritage Institute also provided comments on the report.

SUBSIDENCE MITIGATION IN THE SACRAMENTO-SAN JOAQUIN DELTA

1.0 Introduction and Background

Prior to 1850, the Sacramento-San Joaquin Delta was a tidal wetland. The Delta was drained for agriculture in the late 1800's and early 1900's (Thompson, 1957). The organic or peat deposits of the Delta formed during the past 7,000 to 11,000 years from decaying plants at the confluence of the Sacramento and San Joaquin Rivers (Atwater, 1982 and Schlemon and Begg, 1975). The drained peat soils on over 60 islands and tracts are highly valued for their agricultural productivity and have undergone continuous subsidence since they were initially drained[1]. A network of levees protects the island surfaces that range from 5 to over 20 feet below sea level, from inundation.

Drainage of the Delta islands was essentially complete by the 1930's when the Delta assumed its present configuration of the islands and tracts surrounded by 1,100 miles of man-made levees and 675 miles of channels and sloughs. When most of the original levees were constructed on foundations of sand, peat and organic sediments, the difference between the water level in the channels and island surfaces was less than 5 feet. Because of the decreasing island-surface elevations due to subsidence, there has been a decrease in the landmass resisting the hydraulic pressures on the levees and the levees have been enlarged and strengthened over time.

As the result of subsidence and other factors, levee failure and flooding of islands has occurred since the early 1900's. Prokopovitch (1985) reviewed the history, causes and costs of flooding of Delta islands since the early 1900's and the information in this and the following paragraph was excerpted from pages 409-410 of his journal article. Island flooding in the early 1900's resulted mainly from overtopping of levees during high tides or spring and winter flooding. With the flood control provided by the construction of the Central Valley Project in the 1940's, overtopping became less of a factor and levee foundation instability increasingly became an important factor in island flooding. Over 50 islands or tracts have flooded since 1930.

The data for cost of levee failures and flood damage are incomplete. However, as an example, the cost associated with 11 of the 28 islands that flooded from 1969 to 1983 was about $177 million. Levee failure and island flooding can result in loss of agricultural, commercial, industrial and residential property, recreational use, communication lines and storage and transport of electricity and natural gas. The cost for levee maintenance, upgrades and repair generally ranges from several tens of thousands to over 1 million dollars per mile. Subsidence contributes to the need for levee upgrades

[1] Subsidence is defined here as the decrease of land surface elevation. Subsidence in this report refers to the decrease in land surface elevation on the areas of the islands and tracts on the land side of the levees and is different from the lowering of the levee surface as the result of compaction of foundation materials.

and maintenance. Subsidence mitigation needs to be an integral part of any plan to prevent future flooding of Delta islands.

The cited causes of land subsidence in the Delta include aerobic microbial oxidation of soil organic carbon or microbial oxidation, anaerobic decomposition, consolidation, shrinkage, wind erosion, gas, water and oil withdrawal and dissolution of soil organic matter (Prokopovitch, 1985, Department of Water Resources, 1980; Weir, 1950). Stephens and others (1984) identified 6 causes of subsidence in drained organic soils worldwide; shrinkage due to desiccation, consolidation, compaction as the result of tillage, wind and water erosion, burning and microbial oxidation. Stephens and others (1984) reported that 53 percent of historical subsidence in organic soils in the Florida Everglades was due to microbial oxidation. Schothorst (1977) computed the percentage of the different causes of subsidence in organic soils in the Netherlands to be compaction, 28 percent; shrinkage, 20 percent; and microbial oxidation, 52 percent. The relative percentage of the different causes of subsidence in Delta have heretofore have not been quantified.

1.1 Purpose, Scope and Approach

To effectively mitigate the effects of subsidence in the Delta, the effects, rates and causes of subsidence and methods for stopping or reversing the effects of subsidence need to be identified and quantified. This report 1) summarizes information about the effects, causes and rates of subsidence, and 2) presents information about and recommendations for subsidence mitigation and future data collection.

The approach was to 1) review, synthesize and summarize the available literature and available research results, 2) estimate the relative magnitude of the different causes of subsidence using the available data, 3) use the areal distribution of historic subsidence rates and peat thickness to delineate priority areas for subsidence mitigation and future study and 4) determine and describe mitigation measures and future data collection efforts.

The overall approach for estimating the relative magnitude of the causes of subsidence was to use a computer model to synthesize and integrate the available data for subsidence rates and causes. The model estimated the amount of yearly subsidence due to different causes based on available data. The model results were compared with measured elevation change for five islands; Jersey, Sherman, Bacon and Mildred Islands and Lower Jones Tract.

The approach for the delineation of priority areas for subsidence mitigation was to use a geographic information system (GIS) developed by the Department of Water Resources Central District to analyze available data for the Delta for subsidence rates, depth of peat soils and soil characteristics. The Department of Water Resources (1980) mapped the islands of greatest subsidence and listed the peat thickness for each island. The representation of the areal distribution of subsidence rates and peat thickness presented here is an improvement relative to the previous effort (Department of Water Resources,

1980) because 1) the error in the estimated subsidence rate is generally lower, quantifiable and the result of temporally uniform elevation change determinations, and 2) the estimates for peat thickness are based on more recent and comprehensive data. Also, the data was entered into a GIS which facilitated the evaluation of the data for delineation of priority areas in greater areal detail than entire islands such as generally presented in Department of Water Resources (1980).

2.0 Methodology

2.1 Methodology for Estimating the Relative Magnitudes of the Causes of Subsidence

A computer model was developed to estimate yearly subsidence. The simulated causes of subsidence were aerobic microbial oxidation of organic carbon, consolidation and shrinkage, wind erosion, burning and withdrawal of natural gas and groundwater. Subsidence due to aqueous carbon loss was not simulated because data presented by Deverel and Rojstaczer (1996) indicated that it accounts for less than 1 percent of the measured subsidence. Data presented in Deverel and others (1998) indicated that anaerobic decomposition of Delta organic soils is small relative to other causes of subsidence and was also not included in the model. The data and methodology for simulating the causes of subsidence are summarized here and are described in detail in Appendix A.

2.1.1 Microbial Oxidation

The carbon flux data for Jersey Island collected from 1990 to 1992 (Deverel and Rojstaczer, 1996) was used to approximate the relation of microbial oxidation of organic carbon to soil organic carbon content. This relation was then used to simulate subsidence due to microbial oxidation for Jersey Island at the study location of Deverel and Rojstaczer (1996). The mass of carbon lost by microbial oxidation was assumed to follow Michaelis-Menton kinetics (Conn and Stumpf, 1976). In the Michaelis-Menton equation, the amount of carbon loss due to microbial oxidation is proportional to the amount of organic carbon in the soil.

2.1.2 Consolidation and Shrinkage

When the organic soils of the Delta were initially drained, there was substantial consolidation and shrinkage due to water loss. There is also annual consolidation that is a result of an effective stress on the peat material near the water table. As the soil subsides and oxidizes, the elevation of the bottom of drainage ditches is decreased to lower the water table thus decreasing the buoyant force of water supporting the peat. There is also an increase in loading due to the increasing density of the oxidizing soil. Shrinkage may also cause a loss in volume as the peat soils are dried but this has not been well quantified in the Delta. This annual subsidence due to consolidation was simulated in the model as equal to the volume of water lost when the water table is lowered. The amount of initial shrinkage and consolidation during reclamation was estimated from an empirical equation presented in Eggelsmann and others (1990).

2.1.3 Wind Erosion

Wind erosion of peat soils caused dust storms that affected Stockton, Lodi and Tracy prior to the early 1960's (Alan Carlton, former University of California Extension Specialist for the Delta, personal communication, 1997). The prevailing westerly winds of oceanic air masses moving to the Central Valley caused dust storms primarily during May and June (Schultz and Carlton, 1959; Schultz and others, 1963). There are few reported values of annual amounts of peat soil eroded by wind that range from 0.1 to 0.57 inch per year (Department of Water Resources, 1980; Carlton, 1965).

Crop histories in Thompson (1958) and the Weir transect notes (see Rojstaczer and others, 1991) were used to determined the spatial distribution of crops grown on the islands where land surface elevation changes were simulated. Wind erosion was calculated at varying rates of 0.1 to 0.57 inch per year where asparagus was grown or where the land was fallow. There was generally a shift from the planting of asparagus and other vegetable crops to corn in the Delta in the 1950's and 1960's and the model calculated minimal wind erosion after 1965.

2.1.4 Burning

Weir (1950) and Cosby (1941) estimated that the peat soils were burned once every 5 to 10 years. Data analysis in Rojstaczer and Deverel (1995) and Rojstaczer and others (1991) indicated that burning occurred more frequently during World War II when potatoes were grown extensively. Burning was used to control weeds and diseases and to create ash for potatoes. Weir (1950) stated that 3 to 5 inches of peat were typically lost during a single burning. Burning was simulated differently for the islands depending on the distribution of crops following the information presented in Cosby (1941) and Weir (1950).

2.1.5 Withdrawal of Natural Gas

Since the discovery of the Rio Vista Gas field in the 1930's, several natural gas fields have been developed in the Delta. Compaction of the sediments could occur if the gas reservoirs were substantially depressurized which could result in subsidence of Delta islands. To determine the subsidence due to natural gas withdrawal, sediment cores collected from channel islands were dated by determining the levels of cesium-137 at 1-inch depth intervals (Rojstaczer and others, 1991). Records from the California Department of Conservation, Division of Oil and Gas, indicate that gas production began to increase substantially in the mid-1950's and gas withdrawal was simulated as a contributor to subsidence in the model after 1955.

2.1.6 Simulation of Total Subsidence

The total annual depth of subsidence was estimated by summing the depths of subsidence due to the different causes for each yearly time step. The model accreted the land surface as it progressed backward in time based on the mathematical representation of the causes of subsidence. The soil organic carbon content and bulk density were estimated for the most recent elevation data and were recalculated for each subsequent time step. Subsidence and the microbial oxidation of organic carbon were simulated as a two-layer process based on data presented by Carlton (1966). The soil organic matter content was recalculated for each layer at each time step based on the simulated change in the total mass of carbon for each layer.

2.2 Methodology for Delineation of Priority Areas for Subsidence Mitigation

The delineation of priority areas for subsidence mitigation in the Delta is based on the areal distribution of historical, time-averaged subsidence rates calculated from the early 1900's to the mid-1970's and peat thickness. The first priority area was chosen to include those lands where the time-averaged subsidence rates were high (greater than 1.5 inch per year) and where there is still substantial peat (greater than 10 feet) remaining. The second priority area was chosen to include those areas where the time-averaged subsidence rates were high (greater than 1.5 inch per year) but there was 10 feet or less of peat remaining. It was assumed that the distribution of time-averaged subsidence rates generally reflects the relative distribution of present-day subsidence rates. Areas where time-averaged subsidence rates were lower than 1.5 inch per year were not considered to be high priority areas for immediate subsidence mitigation. A Geographic Information System for the Delta developed by, and housed at the Department of Water Resources Central District was used for the delineation of priority areas. The methodology used is summarized here and described in detail in Appendix B.

Two sets of US Geological Survey topographic maps were used to estimate the time-averaged rates of subsidence throughout the Delta from the early 1900's to 1974 through 1978. The difference in elevation between the two time periods was estimated to be the total depth of subsidence. The time-averaged rate of subsidence was calculated as the total amount of subsidence divided by the time interval that ranged from 60 to 72 years. The error in the subsidence rate estimate results from the error in the elevation estimate from the topographic maps and the change in mean sea level datum from the early 1900's to 1976 to 1978. The methodology for estimating the error associated with the time-averaged subsidence rate is described in Appendix B.

The peat thickness was calculated as the difference between the basal elevation of peat and peaty mud deposits of tidal wetlands as mapped by Atwater (1982) and the land-surface elevation from the USGS topographic maps. Atwater's (1982) peat and peaty mud of tidal wetlands include the organic deposits derived from decayed vegetation that formed during the sea level rise during the last 7,000 years. Atwater's (1982) delineation of peat and peaty mud include the organic soils mapped by Cosby (1941) and more recent soil surveys.

The peat thickness data was compared with the delineation of organic soils or highly organic mineral soils in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993). Where there were discrepancies between the two sources of information for the extent of peat soils, the soil survey data was assumed to be correct.

The delineation of soil series as mapped in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993) were entered in digital form into the GIS developed by the Department of Water Resources Central District. The soil organic matter content was the primary soil characteristic of interest. The soil organic matter content was estimated for the 11 soil series which were either organic soils or highly organic mineral soils based on the data provided in the soil surveys.

3.0 Effects of Subsidence

Levee stability is directly affected by continued subsidence within a zone of influence adjacent to levees. The spatial and temporal definitions of the zone of influence have not been quantified for the Delta and are site specific. The temporal and spatial definitions of the zone of influence should be based on analysis of the effects of future subsidence primarily on seepage and deformation of levee foundations. Deformation analysis (e.g. Foote and Sisson, 1992) of Delta levees heretofore have not considered the effects of future subsidence.

Seepage onto Delta islands will increase due to future subsidence. As the water level on the island is lowered as the result in increased drainage depth, the hydraulic gradient from the water surface in the channel to the groundwater in the interior of the island will increase. This will in turn increase the rate of seepage onto the island and may affect seepage through the levee and the erosion of foundation materials. Future data collection and analysis are needed to determine these effects.

Seepage onto Delta islands is removed, along with agricultural return flows, through a network of drainage ditches and one or more drainage pumps that pump drainage water from the islands into the channels. Templin and Cherry (1997) quantified the volume of drainage water pumped from Delta islands in 1995. Their data indicate that volumes of drainage water ranged from 2 to 4 acre-feet per acre in the central and western Delta. As a point of reference, average reference evapotranspiration for the Delta (Orang and others, 1995) is about 4.5 feet. Actual consumptive use of water by crops is less than reference evapotranspiration. About 260 agricultural drains discharge and contribute to high dissolved organic carbon (DOC) loading into the Delta channels as the result of leaching of the organic soils (Department of Water Resources Municipal Water Quality Investigations Program, 1997). High DOC concentrations can result in unacceptably high concentrations of disinfection byproducts when the water is treated for drinking. Because of increasing seepage volumes, drainage loads for DOC and disinfection byproducts may increase with increasing subsidence.

Unintentional flooding of Delta islands as the result of levee failures can cause additional water quality degradation due to salinity intrusion. Past subsidence has resulted in reduced landmass to support levees and continued subsidence can exacerbate the water quality effects of flooding by increasing the volume of water that will move onto the island during flooding. Cook and Coleman (1973) described the effects of flooding of Andrus and Brannan islands in June 1972. The Brannan-Andrus flooding is the only documented example of water quality degradation as the result of island flooding. The water balance in the Delta was upset as the result of the levee failure as 150,000 acre-feet of water moved onto the islands that in turn resulted in the movement of salt water from the west into the Delta. State and Federal exports of water from the Delta were temporarily reduced and releases from Central Valley Project reservoirs were increased to reduce the salinity intrusion. The total cost of the flooding was $22.5 million. Three hundred thousand acre-feet of additional water were released from storage from State and Federal water projects.

Short-term water quality problems probably would not occur if breaks occur during winter periods of high flow. Nor do water quality problems occur with all flooding during periods of low flow. The extent of water quality degradation is dependent on the location of the flooding and the flow conditions. Island flooding in the western Delta during low flow periods is the primary concern. Several of the western Delta islands have depths of 10 to 60 feet of peat remaining and continued subsidence will increase the volume of water that will move onto the island during flooding. For example, on Sherman Island an additional foot of subsidence over the entire island during the next 24 years (0.5 inch per year) will result in an additional volume of 9,900 acre-feet below sea level that can move onto the island during flooding. Probabilistic analysis developed by the CALFED seismic hazard team suggest that levee failure is inevitable over the long-term regardless of plans to upgrade levees to PL-99 standards. The consequences and costs of levee failure and island flooding will be proportional to the depth of interior-island subsidence.

4.0 Rates and Causes of Subsidence

4.1 Rates of Subsidence

Cited historic and time-averaged rates of subsidence in the Delta range from about 0.5 to 4.6 inches per year (Rojstazcer and others, 1991; Prokopovich, 1985, Department of Water Resources, 1980). Department of Water Resources (1980, p. 1) stated that estimates of subsidence for the years 1911 to 1952 were 3.0 inches per year on 17 Delta Islands or tracts. Department of Water Resources (1980) also listed the total amount of subsidence for 21 islands as ranging from 10 to 21 feet and time-averaged rates ranging from 1 to 4.6 inches per year. Prokopovitch (1985, p. 405) reported the same range for time-averaged subsidence rates. Rojstaczer and others (1991) evaluated subsidence from changes in land-surface elevations against power pole foundations installed in 1910 and 1952 in 1987 on Sherman and Jersey Islands. The time-averaged subsidence rate from 1910 to 1987 ranged from 0.5 to 1.2 inch per year. The time-averaged subsidence rate from 1952 to 1987 ranged from less than 0.3 to 0.7 inch per year. This and information presented by Rojstaczer and Deverel (1993) indicate that subsidence rates have slowed in recent years.

Rojstaczer and Deverel (1993) determined that a logarithmic expression for the decrease in the land-surface elevation over time statistically fit the data best for Bacon and Midlred islands and Lower Jones Tract where the time averaged historic subsidence rates were 2 and 3 inches per year from 1924 to 1981. The estimates for subsidence rates in 1980 for these three islands ranged from 1.2 to 1.6 inch per year (Rojstaczer and Deverel, 1993). Subsidence rates are slowing for two reasons. First, the rate of microbial oxidation is proportional to the amount of organic carbon in the soil which is decreasing with time. Second, other factors such as wind erosion and burning contributed to subsidence in the past but do not appear to contribute significantly to present-day subsidence. Deverel and Rojstaczer (1996) continuously measured present-day subsidence rates from 1990 to 1992 by on Sherman and Jersey Islands and Orwood Tract. These authors reported rates of 0.2, 0.24 and 0.32 inch per year on Sherman, Jersey and Orwood, respectively.

4.2 Causes of Subsidence

4.2.1 Simulation Results

Table 1 shows the range of simulated elevation changes and percentages of the total subsidence due to the different causes. The results in Table 1 for the different simulations reflect variations in the amount of wind erosion for all the islands and the parameters in the Michaelis-Menton equation for microbial oxidation.

Table 1. Simulated changes in elevation and causes of subsidence for Jersey, Sherman, Mildred and Bacon islands and Lower Jones Tract.

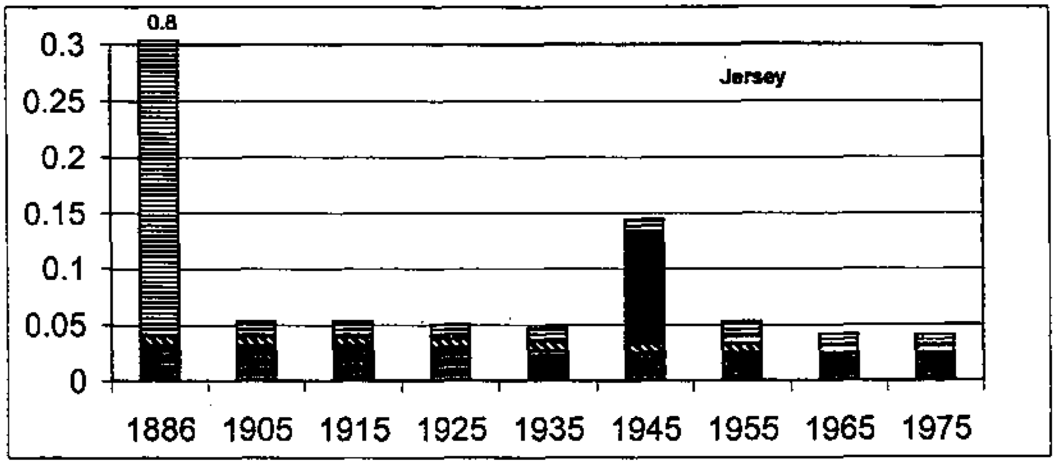
			Simulated range in percent of total subsidence due to:				
Island (years of simulation)	**Simulated changes in elevation (in feet)**	**Measured change in elevation (in feet)**	**Microbial oxidation**	**Consolidation and shrinkage**	**Wind erosion**	**Burning**	**Gas withdrawal**
Jersey (1886 –1975)	5.3 – 8.1	6.7 +/- 2.5	31 – 48	22 – 25	11 –26	9 – 13	2 – 3
Sherman (1910 – 1987)	4.7 – 6.05	6.0 +/- 1.0	29– 47	24 – 25	9 – 34	10 – 14	
Mildred (1924 – 1981)	10.8 – 11.4	11.6 +/- 2.0	37 – 50	29 – 30	3 – 17	18 –19	
Bacon (1924 – 1978)	10.5 – 11.0	10.5 +/- 1.0	36 – 49	24 – 25	3 – 17	23 – 24	
Lower Jones (1924 – 1981)	10.0 – 10.4	9.45 +/- 1.5	41 - 55	24 – 25	3 – 18	18 - 19	
Total range	-	-	29 – 55	22 – 29	3 – 34	10 - 24	2 - 3

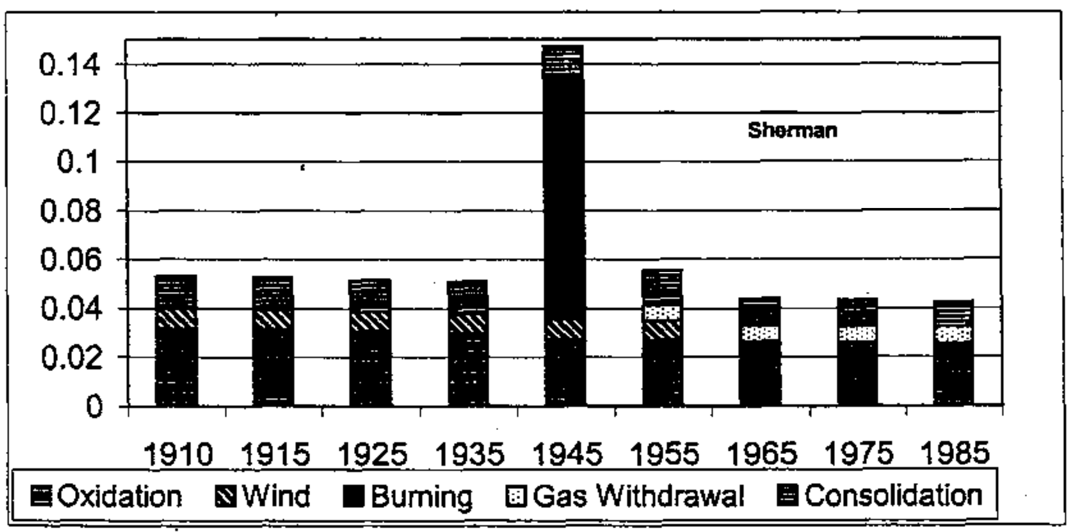
The most recent elevation data for Jersey Island in Table 1 is from the 1978 topographic map that shows topography from photogrammetric methods using aerial photos conducted in 1974 and plane table elevation data collected in 1976. Thompson (1957) indicated that Jersey Island was initially drained in 1886. The measured elevations for Sherman Island in Table 1 were from elevations determined in 1988 against power pole foundations installed in 1910 (Rojstaczer and others, 1991; Rojstaczer and Deverel, 1995). The estimated error for the Sherman data was about 1 foot (Rojstaczer and others, 1991). The estimated error in the Jersey elevation change is about 2.5 feet. The measured changes for Mildred, Bacon and Lower Jones were from the leveling data collected along the Weir transect (Weir, 1950) by University of California personnel (see Rojsatczer and others, 1991).

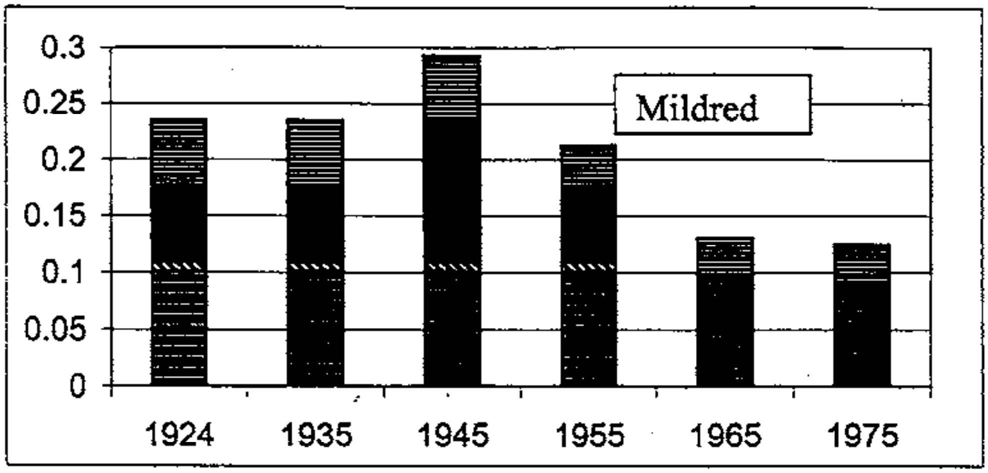
Table 1 shows that the primary causes of historical subsidence simulated on the five islands are microbial oxidation of organic carbon (29 to 55 %) and consolidation and shrinkage (22 to 29 %). Much of the consolidation for Jersey and Mildred islands occurred when these islands were initially drained. This accounts for the relatively large percentage of total simulated subsidence due to consolidation for these islands. The Jersey Island simulation extends from the approximate year of initial drainage to 1975 when the most recent elevation data was collected. The Mildred Island simulation extended from 1924 (the year of initial drainage) through 1981 to coincide with the leveling data reported in Rojstaczer and others (1991).

The amounts of the different causes of subsidence varied with time. Figure 1 shows the amount of subsidence contributed by the different processes for the five islands from 1886 to 1985 in 10-year intervals. Consolidation is the predominant process during the first year after initial drainage. Burning was the predominant cause in 1945. Wind erosion and gas withdrawal are minor causes that account for less than 10 percent of the total yearly subsidence. Simulation results for 1975 on Jersey, Mildred, Bacon and Lower Jones and 1985 on Sherman indicate that present-day subsidence is caused primarily by microbial oxidation and consolidation (75 percent and 25 percent, respectively). Deverel and Rojstaczer (1996) also studied present-day subsidence from 1990 to 1992 on Jersey and Sherman Islands and Orwood Tract. Their results indicated that 60 to 76 % of the measured subsidence was due to microbial oxidation. Comparison of model results and measured elevations shown in Apendix A indicate good agreement between simulated and measured results for Mildred, Bacon and Lower Jones.

Figure 1. Subsidence rates in feet per year from 1886 to 1985 due to different causes for Jersey, Sherman, Bacon and Mildred Islands and Lower Jones Tract.






Mildred
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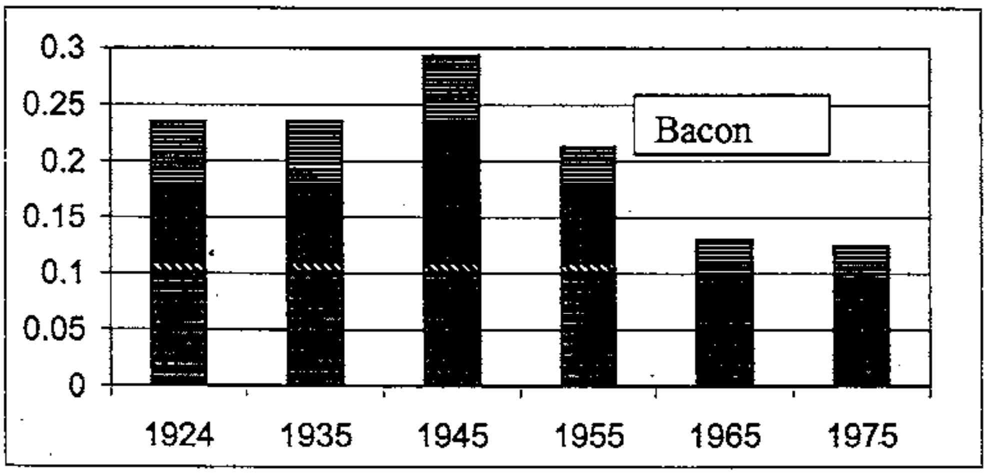
Bacon
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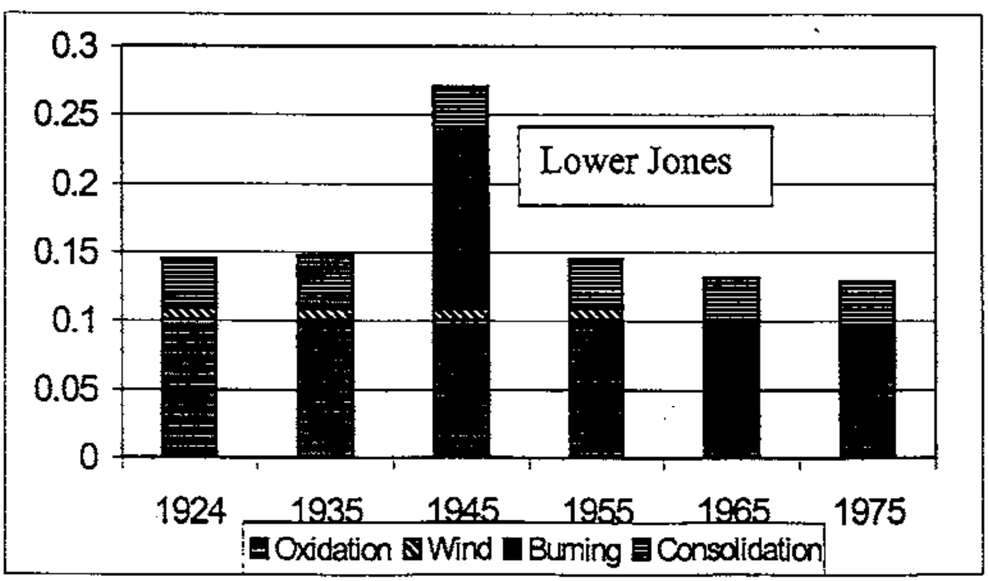
Lower Jones
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1924
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1965
1975
Oxidation Wind Burning Consolidation

4.2.2 Limitations in the Determination of the Causes of Subsidence

Although estimates of the magnitude of the causes of subsidence are consistent with what is known about the processes affecting subsidence in the Delta, the primary limitation of the analysis is the lack of explicit and deterministic simulation of the causes of subsidence. The equation for microbial oxidation is based on limited data and does not explicitly simulate the microbial decomposition of the different components of the soil organic carbon. Consolidation during initial drainage is empirically based. Also, ongoing consolidation of the organic soil after initial drainage is simulated to be the result of water loss only. There is probably a rearrangement of the soil fabric as subsidence and decomposition proceeds that is not currently quantifiable and is not included in the model. Burning of organic soils in the Delta was not well documented and simulation of burning is based on limited data discussed in Cosby (1941) and Weir (1950). The mechanics of wind erosion are also not explicitly modeled due to lack of data. These limitations, especially as related to the simulation of microbial oxidation and consolidation, point to the need for additional data collection and research for improved understanding and prediction of subsidence rates.

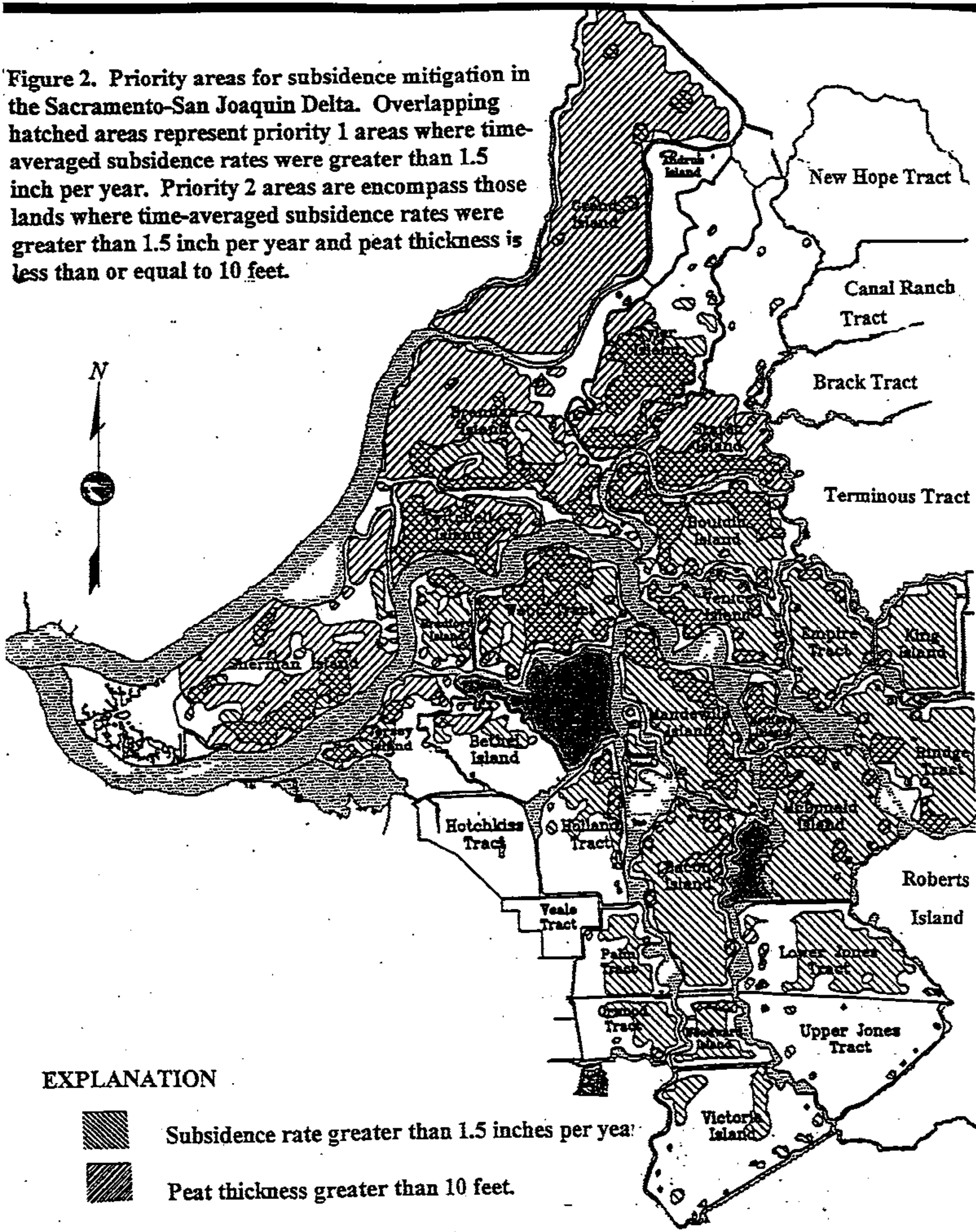
5.0 Distribution of Priority Areas for Subsidence Mitigation

Figure 2 shows the distribution of the two priority areas for subsidence mitigation. The priority 1 area is comprised of lands where the peat thickness is greater than 10 feet and the time-averaged subsidence rate was greater than 1.5 inch per year. The priority 2 area is comprised of lands where the time-averaged subsidence rate was greater than 1.5 inch per year and the peat thickness is 10 feet or less. Peat thickness is generally greatest in the western and northern parts of the Delta; the largest areas of peat thickness greater than 10 feet are on Sherman, Twitchell, Brannan-Andrus, Grand, Staten and Tyler islands and Webb Tract. The amount of area in priority 1 varies among these and other islands according to the distribution of time-averaged subsidence rates. The acres for the two priority areas for the different islands are presented in Appendix B.

The largest acreage for priority 1 is on Webb Tract in the west-central Delta. Venice, Bouldin and Mandeville islands in the central Delta also have large acreage assigned to the priority 1 area. Twitchell, Brannan-Andrus and Sherman islands and Webb Tract in the western and west-central Delta and Tyler Island in the northern Delta also have large areas in this priority. Although Grand Island has a large acreage of peat thicker than 10 feet, the time averaged subsidence rates are almost all less than 1.5 inch per year. The total area for priority 1 is about 22,900 acres.

The islands with the largest acreage in the priority 2 area are in the central Delta where subsidence rates have been historically high and there are large areas of peat that are less than 10 feet thick. MacDonald, Bacon and Mandeville islands and Empire Tract in the Central Delta and Rindge Tract in east-central Delta and Webb Tract in the west-central Delta have large areas in priority 2. Other central Delta islands (Lower Jones Tract, Bouldin Island and Venice Island) have substantial areas in priority 2. The islands and tracts of the western and northern Delta generally have low acreage in the priority 2 area

Figure 2. Priority areas for subsidence mitigation in the Sacramento-San Joaquin Delta. Overlapping hatched areas represent priority 1 areas where time-averaged subsidence rates were greater than 1.5 inch per year. Priority 2 areas are encompass those lands where time-averaged subsidence rates were greater than 1.5 inch per year and peat thickness is less than or equal to 10 feet.



because of the relatively low time-averaged subsidence rates. The total area for priority 2 is about 35,700 acres. The total area for priorities 1 and 2 is about 58,600 acres.

Deverel and others (1998) reported that time-averaged subsidence rates were highly correlated with percent soil organic matter on Sherman Island. The distribution of soil organic matter content in the Delta generally reflects the distribution of subsidence rates shown in Figure 2. For example, the highest organic matter contents (greater than 30 percent) are in the central, east-central and the west-central Delta (Twitchell Island, Bradford Island, Webb Tract, Bouldin Island, Venice Island, Empire Tract, Rindge Tract, King Island, Bacon Island, Lower Jones Tract). The time-averaged subsidence rate for the majority of these islands is greater than 1.5 inch per year (Figure 2). Islands where organic matter contents are generally lower than 15 and 30 percent such as Sherman Island, Brannan-Andrus Island, Staten Island and Victoria Island are generally at the periphery of the Delta. The subsidence rates on these islands are generally less than 1.5 inch per year.

5.1 Uncertainty in the Delineation of Priority Areas

The primary uncertainties in the spatial analysis are the result of uncertainties in the thickness of the peat soil and the error in the estimation of the subsidence rate. The subsidence rate error is the result of errors associated with the use of topographic elevations as described above and the use of different datums for the 2 surveys for the topographic maps published in 1906 to 1911 and 1976 to 1978. In general, large errors in the subsidence rates correspond to areas of the lowest time-averaged subsidence rates. The error in the subsidence rate estimate due to the mapping error is 50 percent or less for much of the Delta where there are peat deposits. The error in the subsidence rate generally increases approaching the periphery of the Delta. The error in the western, eastern, southern and northern edges of the Delta generally approaches or exceeds 100 percent.

The key questions related to the error for the purpose of determining the priority areas based on time-averaged subsidence rates are: 1) Is the distribution of subsidence rates consistent with what is known about the distribution of present-day subsidence rates? and 2) What is the error associated with assignment of areas to one of the two categories (less than and greater than 1.5 inch per year) for subsidence rates?

The first question can be answered qualitatively based on recently collected data for subsidence for selected areas of the Delta. Specifically, data from Rojstaczer and Deverel (1995), Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) are consistent with the spatial distribution of subsidence rates presented here. Time-averaged subsidence rates reported for the central Delta (Lower Jones Track, Bacon and Mildred islands) are greater than in the western Delta (Sherman and Jersey islands) (Rojstaczer and others, 1991). However, subsidence has not been measured extensively throughout the Delta so that it is impossible to compare rates for all the islands. The subsidence rates in Figure 2 are generally consistent with what is known about subsidence and organic soils in the Delta (Prokopovitch, 1985). The highest soil organic matter contents and subsidence rates are in the central Delta. The soils are lower in organic matter content and subsidence rates are lower approaching the margins of the Delta

The second question can be answered based on the distribution of error for subsidence rates. The error analysis is discussed in Appendix B. Data for Sherman Island and Webb Tract were used to evaluate the effect of errors on the acreage within each priority area. The data for these islands represent the variability in the data set and the error analysis illustrates the possible range in calculated acreage in the two priority areas.

The range of acreage on Webb Tract for priority 1 shows that the acreage in priority 1 could be overestimated by 54 % and underestimated by less than 1 %. For priority 2, the range in acreage on Webb Tract shows that the acreage in priority 2 could be overestimated by 24 % and underestimated by 10%. In contrast, the ranges of acreage in each priority for Sherman Island are large, ranging up to 1,000 percent. The time-averaged subsidence rates for Sherman were lower than Webb and therefore the error associated with the subsidence-rate estimate is higher and the range of acreage classified in each priority area is large. The results of this analysis point to a need for additional data collection for subsidence rates, especially in the western Delta.

The areal distribution of the estimation error for the peat thickness was not determined. The density of borehole data and the error in the land-surface elevation primarily determines the error. The land-surface elevation error is due to leveling error in the determination of land-surface elevation that is about plus or minus 2.5 feet and the subsidence that has occurred since 1974 (about 1 to 4 feet). The total land-surface elevation error ranges from about –1.5 to 6.5 feet.

Appendix B shows and discusses the number and average density of data points for borehole logs used to estimate the peat thickness. In general, data densities greater than 200 acres per data point result in moderate to high uncertainty in the estimation of the basal peat elevation for large areas of the islands. Of those islands where the density of peat thickness data is greater than 200 acres per data point, only 7 have acreage in the 2 priorities (Orwood Tract, Victoria Island, Brannan and Andrus islands, King Tract, Tyler Island and Grand Island). Brannan-Andrus Island, King Tract and Tyler Island have significant acreage in the 2 priorities. Grand Island is mapped as having a large area of thick peat but has little acreage in priority area 1 because of the low time-averaged subsidence rates. The percent organic matter in the soils on Grand Island is relatively low. Although there is uncertainty in the delineation of the priority areas for subsidence mitigation, the delineation is based on the available data and provides a starting point for further data collection efforts to better define areas and management practices for subsidence mitigation.

6.0 Land- and Water Management Practices for Subsidence Mitigation

The primary factor contributing to present-day subsidence in the Delta is microbial oxidation of soil organic carbon. The oxidation of soil organic carbon is directly proportional to soil temperature and decreases with increasing soil moisture (Deverel and Rojstaczer, 1996). The results of studies conducted by the US Geological Survey and

Department of Water Resources (Deverel and others, 1998) demonstrated that permanent shallow flooding reversed the effects of subsidence on Twitchell Island. Permanent shallow (about 1 foot) flooding resulted in a net carbon accumulation and accretion of biomass. The plots were first flooded in February 1993. Cattails were the primary species that colonized the plots. During 1993, the cattails covered about 25 percent of the plot. In 1994, 30 to 55 percent of the plot was covered and full vegetative cover was achieved in 1995. Cores were collected in the flooded plot while it was temporarily drained in July 1997. The results of the coring showed that about 3 to 6 inches of firm biomass accreted from 1993 to 1997 during 2 years of growth under full vegetative cover and 2 years of growth under partial cover. Other water-management strategies that were evaluated; seasonal flooding during the late fall and winter with and without irrigation during the spring and summer, resulted in a net carbon loss and are not viable mitigation strategies for stopping subsidence. This is due to large microbial oxidation rates that occur during the spring and summer.

Consistent with the potential of permanent shallow flooding to reverse the effects of subsidence, two projects are funded and one is underway to evaluate the large scale effects of this management practice. First, data collection began in October of 1997 on Twitchell Island on a 15-acres demonstration project for increasing land-surface elevation through biomass accumulation under permanently flooded conditions. The overall approach is to verify the reversal of subsidence in organic soils under permanently flooded conditions at a larger scale than used in previous research (Deverel and others, 1998). The demonstration project will provide information about: 1) the large scale effects of permanent flooding on the carbon balance and land-surface elevation changes; 2) the effects of different water-management practices and vegetation on biomass accumulation and land-surface-elevation changes; 3) the effects of varying soil organic matter content on the carbon balance under permanently flooded conditions and 4) future potential increases in land-surface elevation.

Second, a $3.5 million project has been funded through the CALFED Category 3 process to develop quantitative answers to the key unanswered questions about the reversal of the effects of subsidence and the development of tidal wetland habitat in the Sacramento-San Joaquin Delta. The focus of the project is the development of cost-effective techniques for the reversal of the effects of subsidence. This will be accomplished through research and a demonstration project for tidal wetland habitat restoration on Twitchell Island that will be transferable to other Delta islands. Quantitative answers to questions about the feasibility of depositing sediment on Delta islands and potential water quality impacts of accreting the land surface through biomass accumulation will be addressed during the conduct of this project. This project is scheduled to begin in early 1999.

Other water- and land-management strategies are being evaluated that may stop, or reverse the effects of, subsidence include capping the organic soil with mineral material and reverse wetland flooding. Preliminary results by the USGS (Lauren Hastings, USGS, personal communication, 1998) indicate that capping the unsaturated peat soil with 2 feet of dredge sand reduces the emission of carbon dioxide by about 35%. Capping of partially saturated soil reduced emission of carbon dioxide by 23%. Capping saturated peat soil with dredge material could provide upland habitat in shallow flooded wetlands. Capping of the peat reduces the transport of oxygen and carbon dioxide in and out of the soil causing the rate of carbon dioxide emission to decrease.

Reverse wetland flooding involves shallow flooding during the spring and summer and drainage during the fall and winter. This may reduce oxidation when it is usually the greatest and result in organic matter accumulation. The USGS is currently evaluating this as a subsidence mitigation strategy.

Subsidence mitigation efforts should be coordinated with efforts to restore the ecological health of the Delta. From an ecological perspective, there needs to be freshwater wetlands covering the full range of ecosystem gradients in the Delta. To achieve this range, elevations on western Delta islands must be restored to bring some of the islands back into tidal circulation (Steve Johnson, The Nature Conservancy, 1997).

7.0 Summary and Recommendations

7.1 Summary

- A computer model was used to integrate and synthesize the available data for the historic causes of subsidence in Delta organic soils. The model that simulated the relative magnitude of the causes of subsidence was validated using measured data for carbon fluxes and subsidence rates on Sherman, Jersey, Bacon, and Mildred Islands and Lower Jones Tract.
- The model simulations indicate that 29 to 55 percent of the total amount of historical subsidence on the Delta organic soils that occurred from the late 1800's through the 1970's was due to microbial oxidation of organic carbon.
- The model simulations indicate that consolidation and shrinkage, whether initially or over time because of drainage, accounted for about 22 to 29 percent of the total historical subsidence. Burning has accounted for 9 to 24 percent of the total historical subsidence. Wind erosion has historically accounted for 3 to 34 percent. Gas withdrawal has historically accounted for less than 3 percent.
- Present-day subsidence is caused primarily by the microbial oxidation of organic carbon.
- Time-averaged subsidence rates and peat-thickness were used to determine priority areas for subsidence mitigation in the Sacramento-San Joaquin Delta.
- Two priority areas for subsidence mitigation were determined as follows. The priority 1 area encompasses lands where time-averaged subsidence rates were greater than 1.5 inch per year and peat thickness was greater than 10 feet. The priority 2 area encompasses lands where the subsidence rates were greater than 1.5 inch per year and the peat is less than or equal to 10 feet thick.
- The largest priority-1 areas are in the western, west central and central Delta. The total area for priority 1 is about 22,900 acres.
- The largest priority 2 areas in are in the central Delta and central-eastern Delta where subsidence rates have been historically high. The islands and tracts of the western and northern Delta generally have low acreage in priority 2 because of the low

historical subsidence rates in these areas. The total priority-2 area is about 35,700 acres.

- The total area for both priorities is about 58,600 acres.
- The uncertainty in the estimation of priorities depends on the magnitude of the time-averaged subsidence rate and the uncertainty in the estimation of the peat thickness. The error in the subsidence rate estimate is generally less than 50 percent where subsidence rates are greater than 1.5 inch per year. This primarily corresponds to areas in the central Delta. The error in the subsidence rate increases approaching the margins of the Delta.
- The error in the subsidence rate has relatively less effect in the assignment of priorities on islands where the time-averaged subsidence rates were high such as Webb Tract. However, it has a large effect on the assignment of priorities for islands such as Sherman where historical subsidence rates have been lower.
- Permanent and shallow flooding of organic soils and capping, reduce or stop subsidence rates and shallow flooding can stop or reverse of the effects of subsidence.
- The effects of continued subsidence include levee instability, increased seepage onto islands and water quality effects related to seepage and flooding.

7.2 Recommendations for Research and Additional Data Collection

Eight western Delta islands (Sherman, Jersey, Twitchell, Bradford, Holland, Hotchkiss, Bethel and Webb) encompass a key area for subsidence mitigation because of the potential for water quality deterioration as the result of a levee break on these islands during low flow. Figure 2 shows that large areas of Twitchell, Webb and Bradford are included in the first priority area. Relatively small areas of Sherman, Jersey, Bethel, Hotchkiss and Holland are included in the two priorities. However, the error analysis discussed above indicates that the uncertainty in the assignment of priority areas on Sherman Island is as large as 1,000 percent. The uncertainty on Webb Tract is small. Examination of the subsidence rates and the error in the subsidence rates for Jersey, Holland, Hotckiss and Bethel indicate that the error in the assignment of priorities for these islands is generally similar to the error for Sherman Island.

The uncertainty in the assignment of priorities points to the need for additional data for subsidence rates throughout the Delta prior to implementation of subsidence mitigation measures. Since subsidence mitigation is critical in the western Delta yet the uncertainty in the time-averaged subsidence rates can be high, additional data about the distribution of subsidence rates is recommended in the western Delta for a higher level of certainty for the implementation of subsidence control measures. Also, analysis by Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) demonstrate that subsidence rates are decreasing with time. Therefore, the present-day subsidence rates are lower than those reported here and additional information is required to refine the delineation of priority areas based on present-day subsidence rates.

Uncertainty in the basal peat elevations and current elevations in the Delta also point to the need for additional data. Because the most recent topographic leveling in the Delta was completed in the 1970's, the peat thickness data presented here are about 20 years old. These peat thickness data could be in error by as much as 6.5 feet because of subsidence that has occurred over the past 20 years. The peat thickness values are also uncertain for several islands as discussed above where data is sparse or lacking.

The effects of future subsidence on Delta levee stability have not been studied. Seepage and deformation are key processes that may be affected as the result of future subsidence. The area adjacent to the levee where levee stability is affected by subsidence and the time frame associated with this zone of influence needs to be determined through general and site specific analysis. Analysis should be conducted to determine the effects of future subsidence on levee deformation for different environments where the thickness of the peat and subsidence rates vary. Similarly, seepage analysis should be used to estimate volumes of seepage and the effects on levees for different subsurface materials, varying subsidence rates and different drain configurations.

Specific recommendations for future data collection efforts are as follows.

- Refine the delineation of priority areas by reducing the errors in subsidence rate estimates and peat thickness and determining present-day subsidence rates.
- Collect data for present-day subsidence rates and predict future subsidence rates. Present-day subsidence rates can be determined by measuring land-surface elevations in areas where there is historical data such as Mildred, Lower Jones and Bacon and determining land-surface elevations throughout the Delta at regular intervals. In the short-term, determination of soil organic carbon throughout the Delta in combination with measurement of land-surface elevations on selected islands will improve the delineation of priority areas.
- Future subsidence rates can be predicted by collecting data that will give more precision to the calculation of microbial oxidation described in this report. The evaluation and estimation of consolidation also require more data and analysis.
- Collect data for peat thickness. This can be done using geophysical methods or by determining land surface elevations and calculating the peat thickness using well-log data.
- Determine the effects of future subsidence on levee deformation and seepage.
- Continue to support development and pilot- and large-scale implementation of land- and water-management practices for subsidence mitigation.
- Integrate subsidence mitigation efforts with ecosystem restoration efforts.

APPENDIX A. DESCRIPTION OF COMPUTER MODEL FOR ESTIMATING THE RELATIVE MAGNITUDE OF THE CAUSES OF SUBSIDENCE AND MODEL RESULTS

A.1 Microbial Oxidation

The carbon flux data for Jersey Island collected from 1990 to 1992 (Deverel and Rojstaczer, 1996) was used to approximate the relation of microbial oxidation of organic carbon to soil organic carbon content. This relation was used to simulate subsidence due to microbial oxidation for Jersey Island at the study location of Deverel and Rojstaczer (1996). The mass of carbon lost by microbial oxidation was assumed to follow Michaelis-Menton kinetics (Conn and Stumpf, 1976):

$$CFLUX = (CFLUXMAX \times foc)/(Km - foc) \quad \text{(A.1)}$$

where
$CFLUX$ = CO_2 loss from the soil in grams carbon cm^{-2} yr^{-1} due to microbial oxidation of organic carbon in the peat soil.
$CFLUXMAX$= maximum CO_2 loss from the soil in grams carbon cm^{-2} yr^{-1}
Km = Michealis-Menton constant, and
foc = the fraction of organic carbon in the soil in grams carbon per g soil

The values of CFLUXMAX and Km were determined from annual averages of monthly carbon flux measurements for two sites on Jersey Island where soil organic matter content values of 0.28 and 0.22 were measured (Deverel and Rojstaczer, 1996). The foc values were estimated to be one-half of the soil organic matter content for the sites on Jersey and other sites in the Delta as per Broadbent (1960). The average annual soil temperature and depth of the groundwater at these two sites were nearly identical during the period of measurement (1990 - 1992). These two data points were used to develop a linear plot of the reciprocal of CFLUX versus the reciprocal of the foc. The slope of this plot is equal to Km/CFLUXMAX and the intercept is equal to 1/CFLUXMAX. For each year of model simulation, CFLUX was recalculated based on the change in foc as the result of the change in soil carbon during the previous time step. The change in land surface elevation due to oxidation was estimated by dividing the annual carbon flux by the soil bulk density and the foc.

The parameters for equation A.1 developed from the Jersey Island data were used to simulate microbial oxidation on Sherman Island. For the central Delta Islands, Mildred and Bacon islands and Lower Jones Tract, the elevation data for Mildred Island in Rojstaczer and others (1991) was used to determine the parameters for equation 2.1. The parameters were determined by model calibration against elevation measurements determined from 1924 through 1981 (Weir, 1950; Rojstaczer and others, 1991). The values for CFLUXMAX and Km determined for the Mildred Island calibration were then used to simulate land surface elevation changes for Lower Jones Tract and Bacon Island. Additional information about subsidence due to consolidation, wind erosion, burning, and withdrawal of natural gas and groundwater was also incorporated into the model.

A.2 Consolidation and Shrinkage

The amount of initial shrinkage and consolidation during reclamation was estimated from an empirical equation presented in Eggelsmann and others (1990) in which the consolidation is expressed as a function of the initial drainage depth in meters:

$$Consolidation = a \times (0.08 \times T - 0.066) \quad \text{(A.2)}$$

where a is and empirical constant that is dependent on the degree of decomposition and texture of the peat, and T is the depth of initial drainage (assumed to be 6 feet).

Equation A.2 was used to estimate the total amount of consolidation due to initial drainage and was applied only once during simulation of subsidence for Jersey and Mildred islands. The empirical constant was assumed to have a value of 1.9 based on information presented in Eggelsmann and others (1990). For comparison, the amount of consolidation during initial drainage was also calculated using the drainage curves reported by Hanson and Carlton (1980). The results using the drainage curves were about 13 percent greater than those in which the Eggelsmann and others' (1990) equation was used.

A.3 Wind Erosion

Wind erosion of peat soils caused dust storms that affected Stockton, Lodi and Tracy prior to the early 1960's (Alan Carlton, former University of California Extenstion Specialist, personal communication, 1997). The prevailing westerly winds of oceanic air masses moving to the Central Valley caused dust storms primarily during May and June when wind speeds exceeded 15 miles per hour at a height of about 6 feet (Schultz and Carlton, 1959; Schultz and others, 1963). Carlton and Schultz (1956 – 1966) conducted experiments to determine the frequency and duration of dust storms caused by wind erosion of peat soils and methods for reducing wind erosion. Asparagus fields were a primary source of wind-eroded soil as the soil surface was mostly bare during May and June.

The Department of Water Resources (1980) reported values ranging from 0.1 inch per year based on personal communication from Alan Carlton to 0.25 to 0.5 inch per year from Weir (1950). Weir (1950) made no measurements of wind erosion and stated that "it may be as much as 0.25 to 0.5 inch per year." Carlton (1965) estimated wind erosion on Terminous Tract to be 0.57 inch per year from 1927 to 1957. This estimate was based on the elevation difference between a plot of land owned by Southern Pacific Railroad which was not farmed or cultivated but was surrounded by cultivated cropland. It is unclear whether the Southern Pacific Railroad land had been burned.

Crop histories in Thompson (1957) and the Weir transect notes (see Rojstaczer and others, 1991) were examined to determine the spatial distribution of crops grown on the islands where land surface elevation changes were simulated. Wind erosion was calculated at varying rates of 0.1 to 0.57 inch per year where asparagus was grown or where the land was fallow. There was generally a shift from the planting of asparagus and other vegetable crops to corn in the Delta in the 1950's and 1960's and the model calculated minimal wind erosion after 1965.

A.4 Burning

Weir (1950) and Cosby (1941) estimated that the peat soils were burned once every 5 to 10 years. Burning probably occurred more frequently during World War II when potatoes were grown extensively (Rojstaczer and others, 1991). Burning was used to control weeds and diseases and to create ash for potatoes. Weir (1950) stated that 3 to 5 inches of peat was lost during burning. Burning was simulated differently for the islands depending on the distribution of crops.

It was assumed that most of the Delta organic soils were planted to potatoes from 1938 to 1945. Elevation loss on all five islands due to burning was simulated to be 4 inches per burning during 2.5 burnings during this time period. Individual cropping patterns were used to simulate burning during other time periods for Mildred and Bacon islands. Potatoes were grown on Mildred Island from 1930-1938 and 6 inches of soil loss during 1.5 burning was simulated during this time period. Potatoes were also a predominant crop on Bacon from 1930 to 1938 and 1945 to 1955 and 6 inches of soil loss during 1.5 burning was simulated during each of these time periods. Alan Carlton (former University of California Extension Specialist, personal communication, 1997) stated that there was no burning in the Delta after 1955.

A.5 Withdrawal of Natural Gas and Groundwater

To determine the subsidence due to natural gas withdrawal, sediment cores collected from channel islands were dated by determining the levels of cesium-137 at 1-inch depth intervals (Rojstaczer and others, 1991). The surface elevation of channel islands has remained at sea level since the 1850's even though sea level rose about 0.08 inches per year indicating that sediment has been deposited on these islands. The peak fallout of ceisum-137 occurred in 1963 and was identified 3 to 7 inches below the sediment surface in cores collected on channel islands adjacent to Twitchell, Bradford and Bethel islands and Webb Tract, indicating that the channel islands subsided since 1963.

From 1963 to 1988 when the cores were collected, sea level rose about 2 inches. Therefore, the amount of subsidence due to gas withdrawal was between 0.04 and 0.2 inches per year ((3 – 2 inches) divided by (1988-1963)) = 0.04 inch/year, ((7- 2 inches) divided by (1988-1963) = 0.2 inches/year)). For modeling of subsidence, 0.08 inch per year of subsidence as the result of gas withdrawal was estimated for Jersey Island based on the results of ceisum-137 results reported in Rojstaczer and others (1991) for the channel island adjacent to Bradford Island. Subsidence due to gas withdrawal was not simulated for the Sherman, Mildred and Bacon islands or Lower Jones Tract because elevation changes along the Weir transect were compared to a benchmark and structures that was also affected by these withdrawals. Records from the California Department of

Conservation, Division of Oil and Gas, indicate that gas production began to increase substantially in the mid-1950's and gas withdrawal was simulated as a contributor to subsidence in the model after 1955.

A.6 Simulation of Total Subsidence

The total annual depth of subsidence was estimated by summing the depths of subsidence due to the different causes. The model accreted the land surface as it progressed backward in time based on the mathematical representation of the processes described above. The foc and bulk density were estimated for the most recent elevation data and time step and were recalculated for each subsequent time step. For Sherman and Jersey Islands, the initial foc and bulk density were from Deverel and Rojstaczer (1996). For Mildred and Bacon islands and Lower Jones Tract the foc was estimated from the soil survey for San Joaquin County (Soil Conversation Service, 1992) to be 0.25. The bulk density for the surface (0 to 2 feet) soils for Mildred, Bacon and Lower Jones was estimated at 0.74 g/cm^3 from the relation for data for organic matter content and bulk density collected on Rindge and Empire tracts and Bouldin Island reported in Hanson and Carlton (1980). A regression equation ($r^2 = 0.50$) was fit to the all the data of the form.

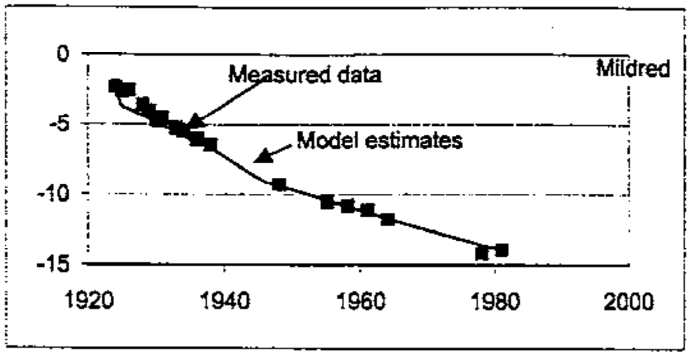
$$\textit{log bulk density} = 0.058 - 0.76 \times \textit{foc}. \qquad \text{(A.3)}$$

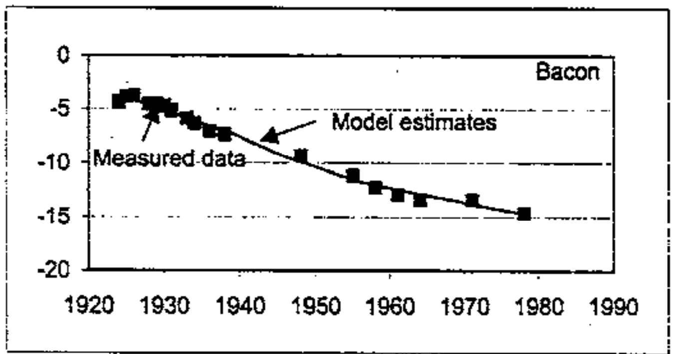
This equation was also used to estimate the bulk density at the beginning of each time step.

Subsidence and the microbial oxidation of organic carbon were simulated as a two-layer process based on data collected by Carlton (1966). The depth of soil affected by subsidence was assumed to be 5 feet. Carlton (1966) measured the depth of subsidence occurring in different layers on Venice Island from 1962 to 1966. Eighty-one percent of the total subsidence occurred in the upper 2 feet of the soil profile. Therefore, eighty-one percent of the organic carbon oxidation was simulated to occur in the upper 2 feet of the soil profile. The remainder was simulated to occur in the lower 3 feet. The foc was recalculated for each layer at each time step based on the change in the total mass of carbon for each layer. The final foc for the most recent and initial time step for the model for the lower layer was estimated at 0.375 based on information in Deverel (1983). The new oxidation rate was calculated for subsequent time steps using equation 2.1. The foc was not allowed to exceed 0.40 for either layer.

A.7 Model Results

Figure A.1 shows that there is good agreement between measured and modeled values for land-surface elevation changes for Bacon, Mildred and Lower Jones.





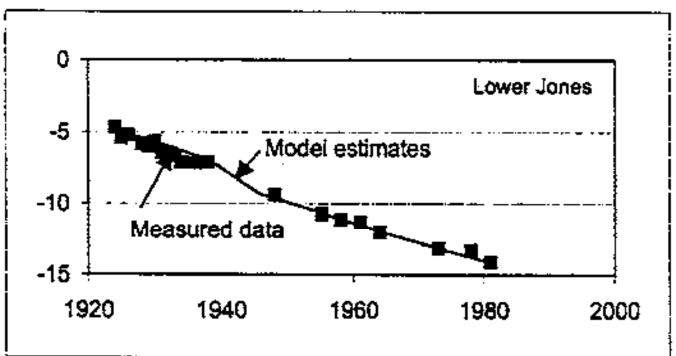


Figure A.1 Measured and model estimates for elevation changes for Mildred, Bacon and Lower Jones from 1924 to 1981. Squares represent measured data and solid lines represent model estimates. Elevation changes on the vertical axis are in feet above sea level.

APPENDIX B. METHODOLOGY, RESULTS, AND UNCERTAINTY ANALYSIS FOR THE DELINEATION OF PRIORITY AREAS FOR SUBSIDENCE MITIGATION.

A Geographic Information System developed by and housed at the Department of Water Resources Central District was used to delineate priority areas for subsidence mitigation based on time-averaged subsidence rates and peat thickness. The following describes the methodology, data, results and error analysis.

B.1 Determination of Areal Variability of Time-averaged Subsidence Rates

Two sets of US Geological Survey topographic maps were used to estimate the time-averaged rates of subsidence throughout the Delta from the early 1900's to 1976 through 1978. Specifically, topographic maps for the 1906-1911 mapping of the Delta at 1:31,680 scale were used to estimate land surface elevation on a 500-meter grid. The 1976 to 1978, 1:24,000 scale topographic maps were used to estimate land surface elevation for the same 500-meter grid. The difference in elevation between the two time periods was estimated to be the total depth of subsidence. The time-averaged rate of subsidence was calculated as the total amount of subsidence divided by the time interval that ranged from 60 to 72 years..

The error in the subsidence rate estimate results from the error in the elevation estimate from the topographic maps and the change in mean sea level datum from the early 1900's to 1976 to 1978. Early leveling in California used the average of tide level gauges in California for the mean sea level datum (Birdseye, 1925). The sea level datum for the 1976 to 1978 maps is the National Geodetic Vertical Datum of 1929 (NGVD-29) that was an average of mean sea level data for 21 tide stations in the United States (Ziloski and others, 1992). The error resulting from the comparison of the two datums for mean sea level was estimated by comparing the elevations for 10 benchmarks on both sets of maps. The elevations for the benchmarks for the maps published in the early 1900's were obtained from Birdseye (1925). The elevations for the same benchmarks using NGVD-29 were obtained from Joe Vukovitch, USGS, Denver.

The benchmark elevations for the maps published in the early 1900's were generally larger than the elevations using NGVD-29. The difference between the benchmark elevations for the maps published in the early 1900's and the elevations using NGVD-29 ranged from 0.008 to 0.704 feet. The average absolute difference was 0.275 feet. This difference was not accounted for in the determination of the time-averaged subsidence rates.

The error due to estimating the elevations from the contours is about one-half of the contour interval (5 feet) for the topographic maps or 2.5 feet (Joe Vukovitch, USGS, Denver, personal communication, 1996). The percent error for each subsidence rate was calculated as follows. The subsidence rate was calculated at each grid point as the difference between the elevations on the two maps plus or minus the error, divided by the time interval between the two mappings:

$$\text{subsidence rate} = (\text{Elev1978} - \text{Elev1906} +/- e)/T \quad (B.1)$$

where Elev1978 is the elevation from the 1976 to 1978 USGS topographic maps,
Elev1906 is the elevation from the 1906 to 1911 USGS topographic maps,
e is the error associated with the elevation contours (1/2 the contour interval) and,
T is the time interval between the two elevation measurements.

The error was calculated as

$$e = E1978 + E1906 = +/- 5 \text{ feet} \quad (B.2)$$

where E1978 and E1906 are the errors associated with the two sets of topographic maps (E1978 = E1906 = +/- 2.5 feet).

The percent error was calculated as the absolute value of 5 feet divided by the total subsidence multiplied times 100. The percentage error in the subsidence rate is dependent on the amount of subsidence that occurred during the approximately 70 years that elapsed between the surveying for the topographic maps.

B.2 Determination of the Areal Distribution of Peat Thickness

The peat thickness was calculated on the 500-meter grid as the difference between the basal elevation of peat or peaty mud deposits of tidal wetlands as mapped by Atwater (1982) and the land-surface elevation from the USGS topographic maps. Peat or peaty mud of tidal wetlands includes the organic deposits derived from decayed vegetation that formed as the result of sea level rise during the last 7,000 years. Atwater's (1982) delineation of peat and peaty mud include the organic soils mapped by Cosby (1941) and more recent soil surveys. The areal distribution of the basal elevations of the peat deposits was delineated from about 1,200 borehole logs collected through 1980.

The majority of the locations of the borehole logs were on or near the levees. The peat thickness data was compared with the delineation of organic soils or highly organic mineral soils in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993). Where there were discrepancies between the two sources of information for the extent of peat soils, the soil survey data was assumed to be correct.

B.3 Areal Variability of Soil Characteristics

The delineation of soil series as mapped in the soil surveys for Contra Costa (Soil Conservation Service, 1978), San Joaquin (Soil Conservation Service, 1992) and Sacramento counties (Soil Conservation Service, 1993) were entered into the GIS developed by the Department of Water Resources Central District in digital form. The soil organic matter content was the primary soil characteristic of interest. The soil organic matter content was estimated for the 11 soil series which were either organic soils or highly organic mineral soils based on the data provided in the soil surveys. Specifically, the soil surveys for San Joaquin and Sacramento counties provided a range of values for percent soil organic matter. The midpoint of this range was assigned to that series in the GIS database. The percent organic matter for the soil series mapped in Contra Costa County was estimated from the data provided in the soil surveys for San Joaquin and Sacramento Counties.

B.4 Geographic and Hydrographic Data

Geographic and hydrographic data was obtained as USGS Digitial Line Graphs at 1:100,000 scale from the Teale Data Center.

B.5 Delineation of Priority Areas for Subsidence

The areal distribution of time-averaged subsidence rates and peat thickness was used to delineate priority areas for subsidence mitigation. The first priority area includes those lands where the time-averaged subsidence rates were greater than 1.5 inch per year and the peat thickness was greater than 10 feet. The second priority area includes lands where the time-averaged subsidence rates were greater than 1.5 inch per year and the peat thickness was less than or equal to 10 feet.

B.6 Results of Delineation of Priority Areas

Table B.1. Acreages by island for the 2 priorities for subsidence mitigation. Priority 1 includes areas where the time-averaged subsidence rate was greater than 1.5 inch per year and the peat thickness was greater than 10 feet. Priority 2 includes areas where the subsidence rate was greater than 1.5 inch per year and the peat thickness was less than or equal to 10 feet.

Priority 1		Priority 2	
Quimby	35	Quimby	35
Grand	250	Staten	144
King	70	King	1,478
Bethel	70	Brannan	1,440
Woodward	130	Bethel	350
Holland Tract	410	Tyler	610
Medford	570	Sherman	390
Rindge	600	Bradford	860
Sherman	1,480	Holland Tract	930
Empire	600	Lower Jones	2,340
McDonald	910	Bouldin	2,940
Bacon	790	Orwood	840
Jersey	670	Victoria	1,000
Bradford	710	Venice	1,270
Twitchell	1,720	Palm	1,020
Tyler	2,180	Empire	2,570
Brannan	1,700	Mandeville	2,350
Staten	1,400	Rindge	3,680
Venice	950	Webb Tract	2,400
Bouldin	1,860	Bacon	3,830
Mandeville	1,940	McDonald	4,940
Webb Tract	3,920	Woodward	310
Total	22,900	Total	35,700

B.7 Uncertainty in the Spatial Analysis

Uncertainty in the spatial analysis is the result of uncertainty in the thickness of the peat soil and the error in the estimation of the subsidence rate. The subsidence rate error is the result of errors associated with the use of topographic elevations as described above and the use of different datums for the 2 surveys for the topographic maps published in 1906 to 1911 and 1976 to 1978. In general, large errors in the subsidence rate correspond to areas of the lowest time-averaged subsidence rates. The error in the subsidence rate estimate due to the mapping error is 50 percent or less for much of the Delta. The error in the estimation of the subsidence rate generally increases approaching the periphery of the Delta. The error in the western, eastern, southern and northern edges of the Delta generally approaches or exceeds 100 percent.

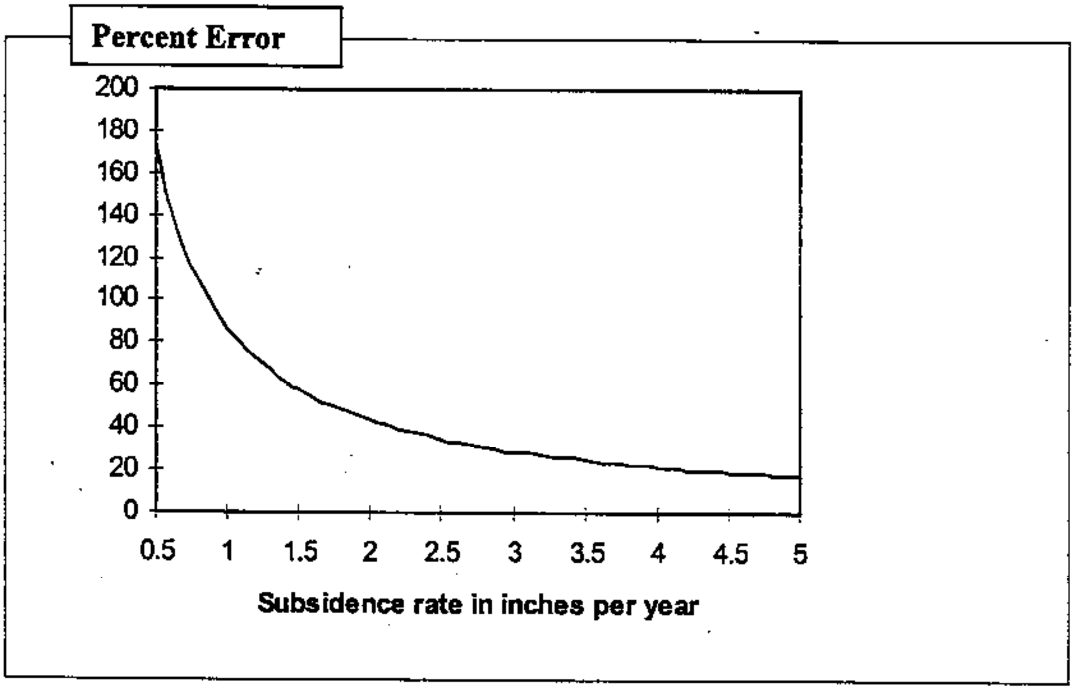
Specifically, the error in the subsidence rate on the central Delta islands, Bouldin, Island, Venice Island, Empire Tract, Mandeville Island, Bacon Island, Lower Jones Tract, McDonald Island and Empire Tract is generally less than 50 percent. Also, the error in the subsidence rates for the west-central and east-central islands, Webb Tract, Twitchell Island, Bradford Island, Rindge Tract and King Island is also generally lower than 50 percent.

Figure B.1 shows the exponential decrease in the percent error in the subsidence rate as the result of mapping errors with increasing time-averaged subsidence rates. The error was calculated for the average time between elevation measurements of 69 years for the topographic maps used in determining the total elevation change. The key questions related to the error for the purpose of determining the priority areas based on time-averaged subsidence rates are: 1) Is the distribution of subsidence rates consistent with the what is known about the distribution of present-day subsidence rates? and 2) What is the error associated with assignment of areas to one of the two categories (less than and greater than 1.5 inch per year) for subsidence rates?

The first question can be answered qualitatively based on recently collected data for subsidence for selected areas of the Delta. Specifically, data from Rojstaczer and Deverel (1995), Rojstaczer and others (1991) and Deverel and Rojstaczer (1996) are consistent with the spatial distribution of subsidence rates presented here. Subsidence rates in the central Delta (Lower Jones Track, Bacon and Mildred islands) are greater than in the western Delta (Sherman and Jersey islands). However, subsidence has not been measured extensively throughout the Delta so that it is impossible to compare rates for all the islands. The subsidence rates in Figure 2 are generally consistent with what is known about subsidence and organic soils in the Delta (Prokopovitch, 1985). The highest soil organic matter contents and subsidence rates are in the central Delta. The soils are lower in organic matter content and subsidence rates are lower approaching the margins of the Delta

The second question can be answered based on the distribution of error for subsidence rates. Further error analysis using the data shown Figure B.1 and the distribution of error in the subsidence rate was used to determine the effect of the distribution of error on the assignment of priorities.

Figure B.1. Relation of error in the estimation of the time-averaged subsidence rate to the subsidence rate.



Using the data shown in Figure B.1 and the distribution of error in the subsidence rate, the lowest time-averaged rate of subsidence that could be erroneously classed as a rate of over 1.5 inch per year is 0.7 inch per year (the error associated with the rate of 0.7 inch per year is 122 percent). The highest time-averaged subsidence rate that could be classed under 1.5 inch per year is 2.3 inches per year (the error associated with the rate of 2.3 inches per year is 36 percent). Data for Sherman Island and Webb Tract was used to evaluate the effect of errors on the acreage within each priority area.

The data for these two islands represent the variability in the data set and the error analysis illustrates the possible range in calculated acreage in the two priority areas. About 80 percent of Sherman Island in the western Delta have peat greater than 10 feet thick but most of the time-averaged subsidence rates were below 1.5 inch per year. In contrast, Webb Tract has experienced time-averaged subsidence rates generally greater than 2.5 inches per year and about 50 percent of the island have peat soils greater than 10 feet thick. Webb Tract has the largest acreage in priority 1. The acreage in priority 1 on Sherman Island is about equal to the median. Sherman has one of the smallest acreage in priority 2.

The results of the error analysis are shown in Table B.2. The range of acreage on Webb Tract for priority 1 shows that the acreage in priority 1 could be overestimated by 54 % and underestimated by less than 1 %. For priority 2, the range in acreage on Webb Tract shows that the acreage in priority 2 could be overestimated by 24 % and underestimated by 10%. In contrast, the ranges of acreage in each priority for Sherman Island are large, ranging up to 1,000 percent. The subsidence rates for Sherman are lower than Webb and the error associated with the subsidence-rate estimate is higher and the range of acreage classified in each priority is large. The results of this analysis point to the need for additional data collection for subsidence rates in the western Delta and other areas where time-averaged subsidence rates are mapped as1.5 inch per year or less.

Table B.2. Range in acreage for each priority for Sherman Island and Webb Tract.

Island	Estimated acreage in priority 1	Range	Estimated acreage in priority 2	Range
Sherman	1,480	0 - 5,410	390	41 – 2,200
Webb	3,920	1,770 - 3,940	2,400	1,860 – 2,650

The areal distribution of the estimation error for the peat thickness was not determined. The density of borehole data and the error in the land-surface elevation primarily determines the error. The land-surface elevation error is due to leveling error in the determination of land-surface elevation that is about plus or minus 2.5 feet and the subsidence that has occurred since 1974 (about 1 to 4 feet). The total land-surface elevation error ranges from about –1.5 to 6.5 feet.

Table B.3 shows the number and average density of data points from borehole logs used to estimate the peat thickness. The data in Table B.3 does not present the entire story relative to the density of data points for peat thickness. Some data points were used for islands besides those for which they are assigned in Table B.3 since the data for peat thickness was extrapolated across channels. Also, most of the data points are on the levees so that the range of area without borehole data for each island varies substantially. In general, data densities greater than 200 acres per point result in moderate to high uncertainty in the estimation of the basal peat elevation for large areas of the islands.

Of those islands where the density of peat thickness data is greater than 200 acres per point, only 6 have acreage in the 2 priorities (Orwood Tract, Victoria Island, Brannan-Andrus Island, King Tract, Tyler Island and Grand Island). Brannan-Andrus Island, King Tract and Tyler Island have significant acreage in the 2 priority areas. Grand Island is mapped as having a large area of deep peat but has little acreage in the two priority areas because of the low time-averaged subsidence rates. Although there is uncertainty in the delineation of the priority areas for subsidence mitigation, the delineation is based on the available data and provides a starting point for further data collection efforts to better define areas for subsidence mitigation.

Table B.3. Number of data points, acreage and data density for each island used to delineate the distribution of peat thickness.

Island	Number of points	Acreage	Data density (acres/point)
Medford	31	1,219	39
Jersey	60	3,471	58
Bradford	28	2,051	73
Palm	32	2,436	76
Mandeville	68	5,300	78
Woodward	23	1,822	79
Bethel	43	3,500	81
Bacon	66	5,625	85
Sherman	105	9,937	95
Webb Tract	58	5,490	95
Twitchell	36	3,516	98
Venice	31	3,220	104
Empire	28	3,430	123
Canal Ranch	23	2,996	130
Holand	31	4,060	131
Coney	7	935	134
Bouldin	44	6,006	137
Staten	61	9,173	150
McDonald	39	6,145	158
Lower Jones	33	5,894	179
Hotchkiss	17	3,100	182
Byron	36	6,933	193
Rindge Tract	35	6,834	195
Terminous	50	10,470	209
Lower Roberts	48	10,600	221
Upper Jones	27	6,259	232
Orwood	13	4,138	318
Brack	14	4,873	348
Victoria	19	7,250	382
Brannan-Andrus	31	13,000	419
Bishop	3	2,169	723
King	4	3,260	815
New Hope	8	9,300	1,163
Tyler	7	8,583	1,226
Grand	3	17,010	5,670
Veale	0	1,298	
Shin Kee	0	1,016	
Rio Blanco	0	705	
Union	0	22,202	
Shima	0	2,394	
Ryer	0	11,880	

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APPENDIX F

EMERGENCY MANAGEMENT AND RESPONSE

DELTA LEVEE EMERGENCY MANAGEMENT AND RESPONSE PLAN

May 17, 2000

INTRODUCTION

Important local, statewide and national resources depend upon maintenance of an effective levee system in the Sacramento-San Joaquin Delta (Delta). A strong, on-going preventive levee repair, reconstruction, and maintenance program will reduce levee vulnerability, reduce (or in some cases, prevent) future emergencies and ensure the availability of the heavy marine construction equipment needed for effective emergency response. Notwithstanding increased efforts to upgrade and maintain Delta levees, the threats to levee system integrity cannot be totally eliminated. Thus an emergency management and response plan is required to protect Delta resources.

SCOPE

This report is intended to outline a major component of the CALFED Levee Program's Long-Term Levee Protection Plan and thereby supplement and suggest needed improvements in state and federal emergency response plans, while remaining consistent with their basic mandates and overall structure. It is focused on levee integrity. There are other types of emergency conditions, such as hazardous material spills, which could occur in Delta waterways and which, while not threatening levee integrity, could endanger water quality to the detriment of public water supplies and biological programs in which CALFED will have made substantial public investments. While such potential emergencies are recognized, they are presently excluded from the scope of this document. Similarly, the more widely recognized emergency response activities such as rescue, emergency medical services and evacuation are not addressed here.

BACKGROUND

The Delta is an area of farmland, waterways and communities. It includes approximately 740,000 acres and is roughly located between the cities of Sacramento, Stockton, Tracy and Antioch. There are about 700 miles of interlaced channels, rivers and sloughs that convey flood waters from the entire Central Valley to the ocean. Over 60 islands and tracts are protected by a network of approximately 1,100 miles of Local Flood Control Non-project Levees and Federal Flood Control Project Levees as shown in the California Department of Water Resources (DWR) Delta Atlas on pages 38 and 40. The Delta provides habitat for fish and wildlife, accommodates shipping, protects population centers and infrastructure including railroads, highways, and pipelines, provides for agriculture and a vast array of recreational activities, and conveys water to over 20 million Californians.

Most of the land in the central and western Delta is below sea level and rapid response to levee threats is unusually critical. A levee failure can endanger public safety, inundate thousands of acres of farmland and habitat, degrade in-Delta and export water quality, and disrupt the operations of the major State and Federal water delivery systems. Of course, multiple levee failures would substantially increase the scale of the emergency and the challenge of prompt response.

Delta levee integrity can be threatened several ways. Levee failure can occur from instability, overtopping and seepage. High water stages in the Delta can occur due to floods, unusually high tides, and atmospheric conditions involving high wind and low pressure. Levee performance during a seismic event is also a concern. Since original reclamation, each of the Delta islands or tracts has flooded at least once. With improved funding for preventive actions since 1986, disaster assistance spending has been reduced substantially.

FUTURE CONDITIONS

Implementation of CALFED's Levee System Integrity Program will not eliminate all threats to the levee system. Threatening circumstances, emergencies, and flooding should be anticipated. Embankments can be more vulnerable to failure during, or immediately after, construction. Thus, levee upgrades involving major earthwork may temporarily reduce levee stability. Commonly, combinations of high tributary flows, strong winds, high tides and low barometric pressure generate flood stage conditions in the Delta. Continued development and construction of upstream flood control features may increase floodwater stages in the Delta. Rise in sea level, channel dredging, and subsidence near the levees may increase seepage through levees and their foundations and reduce levee integrity. Conversion of land near levees to habitat and other land use practices may increase problems related to burrowing animals, may reduce the probability that levee inspection will detect levee defects before the problem becomes a threat, and may hinder emergency flood fight efforts. Lastly, the seismic threat to Delta levees remains a major concern.

GOALS

The goal of the Delta Levee Emergency Management and Response Plan is to enhance existing emergency response programs and capabilities in order to protect the Public or restore critical Delta resources in the event of a levee emergency. A levee emergency is a condition of extreme peril to the safety of persons or property as a result of a threat of levee failure and island inundation. There are three critical components to emergency response.

1. Preparation The ability to respond effectively to a threat, emergency or actual levee failure depends heavily on advanced preparation. All agencies and people involved need to understand their respective roles and responsibilities. There must be emergency planning at all levels of responsibility, clear understanding, scripted procedures for the recognition and declaration of emergency conditions, and an established and rehearsed command and control system. Local, county, State, and federal responses must be better coordinated to enhance decision-making, communication and action protocols. Regulatory and environmental compliance must be incorporated into all response planning. Critical response resources must be immediately available at all levels. Resources include funding, equipment, materiel stockpiles, and appropriately trained personnel.

2. Quick and Effective Emergency Response Time is of the essence in response to any incident or threatening circumstance. An imminent threat of levee failure or a failure requires immediate action that can only be the result of a thoroughly prepared and rehearsed emergency response plan with an identified funding base that ensures immediate, simultaneous, and integrated response by all levels of government. If failure can be prevented or addressed quickly, total losses and expenditures can be dramatically reduced and lives saved.

3. Completion of Post-Emergency Repairs In the event of an emergency, including breach closures, a smooth and quick transition to post emergency recovery work is needed to complete repairs and prepare for continued or new threats. Oftentimes one incident quickly follows another. It is important to facilitate resumption of normal economic activities, restore environmental resources damaged by the incident, prepare for subsequent emergency response, and expedite post-emergency repair efforts.

ANALYSIS OF THE CURRENT EMERGENCY RESPONSE PROGRAM

Significant improvements have been made to the existing emergency response system over the past several years. However, continuous improvements in the system must be made to reduce the risk to resources protected by Delta levees. Improving our emergency response capability is a very cost-effective method of reducing risk and preventing the huge losses, economic disruption, and human suffering resulting from levee failures.

Fluctuations in funding and the environmental regulations applicable to ongoing levee reconstruction, maintenance and repair work have impacted the capability of local, state and federal agencies to respond to imminent threats of levee failure in several ways.

At the current time, there are impediments to year-round in-water construction activities in the Delta. "Work windows," established under biological opinions on endangered species (Chinook Salmon and Delta Smelt), significantly limit the period of time when in-water work can occur in most of the Delta. In addition, environmental permitting practices require constraint in performing work essential to proper levee reconstruction, repair, and maintenance.

Without sufficient work opportunities, the specialized levee building equipment (especially side draft dredges, barge cranes and rock barges) and personnel experienced in operating conditions in the Delta have almost disappeared. These types of equipment and experienced operators are necessary during levee emergencies in those locations and under conditions where work often cannot be performed from the land.

Levee funding resources have been severely impacted by inconsistent and inadequate program funding. Local financial resources have been impacted by bank audit procedures which have reduced the availability of credit to local reclamation districts and by lengthy delays in reimbursement from state and federal disaster assistance programs because of often-unclear inspection, documentation, and audit procedures.

Some levee maintaining agencies do not generate the revenues needed to provide adequate maintenance and emergency response. The role of counties and cities in directly supporting floodfight operations by levee maintaining agencies has not been clearly defined in the past although these organizations can obviously provide rapid and important logistical support to these types of activities.

In some instances, direct State and federal emergency floodfight assistance has been delayed by the required showing that local resources have been exhausted and the lack of an operational plan providing the basis for an immediate, integrated, simultaneous response by all levels of government.

Although historically there has been confusion over the procedures for declaration of a state of emergency and the respective roles of the various local, State and federal interests, these areas have shown considerable improvement as a result of experience gained in the 1997 and 1998 flood emergencies. Three documents were completed in compliance with the Flood Emergency Action Team (FEAT) recommendations and have enhanced emergency operations: 1) Guidelines for Coordinating Flood Emergency Operations, 2) Flood Preparedness Guide for Levee Maintaining Agencies, and 3) Protocol for Closure of Delta Waterways. These guidelines have clarified the responsibilities of local agencies that maintain levees and flood control structures.

By law, State agencies must use the Standardized Emergency Management System (SEMS) when responding to emergencies involving multiple jurisdictions or multiple agencies. The basic framework of SEMS and the Incident Command System (ICS) incorporates multi-agency or inter-agency coordination, the State's master mutual aid agreement and mutual aid program, the operational area concept, and the Operational Area Satellite Information System (OASIS). SEMS has also enhanced the emergency response capability of local and State agencies.

The California Department of Water Resources approved Water Resources Engineering Memorandum No. 63 on January 29, 1999, which establishes the Department's policy and procedures for responding to emergency levee-endangering incidents in the Sacramento-San Joaquin Delta. Similar advance work is necessary relative to potential earthquake emergencies and in the regulatory arena to pre-define environmental regulations applicable to levee emergencies and recovery activities.

Although California Water Code Section 128 gives authority to the Department of Water Resources to flood fight during emergencies, it does not provide funds to support flood fighting. Consequently, the DWR response has generally been limited to technical assistance and coordination of work with the California Conservation Corps, and California Department of Forestry and Fire Protection for crews for placement of sandbags, plastic and other hand-labor-related work. On the other hand, the AB360 Program (Section 12994 of the California Water Code) has been a vehicle for providing funds for emergency response within the context of an emergency plan. These limited funds have historically been primarily used to reimburse local agency expenditures, to establish stockpiles of resources for use by levee maintaining agencies and to provide technical advice.

PROPOSED PROGRAM

CALFED's contribution to an effective Delta levee emergency response program should be concentrated in eight areas:

1. Funding for Ongoing Repair, Reconstruction and Maintenance The vulnerability of the levee system can be reduced by implementing an integrated and comprehensive reconstruction, repair and maintenance program for Delta levees and channels, as described and recommended under the Levee System Integrity Program. This can only be accomplished by supplementing local funding capability through State and federal cost-sharing at adequate and consistent levels, and by establishing workable environmental permitting so that a viable Delta levee building and repair industry can be reestablished and sustained. From a levee emergency response viewpoint, the significant (even crucial) incidental benefit of a well-funded, on-going Delta levee program is to establish a continuous local presence of specialized equipment. Marine-based equipment required to perform levee rehabilitation on some central and western Delta islands will likely be more accessible during emergencies if there is sufficient ongoing work to maintain local operations.

2. Improved Environmental Regulations and Permitting. CALFED will explore conditions under which expanded "work windows," or even year-round work activities, can be implemented and assess other alternatives so a workforce is developed that is sufficient to handle emergency levee situations. Improvements in the permitting process and regulations will also be pursued. CALFED will use a collaborative process that involves ecologists, biologists, engineers and contractors, in addition to the relevant regulatory agencies. During the process, improved construction techniques, protection, and mitigation measures, and more precise definitions of species' needs and related construction impacts will be identified.

3. Emergency Response (and Associated Funding) by State and Federal Agencies In accordance with the "Guidelines for Coordinating Flood Emergency Operations," if a flood fight exceeds the capability of the local levee-maintaining agency or if communities are threatened, the responsible city or county will assist with the flood fight with support from all other SEMS levels. Under SEMS, requests for flood fight assistance from the local LMA's are made to the county Operational Area's Emergency Operations Center, and, if necessary, are escalated to State OES' Regional Emergency Operations Center in Sacramento. The REOC will coordinate information and resources among OA' s and provide a liaison to federal agencies.

Lack of specific funding sources and obstacles within federal public assistance reimbursement rules have hindered direct involvement in flood fight activities by counties, cities, and State agencies. Creation of funding to support a delta levee emergency response plan would eliminate past hesitation and inefficiencies.

a. Federal Assistance The U. S. Army Corps of Engineers has primary federal authority for assisting states with flood fight efforts that meet the criteria established by

Public Law 84-99. Under a Memorandum of Understanding with the Corps, DWR serves as the facilitator for all PL 84-99 flood-fighting efforts. DWR coordinates with the local agency, initiates the PL 84-99 request process, and assists the Corps in determining the applicability of PL 84-99.

Prior to making requests to the Corps, DWR reviews requests and information from the OA on the capability of the local agency. DWR ensures that local and State resources require supplementation and that an emergency situation exists. Once these determinations are made, DWR requests Corps assistance. DWR can also provide technical advice and assistance to local agencies concerning flood fighting and emergency flood control measures.

Every effort is made to expedite the Corps-DWR coordination on PL 84-99 requests consistent with the urgency of the situation. There have been some instances where the response was delayed, with a strong perception by local LMA's that the PL 84-99 decision process is hindered by a need to demonstrate that local and State resources "have been exhausted."

When the Corps does respond under the PL 84-99 emergency flood fight provisions, its efforts are 100 percent federally funded. Under the rehabilitation phase of PL 84-99, the Corps of Engineers repairs the flood-related damage to "federal project levees" and eligible non-project levees. The only non-federal costs are for lands, easements and rights-of-way, and local obligations to hold the government harmless and to operate and maintain the project, and to provide borrow material for repairs.

The role of the Corps should be clarified and confirmed through their participation in the preparation of and commitments to a delta levee emergency response plan so as to eliminate delay in response and avoid any dispute as to whether or not the local and State response is sufficient. This emergency response plan needs to address levee emergencies other than normal rain floods (e. g., earthquakes), and the Corps' role in any such emergencies. Special circumstances, such as multiple breaches within a short time frame, should be identified with criteria established for expedited response.

b. State Assistance For flood control projects sponsored by the Reclamation Board, DWR technical assistance may be requested directly. Existing State funding limits DWR's response to only providing technical assistance. The DWR financial capability to respond to flood emergencies in the Delta should be expanded to include all aspects of a flood fight where levees or other flood control structures are in danger of failure, regardless of whether or not the danger is due to storms, floods, earthquakes, rodents, vessel impacts or any other cause. The funding for support of DWR's efforts, either through expansion of existing programs or through creation of a new program should be ample and clearly committed for comprehensive emergency response[1].

Bond authorization might be particularly helpful to ensure the availability of State funds when needed. For example, authorization of $60 million in bonds to create and replenish a $10 million revolving fund specifically for financing implementation of a delta emergency response plan, as defined in California Water Code Section 12994(b)(2), would provide the assurance that pre-identified response commitments by DWR and other agencies would be funded, should help ensure that the local share requirement of federal disaster assistance programs will be available, and would provide the basis for seeking elimination of obstacles within federal reimbursement policies that hinder multi-jurisdictional flood fight responses.

4. Ensuring Availability of Levee Emergency Resources

a. Specialized equipment and operators: A revitalized levee rehabilitation industry under the Levee System Integrity Program will establish a fleet of specialized equipment essential to a rapid emergency response[2], but will not ensure its availability during emergencies which often extend to other areas. The Emergency Response Plan established under Assembly Bill 360 should establish pre-emergency contracting for specialized equipment to secure the availability of the equipment and experienced operators, and establish pricing for emergency services.

b. Materiel stockpiles: The State Department of Water Resources has established stockpiles for flood fight materiel (sandbags, plastic, stakes, light equipment, pumps, etc.) at locations in the northern, southern, and western Delta. This program needs to be expanded to include rock and sand stockpiles, and to key locations in the central and south Delta regions. Additionally, assurance of supply and/or stockpiling of drain rock and riprap should be included. Coordination between the stockpiling activities of other agencies would be desirable. Transportation of the materials to where they are most needed also needs to be addressed.

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[1] The $200,000 currently provided to DWR under the Delta Levee Subventions Program (Water Code § 12994) is not only inadequate, but will expire under the terms of its authorizing legislation.

[2] Ideally, the resident population of specialized equipment needs to be sufficient to operate in several locations at once, whether because of high flood stages threatening many sites, or because of a strong earthquake damaging several sites. A Delta-based dredging company estimates that it takes at least a $5 million annual levee program expenditure level to generate enough dredger work to justify operating one dredge, with a work window of 3 to 4 months. One barge crane/rock barge unit would be justified in a program of that size with a ten-month work window. By extrapolation, we might expect a $30 million annual program to support approximately 5 dredgers and 5 barge crane/rock barge units in the Delta given appropriate work windows.

c. Labor: The Emergency Response Plan established under AB 360 should consider formal arrangements with the California Department of Forestry and Fire Protection as well as with the California Conservation Corps and with the State prison system for emergency assistance.

5. Integrated Response A detailed response plan should be developed for the Delta that would allow an immediate, simultaneous response to a serious incident (such as a major flood or an earthquake) by all levels of government within a single integrated organizational structure. The plan would identify common needs and functions of all agencies, e.g., housing, feeding, transportation, supplies (including rock and sand), equipment and contracted services and assign the most capable agency/jurisdiction to perform each on behalf of all agencies. The detailed floodfight/earthquake response plans for specific LMAs or areas of the Delta would provide the basis for pre-identifying and assigning specific responsibilities for each agency as well as the level of resources which the individual LMA would be expected to provide in response to the emergency. With detailed assignment of responsibilities, an organizational structure for the "area command" could be delineated so as to assure coordination with the "incident commands." The detailed response plan would serve as the basis for requesting modification to disaster assistance programs, including any needed legislation. The FEAT-produced documents, discussed earlier, may partially serve this purpose.

6. Clarifying Regulatory Procedures Although both State and federal laws suspend environmental regulation during emergencies, some clarifications are desirable.

a. The definitions of emergency for response and regulatory activities need to be consistent. It is especially important that the defined duration of the emergency be consistent for both purposes.

b. Mitigation measures which will be expected during post-emergency recovery work should be defined by a series of examples in order that emergency work will not unnecessarily exacerbate mitigation responsibilities, so that post-emergency recovery work will not be unnecessarily delayed, and so appropriate mitigation can be rapidly defined and implemented.

7. Clarifying Program Eligibility, Inspection, Documentation, Auditing, and Reimbursement Procedures In virtually all of the declared levee emergencies in the last twenty-five years there have been lengthy reimbursement delays, or outright denials which have adversely affected the financial condition and trade-credit and bank-credit opportunities of the local flood control agencies. The requirements of these programs need to be standardized to be consistent with one another, be well and timely communicated to the local agencies, and not be changed or re-interpreted during the completion of the reimbursement process. In addition, legal jurisdiction as a criterion for cost reimbursement needs to be clarified to eliminate obstacles to integrated, multi-jurisdictional emergency response.

8. <u>Dispute Resolution</u> Because events move swiftly during emergency response, there should be a timely dispute resolution process. Currently, the "exhaustion of administrative remedies" followed by court system recourse is truly exhausting both in terms of energy and money. Reimbursement disputes have consumed more than fifteen years in many cases, with local resources being used, which should be going into levee work. A binding arbitration procedure conducted by knowledgeable but impartial arbiters should be established encompassing both the State and federal programs.

APPENDIX G

SEISMIC REPORT

CALFED
BAY-DELTA
PROGRAM

Levees and Channels Technical Team
Seismic Vulnerability Sub-Team

Seismic Vulnerability of the Sacramento - San Joaquin Delta Levees

April 2000

Seismic Vulnerability of the Sacramento - San Joaquin Delta Levees

Levees and Channels Technical Team
Seismic Vulnerability Sub-Team
Members

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CALFED BAY-DELTA PROGRAM
SEISMIC VULNERABILITY
OF THE
SACRAMENTO/SAN JOAQUIN DELTA LEVEES

FORWORD

The CALFED Bay-Delta program is an unprecedented collaboration among state and federal agencies and the state's leading urban, agricultural and environmental interests to address and resolve the environmental and water management problems associated with the Bay-Delta system. The mission of the CALFED Bay-Delta Program is to develop a long-term comprehensive plan that will restore ecological health and improve water management for beneficial uses of the Bay-Delta system. The objective of CALFED's Levee System Integrity Program is to reduce the risk to land use and associated economic activities, water supply, infrastructure, and the ecosystem from catastrophic damage associated with breaching of Delta levees.

Delta levees are the most visible man-made feature of the Bay-Delta system. They are an integral part of the Delta landscape and are key to preserving the Delta's physical characteristics and processes, including definition of the Delta waterways and islands. There is concern that California's Bay-Delta system levees are vulnerable to failure, especially during earthquakes. Levee failures in the Delta could flood farmland and wildlife habitat, and also interrupt water supply deliveries to urban and agricultural users and disrupt highway and rail use. Although there has never been a documented levee failure from a seismic event, the Delta has not experienced a significant seismic event since the levees have been at their current size. One goal of CALFED's Levee Program is to identify the risk of failure of Delta levees due to seismic events and develop recommendations to reduce levee vulnerability and improve levee seismic stability.

A Seismic Vulnerability Sub-Team of CALFED's Levees and Channels Technical Team was formed to assess the seismic risk. This sub-team, composed of seismic experts and geotechnical engineers with experience in the Delta, evaluated levee fragility and assessed the seismic vulnerability of the current levee system. This report presents the findings and conclusions of the Seismic Sub-Team. CALFED's Levee Program will conduct further studies to apply this information to overall risk assessment.

CALFED thanks DWR's Division of Engineering for sponsoring this exceptional study and also recognizes the superior efforts of the experts on the sub-team who contributed their unique technical knowledge, diverse views, and willingness to work long hours.

CALFED BAY-DELTA PROGRAM SEISMIC VULNERABILITY OF THE SACRAMENTO/SAN JOAQUIN DELTA LEVEES EXECUTIVE SUMMARY

The objective of CALFED's Levee System Integrity Program is to reduce the risk to land use and associated economic activities, water supply, infrastructure, and the ecosystem from catastrophic damage associated with breaching of California's Bay-Delta system levees. Delta levees are at risk from many sources of failure, including stability, seepage, overtopping, erosion, unseen defects, and seismic. This report only addresses the seismic risk.

Although there has never been a documented levee failure from a seismic event, the Delta has not experienced a significant seismic event since the levees have been at their current size. A team composed of seismic experts and geotechnical engineers with experience in the Delta assessed the seismic risk.

This report provides an assessment of the Delta levees' current vulnerability to potential damage caused by an earthquake. These seismic risk analyses and assessments are based on the most current available information. It is not likely that additional information in the near future would significantly change the present characterization. This assessment also provides an estimate of the probability or likelihood that a damaging earthquake will occur.

This study subdivided the Delta into four Damage Potential Zones. Seismic vulnerability is highest in Zone I, Sherman Island, due to poor levee embankment and foundation soils, and higher exposure to seismic shaking at the western edge of the Delta. Zone II, the central area of the Delta, has the next highest overall level of seismic levee fragility and exposure to seismic shaking. Zones III and IV, with levees of lower heights more distant from earthquake shaking, have generally lower levels of seismic vulnerability.

The final, overall estimate of potential levee failures during a single seismic event is shown in Figure 5-2 on page 23. This figure shows, for example, that an earthquake with a 100-year return period is predicted to cause 3 to 10 levee failures in the Delta, on one or more islands.

While this report quantifies the magnitude of the current seismic vulnerability of Delta levees, CALFED continues to investigate the overall risk. Two teams have been formed. One team of geotechnical engineers is developing recommendations for seismic upgrades and other measures to reduce levee failures. Another team will perform an overall risk assessment of multiple factors that contribute to levee failure, evaluate the consequences of failure, and develop risk management options. Once these two studies are completed, the level of seismic risk in relation to the total risk to Delta levees will be better understood.

CALFED staff will work with stakeholders, the public, and state and federal agencies to develop and implement a Delta levee risk assessment and risk management strategy. CALFED will incorporate the findings from the Geotechnical and Risk Assessment Subteams into an overall risk assessment. Once the risk to Delta levees is quantified and the consequences evaluated, CALFED will develop and implement an appropriate risk management strategy.

CALFED BAY-DELTA PROGRAM
SEISMIC VULNERABILITY
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1 INTRODUCTION

1.1 BACKGROUND

The CALFED process has produced a draft programmatic environmental impact report that describes three alternatives for improving the Delta's levees, environment, water quality, and water supply reliability. The seismic risk assessment described in this report provides an assessment of the Delta's levees current vulnerability to potential damage caused by an earthquake. This assessment also provides an estimate of the probability or likelihood that a damaging earthquake will occur. This information will be used to evaluate the CALFED alternatives with respect to the seismic impact to the Delta.

1.2 ORGANIZATION

This seismic risk assessment was performed by a sub-team of the Levees and Channels Technical Team of CALFED. The sub-team is comprised of geotechnical engineers and a seismologist. The members represent Federal and State government, local interests, and independent consultants. The members of the sub-team are:

Dr. Norman A. Abrahamson	Consulting Seismologist
Fred N. Brovold	GEI Consultants
Gilbert Cosio	Murray, Burns, and Kienlen, Consulting Engineers
Michael W. Driller	Department of Water Resources
Dr. Leslie F. Harder, Jr.	Department of Water Resources
Dr. N. Dean Marachi	The Mark Group, Consulting Engineers
Christopher H. Neudeck	Kjeldsen, Sinnock, Neudeck, Consulting Engineers
Lynn Moquette O'Leary	CALFED/U.S. Army Corps of Engineers
Michael Ramsbotham	CALFED/U.S. Army Corps of Engineers
Dr. Raymond B. Seed	Seismic Geotechnical Consultant
Raphael A. Torres - Chair	Department of Water Resources

1.3 BASIS FOR THE ASSESSMENTS

The seismic risk analyses and assessments presented in this report are based on the most current available information. Information on the seismic response of peat/organic soils is still being developed. Even though hundreds of borings describing the subsurface conditions of Delta levees were reviewed, these borings can only provide a limited characterization of the hundreds of miles of levees. Yet, it is not likely that a finite number of additional borings would significantly change the present characterization.

Additional investigations cannot be completed within the CALFED time frame. Consequently, a combination of sensitivity analyses and assumptions were used to fill this information void. The sub-team determined that even though there was little information available on some issues, a reasonable assessment of the Delta as a whole could still be achieved. This is described in more detail in the report.

Members of the Seismic Vulnerability Sub-Team:
Top Row, Left to Right: Michael W. Driller, Dr. Raymond B. Seed, Frederick N. Brovold, Dr. Leslie F. Harder, Jr., Dr. Norman A. Abrahamson, Michael Ramsbotham
Bottom Row, Left to Right: Christopher H. Neudeck, Gilbert Cosio, Dr. N. Dean Marachi, Lynn Moquette O'Leary, Raphael A. Torres

2 GEOLOGIC SETTING

2.1 GEOLOGY

The Sacramento-San Joaquin Delta, located at the confluence of the Sacramento and San Joaquin Rivers, is a unique feature of the California landscape (see Figure 2-1). The Delta is part of the Central Valley geomorphic province, a northwest-trending structural basin separating the primarily granitic rock of the Sierra Nevada from the primarily Franciscan Formation rock of the California Coastal Ranges (Converse et al., 1981). The Delta occurs in an area that contains 3 to 6 mile thick/deep sedimentary deposits, most of which accumulated in a marine environment from about 175 million years ago to 25 million years ago.

Since late Quaternary time, the Delta area has undergone several cycles of deposition, non-deposition, and erosion, resulting in the accumulation of a few hundred feet of poorly consolidated to unconsolidated sediments. Delta peats and organic soils began to form about 11,000 years ago during a rise in sea levels (Shlemon and Begg, 1975). This rise in sea level created tule marshes that covered most of the Delta. Peat formed from repeated burial of the tules and other vegetation growing in the marshes.

During the cycles of erosion and deposition, rivers were entering from the north, northeast, and southeast. These included the Sacramento, Mokelumne, and San Joaquin Rivers. As the rivers merged, they formed a complex pattern of islands and interconnecting sloughs. River and slough channels were repeatedly incised and backfilled with sediments with each major fluctuation. These processes were complicated by concurrent subsidence and tectonic changes in the land surface.

Debris produced by hydraulic mining during the gold rush of the mid-1800's disrupted the natural depositional history of the Delta. Hundreds of thousands of tons of silt, sand, and gravel were washed from the Sierra Nevada into the Delta. This sediment filled stream channels, caused flooding, and raised the natural levees along Delta streams and sloughs.

2.2 LEVEE BUILDING HISTORY

In the late 1800's, Delta inhabitants began fortifying existing natural levees and draining inundated islands in the Delta for agricultural use.

Most of the early levees in the Delta were constructed by Chinese laborers (Thompson, 1982) using hand shovels and wheelbarrows, and some were built using scrapers pulled by horses. Later, when the farmers realized that levees of sufficient height could not be efficiently built by hand, the barge-mounted, sidedraft-clamshell dredge was used. The levees were generally built of non-select, uncompacted materials without engineering design and without good construction methods.

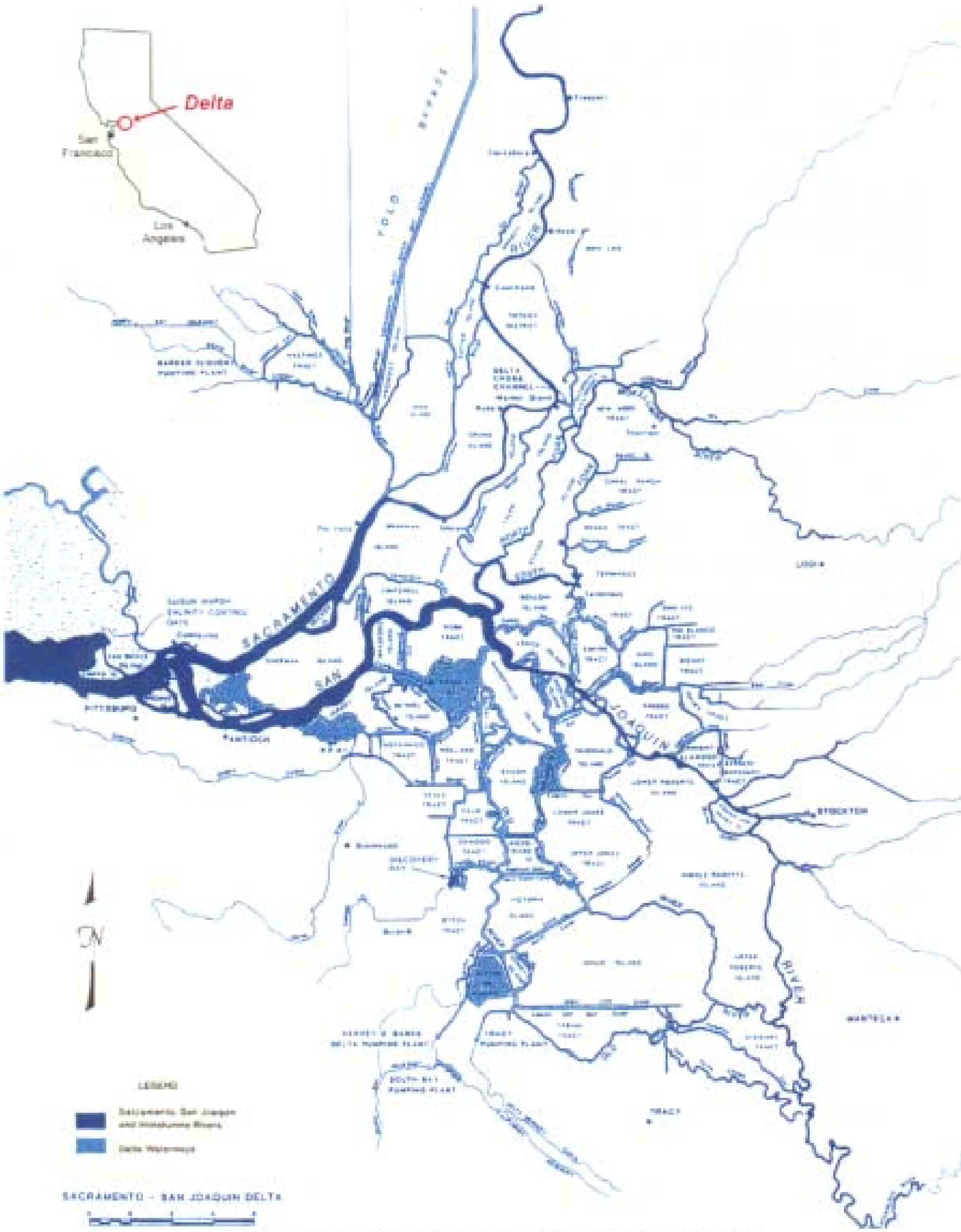


Figure 2-1: Sacramento - San Joaquin Delta

The original levees were usually less than five feet high, but continuous settlement of the levees and subsidence of near levee soils has required the periodic addition of new fill to maintain protection against overtopping by waters of the Delta. The interiors of many islands are now commonly 10 to 15 feet below sea level. Presently, some levee crowns are 25 feet higher than the interior of their respective islands. Figure 2-2 illustrates the evolution of Delta levees over time.

In general, the upper portion of Delta levee embankments are comprised of mixtures of dredged organic and inorganic sandy, silty, or clayey soils that have been placed on either natural peat or natural sand and silt levees. The variability in foundation materials for Delta levees can be great, even between sites that are in close proximity to one another. Such heterogeneity is due to a history of continuous stream meandering and channel migration within the Delta.

2.3 LEVEE DAMAGE CAUSED BY PAST EARTHQUAKES

Historical information indicates that there has been little damage to Delta levees caused by earthquakes (CDWR, 1992). No reports could be found to indicate that an island or tract had been flooded due to an earthquake-induced levee failure. Further, no report could be found to indicate that significant damage had ever been induced by earthquake shaking. The minor damage that has been reported has not significantly jeopardized the stability of the Delta levee system.

This lack of severe earthquake-induced levee damage corresponds to the fact that no significant earthquake motion has apparently ever been sustained in the Delta area since the construction of the levee system approximately a century ago. The 1906 San Francisco earthquake occurred 50 miles to the west, on the San Andreas Fault, and produced only minor levels of shaking in the Delta; as the levees were not very tall yet in 1906, these shaking levels posed little threat. Continued settlement and subsidence over the past 90 years has, however, significantly changed this situation. Consequently, the lack of historic damage to date should not lead, necessarily, to a conclusion that the levee system is not vulnerable to moderate-to-strong earthquake shaking. The current levee system simply has never been significantly tested.

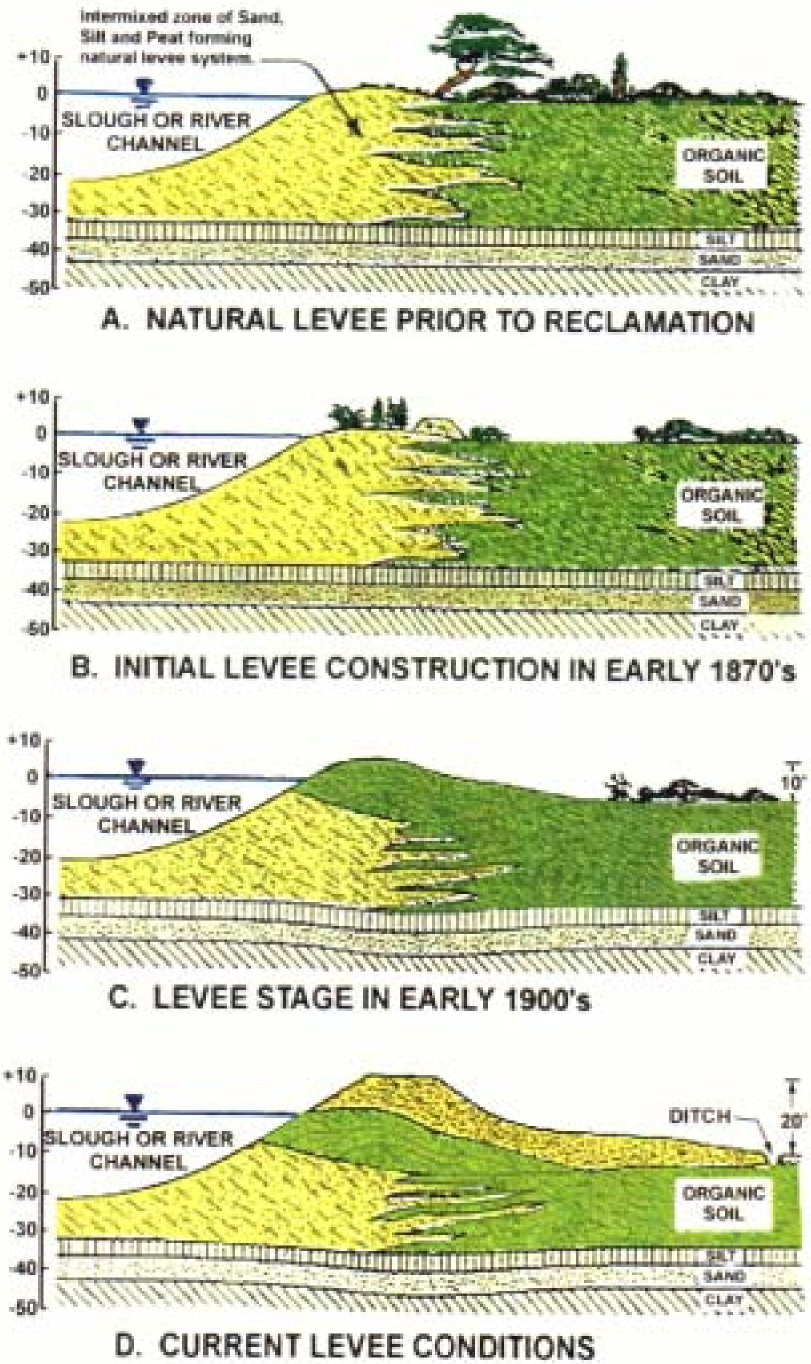


Figure 2-2: Evolution of Delta Levees Over Time

3.0 SEISMICITY OF THE DELTA REGION

3.1 REGIONAL FAULTING AND MODELS

The Delta Levees are located in a region of relatively low seismic activity as compared to the San Francisco Bay area. The major strike-slip faults in the Bay Area (San Andreas, Hayward, Calaveras faults) are located over 16 miles from the Delta region (see Figure 3-1). The less active Green Valley and Marsh Creek-Clayton faults are over 9 miles from the Delta region. There are also small but significant local faults in the Delta region, and there is a possibility that there are blind thrust faults along the western Delta (see Figures 3-1 and 3-2).

3.2 LOCAL FAULTING AND MODELS

In recent seismic studies of the Delta region, a series of blind thrust faults along the western edge of the Central Valley and extending through the Delta has typically been used in the seismic source characterization. However, there is large uncertainty in the location, activity, and even existence of these blind thrust faults in the Delta region. Although various names have been used for this theoretical system of blind thrust faults, in this study we have used the term Coast-Range Central Valley (CRCV) boundary thrust fault system. While there is clear evidence that the CRCV fault system exists and is potentially active to the south and north of the Delta, there is not clear evidence of potentially active blind thrust faults in the Delta region. The possibility that the CRCV fault system exists in the Delta region has a significant effect on the seismic risk to the Delta levees. Due to the large uncertainty in this important aspect of the source characterization, two alternative models of the local faulting have been used in this study: One that includes the CRCV feature in the Delta region, and an alternate one that includes smaller thrust faults west of the Delta region.

The first model is based on the seismic source characterization currently used by the California Division of Mines and Geology (1996) which are part of the state seismic hazard map. In this model, the CRCV is assumed to extend into the Delta region (see Figure 3-1). This model is called the "CRCV" model in this study.

The second model is based on a recent evaluation of the faulting in the Delta region by (Lettis and Associates 1998). This study has concluded that the blind thrust faults do not exist in the Delta region. Instead, thrust faults located further west of the Delta region are postulated as accounting for the crustal shortening across the region (see Figure 3-2). This model is called the "without-CRCV," or "Lettis," model in this study.

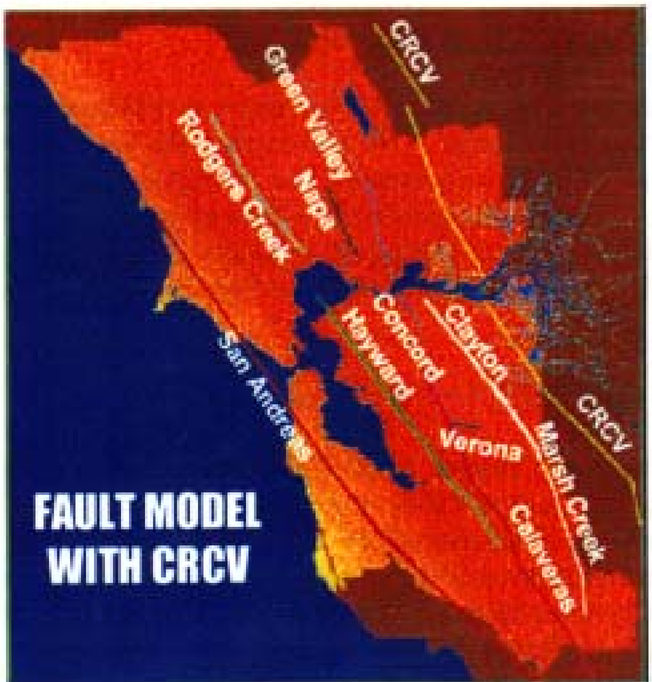


Figure 3-1: Delta Fault Model With CRCV

Figure 3-2: Delta Fault Model Without CRCV

3.3 SEISMIC HAZARD RESULTS

Although the two local faulting models are quite different, they produce similar levels of peak ground acceleration (PGA) at individual sites in the Delta region using a probabilistic analysis. For an outcrop of stiff soil or rock, the 100-year PGA ranges from 0.2g in the western Delta to 0.1g along the northeastern Delta (see Figure 3-3). Figure 3-4 presents the estimated PGA at Sherman Island for a range of return periods. Once again, both the "with CRCV" and "without CRCV" models produce similar predictions of PGA. However, while the individual site PGA is similar for the two models, the magnitudes associated with them are different and this leads to very different predictions of performance of the Delta as a system which is discussed later.

For the western Delta, the dominant earthquake contributing to the 100-year PGA is a magnitude 5.8 to 6.2 earthquake at a distance of about 13 miles from local sources. For the eastern Delta, earthquakes with magnitudes of 7 or higher on the more distant San Andreas and Hayward Faults also contribute significantly to the hazard. However, the main magnitude contributing to the 100-year return period hazard for the eastern Delta is also about magnitude 6.

Since the overall seismic hazard is dominated by moderate local events, it is unlikely that the entire Delta region will be subjected to large motions in any single earthquake. For example, a magnitude 6 event near the northern Delta may cause significant ground motions in the northern Delta, but not in the southern Delta, as peak accelerations produced by events of only moderate magnitude attenuate fairly rapidly with distance from the source (fault rupture).

Appendix A presents additional information regarding the seismic source models of the Delta region and the results of the probabilistic hazard analysis.

Figure 3-3: Peak Ground Acceleration (g) Contours for 100-year Return Interval – both Models

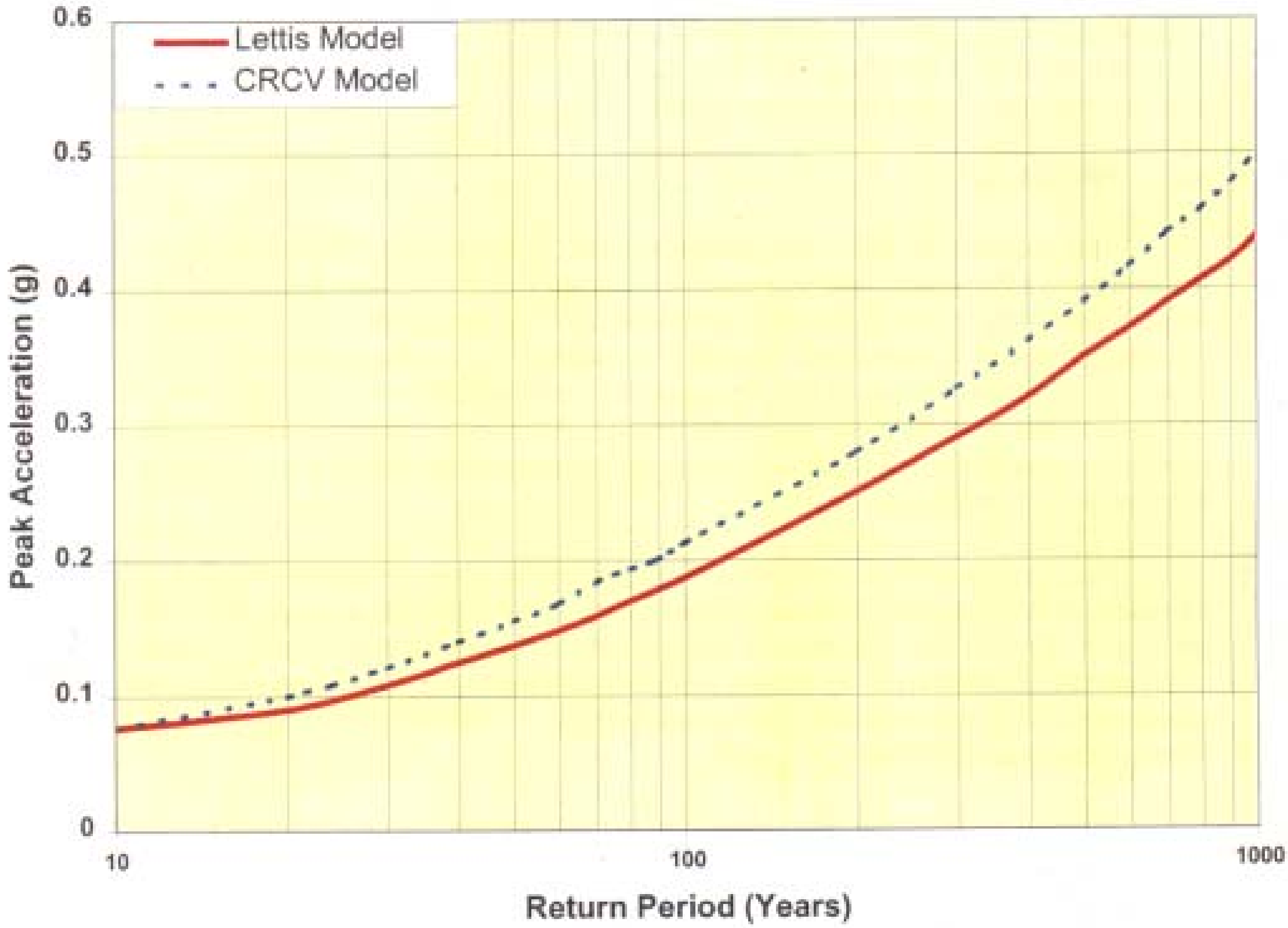


Figure 3-4: Peak Ground Acceleration vs. Return Period for the CRCV and Lettis Models at Sherman Island

4 ESTIMATES OF LEVEE FRAGILITY DUE TO EARTHQUAKE SHAKING

4.1 INTRODUCTION

Levee fragility is defined as a measure of the susceptibility of a levee to fail due to seismic loading. Available geotechnical information and previous seismic stability studies associated with levees in the Delta were used to assess the relative vulnerability of the levees and their foundations to earthquake shaking. Geotechnical reports and data were supplied by the California Department of Water Resources, U. S. Army Corps of Engineers, Kjeldsen Sinnock & Neudeck, and Murray Burns & Kienlen. Appendix E presents a list of some of the reports and studies reviewed.

4.2 PROCESS

The process for assessing potential levee failures during earthquakes was to review the available information and to develop a range of estimates for the number of levee failures that might occur for various levels of earthquake acceleration. This levee fragility was expressed in a normalized form as the number of expected levee failures per 100 miles of levee. Different ranges of fragility were estimated for different regions in the Delta, and for different levels of earthquake shaking. This information is used in a later section, together with the probabilistic seismicity estimates, to develop estimates of the number of failures likely within an exposure period.

Failure was defined as sufficient distress to the levee in the form of lateral spreading, slumping and/or cracking that would lead to a complete breach and uncontrolled flooding of the island. Failure was considered to occur either during the earthquake, or within a very short period of time following the earthquake. Levees could be extensively damaged during or subsequent to earthquake shaking, but unless a full breach of the levee resulted, failure was not considered to have occurred.

Precise quantitative estimates of levee failures cannot be made because geotechnical information for over 600 miles of levees remains limited, particularly for the levees themselves. The sub-team members relied upon the available information and their individual knowledge and experience to develop individual assessments of the frequencies of levee failure for different levels of earthquake shaking. These individual assessments were then discussed by the sub-team and refined into a single consensus range of values.

4.3 EARTHQUAKE MOTIONS CONSIDERED

The likely range of bedrock/stiff soil accelerations that might be experienced on an outcrop of such materials within the Delta within the next 30 to 300 years is between 0.05

and 0.30g (see Section 3). Such motions are expected to be generally associated with a Magnitude 6 event. However, the Delta has thick and deep deposits of soft organic and mineral soils overlying the top of stiff soils. Layers of soft soils overlying stiffer deposits are generally expected to amplify earthquake motions developed in the deeper, stiffer deposits. Based on the studies by CDWR (1992) and Boulanger, et al. (1997), the most likely acceleration amplification factors from deep and stiff base layers to the levee crowns range between 1 and 2. For the purposes of the current assessments, an average amplification factor of 1.6 was used. This crown amplification accounted for both soft soil amplification as well as topographic amplification. Accordingly, the earthquake parameters considered in these fragility assessments can be summarized as follows:

> Earthquake Magnitude: 6.
> Peak Bedrock/Stiff Soil Outcrop Accelerations: 0.05 to 0.30g.
> Base Layer to Levee Crown Amplification Factor: 1.6.

Magnitude scaling factors to adjust acceleration levels for earthquakes having magnitudes other than Magnitude 6 were incorporated in the probabilistic seismicity analyses (see Appendix B). These scaling factors account for the fact that larger magnitude events typically cause longer durations of stronger shaking, and these duration differences affect the severity of the loading.

4.4 DAMAGE POTENTIAL ZONES

Qualitative assessments of high, medium, and low failure potential during earthquake shaking were made for different regions within the Delta. The principal geotechnical parameters affecting this assessment included the following:

- The presence of loose, cohesionless sandy and silty layers in the levee embankment generally lead to a high or medium-high failure potential rating. Such soils are liquefiable when saturated. Since levees are manmade and not formed by intermittent natural processes, loose soils are expected to have greater lateral continuity within a levee than in a natural deposit. The presence of such soil beneath the phreatic line within the manmade levee embankment, as detected by penetration testing, indicates a relatively high potential for a liquefaction-induced levee failure. Levees with substantial amounts of liquefied material are likely to exhibit flow slides and lateral spreading as very loose, cohesionless soils have low post-liquefaction shear strengths.

- The presence of loose, cohesionless sandy and silty layers in the levee foundation was also considered detrimental because of the potential for liquefaction. However, it was not considered as serious as having such materials within the levee. This is because such layers within the natural foundation are more likely to be discontinuous. Foundation liquefaction beneath a levee is also generally less critical than liquefaction within the levee embankment as the post-liquefaction shear resistance necessary to prevent flow and lateral spreading is lower due to geometry and net driving force considerations. In addition, somewhat higher penetration resistance is commonly reported for such foundation layers and this suggests somewhat higher liquefaction resistance and post-liquefaction shear strength.

- High levees on thick, soft foundations were considered more fragile because of their potential to have marginal static stability. Levee sections with only marginal static stability were considered to be likely to slide and experience significant displacements during earthquake shaking even without liquefaction.

- Levees with narrow cross sections, limited freeboard, or histories of previous distress were also considered to have a higher probability of failure.

Two principal modes of potential earthquake-induced levee failure were considered while developing the different damage potential zones: 1) Flow slides and lateral spreading associated with strength loss (liquefaction) of levee embankment or foundation soils, and 2) Inertially-induced seismic deformations of levees experiencing no liquefaction. Potential failure mechanisms included overtopping, seepage erosion due to cracking, and exacerbation of existing seepage problems due to deformations and cracking. Seasonal variations in river and slough water elevations, and their interactions with tides, were also considered. This evaluation resulted in dividing the Delta area into four Damage Potential Zones as described in Table 4-1 and shown in Figure 4-1.

TABLE 4-1: DAMAGE POTENTIAL ZONES WITHIN THE DELTA

Damage Potential Zone	Levee Length in Zone (miles)	Description
I	20	**High susceptibility** to earthquake-induced levee failure. This zone encompasses only Sherman Island and was considered to have high potential for failure due to the presence of substantial liquefiable soils within the non-project levees, especially those along the San Joaquin River. These levee reaches have an unusually high amount of cohesionless sandy and silty soils within the levee section, are relatively narrow, are founded on thick deposits of soft soil, and have a history of distress.
II	301	**Medium to medium-high susceptibility** to earthquake-induced levee failure. This zone is within the central Delta and generally includes levees with high sections founded on thick deposits of soft soil. Most of the levees which have had histories of distress or that have failed during flood events are located within this zone. Vulnerability varies significantly within this region, even along adjacent levee reaches, principally as a function of the presence or absence of liquefiable soils at the base of the levee embankment sections.
III	116	**Low to medium susceptibility** to earthquake-induced levee failure. This zone is located on the southern and western periphery of the Delta and generally involves levees of smaller heights founded on thinner layers of soft soil.
IV	223	**Low susceptibility** to earthquake-induced levee failure. This zone is located on the northern and eastern periphery of the Delta and generally involves levees of smaller heights founded on thinner layers of soft soil.

TOTAL LENGTH 660 miles

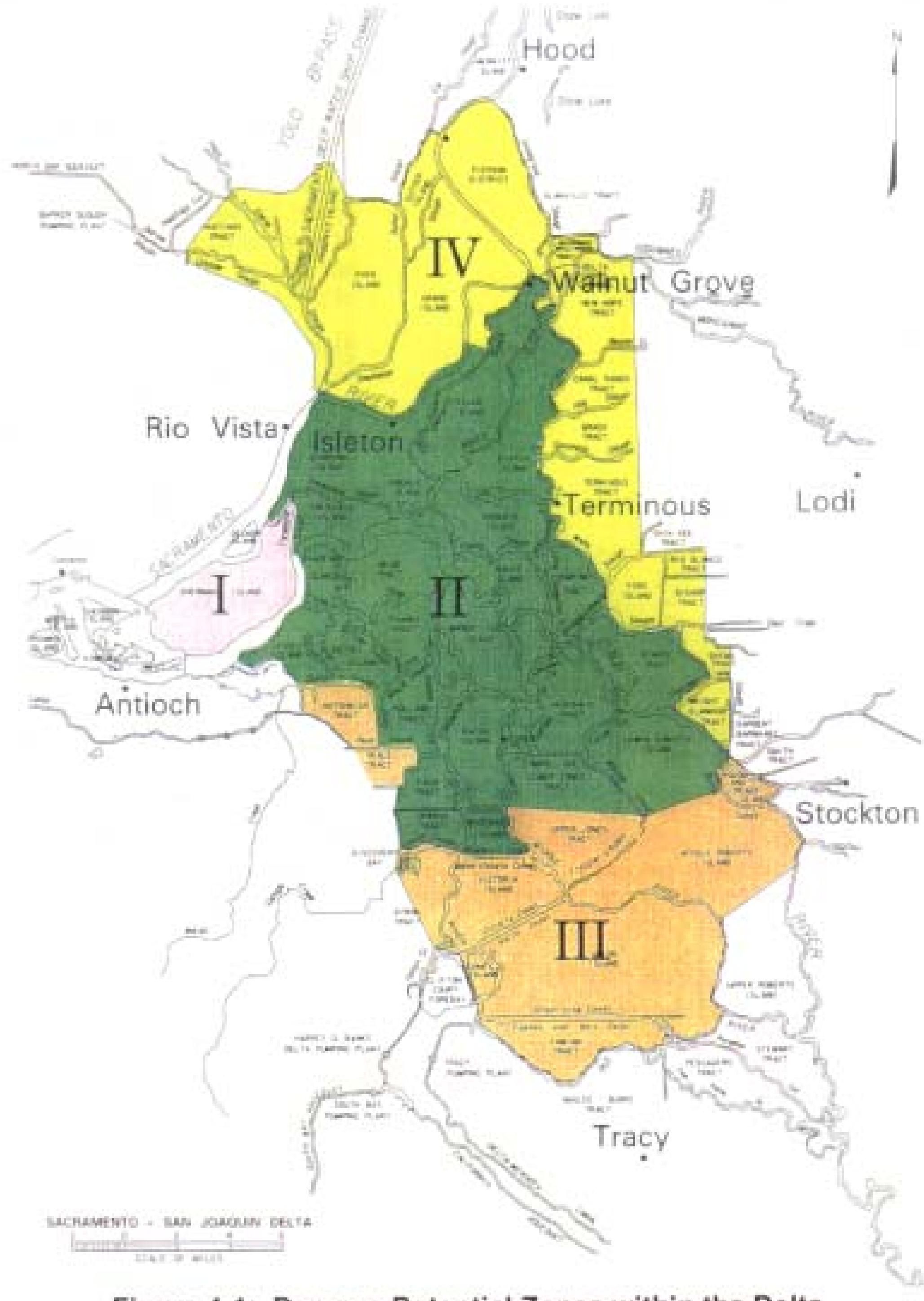


Figure 4-1: Damage Potential Zones within the Delta

4.5 ESTIMATES OF LIQUEFACTION-INDUCED LEVEE FAILURES

Liquefaction fragility estimates (failures per 100 miles of levee) were developed for different earthquake loadings based on the sub-team's experience with the performance of similar earth structures. The three principal steps in developing these estimates were as follows:

1. Levee geometries and geotechnical data from over 34 sites within the Delta were reviewed and evaluated. Each site was a levee reach (or length), and these varied from about 200 feet to 2,000 feet in length. The information reviewed included results from boring logs, Standard Penetration Tests (SPT), Cone Penetration Tests (CPT), soil classification testing, and shear strength testing.

2. The liquefaction potential of sandy and silty soils within both the levee and foundation soil strata was evaluated using the penetration test data and the well-established correlation developed by Seed, et al. (1984), with suitable corrections for magnitude and duration effects. Post-liquefaction shear strengths were evaluated based on the correlation developed by Seed and Harder (1990), and the performance of similar earth structures during recent earthquakes.

   Post-liquefaction shear strength estimates were used to evaluate the associated displacement and deformation potential of levees following liquefaction. The displacement or deformation evaluation was used to obtain an estimate of the potential for levee sections at each site to fail following an earthquake.

3. The resulting estimated levees failures due to liquefaction were then used to statistically characterize the likelihood of liquefaction-induced levee failures, for various levels of shaking, within each of the four Damage Potential Zones shown in Figure 4-1.

The evaluations outlined in these three steps were performed in both qualitative assessments as well as with quantitative approaches. Individual evaluations developed by sub-team members were resolved into a consensus ranges of fragility estimates. These estimates also incorporate differences in risk associated with daily (tidal) and seasonal variations in water levels in the rivers and sloughs.

The resulting liquefaction-related fragility estimates for each of the four Delta Damage Potential Zones are presented in Table 4-2. For peak accelerations less than 0.1g, the estimated fragility values are relatively low. This is in good agreement with the documented performance of Delta levees. Peak base accelerations have been estimated to be less than about 0.08g since reclamation of the Delta began in 1868 (see CDWR, 1992). As base accelerations (seismic loading) increase, the estimated levee fragility also increases for all four damage potential zones.

One of the important findings derived from the liquefaction fragility estimates is that the hazard associated with this mode of failure is much greater for Zone I (Sherman Island) than for the other three zones. This is because extensive layers of liquefiable sandy soils are known to exist within the levees protecting Sherman Island. No other levee is known to have such a large extent of liquefiable soil. In addition, Sherman Island is the western-most island, and is closest to the principal seismic source zones. Thus the island is most likely to experience strong shaking levels.

Another important finding is that for all four Damage Potential Zones, the fragility associated with potential soil liquefaction is much higher than that associated with potential non-liquefaction failure modes. This has important ramifications with regard to potential options for reducing seismic fragility along levee sections. Refer to Section 6 "Mitigation of Seismic Vulnerability".

TABLE 4-2: ESTIMATED FAILURE RATE (FRAGILITY) FOR BOTH LIQUEFIED AND NON-LIQUEFIED REACHES - FAILURES PER 100 MILES

Magnitude 6.0 Rock/Stiff Soil Peak Acc. (g)	Damage Potential Zone	Levee Length (miles)	Estimated Fragility - Number of Levee Failures per 100 miles	
			Liquefied Reaches	Non-Liq. Reaches
0.05	I	20	0.005 - 0.50	0.030 - 0.075
	II	301	0.001 - 0.083	0.015 - 0.036
	III	116	0.001 - 0.033	0.003 - 0.010
	IV	223	0.001 - 0.033	0.003 - 0.010
0.10	I	20	0.20 - 2.5	0.050 - 0.12
	II	301	0.080 - 0.33	0.023 - 0.052
	III	116	0.050 - 0.15	0.004 - 0.017
	IV	223	0.050 - 0.15	0.004 - 0.016
0.15	I	20	2.5 - 10.	0.16 - 0.35
	II	301	0.66 - 1.7	0.070 - 0.15
	III	116	0.29 - 1.2	0.010 - 0.057
	IV	223	0.29 - 1.2	0.011 - 0.049
0.20	I	20	5. - 20.	0.36 - 0.77
	II	301	1.7 - 5.0	0.16 - 0.33
	III	116	0.88 - 2.3	0.022 - 0.13
	IV	223	0.88 - 2.3	0.025 - 0.11
0.30	I	20	15. - 30.	1.5 - 3.2
	II	301	5.0 - 10.	0.66 - 1.4
	III	116	2.4 - 5.9	0.092 - 0.53
	IV	223	2.4 - 5.9	0.11 - 0.46

4.6 ESTIMATES OF LEVEE FAILURES FOR NON-LIQUEFACTION EARTHQUAKE-INDUCED DISPLACEMENTS

Some marginally-stable levees will deform significantly during an earthquake due to cyclic inertial loading. Such deformations could lead to levee failure even if the levee and foundation soils did not experience liquefaction. Estimates of levee fragility for the non-liquefaction deformation mode of failure used the following approach:

- First, an estimate was made of the number of marginally stable levee sites in each Damage Potential Zone. Three levels of marginal stability were considered and the number of marginal sites for each level was estimated for each zone.

- The levee deformation that would be induced by earthquake shaking was estimated for each level of marginal stability using one-dimensional dynamic response analyses coupled with Newmark-type double-integration deformation calculations. The response analyses were used to develop estimates of deformation potential specifically appropriate to the usual foundation soil conditions prevalent throughout the Delta. Levee deformation estimates were generated for a range of base accelerations.

- The estimated levee deformations were then converted into probabilities of failure by considering daily and seasonal variations of channel water levels, varying freeboard, cracking, and seepage erosion and piping potential. The failure probabilities were then summed for each level of marginal stability within a zone, and then expressed as a levee fragility in terms of expected failures per 100 miles of levee within each zone for a range of base accelerations. These results are presented in the last two columns of Table 4-2.

4.7 ESTIMATES OF LEVEE FRAGILITY DURING SEISMIC EVENTS

Table 4-2 presents levee fragility values estimated for both liquefaction and non-liquefaction deformation modes of failure. In comparison with the liquefaction mode of failure, the non-liquefaction deformation levee fragility values are much lower, only approximately 10 percent of the liquefaction values. In addition, while there is a significant difference in the liquefaction fragilities estimated for Zones I and II, there is not as large a difference in the non-liquefaction deformation fragilities. This is principally because the number of marginally stable sites per levee mile are believed to be within the same order of magnitude within both Zones I and II in the central Delta.

4.8 MAGNITUDE CORRECTION FACTORS

The estimates for levee failures and fragility presented in Table 4-2 are for earthquake shaking associated with a magnitude 6.0 event. For the same level of shaking, larger magnitude earthquakes will induce more damage and more levee failures than smaller magnitude events because larger magnitude earthquakes have longer durations of strong shaking. To adjust the fragilities for earthquake magnitudes other than Magnitude 6.0, the following scaling factors were used:

A. Liquefaction Mode of Failure:

A magnitude correction factor for the liquefaction mode of failure was developed using the Idriss (1997) magnitude scaling factors for triggering of liquefaction. These corrections are slightly larger than those previously used by Seed, et al. (1984), and are slightly lower than those recommended by the NCEER Liquefaction Working Group (NCEER, 1997).

B. Non-Liquefaction Deformation Mode of Failure:

A magnitude correction factor for the non-liquefaction deformation mode of failure was developed using the Earthquake Severity Index described by Bureau et al. (1988). This correction is much larger than the one for liquefaction, but is comparable with the cyclic inertial deformation results obtained by Makdisi and Seed (1977).

Appendix B presents additional information regarding the estimates of the levee fragilities and the associated evaluations and calculations used to develop them.

5 PROBABILISTIC EVALUATION OF LEVEE FAILURES

5.1 METHODOLOGY

The seismic hazard analysis (or Probabilistic Seismicity Evaluation, as described in Section 3) was combined with the levee fragility evaluation to develop a probabilistic evaluation of the number of levee failures. The number of levee failures expected to occur in a single earthquake is a function of return period or annual likelihood of occurrence of different levels of earthquake intensity.

The levee failure probability analysis is an extension of standard probabilistic seismic hazard analysis. The difference is that instead of calculating the probability of the ground motion exceeding a specified value at a location, the probability of a specified number of levee failures being exceeded in a single earthquake was computed. In this way, the performance of the entire levee system was considered simultaneously. This avoids the problems of using individual site hazard curves, which may represent different earthquakes at different parts of the Delta.

These analyses consider the performance of the Delta levees for specific earthquake scenarios. For each earthquake scenario, the probability of one or more levee failures occurring within the Delta was computed. This process is repeated for two or more failures, three or more failures, and so on. Following the probabilistic seismic hazard analysis, rather than considering just one or two scenarios, all possible earthquake scenarios were considered and their probabilities of occurring were determined.

The probability of a given number of levee failures for an earthquake scenario is multiplied by the probability of the scenario earthquake actually occurring. This rate of failure is then summed over all of the scenarios to give the total rate of various numbers of levees failing in a single earthquake. A Poisson assumption for the earthquake occurrence is used to convert the rate of failures into a probability of failures. The result is a hazard curve for the "expected" number of levee failures in a single earthquake. The details of the mathematical formulation used in the probability calculation is described in Appendix C.

The resulting median hazard curves for levee failures are shown in Figure 5-1. Two curves are presented; one for the CRCV model and one for the without-CRCV model (see Section 3). The large difference for the two models reflects the impact of an assumed large CRCV blind thrust fault under the west end of the Delta. At low numbers of failures, the two source models lead to similar levee failure hazard because the hazard is controlled by large distant earthquakes on the Hayward and San Andreas fault and small local earthquakes. At larger numbers of failures, the differences between the two fault models become more pronounced.

The final, overall estimate of seismic levee fragility shown in Figure 5-2 was tempered by considering the uncertainties in the two fault models and the uncertainties inherent in the various elements of the overall seismic fragility and hazard evaluation. Thus, the fragility estimates include allowances for current sources of uncertainty with regard to both seismicity (loading) and seismic levee fragility (resistance).

The same Levee Fragility estimates are alternately shown with respect to return periods of 50, 100, and 200 years (see Figure 5-3). These graphs show the probability of exceeding a particular number of levee breaks in a single event during a given exposure time period.

5.2 ILLUSTRATIVE SCENARIO EVENTS

Three illustrative scenario earthquake events were developed to illustrate the potential for levee failures following a single earthquake:

1. Magnitude 7.1 earthquake on the Hayward Fault
2. Magnitude 6.25 earthquake on the Concord Fault
3. Magnitude 6.0 earthquake on the CRCV Fault, immediately northwest of Sherman Island

Figures 5-4 to 5-6 show the estimated number of levee breaks per zone and the peak acceleration contours for stiff soil or rock for each of these three scenario events.

As shown in Figure 5-4, a Magnitude 7.1 event on the relatively distant Hayward Fault produces low to moderate levels of acceleration of fair duration, and results in a low predicted number of levee failures (on the order of 0 to 4 failures throughout the Delta).

As shown in Figure 5-5, a Magnitude 6.25 Concord Fault event produces similar levels of peak acceleration at the western end of the Delta (on the order of 0.1g), but these rapidly decrease to the east. This, coupled with a relatively short duration, results in a lower level of predicted levee failures than for the Hayward fault event shown in Figure 5-4.

Figure 5-6 illustrates the third scenario event, a Magnitude 6.0 on the CRCV Fault at the northwestern edge of the Delta. The proximity of the fault rupture produces much higher levels of acceleration, and results in much higher predicted numbers of levee failures, especially in Zones I and II. The numbers of predicted failures for this scenario event are fairly high (on the order of 13 to 32 through the entire Delta), but the annual likelihood of occurrence of this even is much lower than for the events illustrated in Figures 5-4 and 5-5.

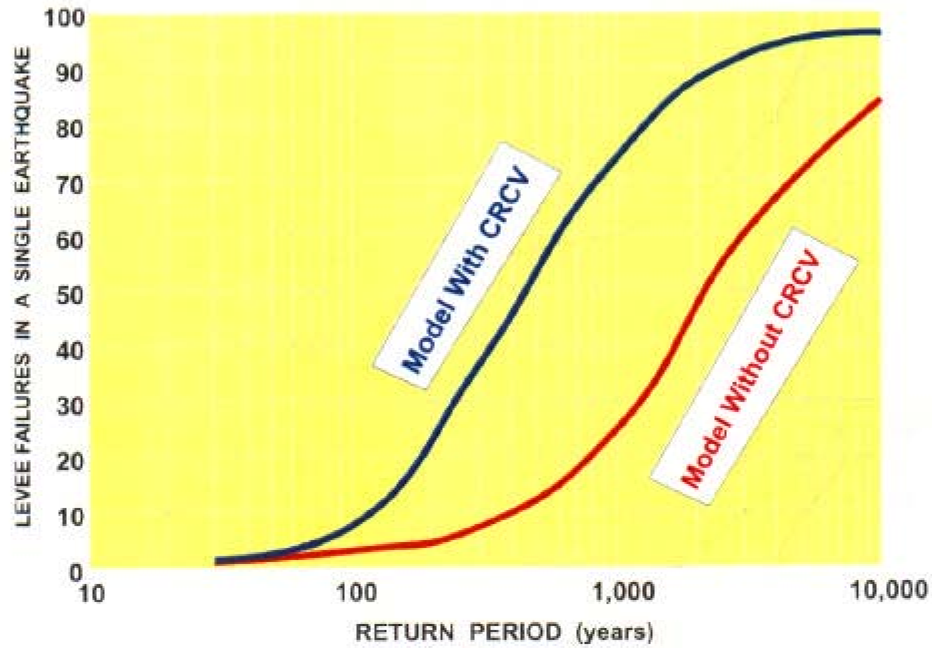


Figure 5-1: Number of Levee Failures in a Single Earthquake–both Fault Models Shov

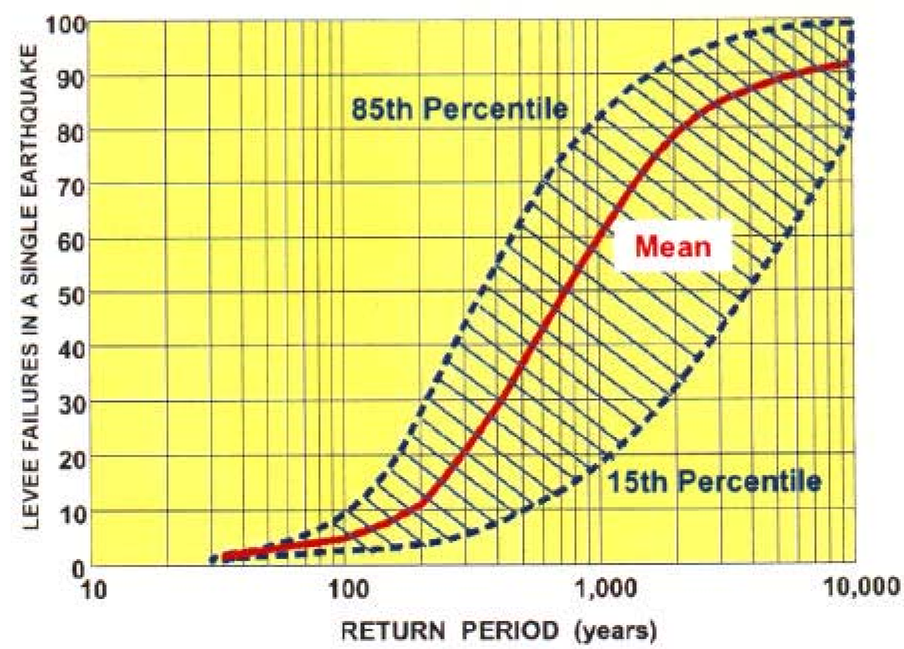


Figure 5-2: Number of Levee Failures in a Single Earthquake-Fault Models Combinec
Note: Number of Levee Failures does not equate to Number of Islands Flooded

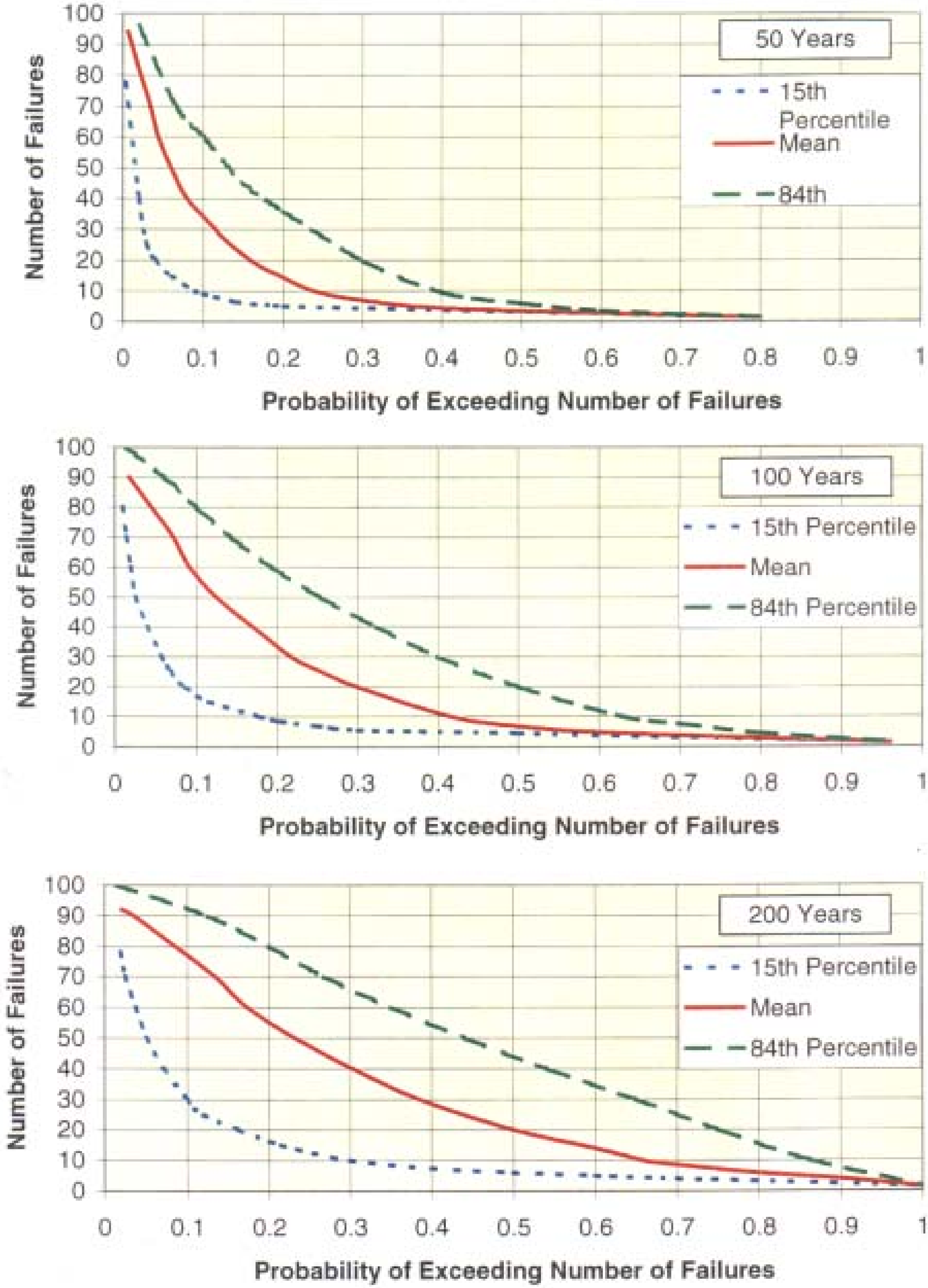


Figure 5-3: Probability of Exceedance vs. Number of Levee Failures for 50, 100 and 200 Year Return Periods

Note: Number of failures does not equate to numbers of islands flooded

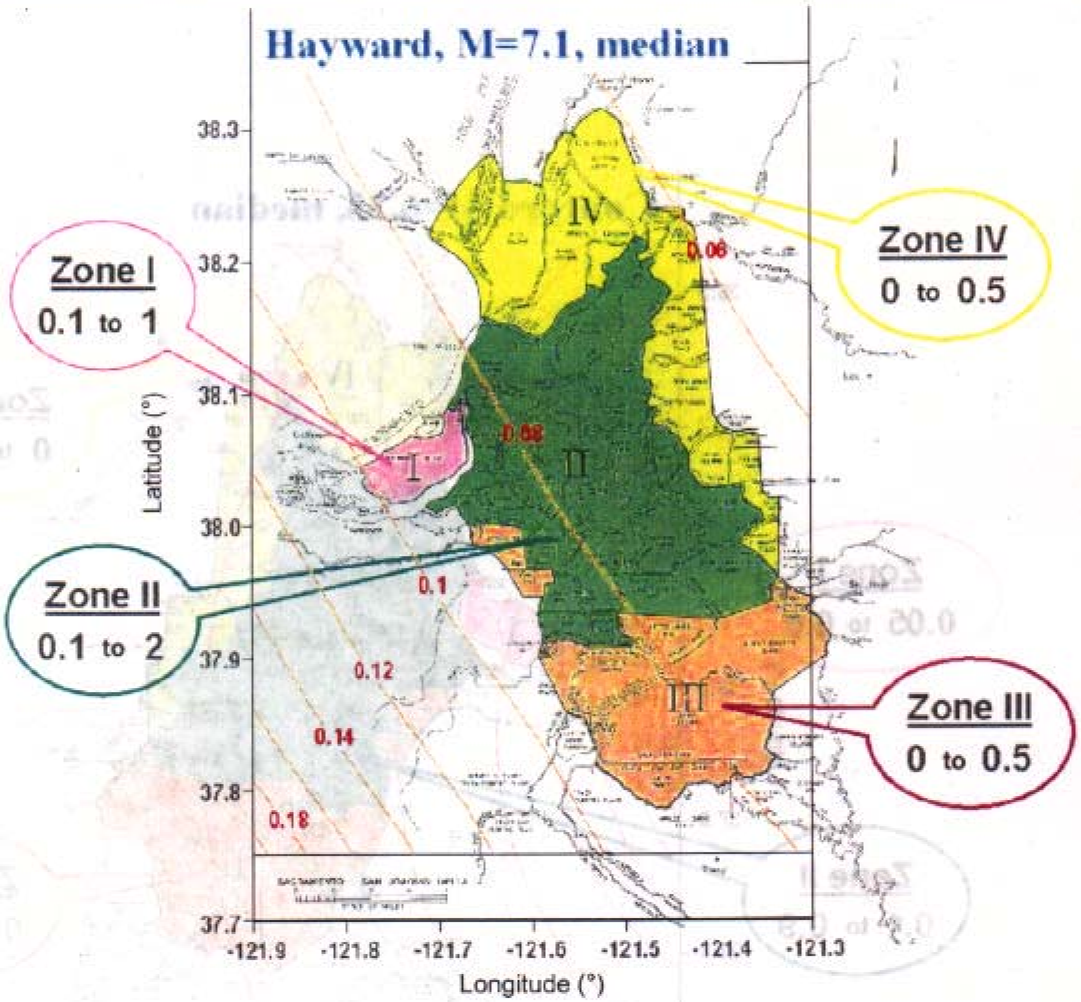


Figure 5-4: Expected Number of Levee Failures for a Magnitude 7.1 Earthquake on the Hayward Fault

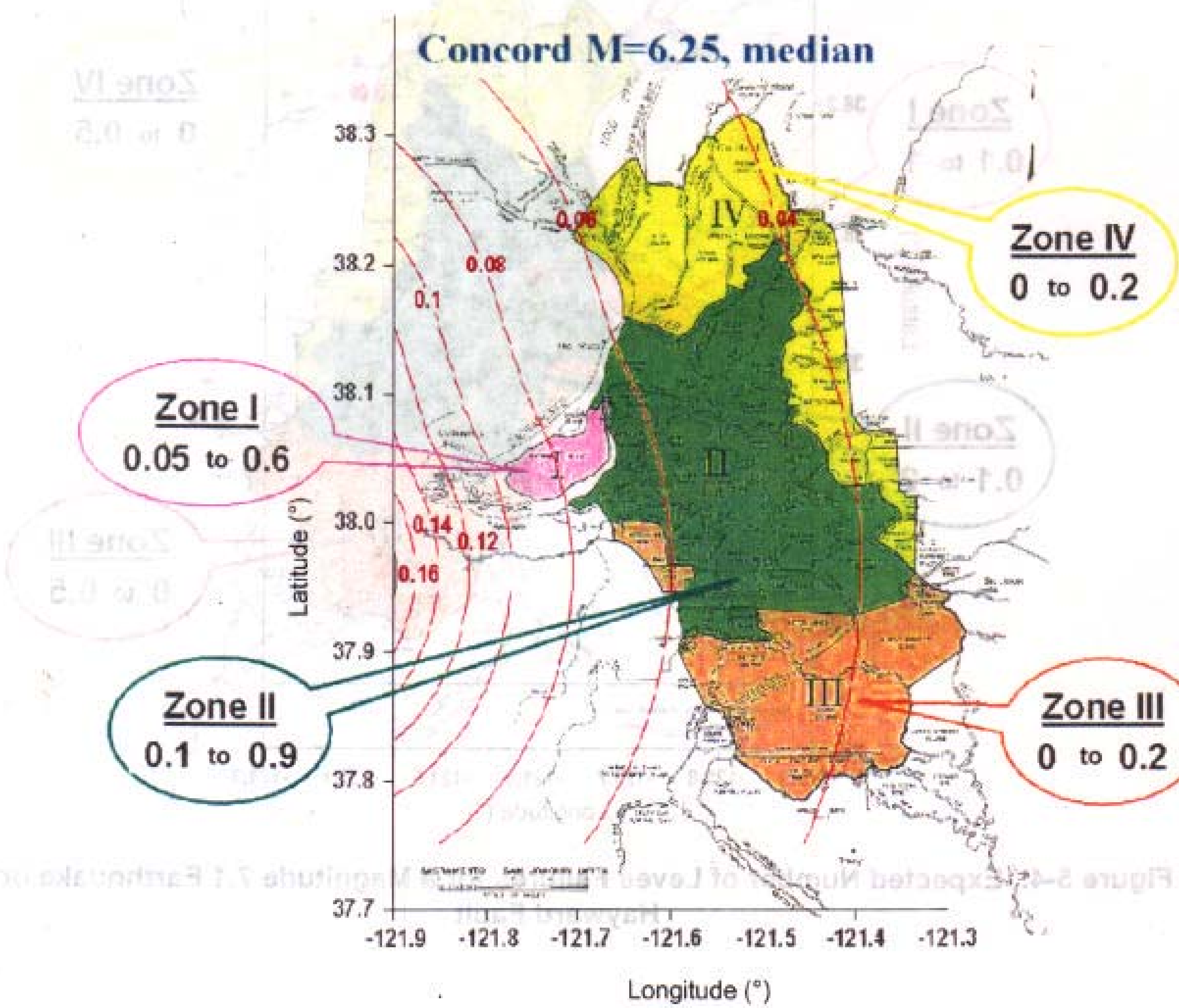


Figure 5-5: Expected Number of Levee Failures for a Magnitude 6.25 Earthquake on the Concord Fault

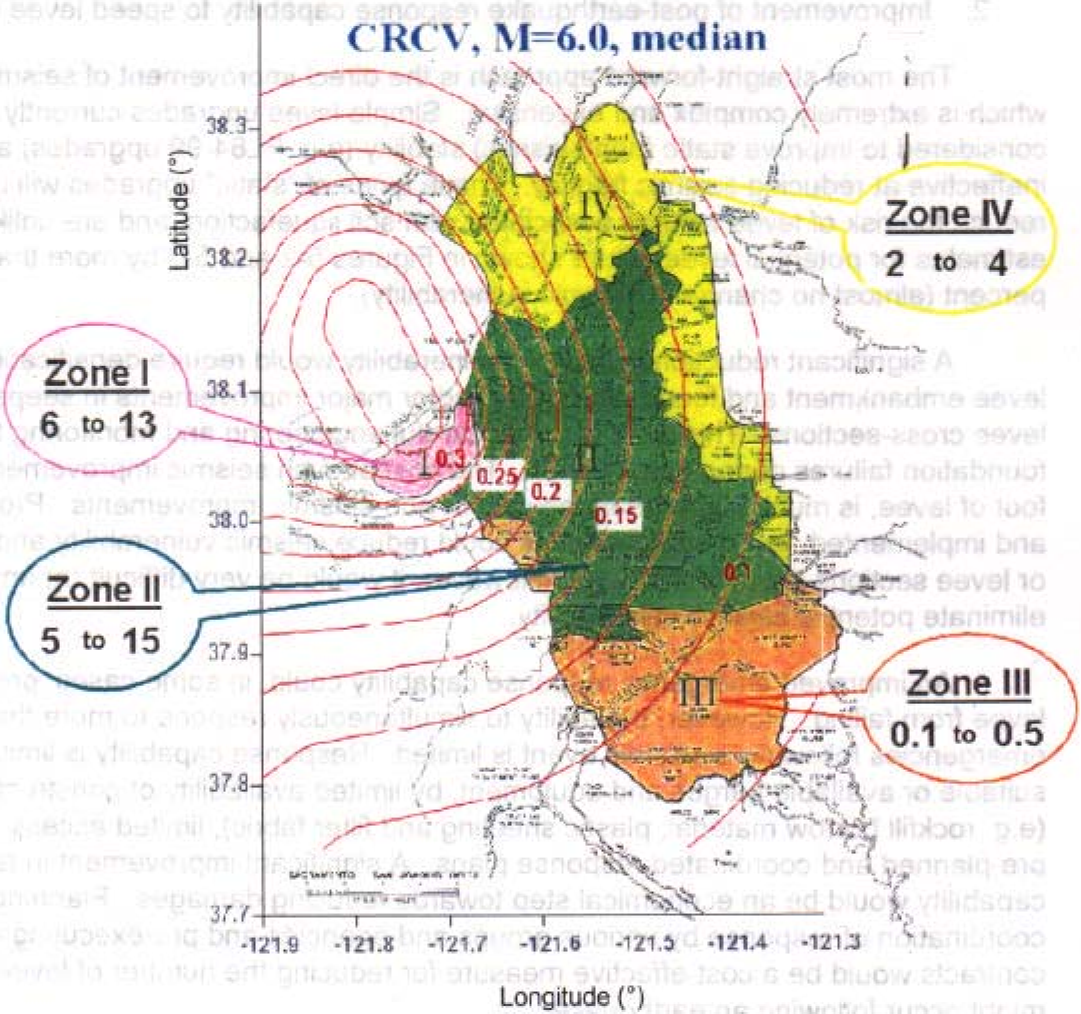


Figure 5-6: Expected Number of Levee Failures for a Magnitude 6.0 Earthquake on th CRCV Fault

6 MITIGATION OF SEISMIC LEVEE VULNERABILITY

There are several approaches which might be considered to reduce seismic levee vulnerability and its potential impacts. Two approaches are:

1. Improvement of seismic levee stability in order to directly reduce seismic vulnerability.

2. Improvement of post-earthquake response capability to speed levee repairs.

The most straight-forward approach is the direct improvement of seismic levee stability, which is extremely complex and expensive. Simple levee upgrades currently being considered to improve static (non-seismic) stability (e.g. PL84-99 upgrades) are largely ineffective at reducing seismic fragility. These types of "static" upgrades will do very little to reduce the risk of levee failures associated with soil liquefaction, and are unlikely to reduce the estimates for potential levee failure shown in Figures 5-2 and 5-3 by more than about 10 percent (almost no change in seismic vulnerability).

A significant reduction in seismic vulnerability would require densification of the loose levee embankment and foundation soils, and/or major improvements in seepage control and levee cross-sections. This work requires careful engineering and monitoring to avoid levee or foundation failures during construction. The cost of such seismic improvements, per linear foot of levee, is much higher than the cost of non-seismic improvements. Properly engineered and implemented, levee improvements could reduce seismic vulnerability and selected islands or levee sections could be targeted. However, it would be very difficult (at any cost) to fully eliminate potential seismic vulnerability.

An improved emergency response capability could, in some cases, prevent a damaged levee from failing. However, the ability to simultaneously respond to more than a few levee emergencies following a seismic event is limited. Response capability is limited by lack of suitable or available barges and equipment, by limited availability of construction materials (e.g. rockfill borrow material, plastic sheeting and filter fabric), limited access, and by a lack of pre-planned and coordinated response plans. A significant improvement in response capability would be an economical step towards reducing damages. Planning and coordination of response by various groups and agencies and pre-executing construction contracts would be a cost-effective measure for reducing the number of levee failures that might occur following an earthquake.

The development of seismically-protected water conveyance routes, either through the Delta or around the Delta, has been considered by others. Evaluating such alternatives was beyond the scope of the sub-team.

Similarly, it was beyond our scope to comment on expanding storage capacity south of the Delta.

7 SUMMARY OF FINDINGS

The studies presented in the previous sections were completed to provide an evaluation of the current seismic vulnerability of levees in the Sacramento-San Joaquin Delta. The major findings of this study are summarized as follows:

- Figures 3-1 and 3-2 show the principal faults considered in the development of a probabilistic assessment of seismicity. Two models were considered in this analysis: one includes a potentially significant blind thrust fault system along the western edge of the Delta, and the other one does not. Although both fault models predict about the same general levels of peak accelerations for a given return period (see Figures 3-3 and 3-4), the earthquake magnitudes associated with the motions are different, with somewhat higher magnitudes resulting from the CRCV fault model with the blind thrust fault.

- This study characterized the levee fragility of the Delta by subdividing the Delta into four Damage Potential Zones (see Figure 4-1). Seismic fragility is highest in Zone I, Sherman Island, due to poor levee embankment and foundation soils. Zone II, the central area of the Delta, has the next highest overall level of seismic levee fragility. Zones III and IV, with levees of lower heights and less saturated soil conditions, founded on generally firmer soils, have generally lower levels of levee fragility.

- Levee fragility within each of the four damage potential zones was estimated for a range of potential earthquake shaking. The two potential modes of levee failure used in this assessment were:

  (1) Soil liquefaction (loss of strength of saturated sandy and silty soils).

  (2) Inertially-driven deformations of "weak," marginally-stable levee sections.

  Levee fragility values for both of these potential modes of failure are presented in Table 4-2.

- Finally, seismic vulnerability was evaluated by combining the probabilistic assessment for various earthquake motions (loading) with the estimated seismic fragility (resistance) of different levee reaches. The fault model without the blind thrust fault gave lower predicted numbers of levee failures (see Figure 5-2: 3 vs. 7 levee failures in a single earthquake for a return period of 100-years). As it is not presently possible to conclusively select between the two faulting models studied, this study ended up averaging the results from the two fault models, with the final levee vulnerability results shown in Figures 5-2 and 5-3.

- A brief discussion of options for reducing the current Delta levee seismic vulnerability was presented in Section 6. It was concluded that attempting to significantly reduce seismic levee fragility will be both difficult and expensive, and that simply making relatively minor geometric modifications (e.g. along the lines of PL84-99 criteria) will not significantly reduce seismic vulnerability. Developing improved emergency response plans and measures (including stockpiling of critical materials and equipment) is thought to have considerable merit, especially in the short-term.

- The next phase of this committees' studies should include further examination of various proposed long-term mitigation alternatives and emergency response measures.

APPENDIX A:

SEISMICITY OF THE DELTA REGION

APPENDIX A: SEISMICITY OF THE DELTA REGION

A1. INTRODUCTION

The Delta is located in a region of relatively low seismic activity. However, if a large earthquake (M≈6.5-7) occurs on a local fault in the Delta region, then there will be large ground motions (with peak horizontal accelerations exceeding 0.2g) at the western edge of the Delta. Although a large local event cannot be ruled out, it has a low probability of occurring. Probabilistic seismic hazard analysis is a method that explicitly considers how often earthquakes of various sizes are likely to occur, and what is the likely ground motion that will result if an earthquake occurs. In this manner, it allows for an evaluation of the seismic risk of the levees.

The probabilistic approach used in this study follows the standard approach first developed by Cornell (1968), with some modifications to more fully address all sources of variability.

There are three main components of variability that are considered in a seismic hazard analysis: what are the likely magnitudes of the earthquakes, where are the earthquakes likely to be located, and what is the likely ground motion given that an earthquake of a specified magnitude has occurred at a specified location.

The source characterization describes the expected rate of earthquakes as well as the distribution of magnitudes and locations. The attenuation relationships describe how strong the resulting ground shaking will be for an event of a given magnitude and location. These components of the hazard analysis are briefly described below. The resulting horizontal peak acceleration hazard is then discussed.

A2. DESCRIPTION OF SEISMIC SOURCES

The faults considered in the hazard analysis are shown in Figure A-1 and A-2, for the two alternative models of the Delta region thrust faults considered in this study. The mean slip-rate, fault width, and maximum magnitude of the faults are listed in Table A-1. The main strike-slip faults in the Bay area (San Andreas, Hayward, Calaveras) contribute to the hazard in the Delta for short return periods, but the smaller (and more local) faults contribute more significantly to the overall hazard at longer return intervals.

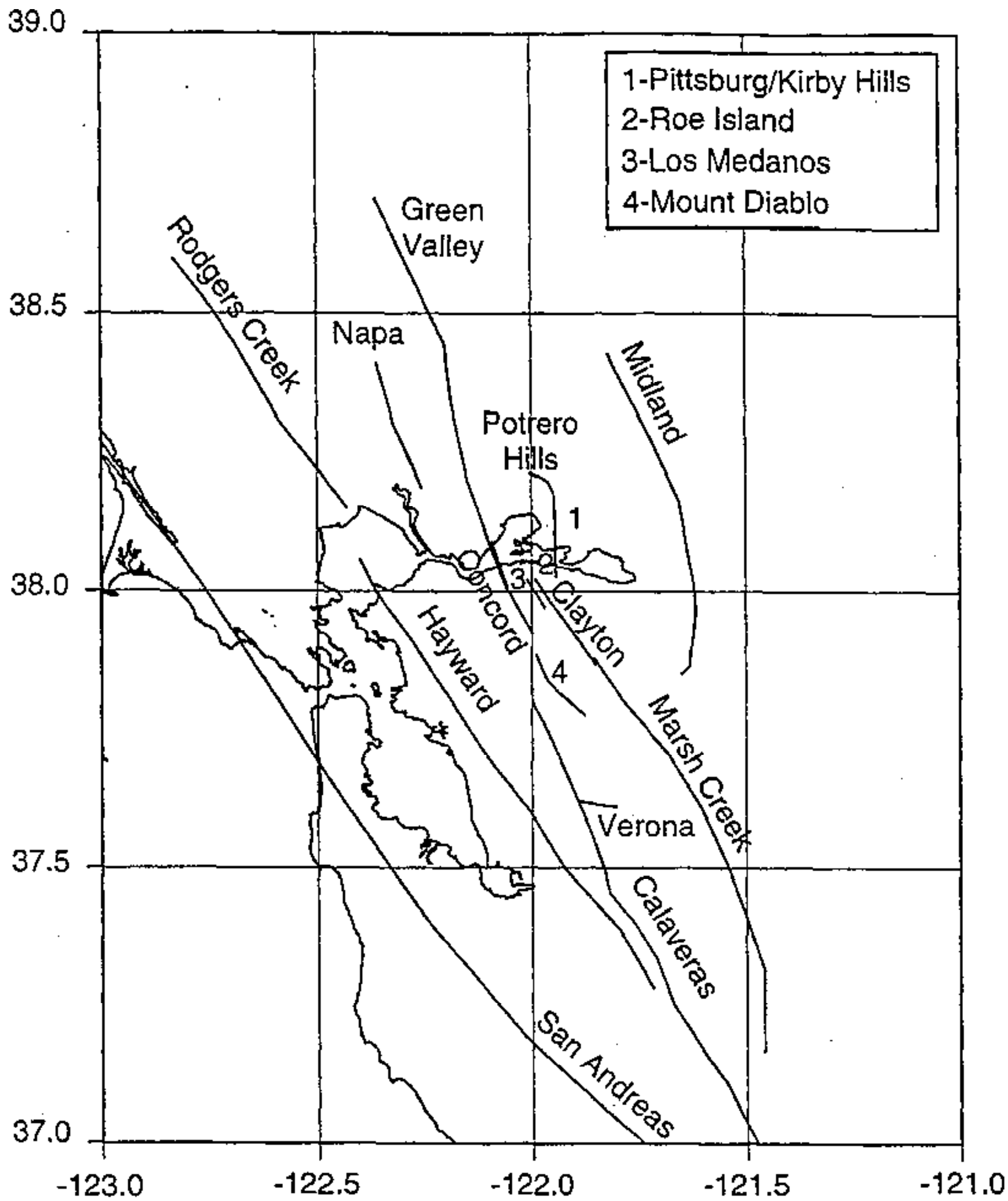


Figure A-1: Map showing the significant faults in the Delta region used in the seismic hazard computations based on the Lettis Delta fault model.

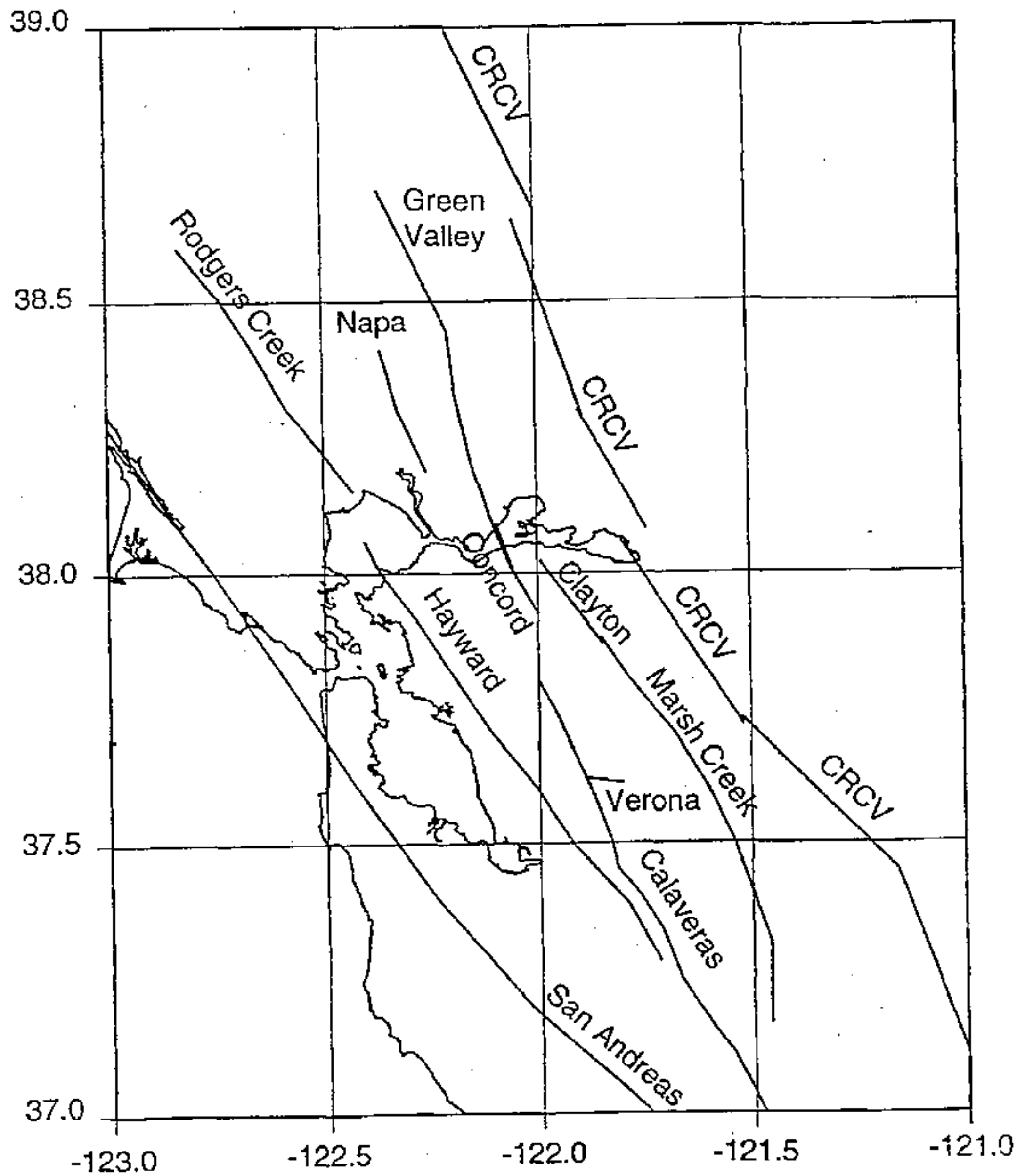


Figure A-2: Map showing the significant faults in the Delta region used in the seismic hazard computations based on the CRCV Delta fault model.

Table A-1. Seismic Source Parameters

Fault	Slip Rate (Weight)	Fault Width (Weights)	Max Magnitude (Weights)
Concord	3.0, 4.0, 6.0 (0.25, 0.5, 0.25)	12.0 (1.0)	6.4, 6.6, 6.8 (0.2, 0.6, 0.2)
Calaveras (North)	2.0, 6.0, 8.0 (0.25, 0.5, 0,25)	12.0 (1.0)	6.7 (1.0)
Calaveras (South)	13.0, 15.0, 17.0 (0.25, 0.5, 0.25)	12.0 (1.0)	6.8 (1.0)
Hayward	7.0, 9.0, 11.0 (0.25, 0.5, 0.25)	12.0 (1.0)	7.1 (1.0)
Marsh Creek/Greenville	0.5, 2.0, 3.0 (0.25, 0.5, 0.25)	12.0 (1.0)	6.7 (1.0)
Clayton	0.2, 0.5, 1.0 (0.25, 0.5, 0.25)	12.0 (1.0)	6.7 (1.0)
Green Valley	1.5, 4.0, 5.0 (0.2, 0.6, 0.2)	12.0 (1.0)	6.6 (1.0)
Napa	0.1, 0.3, 0.5 (0.3, 0.5, 0.2)	12.0 (1.0)	6.5 (1.0)
Rogers Creek	6.0, 8.0, 11.0 (0.25, 0.5, 0.25)	12.0 (1.0)	7.0 (1.0)
San Andreas	19.0, 24.0, 29.0 (0.2, 0.6, 0.2)	15.0 (1.0)	7.8, 8.0 (0.8, 0.2)
Verona	0.1 (1.0)	10.0 (1.0)	6.1 (1.0)
Antioch	0.3 (1.0)	15.0 (1.0)	6.5 (1.0)
Mt. Diablo Thrust[1]	1.3, 1.7, 5.0 (0.3, 0.6, 0.1)	11.0 (1.0)	6.25, 6.75 (0.30, 0.70)
Los Medanos Thrust[1]	0.3, 0.7 (0.8, 0.2)	13.0 (1.0)	6.00, 6.25 (0.8, 0.2)
Roe Island Thrust[1]	0.1, 0.3, 0.7 (0.1, 0.7, 0.2)	14.0 (1.0)	5.75, 6.00 (0.5, 0.5)
Potrero Hills Thrust[1]	0.1, 0.3, 0.6 (0.3, 0.6, 0.1)	14.25 (1.0)	6.00, 6.25 (0.8, 0.2)
Pittsburg/Kirby Hills Thrust[1]	0.2, 0.3, 0.7 (0.5, 0.4, 0.1)	15.0 (1.0)	6.00, 6.50 (0.4, 0.6)
Midland Thrust[1]	0.1, 0.2 (0.6, 0.4)	13.0 (1.0)	6.00, 6.25 (0.7, 0.3)
CRCV[2]	0.5, 1.5, 2.5 (0.25, 0.5, 0.25)	10.0 (1.0)	6.8 (1.0)

1 Lettis source model for the Delta region.
2 CRCV source model for the Delta region.

In addition to the known faults, a background source zone is also included to capture the earthquakes expected to occur on other fault sources. The background zone is based on the smoothed historical regional background seismicity ($M \geq 4.0$) developed by USGS (1996) and used by the CDMG in its state hazard maps. This background seismicity is smoothed over a distance of 50 km, resulting in very smooth background seismicity. The rate of magnitude 5 or greater earthquakes per 100 years per 100 square km is shown in Figure A-3. To avoid double counting seismicity, the background zone is used for magnitudes 5-6 and the individual known faults are used for magnitudes greater than 6.0.

The two alternative models for the thrust faults are discussed in more detail below.

Delta Region Thrust Faults

Geodetic data indicates that there is crustal shortening of about 3 mm/yr in the direction normal to the San Andreas fault between the Pacific Plate and the North American Plate. The primarily strike-slip earthquakes in the Bay Area region accommodate some of this shortening, but some additional thrust faults are needed to explain the remainder of the shortening between the Pacific and North American plates in this region. These thrust faults generally do not reach the surface and are considered "blind thrust" faults.

In most recent studies, most of the additional shortening has been assumed to be accommodated along the western edge of the central valley along a feature called the Coast Range/Central Valley Thrust (CRCV) fault zone (also called the Coast Range Sierran Block Boundary Zone).

There have been several earthquakes over magnitude 6 that have occurred along the CRCV fault zone to the north and to the south of the Delta region, but there are no known CRCV events of $M \geq 6$ in the vicinity of the Delta. The 1983 Coalinga earthquake (M=6.4) and the 1985 Kettleman Hills earthquake (M=6.1) occurred on the CRCV. The 1892 Winters-Vaccaville earthquake (M=6.4) may also have occurred on the CRCV, but its location is not well constrained (Toppozada, Real, and Parke, 1981). The CRCV is clearly an active fault in some regions, but it may not exist in the Delta region, or it may not be active in the Delta region.

In this evaluation, we consider two alternative models of the thrust faults in the Delta region: the CRCV model and the without CRCV model developed by Lettis and Associates model. These two alternative models are discussed in the following sections.

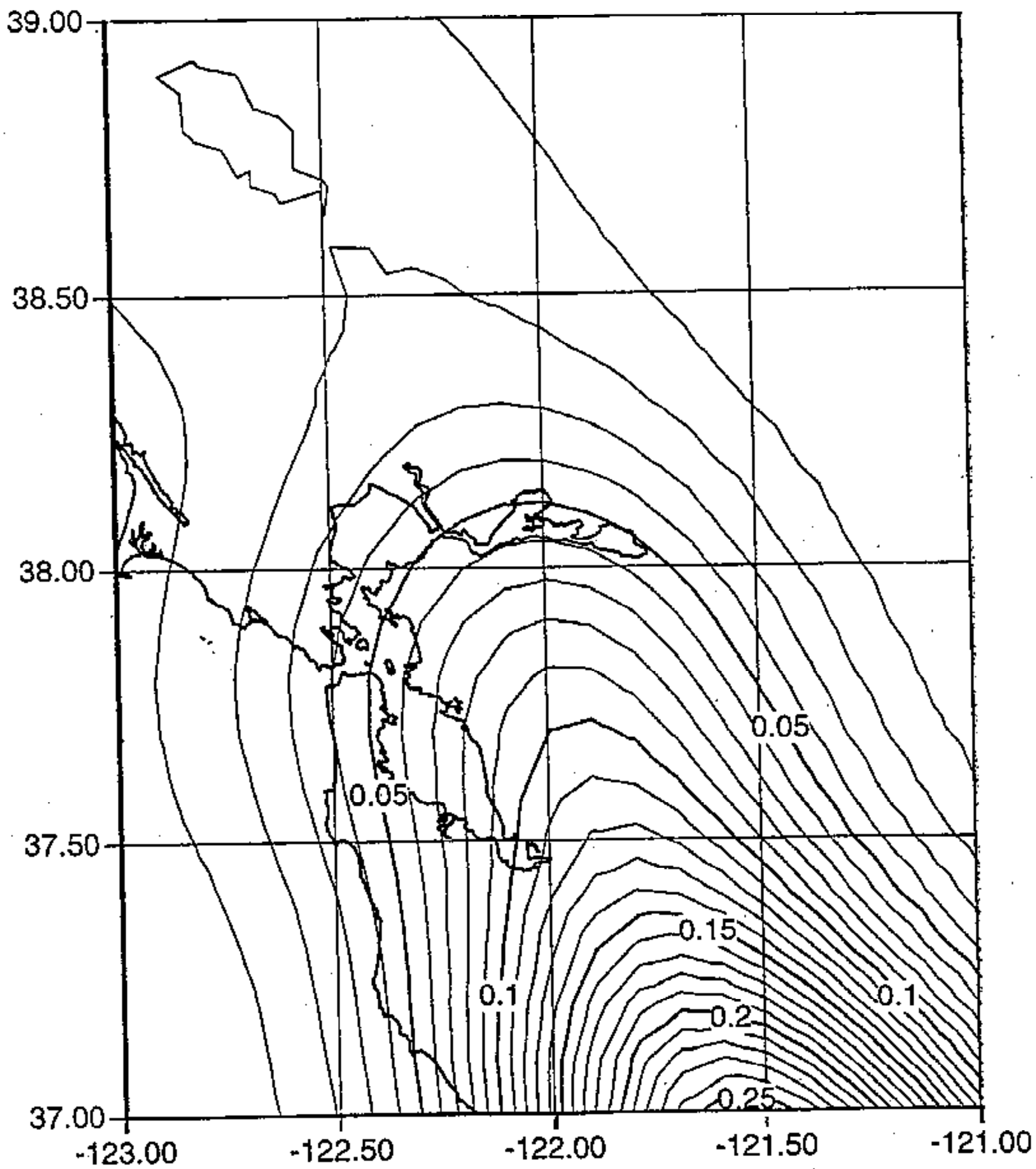


Figure A-3. Map showing the contour of smoothed background seismicity for magnitude 5.0 and greater per 100 years per 100 square kilometers. Based on the USGS gridded seismicity maps (1996).

CRCV Thrust Fault Model

The CRCV extends about 600 km along the western edge of the Central Valley in central and Northern California (Wong et al., 1988), but the faulting is discontinuous. Most of the segment lengths are 5 to 20 km with a maximum segment length of about 50 km. In the CRCV model, this set of thrust faults extends through the Delta region and runs near Sherman Island (see Figure A-2).

The CRCV model has been used in the state hazard maps developed by the California Division of Mines and Geology (CDMG). The slip-rate of the CRCV in the Delta region is uncertain. The sub-team used a range of slip-rates from 0.5 to 2.5 mm/yr. The CDMG (1996) used a slip-rate of 1.5 mm/yr and that is the mean value that is used in this study.

The exact location of the CRCV fault in the Delta region is uncertain. In this study, the top of the fault is located at a depth of 8 km with a dip of 15 degrees. For a down-dip fault width of 15 km and a segment length of 40 km, the Wells and Coppersmith (1994) magnitude vs. fault area relation gives a mean maximum magnitude of $M_w \approx 6.8$.

Without CRCV Model Developed by Lettis and Associates

A recent study by Unruh (Lettis and Associates written comm., 1998) suggests that the CRCV is not present in the Delta region. According to this model, the CRCV begins to decrease in activity north of the San Luis Reservoir and south of Lake Berryessa. In the Delta region, the CRCV ceases to exist, or ceases to be active. As an alternative to the CRCV, the Lettis and Associates model postulates a different set of thrust faults slightly further to the west to accommodate the crustal shortening (see Figure A-1).

These faults, the Pittsburg/Kirby Hills, Roe Island, Los Medanos, and Mount Diablo faults are all short faults with lengths of less than 20 km located 10-20 km west of the western edge of the Delta. The mean slip-rates of these faults range from 0.3 to 2 mm/yr. The maximum magnitudes of the small thrust faults range from $M_w \approx 6.0$ to 6.6.

This model also includes the Midland fault located beneath the Delta, but with a small mean slip-rate of 0.15 mm/yr. Although the Midland fault has a length of about 60 km, the maximum magnitude of the Midland fault in this model is only $M_w \approx 6.2$.

A3. ATTENUATION RELATIONS

There are many attenuation relations that can be used for the deep soil site conditions (below the peat) in the Delta. In this study, we have selected four of the most recent attenuation models: Abrahamson and Silva (1997), Boore, et al. (1997), Campbell

(1997), and Sadigh, et al. (1997) as being appropriate. These models are given equal weight in the hazard analysis.

A4. PROBABILISTIC HAZARD RESULTS

The probabilistic hazard is shown separately for the Lettis and the CRCV models of the Delta thrust faults. The results for the Lettis model are shown first, and the results for the CRCV model are shown second. Sherman Island and Terminous Island are used as example locations representative of the western and eastern edges of the Delta, respectively. All acceleration levels shown are peak horizontal accelerations at surface outcrops of deep, stiff soils (soils underlying the softer and organic superficial Delta deposits.)

Figures A-4 and A-5 show the peak acceleration hazard for Sherman Island and Terminous Island, respectively, based on the Lettis thrust fault model. At a return period of 100 years (annual probability of 0.01), the hazard at Sherman Island is dominated by the local thrust faults, with significant contribution from the background zone and "other" faults. For Terminous Island, the background zone and thrust faults contribute about equally to the overall 100 year return-interval level of hazard.

The magnitudes and distances of the earthquakes dominating the hazard can be estimated by deaggregating the hazard. The distributions of contribution to the hazard are shown in Figures A-6 and A-7. For Sherman Island, the hazard is primarily from moderate magnitude events (M≈5.5-6.5) at distances of 10 to 30 km. For Terminous Island, the more distant sources also contribute significantly to the hazard, and there is a wide range of magnitudes and distances (M≈5-6 at distances of 10-30 km to M≈7-7.5 at 100 km) contributing to the hazard. Figures A-8 and A-9 show the mean magnitude and mean distance of the earthquakes contributing to the hazard as a function of the return period.

A similar set of plots for the CRCV model is shown in Figure A-10 and A-11. The main difference is that for the CRCV model, the local CRCV thrust faults are the principal controlling source for both Sherman Island and Terminous Island.

The hazard for the Lettis and CRCV models is compared in Figure A-12. This figure shows that the hazard from these two models is very similar for both the Sherman Island and Terminous Island sites when expressed in terms of expected peak horizontal acceleration. The models differ, however, in terms of the principal magnitudes that contribute to these acceleration hazard levels. These differences in contributing magnitudes, in turn, imply differences in the duration of shaking, and this has a potentially significant impact on both the liquefaction and cyclic inertial deformation hazard evaluations for Delta levees.

The two models are given equal weight in the final hazard analysis. Contours of the peak acceleration in the Delta region for return period of 43 years, 100 years, 200 years, and 475 years (building code level) are shown in Figures A-13 through A-16. The hazard systematically decreases from the southwest to the northeast.

For the top of stiff soils, the 100 year return-interval horizontal peak acceleration ranges from 0.2 g in the western Delta to 0.1 g in the northeastern Delta. Since the hazard is dominated by moderate magnitude local events, it is unlikely that the entire Delta will be subject to the 100-year ground motion in a single 100-year earthquake.

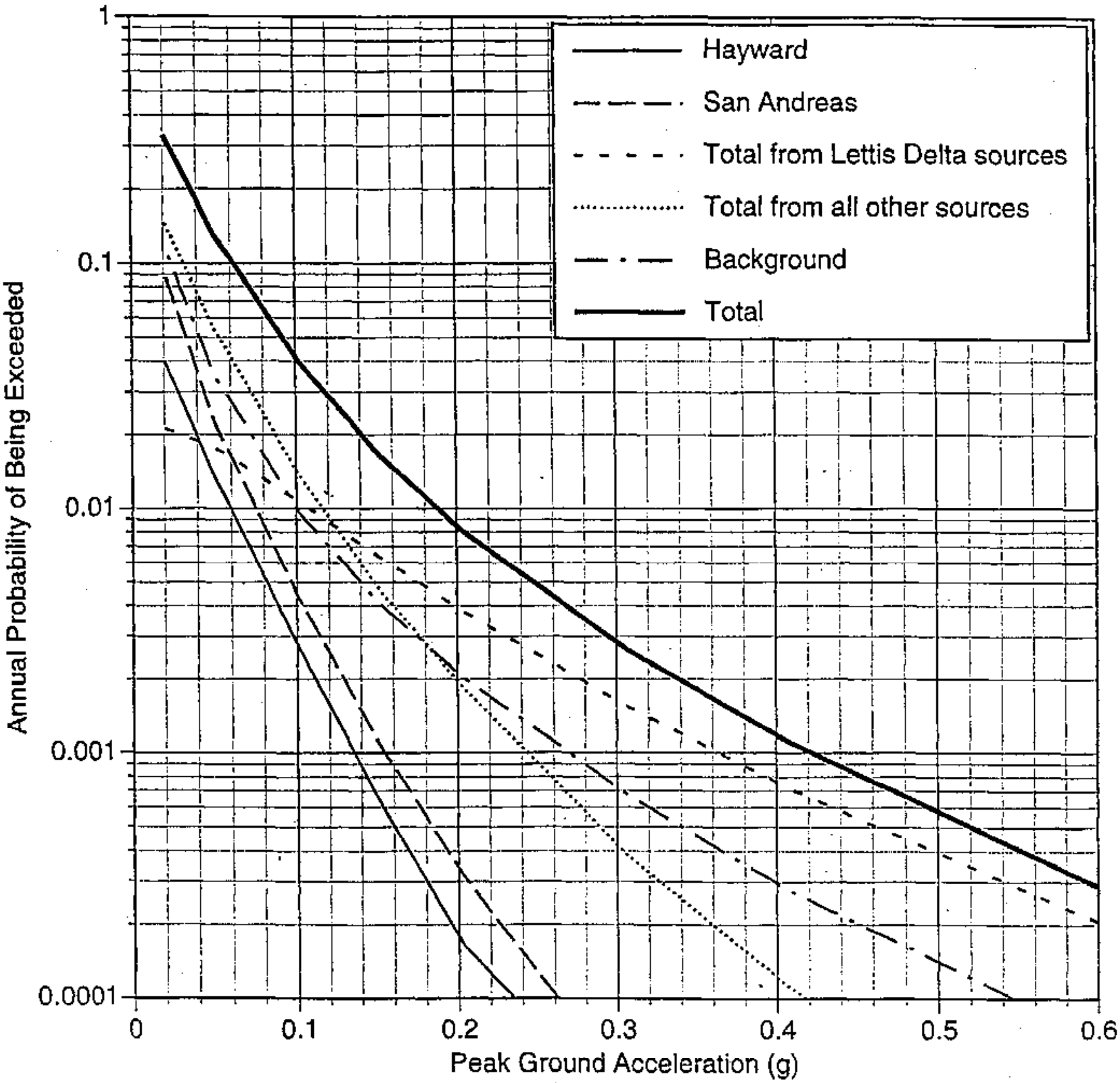


Figure A-4. Seismic hazard curves for the Sherman Island site. The hazard curves are based on the Lettis seismic model for the Delta region. The contribution to the total hazard is shown for the significant faults.

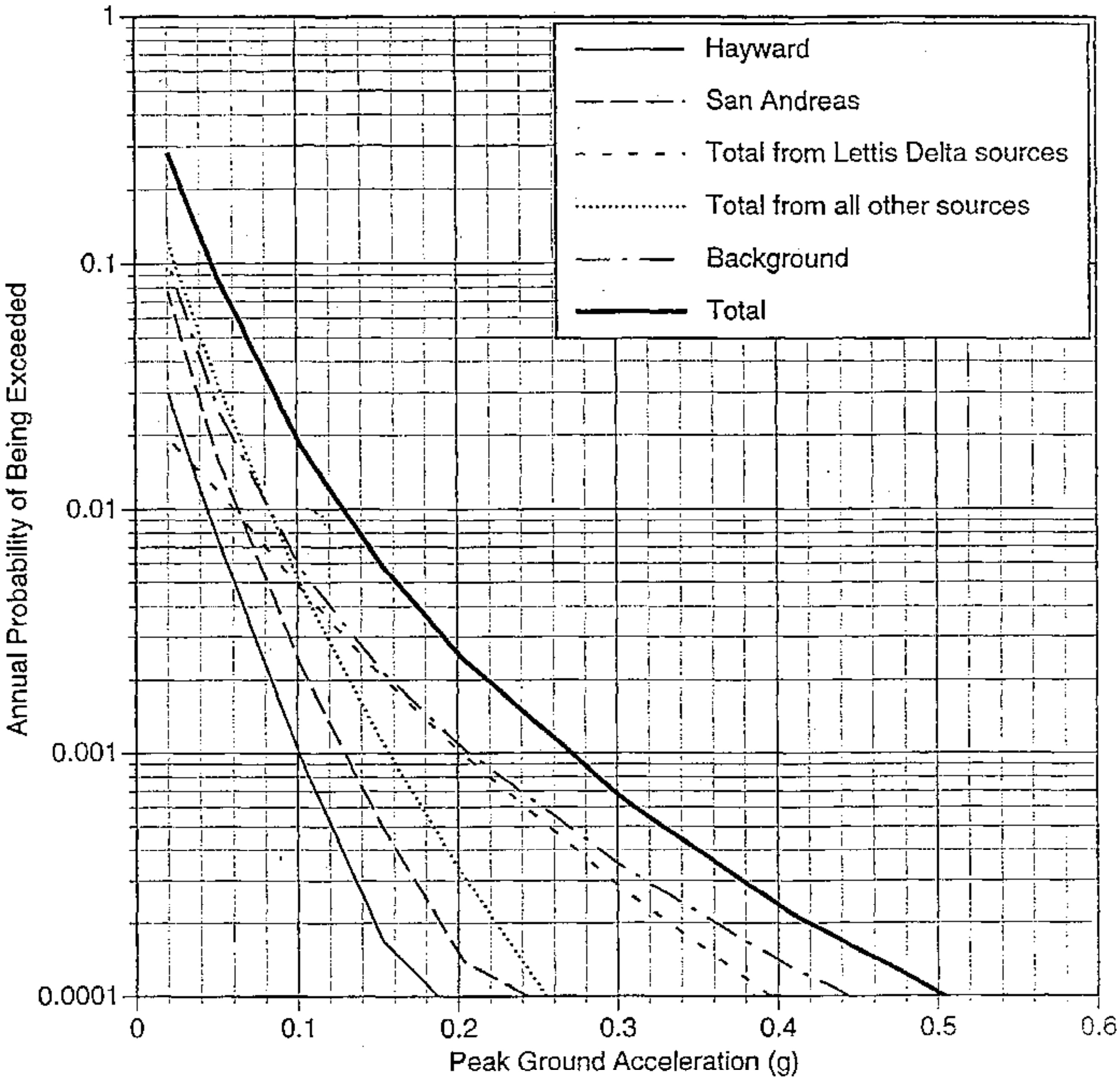


Figure A-5. Seismic hazard curves for the Terminous site. The hazard curves are based on the Lettis seismic source model for the Delta region. The contribution to the total hazard is shown for the significant faults.

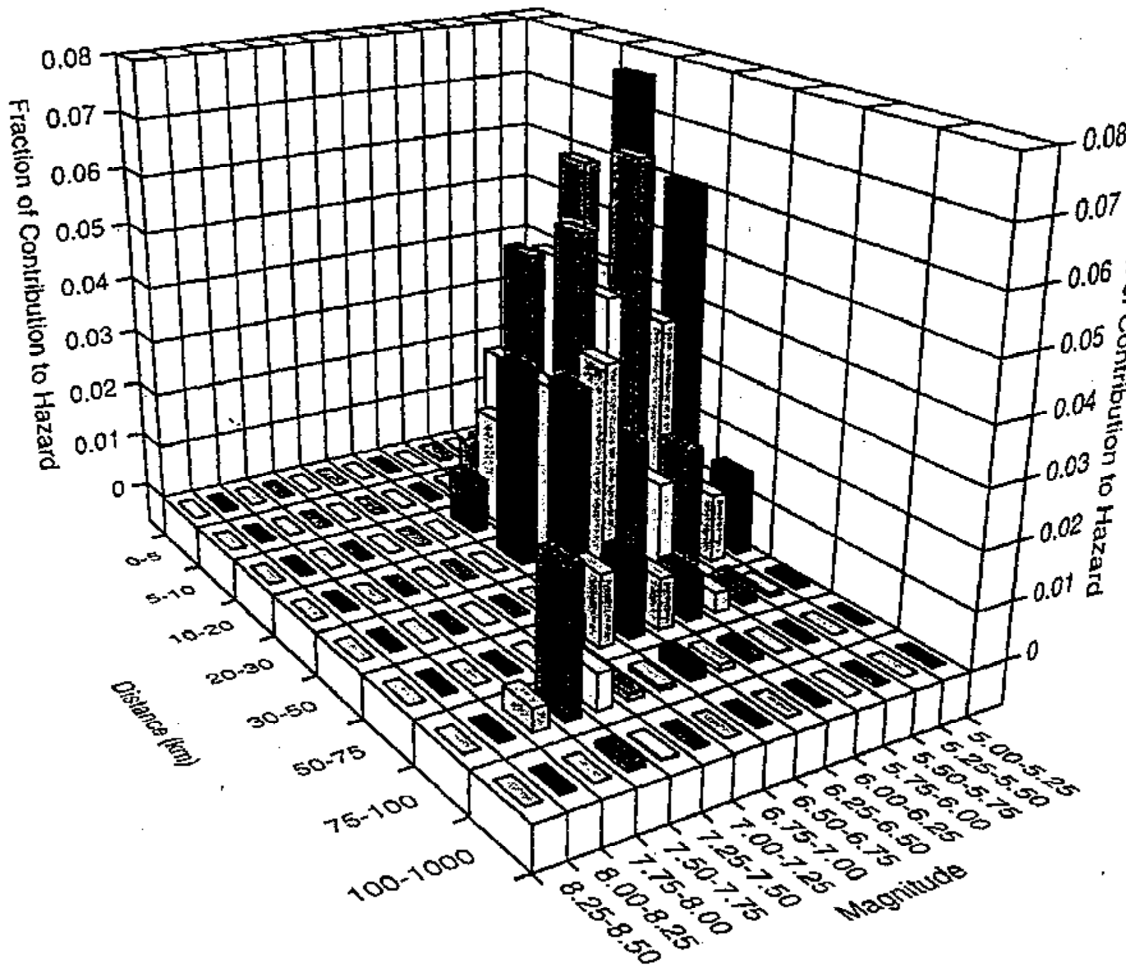


Figure A-6. Deaggregation of the seismic hazard (100 year return period) for the Sherman Island site based on the Lettis seismic source model for the Delta region.

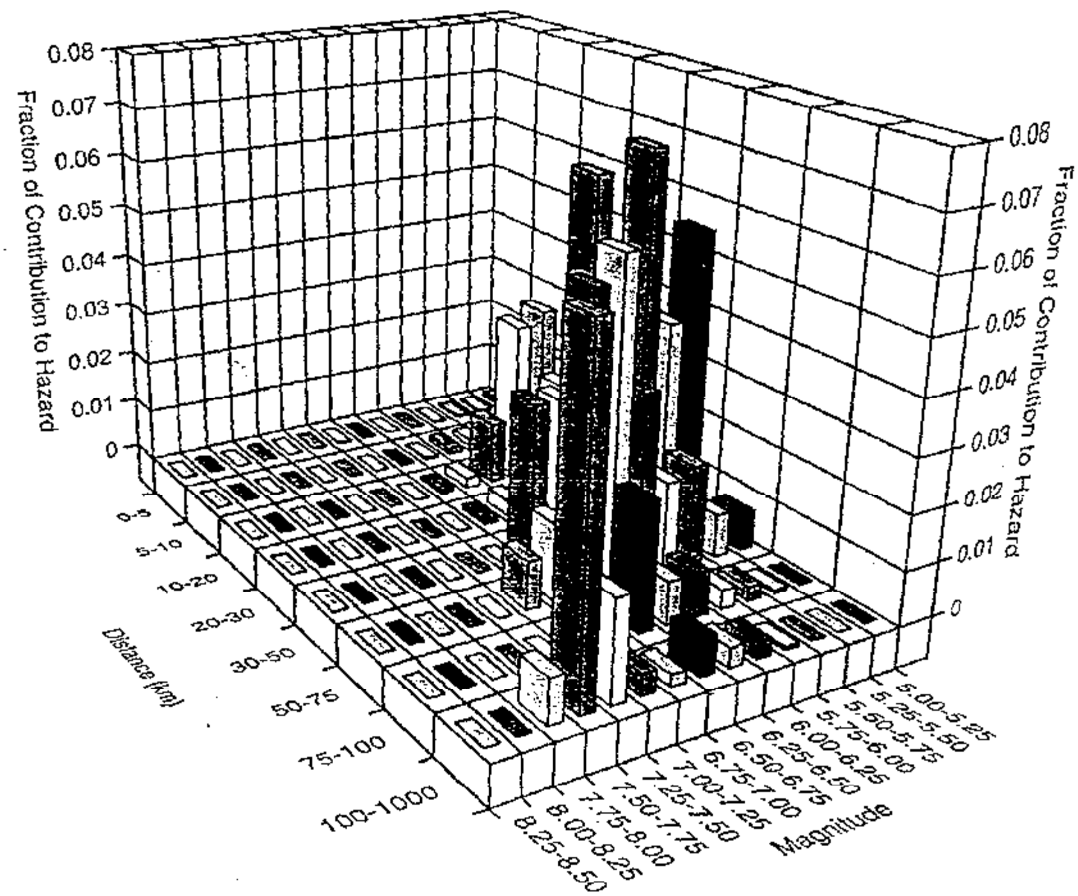


Figure A-7. Deaggregation of the seismic hazard (100 year return period) for the Terminous site based on the Lettis seismic source model for the Delta region.

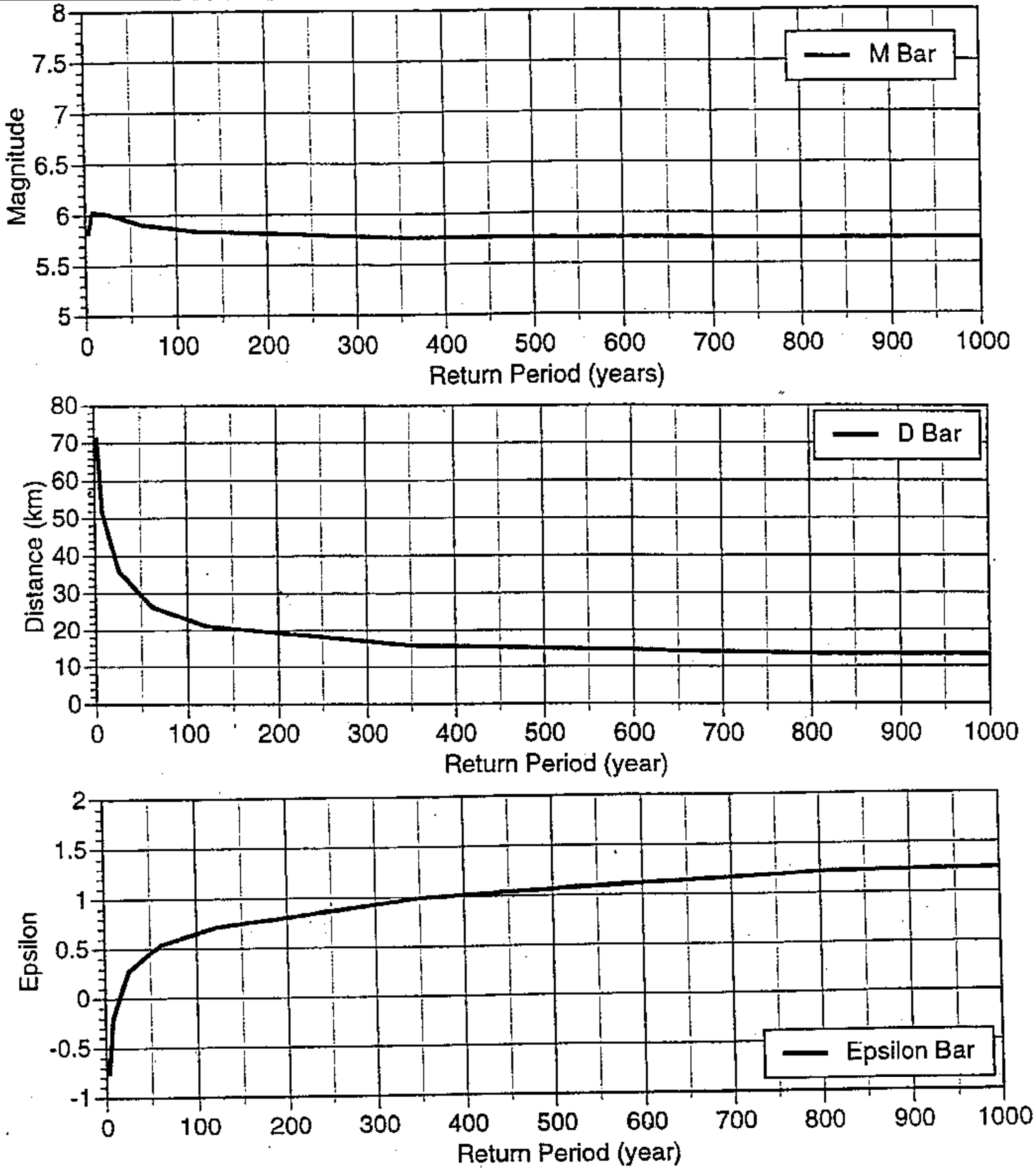


Figure A-8. Magnitude, distance and epsilon bar for the Sherman Island site based on the Lettis seismic source model for the Delta region.

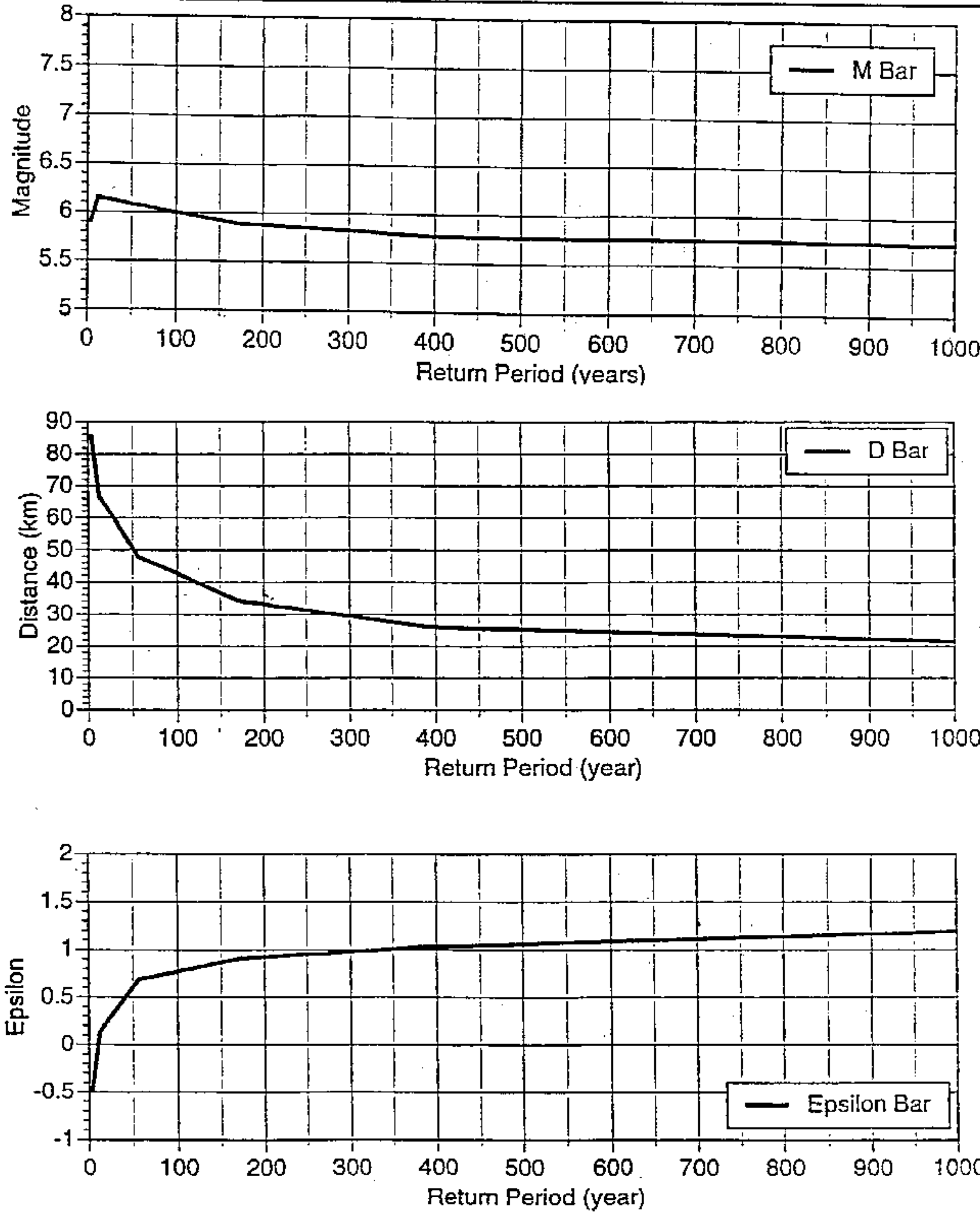


Figure A-9. Magnitude, distance and epsilon bar for the Terminous site based on the Lettis seismic source model for the Delta region.

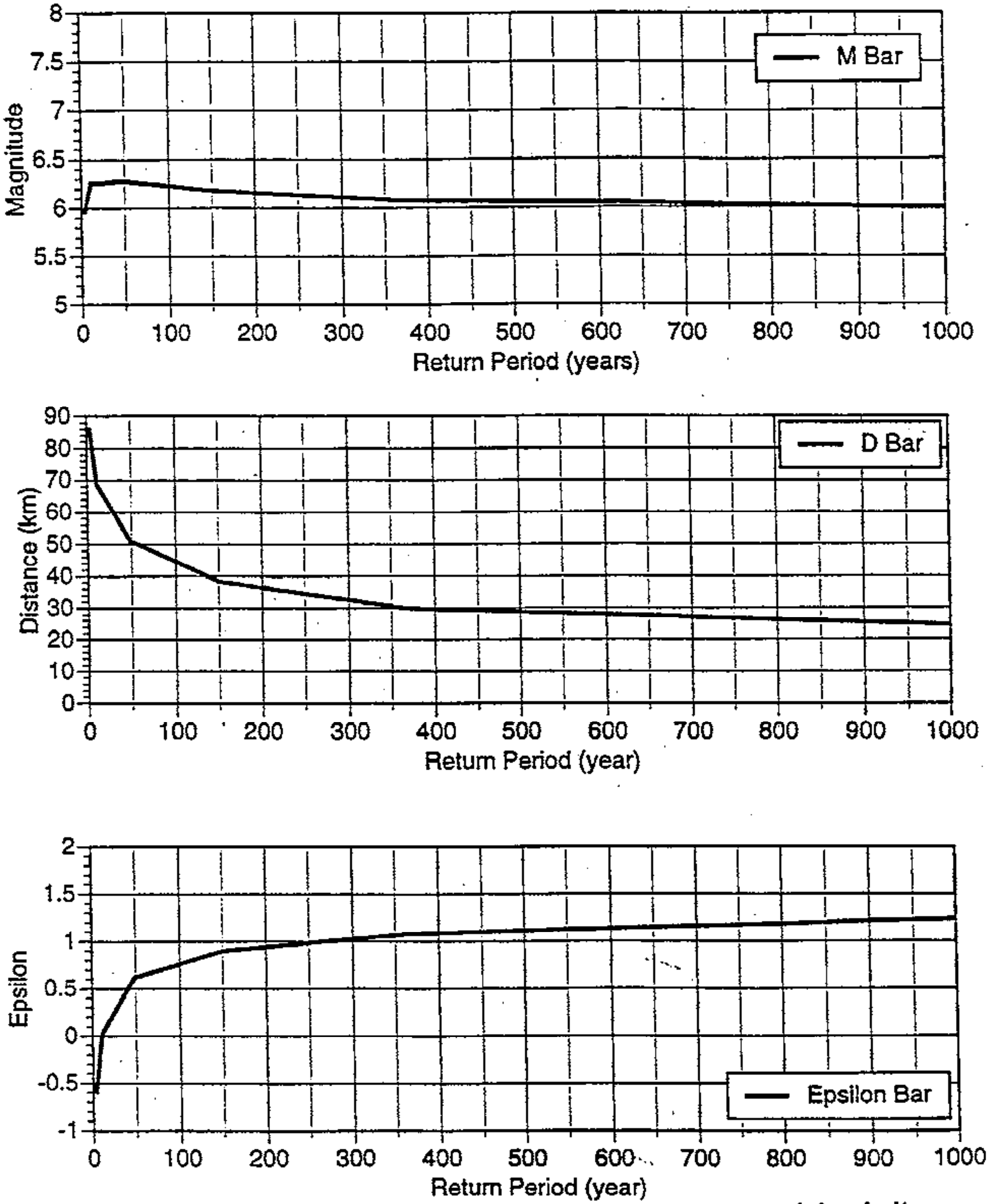


Figure A-10. Magnitude, distance and epsilon bar for the Sherman Island site based on the CRCV seismic source model for the Delta region.

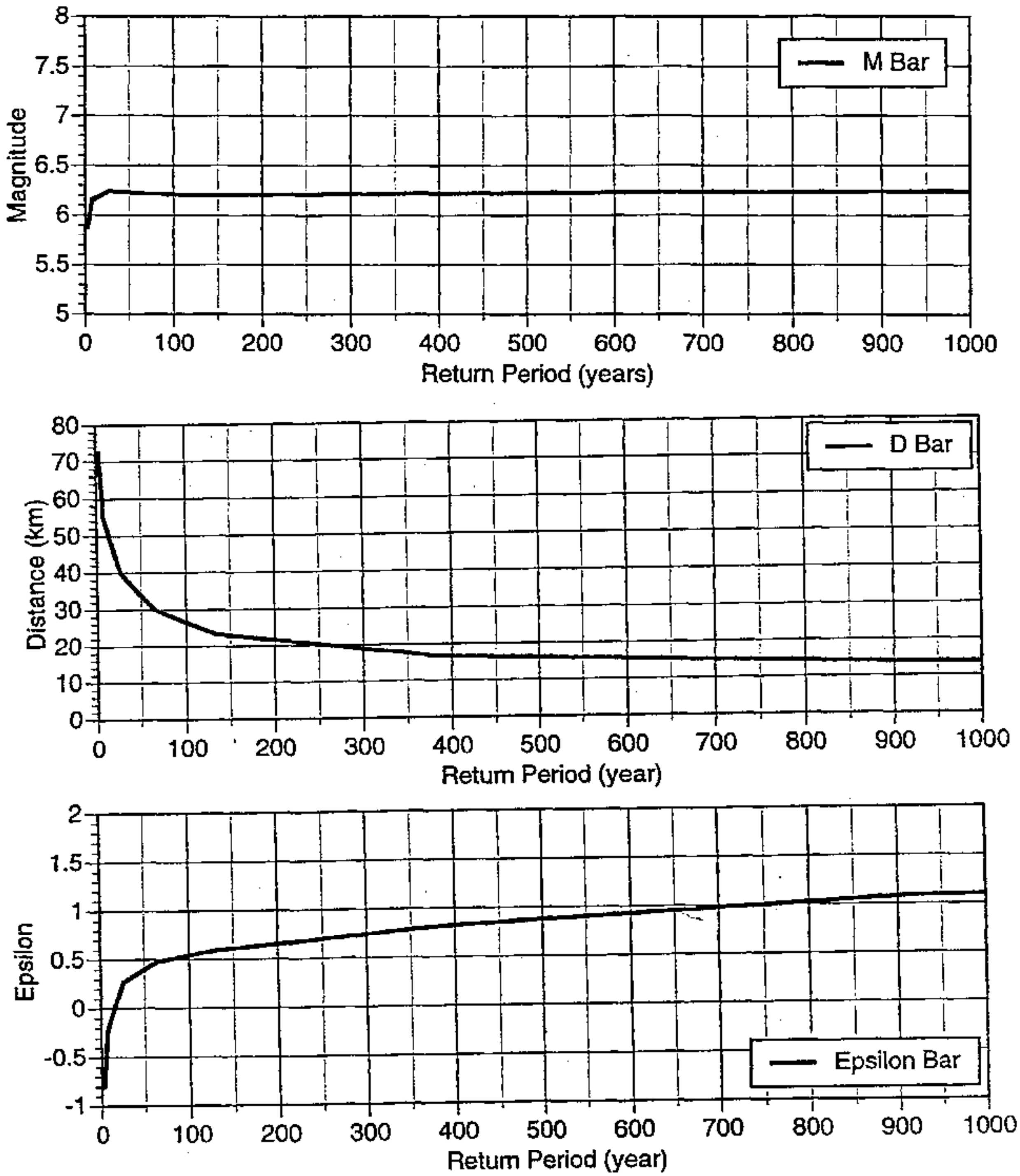


Figure A-11. Magnitude, distance and epsilon bar for the Terminous site based on the CRCV seismic source model for the Delta region.

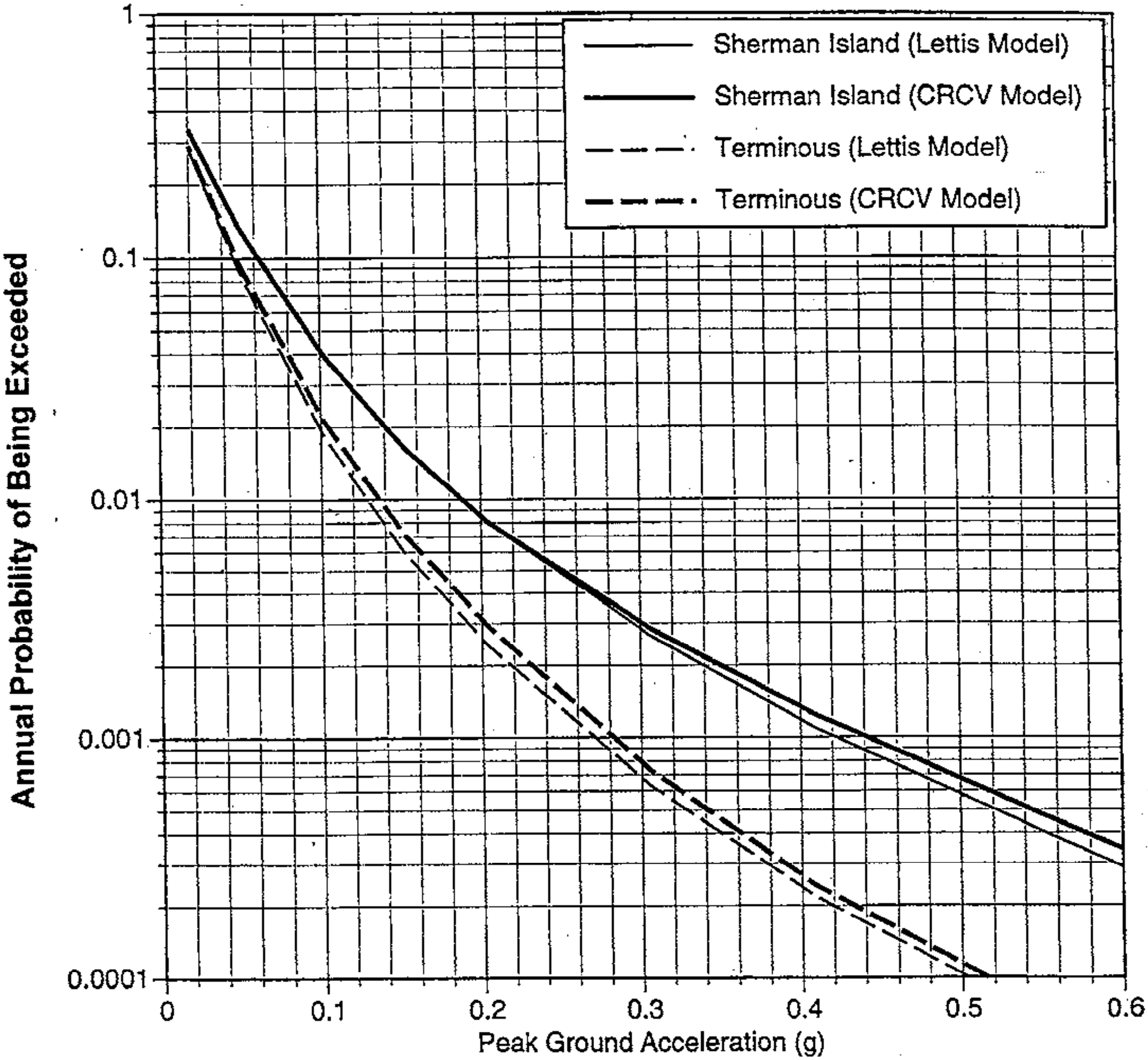


Figure A-12. Comparison of the seismic hazard for the Sherman Island and Terminous sited based on both the Lettis and CRCV seismic source model for the Delta region.

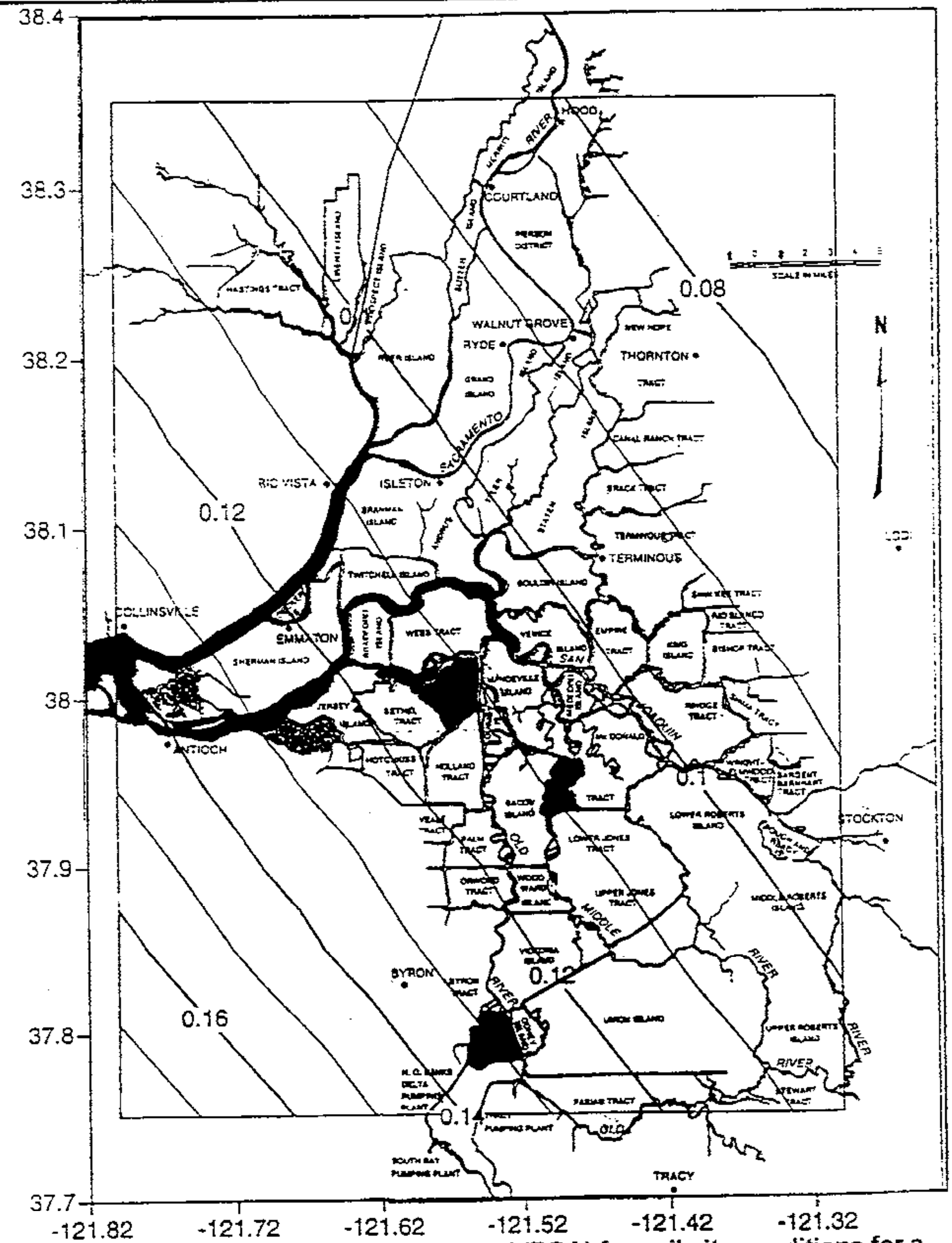


Figure A-13. Contour map of seismic hazard (PGA) for soil site conditions for a return period of 43 years.

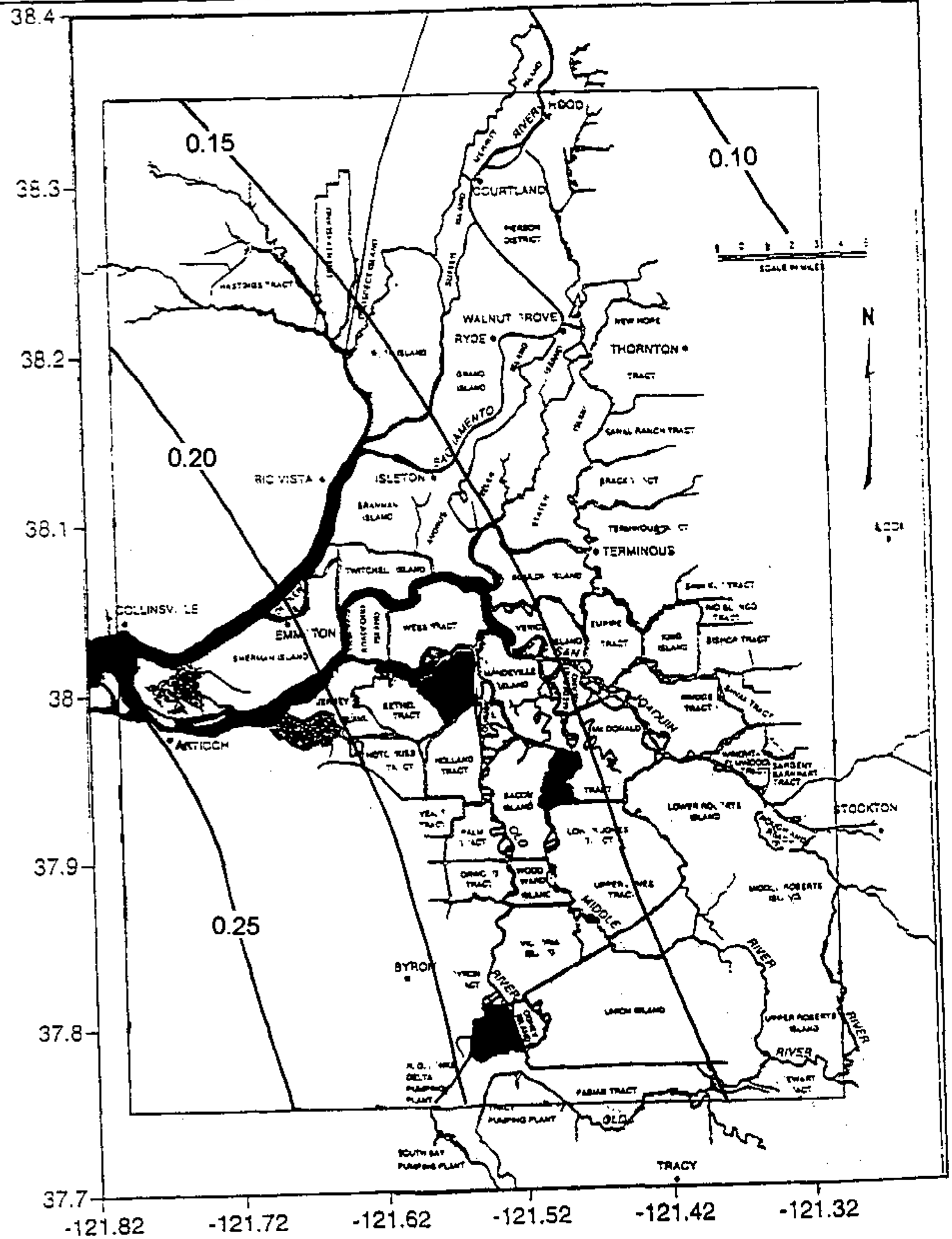


Figure A-14. Contour map of seismic hazard (PGA) for soil site conditions for a return period of 100 years.

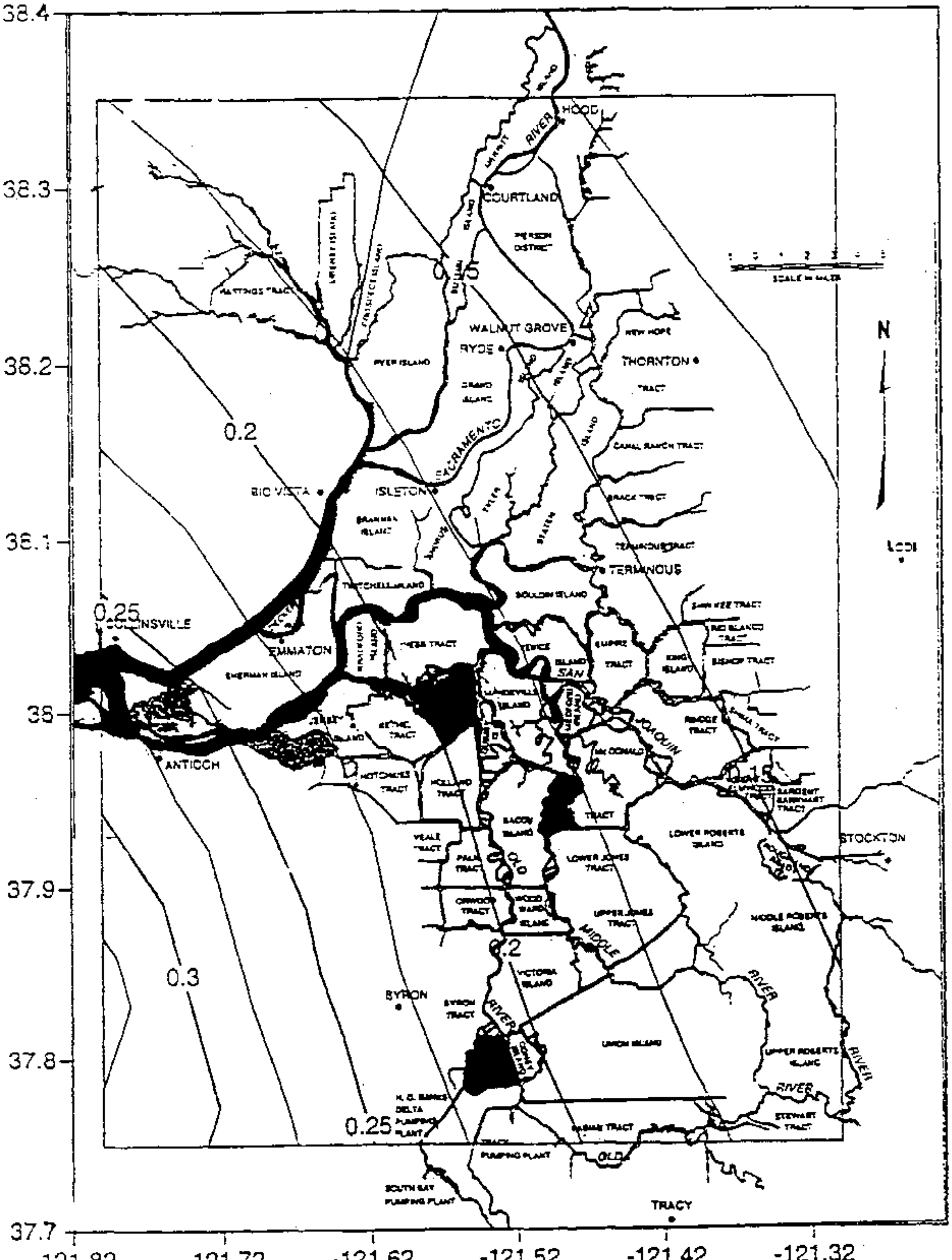


Figure A-15. Contour map of seismic hazard (PGA) for soil site conditions for a return period of 200 years

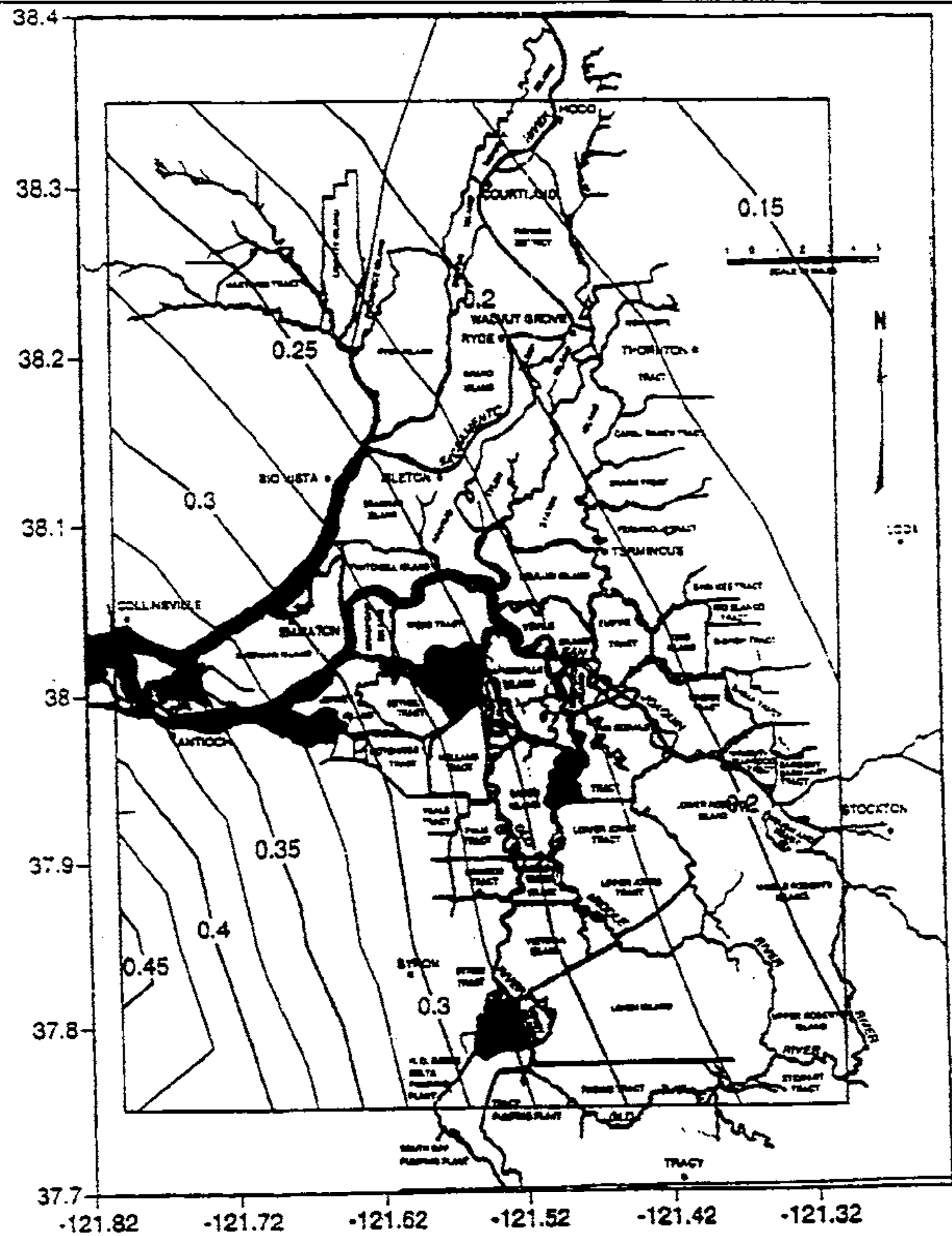


Figure A-16. Contour map of seismic hazard (PGA) for soil site conditions for a return period of 475 years.

APPENDIX B:

EVALUATION OF LEVEE FRAGILITY

- **Liquefaction Mode of Failure**
- **Non-Liquefaction Deformation Mode of Failure**

APPENDIX B: EVALUATION OF LEVEE FRAGILITY

B1. GENERAL

This appendix presents more detailed information regarding the development of levee fragility estimates for potential levee failures due to future seismic events. The fragility estimates were previously described in general terms in Chapter 4. Many of the estimates were based on consensus judgements made by the sub-team members. Sub-team members applied their knowledge of the performance of similar earth structures to the conditions which currently exist in the Delta, and to the potential seismic loadings which might develop in the future. In addition, a number of geotechnical earthquake engineering analyses were also performed to provide information for these judgements, and to extend the estimates for a range of loadings.

The seismic risk analyses and assessments presented in this report are based on the most current available information. Information on the seismic response of peat/organic soils is still being developed. Also, even though hundreds of borings describing the subsurface conditions of Delta levees were reviewed, these borings can only provide a limited characterization of the hundreds of miles of levees in the Delta. It does not appear likely that additional borings will significantly change the present characterization in the near future.

B2. DAMAGE POTENTIAL ZONES

As previously described in Chapter 4, the central portion of the Delta was divided into four Damage Potential Zones in order to allow for different levels of levee fragility in different areas of the Delta (see Figure 4-1). The criteria used for establishing the zoning was discussed previously in Chapter 4. The four zones encompass essentially all of the Delta land which lies below sea level and includes approximately 660 levee miles. Another 440 miles of levee exist at higher elevations within the legal limits of the Delta, but were not included because these levees retain significant depths of water only during flood season. Table B-1 summarizes the Delta islands and tracts included in the four zones along with the lengths of levees to be found in each zone.

B3. ESTIMATES OF LIQUEFACTION-INDUCED LEVEE FAILURES

The sub-team gathered data from borings and CPT soundings to establish "typical" conditions at a number of representative levee reaches throughout the Delta. Data from prior seismic fragility studies, DWR data, and data supplied by individual sub-team members were all reviewed. Liquefaction potential (i.e. resistance to "triggering" or

TABLE B-1: DELTA ISLANDS AND LEVEE LENGTHS CONSIDERED IN EVALUATING POTENTIAL EARTHQUAKE-INDUCED LEVEE FAILURE

Damage Potential Zone	Delta Island/ Reclamation District	Project Levee[1] (miles)	Non-Project[1] Levee (miles)	Total Levee Length[1] (miles)
I	Sherman	9.7	9.8	19.5 [19.5]
II	Bacon		14.3	14.3
	Bethel		11.5	11.5
	Bouldin		18.0	18.0
	Bradford		7.4	7.4
	Brannan	9.3	10.1	19.4
	Empire		10.5	10.5
	Holland		10.9	10.9
	Jersey		15.6	15.6
	Lower Jones		8.8	8.8
	Lower Roberts		16.0	16.0
	Mandeville		14.3	14.3
	McDonald		13.7	13.7
	Medford		5.9	5.9
	Orwood		10.9	10.9
	Palm		7.5	7.5
	Quimby		7.0	7.0
	Rindge		15.7	15.7
	Staten		25.4	25.4
	Twitchell	2.5	9.3	11.8
	Tyler	12.2	10.7	22.9
	Venice		12.3	12.3
	Webb		12.8	12.8
	Woodward		8.8	8.8 [301.4]
III	Byron		9.7	9.7
	Coney		5.4	5.4
	Fabian		18.8	18.8
	Hotchkiss		6.3	6.3
	Middle Roberts	6.1	3.7	9.8
	Rough and Ready		5.5	5.5
	Union	1.0	29.2	30.2
	Upper Jones		9.3	9.3
	Veale		5.7	5.7
	Victoria		15.1	15.1 [115.8]
IV	Andrus	10.0		10.0
	Bishop		5.8	5.8
	Brack		10.8	10.8
	Canal Ranch		7.5	7.5
	Dead Horse		2.6	2.6
	Grand	29.0		29.0
	Hastings	4.0	1.0	5.0
	King		9.0	9.0
	Liberty Island	9.0	9.0	18.0
	McCormack-Williamson		8.8	8.8
	New Hope		18.6	18.6
	Pierson	10.0		10.0
	Prospect	7.0	5.0	12.0
	Rio Blanco		4.0	4.0
	Ryer	20.6		20.6
	Sacramento Co.	2.0	5.0	7.0
	Shima		6.6	6.6
	Sutter	12.5		12.5
	Terminous		16.1	16.1
	Walnut Grove	1.0	1.2	2.2
	Wright Elmwood		6.8	6.8 [222.9]

1 Levee lengths listed in Sacramento-San Joaquin Delta Atlas, DWR (1993) [659.6]Miles

initiation of liquefaction) for sandy and silty soils of low plasticity was evaluated using the SPT-based methodology described by Seed and Harder (1990), as updated by the NCEER Liquefaction Workshop expert panel (NCEER, 1997). Of particular concern to the sub-team was the presence of cohesionless sandy and/or silty soils within the manmade levee embankment. When present, such soils often had SPT $(N_1)_{60}$ blowcounts of less than 10, and commonly less than 5. Post-liquefaction residual strengths were estimated using the correlation proposed by Seed and Harder (1990), and these indicated very low values, commonly only about 50 to 200 psf. With such low residual shear strengths, major levee displacements and/or failure would be expected if major portions of the levee embankment were triggered to liquefy.

Of somewhat lesser concern, but still potentially serious, was the occurrence of potentially liquefiable sandy and silty soils in the foundation zone (beneath the levee embankments). These soils tended to have variable SPT blowcounts, but generally somewhat higher than those in the loose embankment soils. The liquefiable foundation soils were also less hazardous due to levee and foundation geometries, as well as due to the irregular and discontinuous nature of some of these natural foundation deposits. Potential liquefaction of foundation soils was not a benign condition, however, and liquefaction of foundation soils was eventually judged to contribute approximately 25% to 30% of the overall liquefaction-related hazard (with liquefaction of levee embankment fills contributing the remainder.)

The sub-team worked together to assemble and review the available geotechnical data. Each of the individuals then prepared independent assessments of expected levee failure frequencies for various levels of shaking within each of the four Damage Potential Zones. These individual assessments, and their basis, were then shared and discussed to develop a single set of overall consensus estimates. These consensus estimates of potential number of levee failures were presented as a range for each level of shaking and for each of the four Damage Potential Zones. Each range was considered to represent about an 80-percent confidence level for the range of "expected" number of liquefaction-induced levee failures for a particular level of shaking.

B4. ESTIMATES OF LEVEE FAILURES FOR NON-LIQUEFACTION EARTHQUAKE-INDUCED DISPLACEMENTS

Based on Newmark-type cyclic inertial deformation analyses for a range of levels of static (non-seismic) stability, the sub-team concluded that any levee reaches which might fail without major strength losses such as liquefaction would have to be only marginally stable during static conditions. The effect of seismic shaking would be to either trigger or induce deformations as a result of inertial effects. To estimate the number of failures associated with a non-liquefaction deformation mode of failure, the sub-team proceeded in the following steps:

1. The number of marginally stable levee sites in each Damage Potential Zone was first estimated based on the experience of the sub-team members in dealing with problem sites. Three levels of marginal stability were considered. The estimated numbers of potentially marginal sites in each zone are listed in Table B-2. Also presented in Table B-2 are the estimated ranges of yield acceleration, k_y, for each level of marginal stability (k_y is the level of acceleration at which yielding and onset of permanent deformations will occur).

2. Estimates of earthquake-induced deformations were calculated using the Newmark double-integration method for a selected number of accelerograms. Seven accelerograms were selected to provide a reasonable range of duration and frequency content characteristics representative of the levels of seismic excitation being considered (M~5 to 7). These records from "stiff soil" or "rock" sites were then modified by means of site response analyses, using computer program SHAKE91 (Idriss et al., 1991), to develop motions representative of typical Delta levee embankment and foundation soil conditions. The base accelerograms were input as outcrop motions at a stiff soil base layer and then propagated through a deep Delta soil profile up to the surface of the levee. Near-surface motions (at the bases of potential deformation zones) were then scaled to different peak accelerations, and these were then double-integrated to obtain displacements for a range of yield accelerations. An allowance was made to account for spatial and temporal incoherence across a potential slide mass or deformation zone. Figure B-1 and Table B-3 present the results of these calculations. For the purposes of relating probabilistic base accelerations developed in Chapter 3 to a deformation mode of failure, the following was assumed:

   - The base acceleration would be amplified through soft Delta deposits by a factor of 1.6. Thus, a "stiff soil" acceleration of 0.1g would lead to a peak acceleration of 0.16g at the crown of the levee.

   - The average peak acceleration of a potential sliding mass would be approximately 40 percent of the levee crown acceleration. This is based on the work by Makdisi and Seed (1977) and assuming that the marginal sites have relatively deep potential sliding surfaces.

   - Thus, the average acceleration of potential sliding surface, k_{max}, is approximately 65 percent of the base acceleration of a stiff soil outcrop motion [$1.6 \times 0.4 \approx 0.65$].

TABLE B-2: ESTIMATED NUMBER OF MARGINALLY STABLE LEVEE SITES IN NON-LIQUEFIED REACHES WITHIN DAMAGE ASSESSMENT ZONES

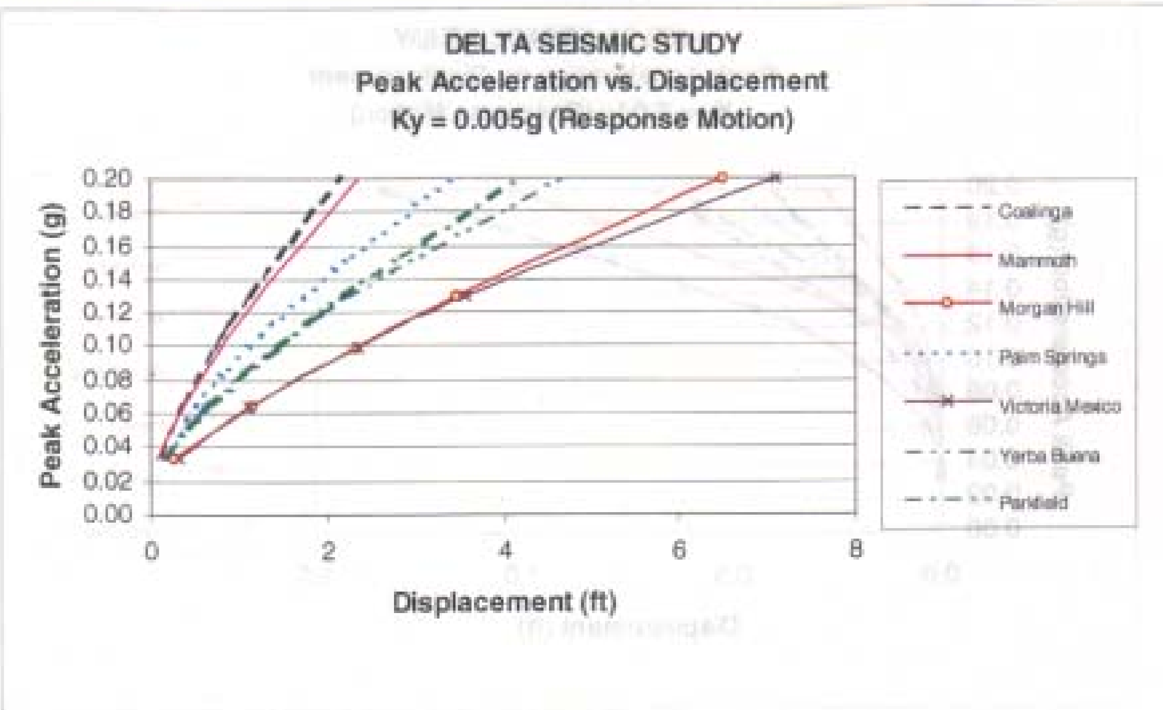
Stability Category	Approximate Yield Acceleration k_y(g)	Estimated Number of Sites in each Damage Potential Zone				
		Zone I (20 miles)	Zone II (301 miles)	Zone III (116 miles)	Zone IV (223 miles)	Total (660 miles)
A	0.00 - 0.01	1 - 2	6 - 12	0.3 - 2	0.7 - 3	8 - 19
B	0.01 - 0.03	1 - 3	12 - 24	0.7 - 3	1.3 - 7	15 - 37
C	0.03 - 0.05	3 - 8	20 - 60	1.7 - 5	3.3 - 10	28 - 83

TABLE B-3: ESTIMATED EARTHQUAKE-INDUCED DISPLACEMENTS IN NON-LIQUEFIED REACHES WITHIN DAMAGE ASSESSMENT ZONES

Magnitude 6.0 Bedrock/Stiff Soil Peak Acceleration (g)	Average Peak Acceleration[1] k_{max}(g)	Earthquake-Induced Displacement for Stability Categories[2]		
		A (k_y=0.005g)	B (k_y=0.02g)	C (k_y=0.04g)
0.05	0.033	0.1 - 0.3 ft [0.2 ft.]	0.0 - 0.0 ft. [0.1 ft.]	0.0 - 0.0 ft. [0.1 ft.]
0.10	0.065	0.3 - 1.1 ft [0.6 ft.]	0.1 - 0.2 ft. [0.1 ft]	0.0 - 0.0 ft. [0.1 ft.]
0.15	0.10	0.7 - 2.3 ft [1.4 ft]	0.1 -0.7 ft. [0.3 ft.]	0.0 - 0.2 ft. [0.1 ft.]
0.20	0.13	1.1 - 3.6 ft [2.2 ft]	0.3 - 1.2 ft. [0.6 ft.]	0.1 - 0.4 ft. [0.15 ft.]
0.30	0.20	2.2 - 7.1 [4.2 ft]	0.9 - 2.8 ft. [1.5 ft.]	0.3 - 1.4 ft. [0.6 ft.]

Notes: 1. Average Peak Acceleration assumed to be equal to 65 percent of the base bedrock/stiff soil motion.

2. Range and best estimate of earthquake-induced displacements calculated using the Newmark double-integration method.



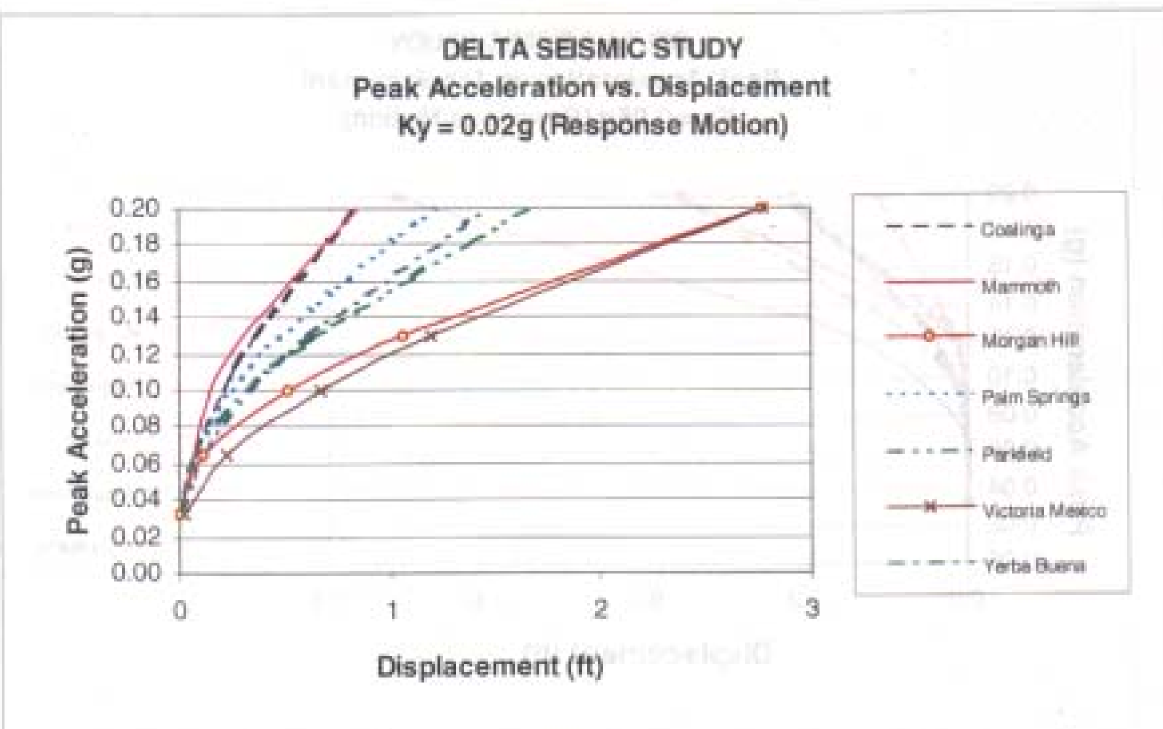
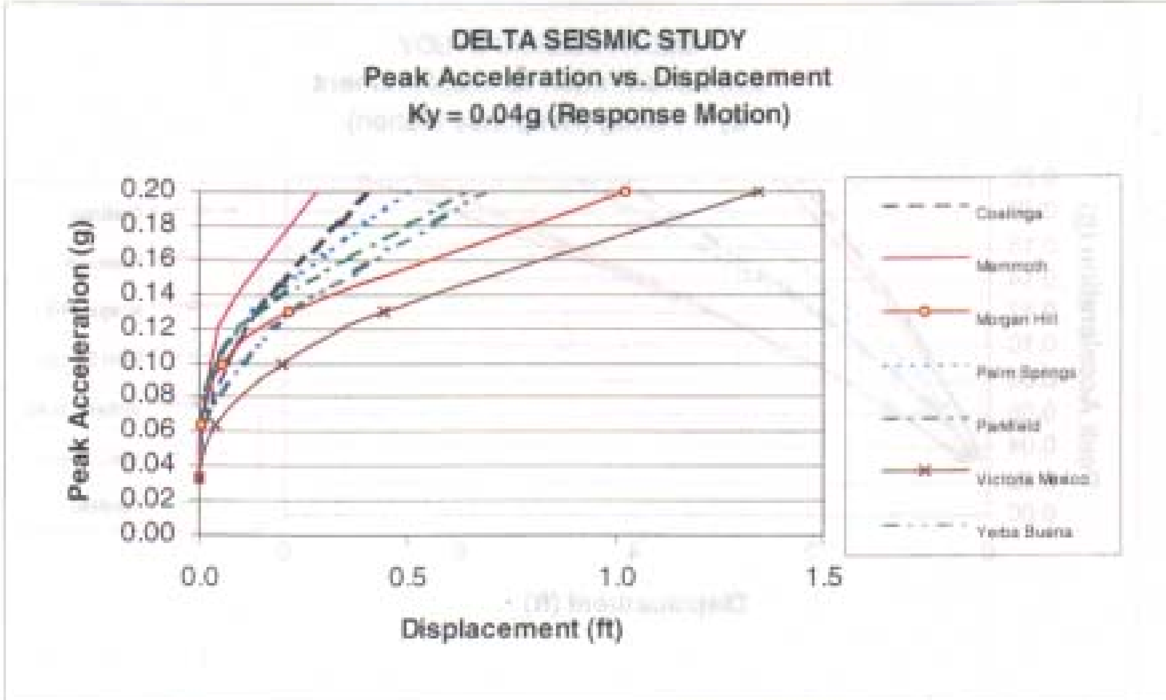


Figure B-1a: Range of Calculated Deformations for Selected Accelerograms



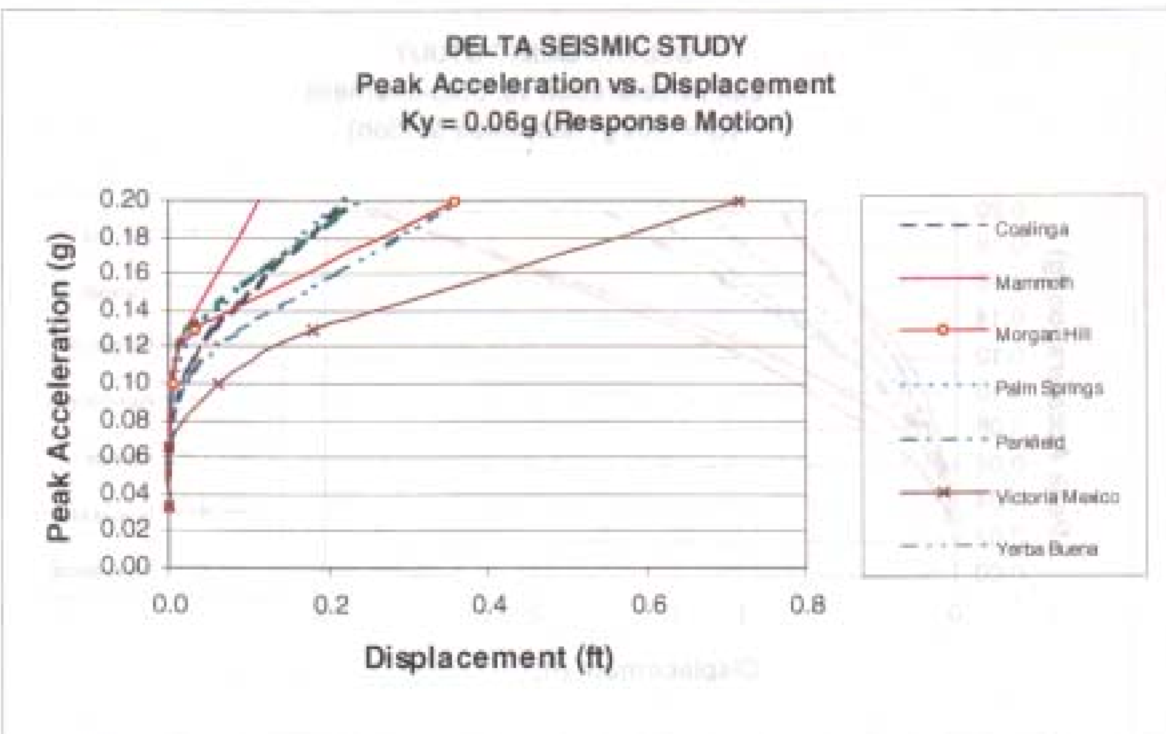


Figure B-1b: Range of Calculated Deformations for Selected Accelerograms

For the purposes of these evaluations, the median values of calculated displacement from the seven accelerograms were selected for use. This was judged to be representative of the cyclic inertial deformations expected to result from earthquakes of $M_w \approx 6$. For larger and smaller magnitudes, the induced deformations would be greater or smaller due to the longer or shorter durations of shaking (larger or smaller numbers of cycles of loading). Accordingly, these deformation estimates were later scaled for magnitude (duration) effects.

3. The estimated levee deformations were then converted into probabilities of failure using an approximate relationship developed by the sub-team based on their experience with static levee distress in the Delta (see Figure B-2 and Table B-4). As discussed previously, the hazard curve in Figure B-2 jointly accounts for the following issues and variables:

   a. cracking associated with various deformation levels,
   b. potential exacerbation of seepage problems due to cracking and slumping,
   c. potential overtopping,
   d. potential inboard toe and/or face erosion and piping, and
   e. varying outboard water levels in rivers and sloughs due to both daily tidal fluctuations, and seasonal flow variations.

4. The failure probabilities were then summed for the different levels of marginal stability within a Damage Potential Zone, and then totaled as the number of failures for the non-liquefaction deformation mode of failure (see Table B-5).

B5. ESTIMATED POTENTIAL NUMBER OF LEVEE FAILURES

The total number of potential levee failures for both liquefaction and non-liquefaction deformation modes of failure are presented in Table B-6 and Figure B-3. As may be noted in both places, the failure potential associated with liquefaction is far greater than that estimated for non-liquefaction failures. This is probably related to the relatively low magnitude and corresponding short duration of a typical Magnitude 6 earthquake. Accordingly, there are only a very small number of acceleration peaks which would exceed any particular yield acceleration.

B6. ESTIMATED POTENTIAL LEVEE FRAGILITY

It should also be noted that the estimated numbers of failures shown in Table B-6 and Figure B-3 assume that the entire Delta is shaken to the same level of earthquake motion (e.g. 0.2g). This is unrealistic as no one earthquake event will ever do this. A better way of representing the potential for failure is to normalize the estimated number of failures by levee length for each Damage Potential Zone. A normalized levee fragility can then be determined in the form of estimated number of failures per 100 miles of levee (these values were obtained by taking the values in Table B-6 and then dividing by the levee length in each zone and then multiplying by 100). The estimated levee fragility values for both liquefaction and non-liquefaction modes of failure, for causative events of $M_w \approx 6.0$, are shown in Table B-7.

SEISMIC STABILITY OF LEVEES IN THE SACRAMENTO - SAN JOAQUIN DELTA
PROBABILITY OF FAILURE ASSOCIATED WITH EARTHQUAKE-INDUCED DISPLACEMENTS

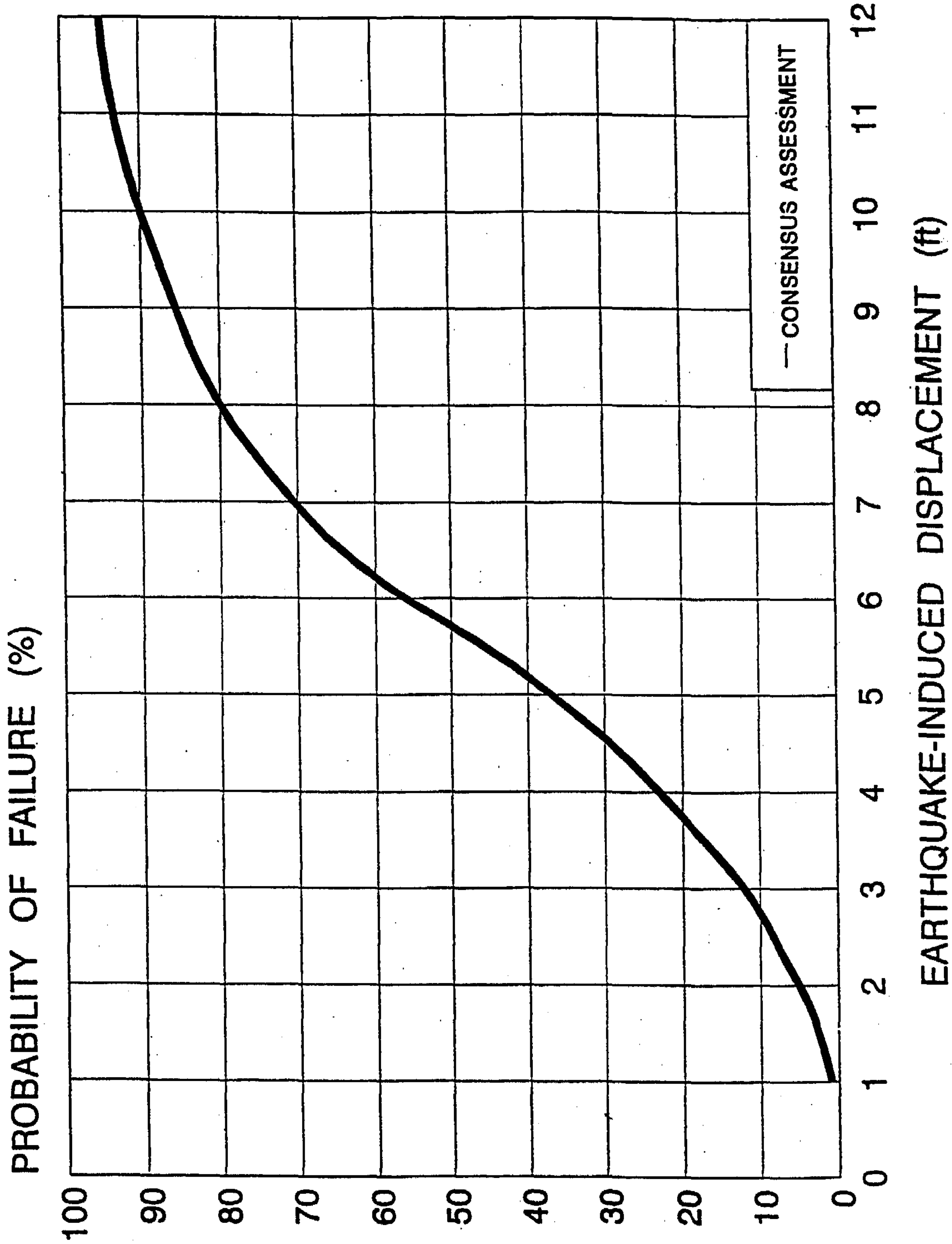


FIGURE B-2: PROBABILITY OF FAILURE ASSOCIATED WITH EARTHQUAKE-INDUCED DISPLACEMENTS

TABLE B-4: ESTIMATED PROBABILITIES OF LEVEE FAILURE ASSOCIATED WITH EARTHQUAKE-INDUCED DISPLACEMENTS IN NON-LIQUEFIED REACHES

Magnitude 6.0 Bedrock/Stiff Soil Peak Acceleration (g)	Average Peak Acceleration[1] k_{max}(g)	Estimated Probability of Levee Failure for Stability Categories[2]		
		A (k_y=0.005g)	B (k_y=0.02g)	C (k_y=0.04g)
0.05	0.033	**0.2%** [0.2 ft.]	**0.1%** [0.1 ft.]	**0.1%** [0.1 ft.]
0.10	0.065	**0.6%** [0.6 ft.]	**0.1%** [0.1 ft]	**0.1%** [0.1 ft.]
0.15	0.10	**2.6%** [1.4 ft]	**0.3%** [0.3 ft.]	**0.1%** [0.1 ft.]
0.20	0.13	**6.0%** [2.2 ft]	**0.6%** [0.6 ft.]	**0.2%** [0.15 ft.]
0.30	0.20	**25.0%** [4.2 ft]	**3.0%** [1.5 ft.]	**0.6%** [0.6 ft.]

Notes: 1. Average Peak Acceleration assumed to be equal to 65 percent of the base bedrock/stiff soil motion.
2. Estimated Probability of Levee Failure for non-liquefied levees based on estimated earthquake-induced deformations calculated using the Newmark method (see Table B-3).

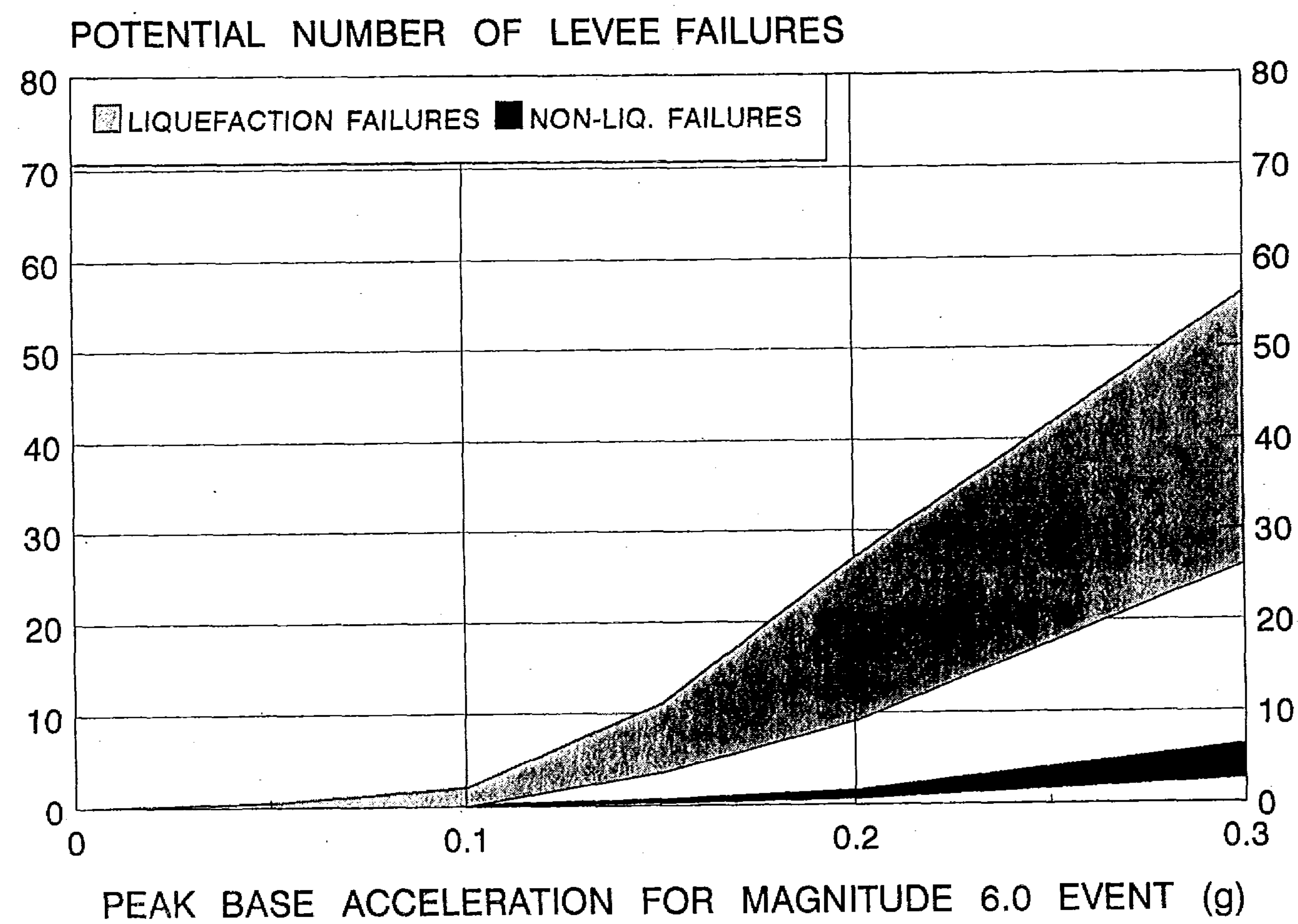
TABLE B-5: ESTIMATED NUMBER OF LEVEE FAILURES ASSOCIATED WITH EARTHQUAKE-INDUCED DISPLACEMENTS IN NON-LIQUEFIED REACHES

Magnitude 6.0 Rock/Stiff Soil Peak Acc. (g)	Damage Potential Zone	Levee Length (miles)	Estimated Number of Levee Failures in Non-Liquefied Reaches		Estimated Failure Rate (Fragility) Failures per 100 miles
0.05	I	20	[1x0.002+1x0.001+3x0.001]-[2x0.002+3x0.001+8x0.001]=	**0.006 - 0.015**	**0.030 - 0.075**
	II	301	[6x0.002+12x0.001+20x0.001]-[12x0.002+24x0.001+60x0.001]=	**0.044 - 0.108**	**0.015 - 0.036**
	III	116	[0.3x0.002-0.7x0.001+1.7x0.001]-[2x0.002+3x0.001+5x0.001]=	**0.003 - 0.012**	**0.003 - 0.010**
	IV	223	[0.7x0.002+1.3x0.001+3.3x0.001]-[3x0.002+7x0.001+10x0.001]=	**0.006 - 0.023**	**0.003 - 0.010**
0.10	I	20	[1x0.006+1x0.001+3x0.001]-[2x0.006+3x0.001+8x0.001]=	**0.010 - 0.023**	**0.050 - 0.12**
	II	301	[6x0.006+12x0.001+20x0.001]-[12x0.006+24x0.001+60x0.001]=	**0.068 - 0.156**	**0.023 - 0.052**
	III	116	[0.3x0.006+0.7x0.001+1.7x0.001]-[2x0.006+3x0.001+5x0.001]=	**0.004 - 0.020**	**0.004 - 0.017**
	IV	223	[0.7x0.006+1.3x0.001+3.3x0.001]-[3x0.006+7x0.001+10x0.001]=	**0.009 - 0.035**	**0.004 - 0.016**
0.15	I	20	[1x0.026+1x0.003+3x0.001]-[2x0.026+3x0.003+8x0.001]=	**0.032 - 0.069**	**0.16 - 0.35**
	II	301	[6x0.026+12x0.003+20x0.001]-[12x0.026+24x0.003+60x0.001]=	**0.212 - 0.444**	**0.070 - 0.15**
	III	116	[0.3x0.026+0.7x0.003+1.7x0.001]-[2x0.026+3x0.003+5x0.001]=	**0.012 - 0.066**	**0.010 - 0.057**
	IV	223	[0.7x0.026+1.3x0.003+3.3x0.001]-[3x0.026+7x0.003+10x0.001]=	**0.025 - 0.109**	**0.011 - 0.049**
0.20	I	20	[1x0.060+1x0.006+3x0.002]-[2x0.060+3x0.006+8x0.002]=	**0.072 - 0.154**	**0.36 - 0.77**
	II	301	[6x0.060+12x0.006+20x0.002]-[12x0.060+24x0.006+60x0.002]=	**0.472 - 0.984**	**0.16 - 0.33**
	III	116	[0.3x0.060+0.7x0.006+1.7x0.002]-[2x0.060+3x0.006+5x0.002]=	**0.026 - 0.148**	**0.022 - 0.13**
	IV	223	[0.7x0.060+1.3x0.006+3.3x0.002]-[3x0.060+7x0.006+10x0.002]=	**0.056 - 0.242**	**0.025 - 0.11**
0.30	I	20	[1x0.250+1x0.030+3x0.006]-[2x0.250+3x0.030+8x0.006]=	**0.298 - 0.638**	**1.5 - 3.2**
	II	301	[6x0.250+12x0.030+20x0.006]-[12x0.250+24x0.030+60x0.006]=	**1.980 - 4.080**	**0.66 - 1.4**
	III	116	[0.3x0.250+0.7x0.030+1.7x0.006]-[2x0.250+3x0.030+5x0.006]=	**0.106 - 0.620**	**0.092 - 0.53**
	IV	223	[0.7x0.250+1.3x0.030+3.3x0.006]-[3x0.250+7x0.030+10x0.006]=	**0.234 - 1.020**	**0.11 - 0.46**

TABLE B-6: ESTIMATED NUMBER OF FAILURES FOR BOTH LIQUEFIED AND NON-LIQUEFIED REACHES

Magnitude 6.0 Rock/Stiff Soil Peak Acc. (g)	Damaged Potential Zone	Levee Length (miles)	Estimated Number of Levee Failures		
			Liquefied Reaches	Non-Liq. Reaches	Total
0.05	I	20	0 - 0.13	0.01 - 0.02	**0.01 - 0.15**
	II	301	0 - 0.25	0.04 - 0.11	**0.04 - 0.36**
	III	116	0 - 0.03	0 - 0.01	**0 - 0.04**
	IV	223	0 - 0.07	0.01 - 0.02	**0.01 - 0.09**
	Total	**660**	**0 - 0.48**	**0.06 - 0.16**	**0.06 - 0.64**
0.10	I	20	0 - 0.5	0.01 - 0.02	**0.01 - 0.52**
	II	301	0 - 1.0	0.07 - 0.16	**0.07 - 1.16**
	III	116	0 - 0.2	0 - 0.02	**0 - 0.22**
	IV	223	0 - 0.3	0.01 - 0.04	**0.01 - 0.34**
	Total	**660**	**0 - 2**	**0.09 - 0.24**	**0.09 - 2.24**
0.15	I	20	0.5 - 2	0.03 - 0.07	**0.53 - 2.07**
	II	301	2 - 5	0.21 - 0.44	**2.21 - 5.44**
	III	116	0.3 - 1.4	0.01 - 0.07	**0.31 - 1.47**
	IV	223	0.7 - 2.6	0.03 - 0.11	**0.73 - 2.71**
	Total	**660**	**3.5 - 11**	**0.28 - 0.69**	**3.78 - 11.69**
0.20	I	20	1 - 4	0.07 - 0.15	**1.07 - 4.15**
	II	301	5 - 15	0.47 - 0.98	**5.47 - 15.98**
	III	116	1 - 3	0.03 - 0.15	**1.03 - 3.15**
	IV	223	2 - 5	0.06 - 0.24	**2.06 - 5.24**
	Total	**660**	**9 - 27**	**0.63 - 1.52**	**9.63 - 28.52**
0.30	I	20	3 - 6	0.30 - 0.64	**3.30 - 6.64**
	II	301	15 - 30	1.98 - 4.08	**16.98 - 34.08**
	III	116	3 - 7	0.11 - 0.62	**3.11 - 7.62**
	IV	223	5 - 13	0.23 - 1.02	**5.23 - 14.02**
	Total	**660**	**26 - 56**	**2.62 - 6.36**	**28.62 - 62.36**

SEISMIC STABILITY OF LEVEES IN THE SACRAMENTO - SAN JOAQUIN DELTA
ASSESSMENT OF POTENTIAL NUMBER OF LEVEE FAILURES



Note: Assessment assumes that the entire Delta area is shaken by the postulated earthquake shaking

FIGURE B-3: ESTIMATED NUMBER OF LEVEE FAILURES FOR DIFFERENT LEVELS OF EARTHQUAKE SHAKING

TABLE B-7: ESTIMATED FAILURE RATE (FRAGILITY) FOR BOTH LIQUEFIED AND NON-LIQUEFIED REACHES - FAILURES PER 100 MILES

Magnitude 6.0 Rock/Stiff Soil Peak Acc. (g)	Damaged Potential Zone	Levee Length (miles)	Estimated Fragility - Number of Levee Failures per 100 miles: Liquefied Reaches	Estimated Fragility - Number of Levee Failures per 100 miles: Non-Liq. Reaches
0.05	I	20	0.005 - 0.50	0.030 - 0.075
	II	301	0.001 - 0.083	0.015 - 0.036
	III	116	0.001 - 0.033	0.003 - 0.010
	IV	223	0.001 - 0.033	0.003 - 0.010
0.10	I	20	0.20 - 2.5	0.050 - 0.12
	II	301	0.080 - 0.33	0.023 - 0.052
	III	116	0.050 - 0.15	0.004 - 0.017
	IV	223	0.050 - 0.15	0.004 - 0.016
0.15	I	20	2.5 - 10.	0.16 - 0.35
	II	301	0.66 - 1.7	0.070 - 0.15
	III	116	0.29 - 1.2	0.010 - 0.057
	IV	223	0.29 - 1.2	0.011 - 0.049
0.20	I	20	5. - 20.	0.36 - 0.77
	II	301	1.7 - 5.0	0.16 - 0.33
	III	116	0.88 - 2.3	0.022 - 0.13
	IV	223	0.88 - 2.3	0.025 - 0.11
0.30	I	20	15. - 30.	1.5 - 3.2
	II	301	5.0 - 10.	0.66 - 1.4
	III	116	2.4 - 5.9	0.092 - 0.53
	IV	223	2.4 - 5.9	0.11 - 0.46

B7. MAGNITUDE CORRECTION FACTORS

The estimates for levee failures and fragility presented in the previous tables are for earthquake shaking associated with a magnitude 6.0 event. For the same level of shaking, larger earthquake magnitudes will induce more damage and levee failures than smaller events because larger magnitude earthquakes have longer durations and larger numbers of strong cycles of shaking. To adjust the fragilities for earthquake magnitudes other than Magnitude 6.0, the following corrections were used:

A. Liquefaction Mode of Failure:

A magnitude correction factor for the liquefaction mode of failure was developed using the Idriss (1997) magnitude scaling factors for triggering liquefaction. These corrections are slightly larger than those previously used by Seed et al. (1984).

B. Non-Liquefaction Deformation Mode of Failure:

A magnitude correction factor for the non-liquefaction deformation mode of failure was developed using the Earthquake Severity Index described by Bureau et al. (1988). This correction is much larger than the one for liquefaction, but is comparable with the deformation results obtained by Makdisi and Seed (1977).

For both failure modes (liquefaction, and non-liquefaction cyclic inertial deformation), the principal fragility estimates (Table B-7) were developed for events of $M_w \approx 6.0$, as that was central to the range of magnitudes principally contributing to the overall risk for the Delta. Figure B-4 shows the magnitude correction factors used for both modes of failure.

SEISMIC STABILITY OF DELTA LEVEES

MAGNITUDE CORRECTION FACTORS TO LEVEE FRAGILITY

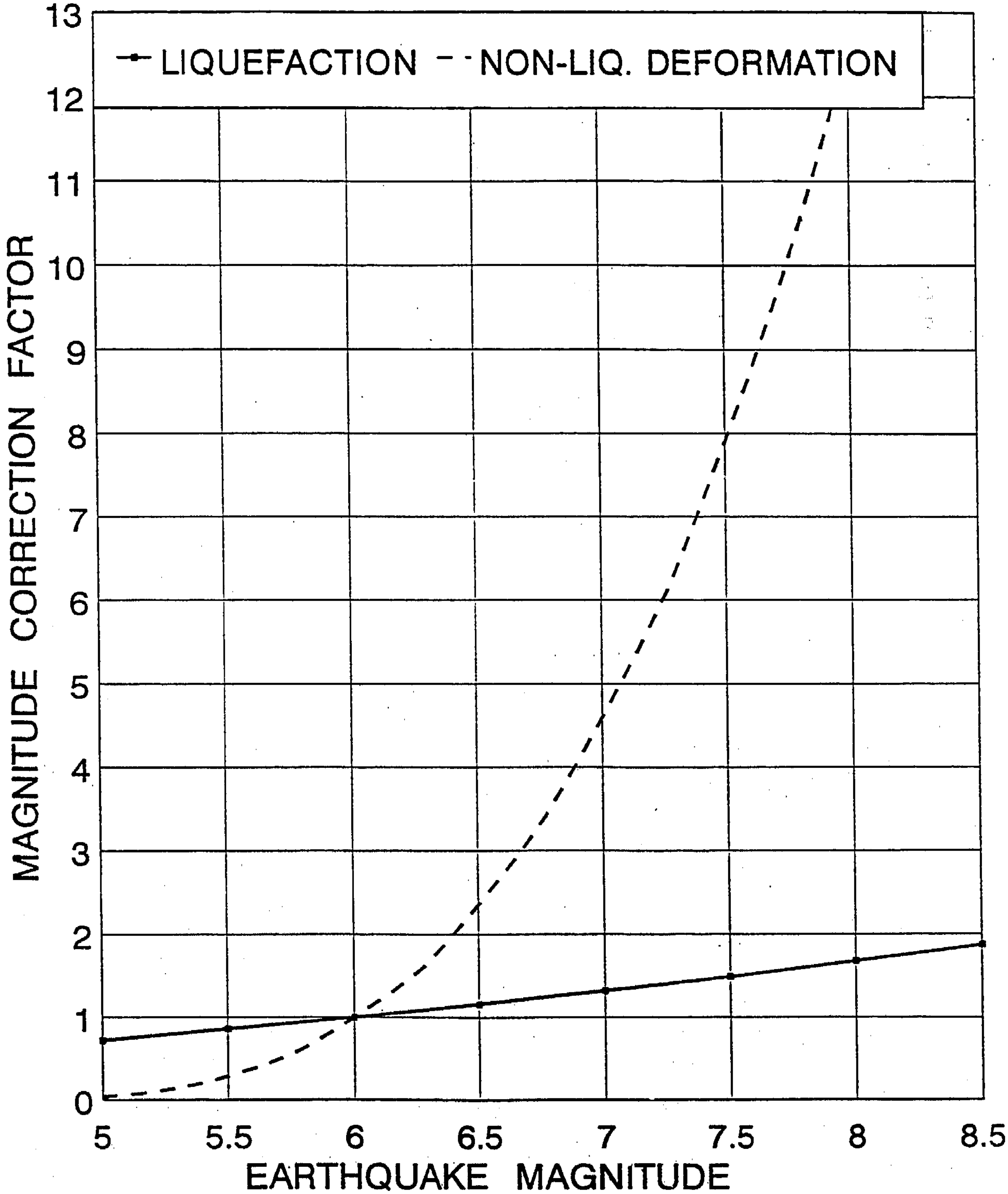


FIGURE B-4: MAGNITUDE CORRECTION FACTORS FOR LIQUEFACTION AND NON-LIQUEFACTION DEFORMATION MODES OF FAILURE

APPENDIX C

PROBABILISTIC LEVEE FAILURE METHODOLOGY

APPENDIX C
PROBABILISTIC LEVEE FAILURE METHODOLOGY

The mathematical models used in the calculation of the probability of levee failures are described in this Appendix. To apply the probabilistic approach, we need to first parameterize the point estimates of the fragilities.

C1. PARAMETRIC MODELS FOR LEVEE FRAGILITIES

The point estimates of the levee fragilities developed for this study were fit to simple equations to facilitate the probabilistic calculations. The simplified models for the median and coefficient of variation (cov) for both liquefaction and non-liquefaction induced failures are given below.

Fragility Curves for Liquefaction Induced Failures

The median fragility liquefaction for In liquefaction induced failures is modeled by

$$frag_{Li}(pga,M)=0.8\exp(p_1+p_2[\ln(pga)+c_1+c_2M+c_3M^2+c_4M^3]+c_{5i})$$

The coefficients p_1, p_2, c_1, c_2, c_3, c_4, and c_5 were estimated from the central value of the range given in the point estimates. The 0.8 factor represents the interpretation of the sub-team that the median fragility is not at the center of the range given in the point estimates, but rather it is approximately at 40% of the range.

The coefficient of variation for all zones is modeled by

$$cov_L=(b_1+b_2pga)/1.3$$

with a constraint that it not be less then 0.3/1.3. The factor of 1.3 represents the interpretation of the sub-team that the range on the fragility given in the point estimates represents the 80% confidence interval.

The distribution of the fragility is modeled as an asymmetric distribution based on the judgement of the sub-team. This asymmetry is modeled using two different normal distributions above and below the median. The standard deviation (cov*median) is scaled by 1.2 for values above the median and by 0.8 for values below the median. This results in a distribution that is skewed to the right (skewed to higher numbers of failures).

The levee fragility group estimates of the ranges of numbers of failures for each zone is based on the total number of failures for each zone. That is, the standard deviation does not apply to a single levee, but rather to the total number of levees in each zone. This impacts the use of the standard deviation in the probabilistic evaluation. Specifically, the distribution is applied to the median number of breaks in each zone (summation of the median number of breaks for each levee in a zone). This distribution is truncated at 1.5 standard deviations above and below the median.

The coefficients for these models are listed in Table C-1.

Fragility Curves for Non-Liquefaction Induced Failures

The median fragility for non-liquefaction induced failures is modeled by a bilinear model:

If

$$\ln(pga)+c_1+c_2M+c_3M^2+c_4M^3\leq-2.3,$$

then

$$frag_{Ni}(pga,M)=\exp\{p_1+p_2[\ln(pga)+c_1+c_2M+c_3M^2+c_4M^3]+c_{5i}\}$$

otherwise,

$$frag_{Ni}(pga,M)=\exp\{p_1+p_2[\ln(pga)+c_1+c_2M+c_3M^2+c_4M^3]+c_{5i}+p_3\ln(pga)\}$$

The coefficient of variation is modeled by

$$cov_{Ni}=b_{1i}/1.3$$

The factor of 1.3 represents the interpretation that the range on the fragility given in the point estimates represents the 80% confidence interval. A normal distribution is used for the number of failures. This distribution is truncated at 1.5 standard deviations above or below the median.

The coefficients for these models are listed in Table C-2. All of the coefficients are constant for all zones except for C_5 and b_1 which can vary by zone as shown in Table C-2.

C2. PROBABILISTIC METHODOLOGY

The levee failure probability is an extension of standard probabilistic seismic hazard analysis. The difference is that instead of calculating the probability of the ground motion exceeding a specified value at a location, we compute the probability of specified number of levee failures being exceeded in a single earthquake. That is, we consider the entire levee system simultaneously.

In the following probabilistic seismic hazard analysis, we consider all possible earthquake magnitudes, locations, and ground motion. For each possible earthquake, we then compute the probability of one or more levee failures occurring within the Delta. This process is repeated for two or more failures, three or more failures, and so on.

Let μ_{Lij} be the median number of failures due to liquefaction for the j^{th} levee in the i^{th} zone. Then

$$\mu_{Lij} = frag_{Li}(pga, M) * L_j$$

where $frag_{Li}$ is the median fragility, pga is the median peak acceleration at the center of the island, M is the magnitude of the earthquake, and L_j is the length of the j^{th} levee in miles. The median number of failures for the i^{th} zone is given by:

$$\mu_{Li} = \sum_{j=1}^{Ni} \mu_{Lij}$$

and the standard deviation of the number of failures due to the uncertainty in the ground motion is given by:

$$\sigma_{GLij} = \mu_{Lij} P2 \sigma_{pga}(M)$$

based on propagation of errors. Assuming that the peak acceleration variability is uncorrectable between levees (which is reasonable for separation distance of greater than 500m), then the standard deviation of the total number of failures within the zone is given by:

$$\sigma_{GLi} = \sqrt{\sum_{j=1}^{Ni} \sigma_{GLij}^2}$$

Since the standard deviation due to uncertainty in the fragility is for the zone and not for individual levees, the fragility uncertainty is fully correlated for each levee within a zone. Therefore, the standard deviation of the total number of failures within a zone due to fragility variability is given by:

$$\sigma_{FLi} = \sum_{j=1}^{Ni} \text{cov}_L \, \mu_{Lij}$$

Similar equations are developed for the non-liquefaction induced failures.

We then use a Monte Carlo approach to sample the distributions for the number of failures in each zone and sum the number of failures from liquefaction and non-liquefaction failures for each zone. Finally, we sum up the number of failures for all the zones to get the total number of failures in the levee system. The frequency of failures in the Monte Carlo sampling defines the conditional probability of the number of failures for a given earthquake magnitude and location.

Let (P(fail>N_F I M, A, W, Hx, Hy) be this conditional probability of the number of failures exceeding N for the given magnitude (M), rupture area (A), rupture width (W), energy center along strike (Hx), and energy center along dip (Hy).

Then the rate of failures is given by:

$$v(Fail > N) = \sum_{k=1}^{NF} N_k \int_M \int_A \int_W \int_x \int_y f_m(M) f_A(M) F_W(M) f_x(x) f_y(y) P(fail > N_F | M, A, W, x, y) dM dA dW dx dy$$

where f_m, f_A, f_W, f_x, f_y are the probability density functions for magnitude, rupture area, rupture width, and energy center. The N_k is the rate of earthquake above the minimum magnitude (here taken as 5.0) for the k^{th} source and NF is the number of faults.

In this equation, the conditional probability of failure is multiplied by the probability of the specified earthquake occurring (given that an earthquake has happened) and then multiplied by the rate of earthquake for the given seismic source. This rate of failure is then summed over all the seismic sources to give the total rate of various numbers of levees failing in a single earthquake. A Poisson assumption for the earthquake occurrence is used to convert the rate of failures into a probability of failures. The result is a hazard curve for the number of levee failures in a single earthquake.

Table C-1.
Fragility Model Coefficients for Liquefaction Induced Failures

Coefficient	All Zones	I	II	III	IV
p1	7.33				
p2	3.02				
c1	-3.47				
c2	0.97				
c3	-0.0838				
c4	0.0031				
c5		0.0	-1.55	-2.23	-2.23
b1	0.94				
b2	-2.05				

Table C-2.
Fragility Model Coefficients for Liquefaction Induced Failures

Coefficient	All Zones	I	II	III	IV
p1	-1.32				
p2	0.54				
p3	2.49				
c1	-75.7				
c2	28.6				
c3	-3.61				
c4	0.156				
c5		0.0	-0.115	-0.810	-2.08
b1		0.38	0.38	0.60	0.60

APPENDIX D

REVIEW COMMENTS BY DRS. BRUCE BOLT AND I. M. IDRISS

June 24, 1999

Mr. Raphael A. Torres
Chief
Civil Engineering Branch
Department of Water Resources

Seismic Vulnerability of the Sacramento-San Joaquin Delta Levees

Dear Mr. Torres:

As you requested, I have reviewed the final draft report (December 1998) and set out below some comments and conclusions related to it. I have previously, in 1982, prepared a short report in which I estimated likely earthquake ground motions in the Delta region (included in Report references). Of course, in the ensuing seventeen years more relevant information has become available, and the CALFED report is much more extensive and detailed.

More recently, I have served on your DWR Consulting Board, which considered Phase I and Phase II of "The Seismic Stability Evaluation of Sacramento-San Joaquin Delta Levees." Several questions addressed to this Consulting Board were responded to formally and various aspects of the work in progress were discussed on an individual basis. My comments on the CALFED report address mainly Chapters 2 and 3 and then the Summary of Findings (Chapter 7).

General Comments

The Report is a comprehensive, well-written, and sound review of the problem of seismic vulnerability of these levees. It is unfortunately the case that little relevant information is available specific to the seismic response of levees with the Sacramento

Delta evolutionary construction history. Almost every qualitative parameter involved in the assessment has considerable uncertainty. What is sure is that the levees will someday be subject to a repetition of the 1868 Hayward earthquake, or a similar one centered further north, or a 1906-type earthquake, or one or more derived from thrust faulting under the west margin of the Central Valley. In addition, we know little instrumentally about the propagation of large amplitude seismic waves through the thick sedimentary deposits underlying the Delta. Also, the estimation problem is much hampered by the paucity of data on the strong wave response of the surficial Delta peats and organic soils.

On the last point, it is encouraging that DWR has responded to the 1992 Consulting Board's recommendation to install surface and downhole strong motion instruments "at the earliest possible date." Although there have not been even moderate magnitude earthquakes in the region since that time, some small ground motions have already been measured at Delta sites (e.g., March 27, 1997 from Fairfield-Vacaville). Of course, there is the problem of valid extrapolation from weak to strong motions. Nonlinear effects have been claimed to have been substantial in some recent California earthquakes (see, e.g., E.H. Field et al., Seis*mological Research Letters*, 69, pg. 230, 1998). It is not clear to me, however, that many of the reported spectral and duration effects are not the result of source asperities, and especially phase conversion scattering in sedimentary basin structures (see Dan O'Connell of the Bureau of Reclamation, *Science*, 1999).

The Report follows a more-or-less direct probabilistic hazard analysis, which is appropriate given the seismicity uncertainties summarized above. A deterministic approach may well lead to similar average ground motion results, but without the more robust temporal estimates (return periods) given here.

According to the present Report (Figure A-12), peak ground accelerations at Sherman Island of about 0.25g have an annual probability of being exceeded of one in two hundred. It is of passing historical interest that in a 1982 Report to the East Bay Municipal Utility District my quite independent estimate was, for accelerations exceeding 0.25g per year, "about 1 in 200 or so"!

Section 3: Seismicity

The seismicity catalogs and fault information appears complete and sound. I lean towards Model 1, but it seems advisable to consider also the mapping of capable blind thurst faults more to the west (Lettus's model). Both may be true. The hazard result (M6 in 100y RT) for the eastern Delta again agrees with earlier assessments of mine inferred on a more deterministic basis.

Section 4: Fragility

The discussion of levee fragility seems well based to me. It is particularly satisfactory to have probability estimates of the number of failures per exposure period (Appendix B). Given the various uncertainties, however (both intrinsic and from the assumptions), it might have been better to describe the failure functions as bands rather than lines.

Incidentally, it is not quite clear (pg. 13, Section 4.3) how the critical ground motion property of shaking duration was handled. The sentence here leaves open the question of adequate incorporation of the physical response of peaty soils to many cycles of moderate srrong motion.

The results of the study, based on present knowledge, are not very encouraging. According to Table 4.2, peak accelerations of about 0.2g lead to one or more levee failures per 100 miles. As I and others concluded years ago, Sherman Island is particularly vulnerable to flooding. I am still not entirely convinced, however, that an amplification factor of 1.6 (pg. 13) will occur. More relevant strong-motion measurements are vital.

Section 7: Summary of Findings

I judge all six paragraphs to be adequately supported by the studies discussed or referenced. There are really no surprises, so the last two recommendations are, until further earthquake measurements become available, particularly valuable and in need of follow up.

Signed,

Bruce A. Bolt

Bruce A. Bolt

Professor of Seismology, Emeritus.

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7 July 1999

Mr. Ralph A. Torres, Chief
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Dear Mr. Torres:

As requested in your letter, I have reviewed the copy of the final draft report on "Seismic Vulnerability of the Sacramento-San Joaquin Delta Levees", which you enclosed with that letter. A committee chaired by you prepared this report for CALFED.

The report does provide an excellent framework for assessing the vulnerability and the potential risks associated with maintaining the Sacramento-San Joaquin Delta Levees. Your Committee is to be congratulated on completing a comprehensive study and documenting the results in a reasonably complete report. The appendices contain a wealth of information useful for this and other projects in this area.

One issue that deserves further consideration is the resolution regarding the blind thrust faults in the area (page 7 of the report).

The other issue that deserves further detailed evaluation is that related to assessing the seismic response of the levees. I believe that it would be very useful to complete a series of two-dimensional analyses to estimate the response of these levees during various size earthquakes and at various levels of shaking. These analyses can then be used to estimate the hazard (i.e., levels of shaking for given return periods) for the levees. These levels of shaking can be significantly different from those calculated for the rock outcrop. The use of a constant amplification factor (i.e., independent of height of levee, independent of earthquake magnitude, and independent of the level of shaking) may not be justifiable and deserves further study.

While the fragility discussion is presented in elegant equation format, the derivation and the utilization of specific parameters does need further explanations and documentation. This report will have long-term usefulness and it is essential that each part be fully documented and reasonably well supported.

Please accept my apologies for the delay in transmitting these comments to you. I read the report shortly after receiving it from you, but my travel schedule precluded transmitting the comments in a more timely manner. I trust, nevertheless, that you will find these comments useful in finalizing the report and in scheduling and implementing future tasks.

Please let me know if you wish any amplification or additional input regarding the above comments.

Sincerely,

I. M. Idriss

APPENDIX E

BIBLIOGRAPHY

APPENDIX E
BIBLIOGRAPHY

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APPENDIX H

PROPOSALS FOR ECOSYSTEM RESTORATION

STATE OF CALIFORNIA

PETE WILSON, Governor

DELTA PROTECTION COMMISSION
14215 RIVER ROAD
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July 10, 1998

To: Delta Protection Commission

From: Margit Aramburu, Executive Director

Subject: Alternative Proposal for CALFED Ecosystem Restoration Program in the Delta

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BACKGROUND:

In the Delta Protection Commission's comment letter on the CALFED Draft Ecosystem Restoration Program Plan (ERPP), the Commission made a number of suggestions for high priority projects to enhance and restore habitat. This memo outlines more specific ideas for implementation of those recommended priorities. The memo has been prepared in partnership with representatives of the North, Central, and South Delta Water agencies, and represents ideas acceptable to those entities. None of the Water Agencies have taken a formal position on the memo or the ideas in the memo. The purpose of the review by the Delta Protection Commission is to help refine this list of suggested "alternative" projects to forward to the CALFED Bay Delta Advisory Committee (BDAC), the public entity providing input to the CALFED process. The list is a draft list which should change after public and Commission review and input.

The Commission should review the attached memo, seek public comments and input on the suggestions in the memo, and direct staff to continue working on refinement of the memo with other Delta interests to present to BDAC at its September 1998 meeting to be held in Stockton.

CALFED ERPP HABITAT RESTORATION TARGETS FOR DELTA ECOLOGICAL ZONE (See Exhibit 1):

Tidal Perennial Aquatic	7,000 ac
Shoal	500 ac
Nontidal Perennial Aquatic (deep open water)	500 ac
Nontidal Perennial Aquatic (shallow open water)	2,100 ac
Midchannel Islands	200 to 800 ac

Fresh Emergent Wetland (tidal)	30,000 to 45,000 ac
Fresh Emergent Wetland (nontidal)	20,000 ac
Seasonal Wetland Improve:	4,000 ac
Restore:	30,000 ac
Inland Dune Scrub	50 to 100 ac
Perennial Grassland	4,000 to 6,000 ac
Wildlife Friendly Agricultural Land	40,000 to 75,000 ac

DELTA PROTECTION COMMISSION COMMENTS ON DRAFT ERPP:

The Delta Protection Commission comments regarding the ERPP recommended that the ERPP be modified to prioritize the following restoration programs:

Restoration and/or enhancement of lands currently in public and/or nonprofit ownership (or currently in the acquisition process) and designated for restoration, including Twitchell Island, Sherman Island and Prospect Island. Approximately 35,000 acres fall in this category.

Acquisition and/or enhancement of currently flooded lands to create and/or enhance emergent habitat, including Franks Tract, Big Break, Mildred Island, Little Mandeville, Island, etc. Approximately 7,000 acres fall in this category.

Development and implementation of management plans for upland areas already in public or nonprofit ownership, including Calhoun Cut Ecological Preserve (approximately 1,000 acres), Rhode Island, etc.

Development and implementation of individual management plans for private agricultural properties and development of funds to offset costs of voluntary implementation of such plans (plans could include flooding programs, enhanced levees and pumps to enhance flooding and drainage, recommended crop rotation cycles, size and location of permanent brood ponds, etc.)

Development and implementation of individual management plans for privately-owned lands managed for wildlife habitat, such as duck clubs and upland hunting clubs, and development of funds to offset costs of voluntary implementation of such plans.

Control of stressors should be revised to avoid duplication with existing regulatory programs, such as existing dredging "windows", and the programs that are developed should respect the needs of existing land uses, such as water-oriented recreation. Where funds are needed to carry out specific programs, those funds should be made available to private land owners to implement CALFED programs.

Protection, enhancement and restoration of in-channel islands and waterside berms.

LISTING OF SITES BY TYPE OF HABITAT TO BE CREATED/ENHANCED:

Managed Wetlands (within levees):

GOAL: Prepare specific enhancement and management plans and obtain funding for restoration and management on all lands already owned by public agencies or nonprofits before funding any additional retirement of privately-owned agricultural lands.

OPPORTUNITIES:

Yolo Bypass Wetlands:	3,600 ac /DFG
Sherman Island:	10,000 ac /DWR
Twitchell Island:	3,500 ac /DWR
Stone Lakes Wildlife Refuge:	1,090 ac /DPR
	1,000 ac /Sacramento County
[plus additional acquisition and management to complete the 9,000 ac refuge]	
Jepsen Prairie Preserve:	1,600 ac /Solano County Farmlands and Open Space Trust
Calhoun Cut:	970 ac /DFG
Tip of Grand Island:	250 ac /Corps of Engineers
Prospect Island:	1,200 ac /Bureau of Reclamation
North Delta Cross Channel:	100 ac /Bureau of Reclamation
Wright-Elmwood Mitgn.Bank:	80 ac /Private
Medford Island Mitign. Bank:	1,200 ac /Private

Enhancement of Existing Shallow Water Areas and Other Areas Outside Levees:

GOAL: Identify publicly-owned, water-covered sites and privately-owned, water-covered sites that could be enhanced and managed to provide improved shallow water habitat suitable for fish nursery areas. Identify other sites outside existing levees that could be enhanced for shallow water or other related habitats.

OPPORTUNITIES:

Big Break:	800 ac /EBRPD
Browns Island:	600 ac / EBRPD
Franks Tract:	3,500 ac /DPR
Little Franks Tract:	330 ac /DPR
Mildred Island:	1,000 ac /Private
Little Mandeville Island:	375 ac /Private
Venice Tip:	160 ac /Port of Stockton
Tip of Prospect:	300 ac /Port of Sacramento
Decker: North Tip:	40 ac /DFG
Decker: East Side:	140 ac /Port of Sacramento
Lower Sherman Island Wildlife Area:	3,100 ac /DFG

Delta Meadows:	134 ac /DPR
Little Holland Tract:	1,600 ac /Private
Kimball Island:	100 ac /Private
Rhode Island:	DFG
Fern Island:	80 ac/ Private
Little Hastings Tract:	125 ac/ Private
Port of Stockton Lands such as:	
Browns Island:	100 ac
Donlon Island:	225 ac
Mandeville Tip:	176 ac
Venice Cut	211 ac
North Headreach:	53 ac
Tule Island:	36 ac
North Spud:	28 ac
South Spud:	60 ac
Acker Island:	7 ac
Webb Tract Berms and Islands:	285 ac /DFG
Sycamore Island:	13 ac /DFG
Acker Island:	25 ac /DFG
Cabin Slough Islands:	15 ac /DFG
Miner Slough Islands:	34 ac /DFG
Lost Slough Islands:	38 ac /DFG

DESCRIPTION OF SITES SHOWN ON MAPS:

One map illustrates sites which are publicly owned, owned by a nonprofit entity, or which are subject to a conservation easement, which are currently managed for ecosystem values:

Yolo Bypass Wetlands Project, DFG and Yolo Basin Foundation
Various Duck Clubs in the Yolo Bypass with a Conservation Easement, Private
Jepsen Prairie Preserve, Solano County Farmlands and Open Space Foundation
Cosumnes Preserve, Nature Conservancy, Bureau of Reclamation and others
Stone Lakes Wildlife Refuge Lands Under Management, U.S. Fish and Wildlife Service
Lower Sherman Island Wildlife Management Area, DFG
Palm Tract/Portions Subject to Conservation Easement, Private
White Slough Wildlife Area, DFG/DWR
Medford Island/Portions included in Mitigation Bank, Private
Woodbridge Ecological Preserve, DFG/DWR
Kimball Island Mitigation Bank, Private
Wright Elmwood Mitigation Bank, Private

One map illustrates publicly owned lands **not** actively managed for ecosystem values:

Calhoun Cut, DFG
Port of Sacramento Lands
Port of Stockton Lands
Twitchell Island, DWR
Sherman Island, DWR
Tip of Grand Island, Corps
Browns Island, EBRPD/SLC
Big Break, EBRPD
Franks Tract, DPR
Little Franks Tract, DPR
Lands in the East Delta, DWR

One map illustrates private lands with opportunity for enhancement and/or restoration:

Lands in the Yolo Bypass already subject to flood easements
Other lands subject to levee height restrictions
Lands in the boundary of Stone Lakes Wildlife Refuge south of Lambert Road (management agreements)
Water-covered Lands in the Meadows (east of Locke)
Lands proposed by the owner for restoration/enhancement (Bouldin and portions of Holland)
In-Channel Islands

ENHANCEMENT OF RIPARIAN CORRIDORS:

One of the key concepts of the ERPP is restoration and enhancement of Delta riparian corridors. This memo describes alternative concepts for enhancement of three key riparian corridors consistent with the need to maintain and enhance the flood control and water conveyance functions of the major tributaries to the Delta.

The CALFED program has identified the need for riparian habitat enhancement to improve migratory corridors for anadromous fish, such as salmon, and spawning habitat for those fish species that spawn in the Delta environment, such as Delta smelt. In addition, the riparian habitat corridors provide habitat for birds, mammals, insects, reptiles, amphibians, and indigenous plants.

Sacramento River Corridor Enhancement: Currently the Sacramento River corridor is bounded by large, project levees which are largely unvegetated.

The ERPP recommends enhancing riparian corridors along several smaller sloughs and waterways between the Sacramento River and the Deep Water Ship Channel to the west, including Steamboat, Miner, Oxford, and Elk Sloughs. Additional enhancement is proposed on the main channel of the Sacramento River from Sacramento to Rio Vista.

As an alternative, CALFED should consider possible enlargement and enhancement of a corridor west of the Deep Water Ship Channel, within the Yolo Bypass. Such a waterway could connect to the main stem of the Sacramento River at either or both the Sutter Weir or the Sacramento Weir. There is an existing channel, the Toe Drain, which lies west of the Ship Channel. The Toe Drain is largely unvegetated but lies within the Yolo Bypass, where the lands are already subject to a flood easement purchased by the federal government to provide additional flood protection to the City of Sacramento and the Delta area. While the Sacramento River can contain flows of about 150,000 cfs, the Yolo Bypass can contain about 450,000 cfs. Locating an enhanced riparian corridor within the Yolo Bypass would also address the identified issues of stranding of fish within the Yolo Bypass at the end of the flood season. Creation of an enlarged, excavated channel would enhance flood water carrying capacity of the Yolo Bypass, which would then allow introduction and maintenance of beneficial plant material into the floodway.

Mokelumne River Corridor Enhancement: Currently the Mokelumne River, downstream of the confluence with the Cosumnes River, is within non-project levees. Downstream of McCormack Williamson Tract, the Mokelumne River splits into the North Fork, which lies between Tyler and Staten Islands, and the South Fork, which lies between Staten Island and New Hope, Brack, Canal Ranch and Terminous. At the south end of Staten Island, the South Fork turns toward the west and rejoins the North Fork near the south end of Tyler Island, at the northwest end of Bouldin Island, and near the crossing of Highway 12. The South Fork has been the subject of several projects on Staten Island to recreate berms at the waterside toe of the levees. At the south end of Staten Island, several in-channel islands have been protected with riprap and bolstered with placement of earthen material. Along the North Fork on the shoreline of Tyler Island, a Category III funded project is being planned to protect existing riparian vegetation on the waterside berms and at the toe of the levees.

The CALFED program and the ERPP recommend use of the North Fork as a water conveyance channel, and the use of the South Fork as a riparian corridor, with enhancement of the adjacent waterways of Beaver, Hog, and Sycamore Sloughs, and with new setback levees and flooding of large tracts of existing farmed lands on New Hope, Brack, Canal Ranch and Terminous Tracts. The deeply subsided lands would be temporarily flooded during flood season and the upper elevation areas in New Hope, Brack, Canal Ranch and Terminous would be permanently flooded, thereby eliminating some of the most productive farmland in the Delta.

As an alternative, CALFED should consider enhancing the South Fork for water conveyance and flood control, in effect dividing the flow of the Mokelumne River between its North and South Forks. Both Forks should be examined for additional habitat opportunities as channel capabilities are increased by dredging and/or necessary levee setbacks. There are major constrictions in the upper reaches of the South Fork. Relieving those restrictions will present important opportunities for flood control and habitat enhancement.

The easternmost location of a water conveyance alignment will keep the maximum possible distance between the saline waters of the Bay (the principal source of bromides and other salts), and water to be exported for irrigation and for drinking water.

In order to optimize the quality of the water conveyed through the Mokelumne corridor, the conveyance alignment should continue south from Staten Island, passing to the east of Bouldin and Venice Islands.

The Mokelumne River corridor must serve multiple purposes: water conveyance through the Delta, flood control for Sacramento and San Joaquin Counties, and a riparian habitat corridor for aquatic and terrestrial species.

San Joaquin River Corridor: The San Joaquin River is channelized, with newly enhanced levees along urban development in the South Stockton area.

The ERPP recommends restoration of floodplain habitat along the lower San Joaquin River between Mossdale and Stockton with levee setbacks and an overflow basin, and improved riparian habitat along leveed sloughs. The ERPP includes installation of a barrier at the head of Old River to keep migratory fish in the mainstem of the San Joaquin River. The purposes of the enhancement of the San Joaquin River are joint benefits associated with flood water transport and enhancement of fisheries migration corridors.

Currently, south of Mossdale to the San Joaquin County boundary, the San Joaquin River provides multiple opportunities to enhance riparian vegetation. For most months of most years, flows in these reaches of the San Joaquin River do not exceed 3,000 cfs. The low-flow channel could be established generally near the west or left bank of the existing levee system which, once stabilized and bermed, could support nearly continuous areas of large riparian vegetation to shade the low flow channel. Oxbows and bends currently cut off from the river flows could be re-opened and maintained providing feeding and resting areas for aquatic species.
North of Mossdale to Stockton, the mainstem of the San Joaquin could continue to be enhanced for seasonal migratory fish passage through the release of pulse flows necessary to stimulate inland migration, and enhance seaward migration.

Enhancement of riparian vegetation corridors could proceed on two other waterways: Paradise Cut to Old River to Grant Line Canal to Old River, and Old River to Middle River to San Joaquin River. Paradise Cut is a flood control channel designed to carry 15,000 cfs, which has not been maintained. To improve Paradise Cut, the weir to Paradise Cut could be enlarged, the Cut could be enlarged by incorporating mitigation lands east of the Cut to be provided by the Gold Rush City project (900 acres) and by clearing and dredging the connection to Grant Line Canal. Grant Line Canal connects to Old River, a waterway with numerous in-channel islands suitable for management and enhancement. The result could be flood flow capacity enlarged to 20,000 cfs, and a riparian corridor suitable for avian and terrestrial species. Middle River leaves the main stem of the San Joaquin north of Stewart Tract, flows north between Union and Roberts Islands, and rejoins the San Joaquin River between Medford and Mandeville Islands. The portions of this waterway between Roberts and Union Islands should be cleared of brush to increase flood flow capacity and the levees should be improved to accommodate the planting of trees that will not adversely affect flood flows and will provide habitat for avian and terrestrial species.

WILDLIFE FRIENDLY FARMING PRACTICES PROGRAM:

In the 1993-94 period, a Crop Shift Demonstration Project was conducted on Rindge Tract. The Department of Fish and Game recommended certain measures to mitigate any impact to wildlife from the demonstration project. Most of those measures were implemented as a part of the demonstration project, and the results were monitored and positive results were reported.

Based on this positive demonstration project, many years of previous and subsequent experiences with post-harvest flooding of agricultural lands in the Delta, and intuition, a wildlife friendly agricultural practices program might be formulated and described as follows:

Objectives:

1. Extend availability of post-harvest flooded grain fields to cover full period of usage by migratory birds.

2. Enhance food value of post-harvest flooded grain fields by intentionally leaving more grain in the fields by either modifying harvest practices or intentionally not harvesting portions of the fields to be flooded.

3. Create fringe areas during important periods to enhance forage opportunities for certain species (e.g. Sandhill cranes, Swainsons hawks)

4. Extend availaibity of program across the Delta lands utilized by important migratory speicies to discourage over-concentration in one area.

5. Avoid interference with exisitng agricultural economy of the region.

Program:

1. Participation would be voluntary.

2. Include a combination of early-harvested and late-harvested small grain crops to increase time availability of post-harvest flooded habitat.

3. Participants would agree to leave small percentages (5 to 10%) of crop unharvested in small plots in participating fields distributed across area to be flooded.

4. Harvest specifications:

A. Wheat/Barley stubble 12 inches or less in height and not disced prior to flooding.

B. Corn stubble 24 inches or less in height (harvested portions can be single-disced prior to flooding.

5. Flooding specifications:

A. Wheat/Barley flooded as soon as practicable after September 15th.

B. Corn fields flooded as soon as practicable after harvest and left flooded until at least January 15th.

C. Where practicable, some marginal area of flooded fields to be left dry or shallowly flooded for raptor, crane, and shorebird foraging during flood-up periods.

6. Compensation. Payment for additional costs incurred and revenues foregone would be based on a dual scale:

A. A payment to the entity incurring the additional drainage cost would be made for additional drainage costs resulting from increased drainage caused by the program (estimated to be approximately $15.00 per flooded acre).

B. An additional payment would be made to the farming entity for unharvested acreage based on the value of the unharvested crop less harvest, drying (if any), hauling, and other similar costs not otherwise incurred (estimated to be approximately $100/ton of crop not harvested, or $20 to $40 per acre for participating acreage, depending on percentage of crop not harvested).

SUMMARY OF ERPP HABITAT RESTORATION TARGETS AND PROGRAMMATIC ACTIONS FOR THE SACRAMENTO-SAN JOAQUIN DELTA ECOLOGICAL ZONE.

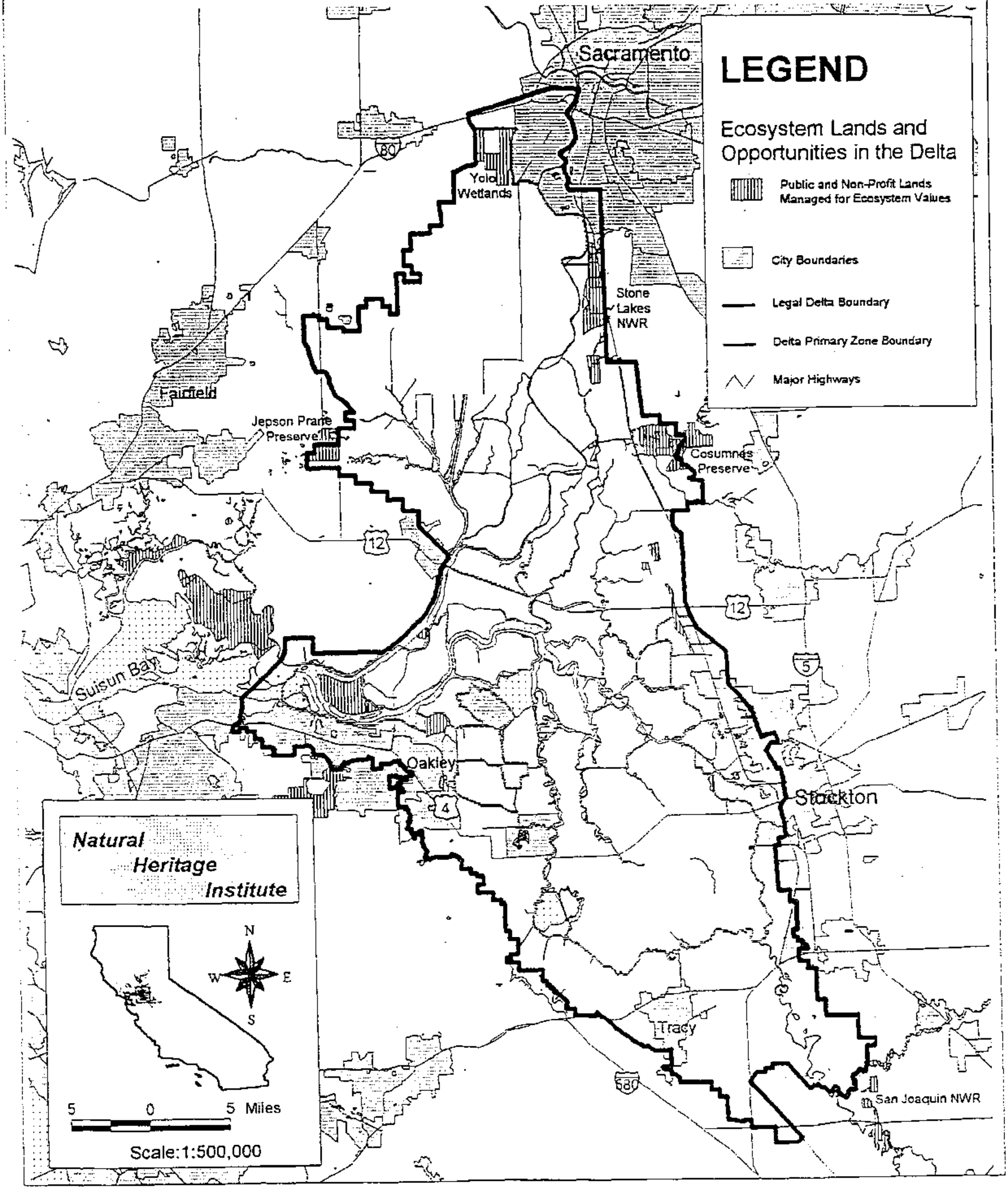
Habitat Type	North Delta Acreage	East Delta Acreage	South Delta Acreage	Central and West Delta Acreage	Total Acreage
Tidal Perennial Aquatic	1,500	1,000	2,000	2,500	7,000
Shoal	0	0	0	500	500*
Nontidal Perennial Aquatic (deep open water)	0	200	200	100	500
Nontidal Perennial Aquatic (shallow open water)	1,000	300	300	500	2,100
Midchannel Islands	50 to 200	50 to 200	50 to 200	50 to 200	200 to 800*
Fresh Emergent Wetland (tidal)	TBD [to be determined]	TBD	TBD	TBD	30,000 to 45,000
Fresh Emergent Wetland (nontidal)	3,000	3,000	4,000	10,000	20,000
Seasonal Wetland	Improve: 1,000 Restore: 4,000	1,000 6,000	500 12,000	1,500 8,000	4,000 30,000
Inland Dune Scrub	0	0	0	50 to 100	50 to 100*
Perennial Grassland	1,000	1,000	1,000 to 2,000	1,000 to 2,000	4,000 to 6,000
Wildlife Friendly Agricultural Land	TBD	TBD	TBD	TBD	40,000 to 75,000*
				Total acres	138,000 to 191,000

* Denotes acreages that have minimal impact to existing agricultural land uses and practices.

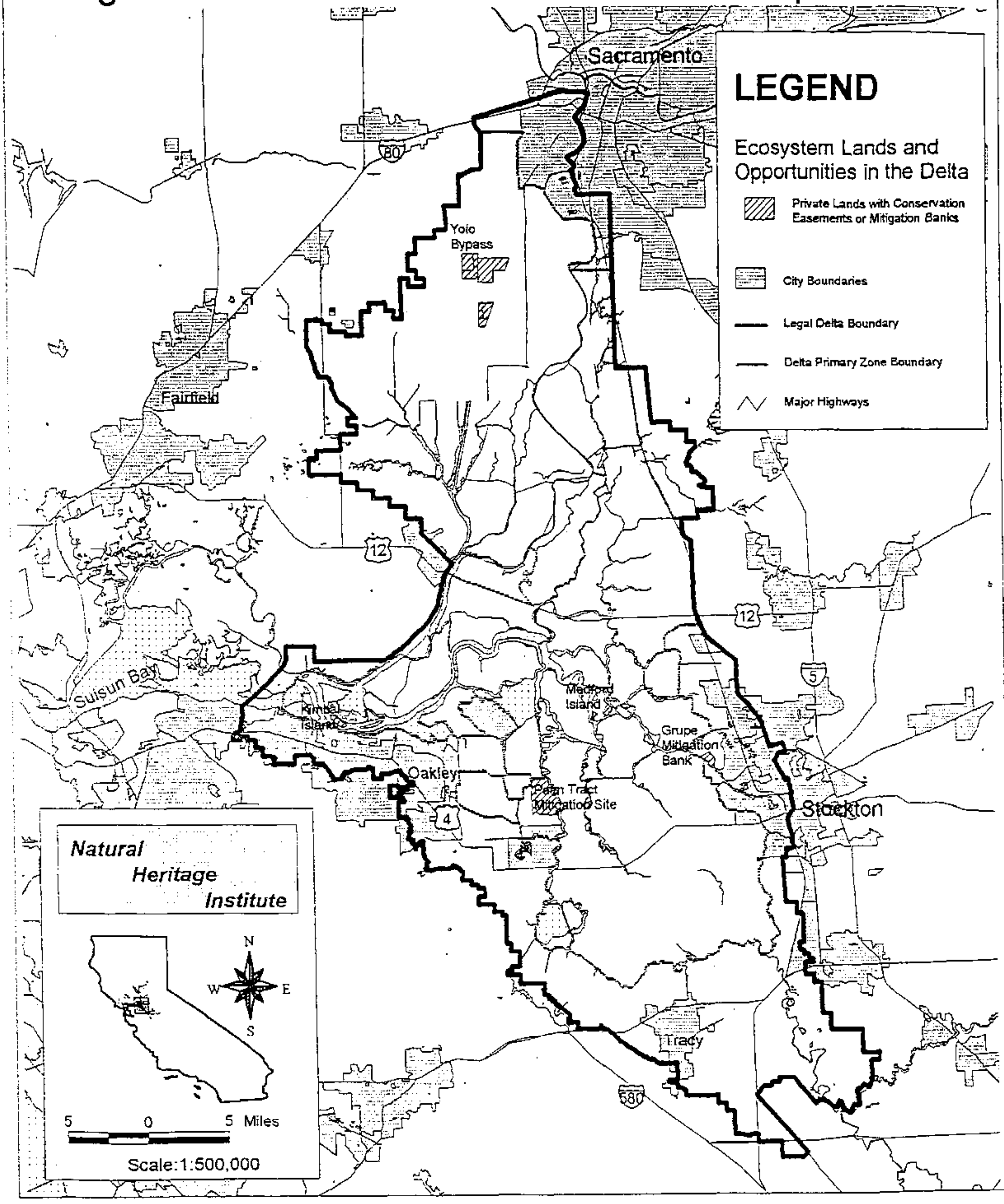
Note: Table does not include acreages for riparian and riverine aquatic habitat, Delta sloughs, levee reliability program, or conveyance facilities.

Exhibit 1

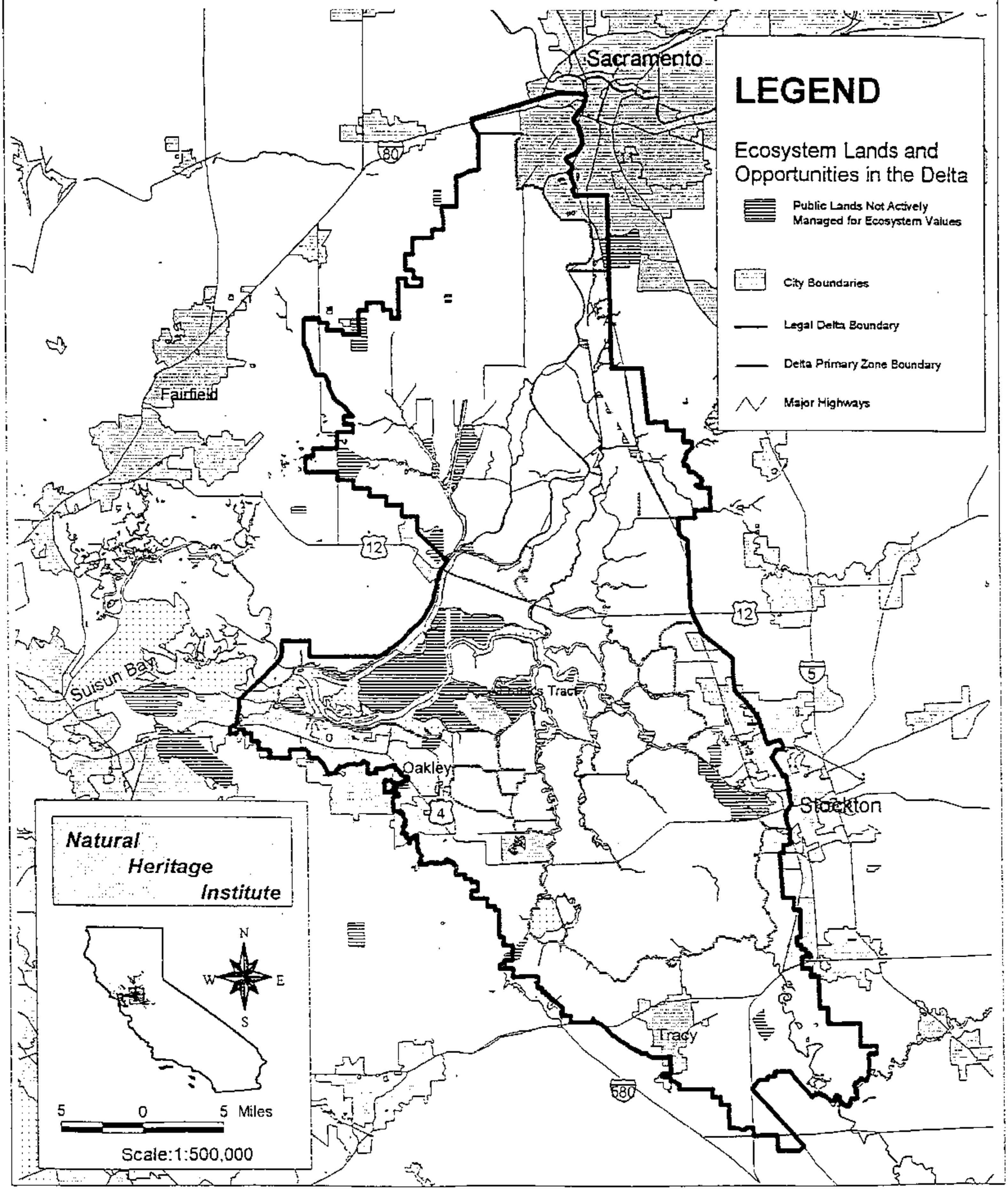
Public and Non-Profit Lands Managed for Ecosystem Values in the Sacramento-San Joaquin Delta



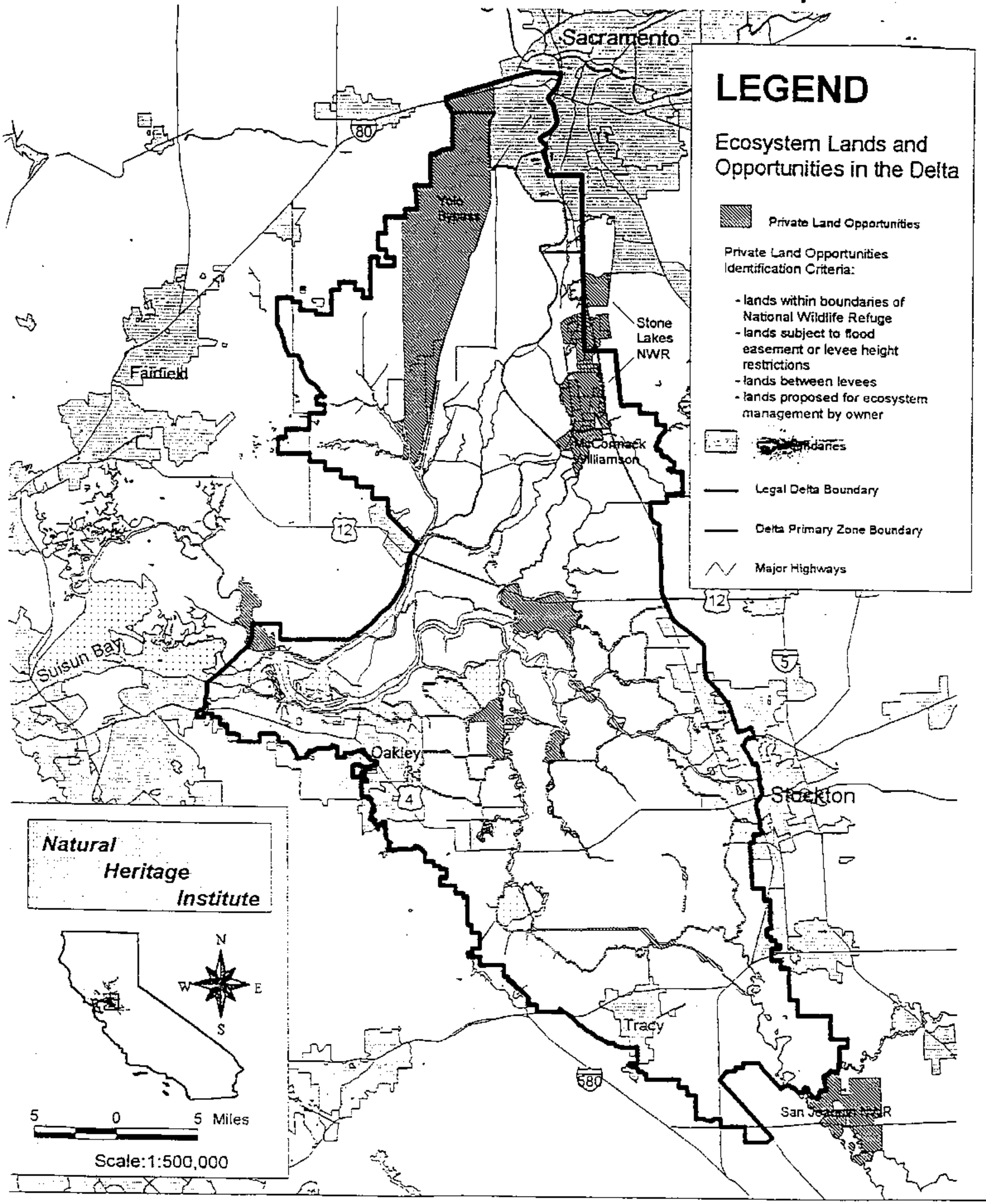
Private Lands with Conservation Easements or Mitigation Banks in the Sacramento-San Joaquin Delta



Public Lands Not Actively Managed for Ecosystem Values in the Sacramento-San Joaquin Delta



Opportunities for Ecosystem Protection and Restoration on Private Lands in the Sacramento-San Joaquin Delta



Ecosystem Management and Restoration Opportunities in the Sacramento-San Joaquin Delta