Coastal Planning on the U.S. National Wildlife Refuge System with the Sea Level Affecting Marshes Model (SLAMM)

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The U.S. National Wildlife Refuge System (Refuge System) includes 173 marine coastal refuges that provide exceptional benefits for fish and wildlife as well as valuable ecosystem services to local and regional economies. Many of these refuges have historic and cultural significance. For example, Pelican Island (FL) was the first national wildlife refuge (NWR), Chincoteague NWR (VA) has the visitation of a national park, and Dungeness NWR (WA) remains a stronghold of tribal culture. Most coastal refuges, with notable exceptions primarily in Oregon and Alaska, also have gently sloping shoreline topography, leaving them vulnerable to sea-level rise.

Global sea levels rose 10-25 cm during the 20th century (Douglas et al. 2000). A commonly cited range of sea-level rise projections for the 21st century is 0.13-0.69 m. This range corresponded to the “A1B” family of scenarios identified by the Intergovernmental Panel on Climate Change in its Third Assessment (IPCC 2001). However, several peer-reviewed projections exceed 0.69 m by 2100. For example, Chen et al. (2006) and Monaghan et al. (2006) found that eustatic sea-level rise is progressing more rapidly than the IPCC estimates, probably due to the dynamic changes in ice flow omitted from the IPCC calculations. Higher estimates are consistent with the fact that the rate of sea-level rise increased in recent decades and continues to accelerate (Grinsted et al. 2009; Cazanave and Llovel 2010). Vermeer and Rahmstorf (2009) projected sea-level increases from 0.75-1.90 for the period 1990–2100. Grinsted et al. (2009:469) found that “all IPCC scenarios produce sea level rise about a factor of three smaller than our predictions.” Pfeffer et al. (2008) posited that 2 m of sea-level rise is at the upper end of 21st Century plausible scenarios due to physical limitations on glaciological conditions and trends, while Levermann et al. (2013:1) emphasized post-2100 sea-level rise scenarios in which, over the next two millennia, “we are committed to a sea-level rise of approximately 2.3 m” for every 1 °C increase in global mean temperature.

Rates of relative sea-level rise may differ greatly from global eustatic rates due to a variety of geological, ecological, and oceanic processes (Sallenger et al. 2012; Stammer et al. 2013). For example, isostatic rebound is fast enough at some Alaskan refuges that land-building occurs despite eustatic sea-level rise. On the other hand, for many refuges erosion and subsidence exacerbate the effects of sea-level rise. Due to a combination of factors, some of the highest rates of coastal land loss in the world occur in Louisiana, including at refuges such as Breton, Delta, and Shell Keys (Tidwell 2003).

Most coastal refuges were established due to the value of their tidal ecosystems to migratory waterfowl, shorebirds, anadromous fishes, marine mammals, sea turtles, and other species of special concern. Many of these are federally or state-listed threatened or endangered species or are otherwise imperiled, due largely to the economic geography of coastal regions (Czech 2002). The intensive economic activity along coastlines replaces and impacts remaining wildlife habitats, simultaneously contributing disproportionately to the greenhouse gas emissions associated with global warming and sea-level rise (Czech et al. 2000).

The high value of coastal refuges along with their geographic and topographic vulnerability calls for planning for sea-level rise on the Refuge System. Such planning was required no later than January 19, 2001, when Secretarial Order No. 3226 called for Department of the Interior agencies to “consider and analyze potential climate change impacts when undertaking long-range planning exercises, when setting priorities for scientific research and investigations, when developing multi-year management plans, and/or when making major decisions regarding the potential utilization of resources under the Department’s purview” (Babbitt 2001:1). Such consideration and analysis was to be manifest in, among other things, “management plans and activities developed for public lands.” By now, there are numerous additional policies and directives requiring the Refuge System to plan for climate change and sea-level rise. One of the most relevant for Refuge System staff is the U.S. Fish and Wildlife Service (FWS) climate change strategic plan, Rising to the Urgent Challenge, which calls for conducting “sea level rise modeling (e.g., Sea Level Affecting Marshes Model) for all coastal refuges and expand modeling to additional coastal areas, as practicable, to determine the vulnerability of these areas” (FWS 2010:24).

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The purpose of this article is to explore what the Refuge System has done thus far with regard to sea-level rise planning. The focus is on the Refuge System's use of the Sea Level Affecting Marshes Model (SLAMM) due to its prominence in wildlife-oriented sea-level rise planning. The discussion includes historical and technical overviews of SLAMM, its use on the Refuge System, limitations of SLAMM, and suggestions for improving SLAMM.

SEA LEVEL AFFECTING MARSHES MODEL (SLAMM)

History SLAMM has been the predominant model for sea-level rise planning on the Refuge System. It accounts for the major processes involved in wetland conversion and shoreline modification during long-term sea-level rise (www.warrenpinnacle.com/prof/SLAMM). The first version of SLAMM was developed in the 1980s by Dick Park at Butler University with a grant from the U.S. Environmental Protection Agency (EPA) (Park et al. 1989). Park continued developing SLAMM over the next 15 years with colleagues including Manjit Treham (Version 2) at Butler and Jay Lee (Version 3) at Indiana University. During the late 1990s Jonathan Clough of Warren Pinnacle Consulting (Waitsfield, VT) became involved in the development of SLAMM 4 and has been the primary SLAMM developer and modeler through versions 5 and 6.

In 2005 the Conservation Biology Program of the Refuge System initiated a cooperative project with the University of Maryland's Conservation Biology and Sustainable Development Program (CONS). CONS graduate students were challenged to develop a sea-level rise model for use on the Refuge System. This model was tentatively called the Zonal Inundation and Marsh Model (ZIMM), but background research revealed that SLAMM was already well-suited for Refuge System planning purposes. Furthermore, it was found to be readily accessible and relatively affordable, and the Refuge System already had the capacity to perform or contract for SLAMM analysis.

Shortly after the CONS project, the National Wildlife Federation (NWF) and the Florida Wildlife Federation (FWF) published An Unfavorable Tide, a SLAMM-based report on the projected effects of sea-level rise on fisheries in Florida (NWF and FWF 2006). Building on the report and in collaboration with the Conservation Biology Program, Sean McMahon (NWF and Virginia Tech) parsed out portions of the report specific to national wildlife refuges (McMahon 2007). Simultaneously, fellow Virginia Tech graduate student Delissa Padilla used SLAMM to model the effects of sea-level rise at Vieques NWR (Puerto Rico; Padilla 2008). Padilla was later hired by FWS and performed SLAMM analysis for several Atlantic and Gulf Coast refuges, including an advanced SLAMM analysis of Chincoteague NWR tailored to addressing the beach dynamics of Assateague Island.

By 2009, SLAMM had become the "workhorse model" for sea-level rise planning on the Refuge System due to

TABLE 1. REFUGES WITH SLAMM ANALYSIS.

National Wildlife Refuge	*FWS Region*	*State*	*Year of SLAMM Analysis*	*Year of SLAMM Reanalysis*	*SLAMM Version (Most Recent Analysis)*
ACE Basin	4	SC	2008	2013	6
Alligator River	4	NC	2008	2013	6
Amagansett	5	NY	2009		5
Anahuac	2	TX	2011		6
Aransas	2	TX	2010		6
Archie Carr	4	FL	2010		6
Back Bay	5	VA	2011		6
Bandon Marsh	1	OR	2010		6
Bayou Sauvage	4	LA	2008	2012	6
Bayou Teche	4	LA	2008		5
Big Boggy	2	TX	2011		6
Big Branch Marsh	4	LA	2008	2012	6
Blackbeard Island	4	GA	2008	2012	6
Blackwater	5	MD	2009		5
Block Island	5	RI	2009		5
Bombay Hook	5	DE	2010		6
Bon Secour	4	AL	2008		5
Brazoria	2	TX	2011		6
Breton	4	LA	2011		6
Cabo Rojo	4	PR	2008		5
Caloosahatchee	4	FL	2008		5
Cape May	5	NJ	2009	2011	6
Cape Romain	4	SC	2008		5
Cedar Island	4	NC	2010		6
Cedar Keys	4	FL	2011		6
Chassahowitzka	4	FL	2008		5
Chincoteague	5	VA	2009		5
Conscience Point	5	NY	2009		5
Crocodile Lake	4	FL	2010		6
Crystal River	4	FL	2008		5
Culebra	4	PR	2007		5
Currituck	4	NC	2010		6
Delta	4	LA	2011		6
Don Edwards San Francisco Bay	8	CA	2010		6
Dungeness	1	WA	2010		6
Eastern Neck	5	MD	2009		5
Eastern Shore of Virginia	5	VA	2009		5
Edwin B. Forsythe	5	NJ	2008	2012	6
Egmont Key	4	FL	2012		6
Elizabeth A. Morton	5	NY	2008		5
Featherstone	5	VA	2010		6
Fisherman Island	5	VA	2009		5
Grand Bay	4	MS	2011		6
Grays Harbor	1	WA	2011		6
Great Bay	5	NH	2009		5
Great White Heron	4	FL	2011		6
Green Cay	4	VI	2008		5

a unique combination of characteristics. Most notably, it was a long-tested, freely available, transparent, spatially explicit model which was necessary for producing maps. It was applicable at the refuge, regional, and national level and conducive to systematic usage and economies of scale. Furthermore, it was tailored to use with the FWS's wetland classification system (Cowardin et al. 1979). (Note: In 1996 the updated Cowardin et al. system was designated as the national standard - "FGDC-STD-004" - for wetland classification; FGDC 2013). The use of this system in SLAMM was important for technical and administrative reasons, as the Cowardin et al. system had a long history of development by FWS and a well-developed program – the National Wetlands Inventory (NWI) – dedicated to maintaining a spatially explicit inventory of nation's wetlands.

In their review of sea-level rise models useful for conservation purposes, Mcleod et al. (2010) evaluated numerous types of models and featured three for detailed assessment, including SLAMM. No models besides SLAMM were found to have the suite of characteristics noted in the preceding paragraphs. For example, the Dynamic Interactive Vulnerability Assessment (DIVA) "is designed for global, regional, and national-level assessments" and "not appropriate for local scale coastal management" (Mcleod et al. 2010:510). Another model, SimCLIM, is used more in international affairs and academic settings than for conservation purposes in the United States. It has been used primarily in Southeast Asia and Australia and is a broad-based climate change software package. SimCLIM may be used in coastal areas and has several features in common with SLAMM, but it requires licensing and training courses. Mcleod et al. (2010) briefly discussed simple types of inundation models including "bathtub ring models" that project future shorelines based entirely on eustatic sea-level rise and topography. They can be useful for a quick, preliminary assessment of

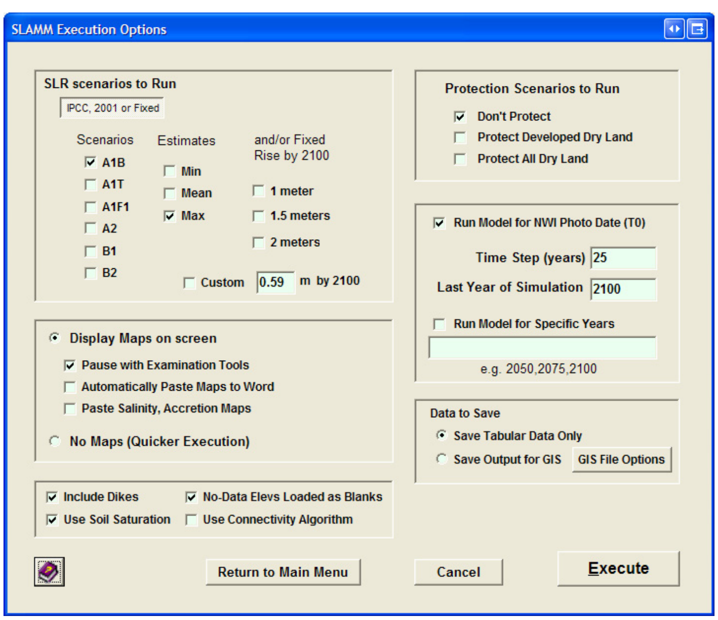


Figure 1. Sea-level rise scenario menu in SLAMM, a typical interface for the SLAMM modeler.

vulnerability, but provide no detail on habitat transitions except at the crudest level of land to open water. Mcleod et al. (2010:510) also described a category of "ecological landscape spatial simulation models" such as the Barataria-Terrebonne ecological landscape spatial simulation, which was developed to predict wetland habitat change in the Mississippi Delta over a 30-year period. Some of these models (inundation and ecological) will be of use to particular refuges. A common problem, however, is that they require substantial expertise to run, due to model complexity, and "can be extremely expensive" (Mcleod et al. 2010:510). The findings of Mcleod et al. (2010) corroborate the FWS rationale for the selection of SLAMM for most sea-level rise planning on the Refuge System. Although Rising to the Urgent Challenge (FWS 2010:24) did not mandate the use of SLAMM for modeling the effects of sea-level rise, it did recommend modeling the impacts of sea-level rise, and SLAMM was the only model noted.

The identification of SLAMM as a model of choice in systematic FWS planning also resulted partly from intra-agency collaboration. The National Wetlands Inventory (NWI) had taken an early interest in the use of the model and, along with the Division of Fisheries and Habitat Conservation, was helpful in funding much of the early Refuge System SLAMM work. NWI also scheduled their wetland map updates based partly on Refuge System SLAMM analysis needs. NWI remains a key partner in Refuge System SLAMM analysis and plays the leading role in facilitating the use of SLAMM-View, a web-based SLAMM-analysis viewer that enables the reader to modify input variables and compare SLAMM results.

SLAMM has also been one of the most widely used models of sea-level effects on coastal marshes beyond the Refuge System as well. Earlier and recent versions of SLAMM were applied to numerous sites along U.S. coastline by the EPA, NWF, Ducks Unlimited, The Nature Conservancy, Indiana University, University of Florida, State of Delaware, and the Gulf of Mexico Alliance, along with numerous partners. Most SLAMM reports would be classified as "gray literature" (e.g., Titus et al. 1991; Lee et al. 1992; Park et al. 1993; NWF and FWF 2006; McMahon 2007; Glick et al. 2007; Padilla 2008). However, several peer-reviewed articles based on or about SLAMM analysis have also been published (Galbraith et al. 2002; Craft et al. 2009; Chu-Agor et al. 2011; Traill et al. 2011; Geselbracht et al. 2011; Glick et al. 2013). Several of the peer-reviewed studies incidentally but directly benefited the Refuge System. For example, SLAMM reports for nine refuges were parsed out of the analysis conducted by Craft et al. (2009), and one for Delta NWR was parsed out of the analysis conducted by Glick et al. (2013).

How SLAMM Works SLAMM is a menu-driven program allowing the modeler to enter GIS data and values for the input variables (Figure 1). The SLAMM interface is functional with Microsoft Windows (the standard operating system used by FWS). Some of the key input variables include wetland type, elevation, tidal range, and accretion rate. These and other variables are either mapped as continuous functions on the landscape (e.g., elevation) or in discrete units (e.g., wetland type) (Figure 2). SLAMM incorporates investigative tools for purposes of quality control and model calibration (Figures 3 and 4).

The modeler must also select which sea-level rise scenarios or schedules to run SLAMM with. Scenarios are typically run out to the year 2100, with results shown at several increments such as 2025, 2050, 2075 and 2100. On the Refuge System, scenarios selected for analysis usually include 0.39 m (A1B Mean), 0.69 m (A1B Max), 1 m, 1.5 m, and 2 m, reflecting the range of sea-level rise literature reviewed in the introduction. Although numerous scenarios are selected for SLAMM analysis, Refuge System personnel typically focus on the 1-1.5 m range for planning and management purposes (Czech et al. 2014).

The primary processes that SLAMM models and integrates are inundation by saltwater, erosion of shoreline, vertical accretion of sediments and plant material, barrier island overwash, and saturation of uplands with fresh water resulting from rising water tables. Each of these processes is instrumental in determining the development or devolution of coastal marshes and related habitats (including beaches, mudflats, and swamps) in response to sea-level rise. Details of the logical structure, assumptions, equations and algorithms represented in SLAMM are found in the technical documentation (Clough et al. 2010).

The NWI data used as SLAMM inputs are converted into 26 output categories (Clough et al. 2010). These categories represent distinct combinations of geomorphology, physiognomy, tidal regime, salinity, and vegetative composition. They are also labeled in a manner that is conducive to efficient communication among wildlife managers. Basic habitat characteristics of a SLAMM category such as "cypress swamp" are immediately recognizable; such is not the case with its corresponding NWI alpha-numeric code used for mapping - PFO2C. For wetland scientists and certain wildlife management applications, however, SLAMM categories can be relatively coarse, since there are well over a thousand NWI wetland types that are converted into the 26 SLAMM categories. Occasionally SLAMM is tailored to produce maps and tables with finer categories than the basic 26, sometimes using insights from other land classification systems such as the National Vegetation Classification (http://usnvc.org/).

One recent development warrants some elaboration here to address concerns about how SLAMM processes accretion rates. In earlier versions of SLAMM, accretion rates were held constant for particular SLAMM categories. Recent research suggests that increasing inundation leads to higher sediment deposition and organic-matter production

TABLE 1. REFUGES WITH SLAMM ANALYSIS. *(CONTINUED)*

National Wildlife Refuge	*FWS Region*	*State*	*Year of SLAMM Analysis*	*Year of SLAMM Reanalysis*	*SLAMM Version (Most Recent Analysis)*
Guadalupe-Nipomo Dunes	8	CA	2008		5
Guam	1		2010		6
Harris Neck	4	GA	2008	2011	6
Hobe Sound	4	FL	2010		6
Huleia	1	HI	2010		6
Humboldt Bay	8	CA	2011		6
Island Bay	4	FL	2008		5
J.N. `Ding` Darling	4	FL	2011	2013	6
James River	5	VA	2010		6
John H. Chafee	5	RI	2009		5
John Heinz	5	PA	2009		5
Julia Butler Hansen	1,8	OR,WA	2011		6
Kakahai'a	1	HI	2010		6
Key West	4	FL	2011		6
Kilauea Point	1	HI	2010		6
Laguna Atascosa	2	TX	2011		6
Lewis and Clark	1	WA	2011		6
Lido Beach WMA	5	NY	2009		5
Lower Rio Grande Valley	2	TX	2011		6
Lower Suwannee	4	FL	2011		6
Mackay Island	4	NC	2010		6
Mandalay	4	LA	2008		5
Marin Islands	8	CA	2010		6
Martin	5	MD	2009		5
Mashpee	5	MA	2009	2012	6
Mason Neck	5	VA	2010		6
Matlacha Pass	4	FL	2008		5
McFaddin	2	TX	2011		6
Merritt Island	4	FL	2008	2011	6
Mississippi Sandhill Crane	4	MS	2012		6
Monomoy	5	MA	2009	2012	6
Moody	2	TX	2011		6
Moosehorn	5	ME	2008		5
Nansemond	5	VA	2009		5
Nantucket	5	MA	2009		5
National Key Deer Refuge	4	FL	2008		5
Nestucca Bay	1	OR	2010		6
Ninigret	5	RI	2009		5
Nisqually	1	WA	2011		6
Nomans Land Island	5	MA	2009		5
Occoquan Bay	5	VA	2010		6
Oyster Bay	5	NY	2009		5
Parker River	5	MA	2009		5
Passage Key	4	FL	2008		5
Pea Island	4	NC	2008		5

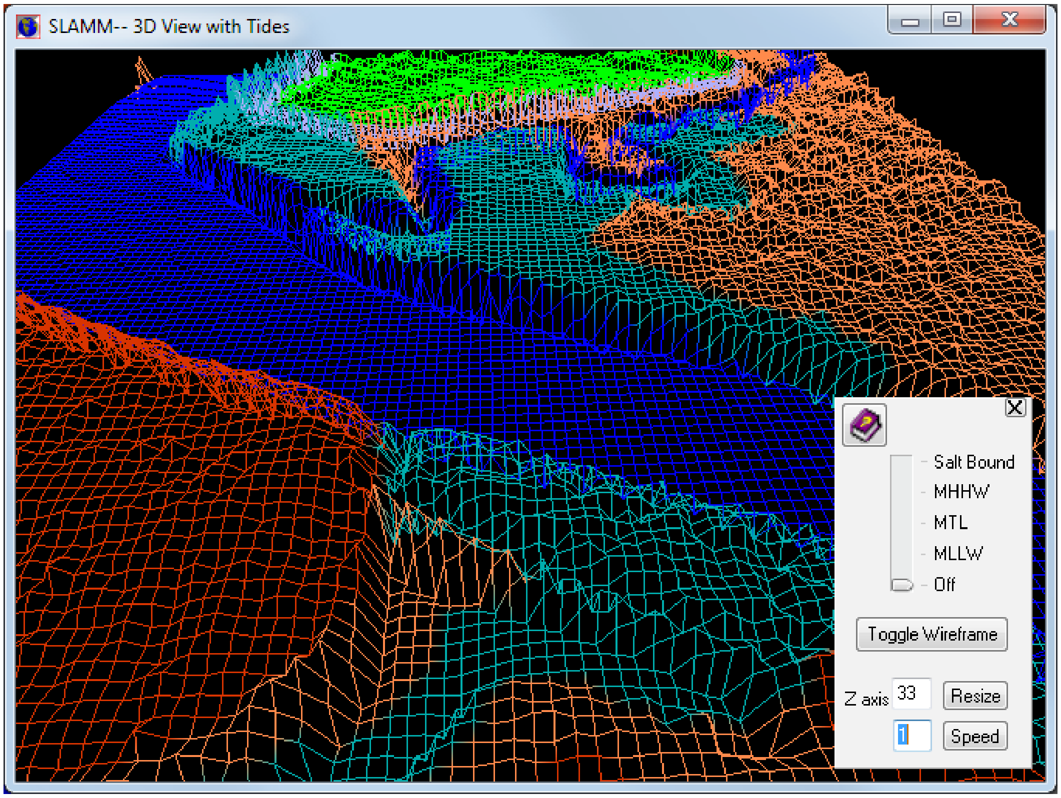


Figure 2. Three-dimensional viewing capability of SLAMM allows modelers to review wetland and elevation conditions.

which can help tidal wetlands keep up with sea-level rise (Kirwan et al. 2010). This relationship has been incorporated into SLAMM since version 6 was released in 2009. Within SLAMM, for tidal marsh and tidal swamp categories, a user can specify relationships between wetland platform elevations (representing frequency of inundation) and vertical rates of accretion. The relationships between elevations and accretion rates may vary spatially and by vegetation category and may be specified via mechanistic accretion-rate modeling or empirical relationships when data are available.

The primary SLAMM outputs are land cover maps and tables (Figure 5). Several other outputs, products, and interpretive tools are optional. For example, a recently developed roads module produces maps of projected road (and other transportation infrastructure) inundation for assistance in transportation planning. An uncertainty module may be used to generate probability distributions of most input and output variables, giving modelers and managers insights to the sensitivity of SLAMM to particular variables and the robustness of results. The related SLAMM Uncertainty Viewer is useful for concise briefings of decision makers. Meanwhile the web-based platform noted above, SLAMM-View, allows non-modelers at various levels of expertise to investigate SLAMM results interactively. A user's manual is available to assist modelers with the use of SLAMM (Warren Pinnacle Consulting 2010). The SLAMM Uncertainty Viewer (http://www.warrenpinnacle.com/prof/SLAMM/SLAMM_Uncertainty.pdf) and SLAMM-View (http://www.slammview.org/) are separate, stand-alone products.

What SLAMM Doesn't Do

SLAMM has numerous limitations pertaining to the physical processes affecting coastlines and their ecosystems. For example, SLAMM does not model storm surge patterns, intensities, or changes in the context of climate change. SLAMM is not a sediment balance model and does not forecast the movements of sediments along the coastline. Nor does SLAMM differentiate among coastal substrates that may influence subsurface processes such as the salt-wedging upward of inland aquifers that causes saturation of inland soils and the formation of freshwater marshes. SLAMM also does not incorporate complex hydrodynamic modeling, and does not have the ability to forecast the convoluted channelization that may spread through an inundated marsh platform (Kirwan and Guntenspergen 2010). It also has limitations pertaining to the ecological transformations caused by sea-level rise. For example, it does not model any species' distributions. Nor does it provide any indication of the condition or health of a wetland or other ecosystem; it simply assigns an ecosystem category to each cell.

As with any model, the accuracy and precision of SLAMM analysis is a function of input data quality. Examples of crucial input variables are elevation, accretion rates, and wetland types. At this point in the development and use of SLAMM, it is not usually worthwhile to run the model in the absence of elevation data derived from LiDAR (Light Detection and Ranging) technology, but care must also be taken to ensure that LiDAR data were properly processed to accurately derive elevations (Gesch 2009). Since accretion rates may be highly variable within a study area and can be difficult to ascertain, monitoring accretion with sedimentation-erosion tables (SETs) is recommended (Cahoon et al. 1995, 2002; Callaway and Siegel 2002). Wetland types must be monitored and mapped over large areas and with reasonably fine resolution; a challenge to NWI and related programs in an age of fiscal austerity.

SLAMM ANALYSIS ON THE REFUGE SYSTEM

Extent of SLAMM Analysis Detailed SLAMM results are found in all refuge-specific reports, which may be downloaded at the Refuge System planning website (http://www.fws.gov/refuges/planning/seaLevelRise.html). Cumulative analyses are also underway. For example, Refuge System staff and partners are analyzing the cumulative SLAMM results from Atlantic Coast refuges for informing Atlantic Flyway planning decisions, among other purposes. The results of specific SLAMM analyses are not provided in this paper except for two refuges – Bayou Sauvage (LA) and St. Marks (FL); see Figures 5 and 6, respectively.

Of the 173 marine coastal refuges, SLAMM is not significantly applicable to 26 refuges where rocky islands are the predominant feature (most common in the Pacific Northwest). Also, SLAMM is not applicable or appropriate for the foreseeable future for the ten Alaskan coastal refuges (with some localized exceptions) or Palmyra Atoll (central Pacific Ocean) because of a lack of high-quality elevation and wetlands data. That leaves 136 coastal refuges for which SLAMM is applicable, and each of these refuges has a SLAMM analysis (Table 1). From 2007 to 2012, the Refuge System produced more SLAMM reports than were done by all other parties combined.

The large number of Refuge System SLAMM reports is, of itself, not a measure of success in sea-level rise planning or adaptation, much less mitigation. However, it ensures that each coastal refuge for which sea-level rise is a significant issue is equipped with an analysis based on sound science. A SLAMM analysis allows refuge managers and planners to readily meet the charge of Secretarial Order 3226, the FWS Climate Change Strategic Plan, and other policies calling for climate change and sea-level rise planning (Czech et al. 2014).

SLAMM and Comprehensive Conservation Planning Every refuge is required to prepare a 15-year Comprehensive Conservation Plan (CCP) pursuant to the National Wildlife Refuge System Improvement Act of 1997 (16 USC § 668dd). The first round of CCPs is near completion and some refuges are preparing their second iteration. Although many coastal CCPs were published prior to SLAMM analysis, SLAMM analysis clearly helped later CCP authors address sea-level rise, even in cases where SLAMM results were not explicitly incorporated. As Babko et al. (2012:10) noted, “In 2007, around the time FWS started employing the SLAMM model, the number of CCPs including sea-level rise as a threat began to increase.” Some of these CCPs incorporated SLAMM results explicitly (e.g., Cape Romain NWR), while other refuges received SLAMM reports slightly too late for incorporation but included some sea-level rise information based partly on SLAMM analysis (e.g., Back Bay NWR). A small fraction of coastal refuges are still in the process of developing first-round CCPs, and several of these will include significant discussion on sea-level rise with the use of SLAMM results (e.g., Chincoteague NWR). Even refuges lacking SLAMM analyses during CCP preparation are nevertheless now using SLAMM reports for planning purposes. For example, at Blackwater NWR, SLAMM analysis is used in land protection planning as well as habitat management.

TABLE 1. REFUGES WITH SLAMM ANALYSIS. *(CONTINUED)*

National Wildlife Refuge	*FWS Region*	*State*	*Year of SLAMM Analysis*	*Year of SLAMM Reanalysis*	*SLAMM Version (Most Recent Analysis)*
Pearl Harbor	1	HI	2010		6
Pelican Island	4	FL	2010		6
Petit Manan	5	ME	2010		6
Pinckney Island	4	SC	2008	2012	6
Pine Island	4	FL	2011		6
Pinellas	4	FL	2008		5
Plum Tree Island	5	VA	2009		5
Presquile	5	VA	2009		5
Prime Hook	5	DE	2009		5
Protection Island	1	WA	2011		6
Rachel Carson	5	ME	2008		5
Rappahanock River Valley	5	VA	2009		5
Sabine	4	LA	2008		5
Sachuest Point	5	RI	2009		5
Salinas River	8	CA	2008		5
San Bernard	2	TX	2011		6
San Diego Bay - South Bay	8	CA	2009		5
San Diego Bay – Sweetwater Marsh	8	CA	2009		5
San Juan Islands	1	WA	2011		6
San Pablo Bay	8	CA	2010		6
Sandy Point	4	VI	2008		5
Savannah	4	GA	2008	2012	6
Seal Beach	8	CA	2008		5
Seatuck	5	NY	2009		5
Shell Keys	4	LA	2008		5
Siletz Bay	1	OR	2010		6
St. Marks	4	FL	2008	2012	6
St. Vincent	4	FL	2008		5
Stewart B. McKinney	5	CT	2009		5
Supawna Meadows	5	NJ	2009		5
Swanquarter	4	NC	2007	2012	6
Target Rock	5	NY	2009		5
Ten Thousand Islands	4	FL	2011		6
Texas Point	2	TX	2011		6
Tijuana Slough	8	CA	2009		5
Trustom Pond	5	RI	2009		5
Tybee	4	SC	2008	2012	6
Vieques	4	PR	2007		5
Waccamaw	4	SC	2008		5
Wallops Island	5	VA	2009		5
Wassaw	4	GA	2008	2012	6
Wertheim	5	NY	2008		5
Willapa	1	WA	2010		6
Wolf Island	4	GA	2008	2012	6

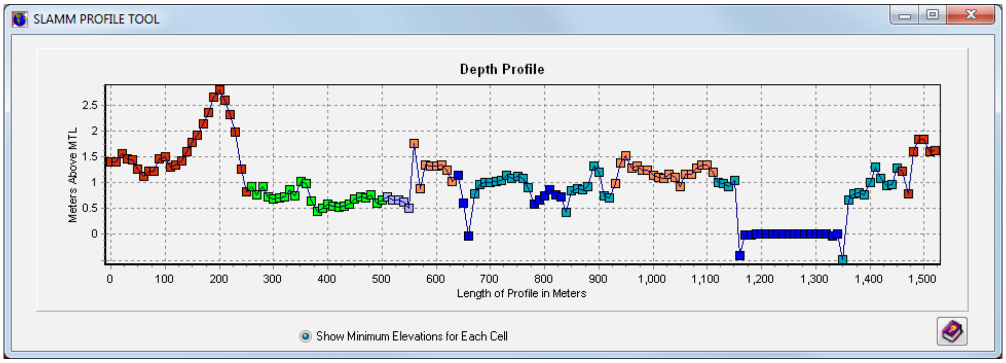


Figure 3. Profiling tool describes a cross-section of the study area, giving insights to hydraulic connectivity. For example, "A" indicates a hill or a levee that may block hydraulic connectivity, while "B" indicates that some low-lying irregularly-flooded marsh (orange) is located at the same elevation as regularly-flooded marsh (green) and may be converted when the SLAMM conceptual model is applied. Indications such as these may be investigated in the field if necessary, and SLAMM may be calibrated to fit the actual conditions.

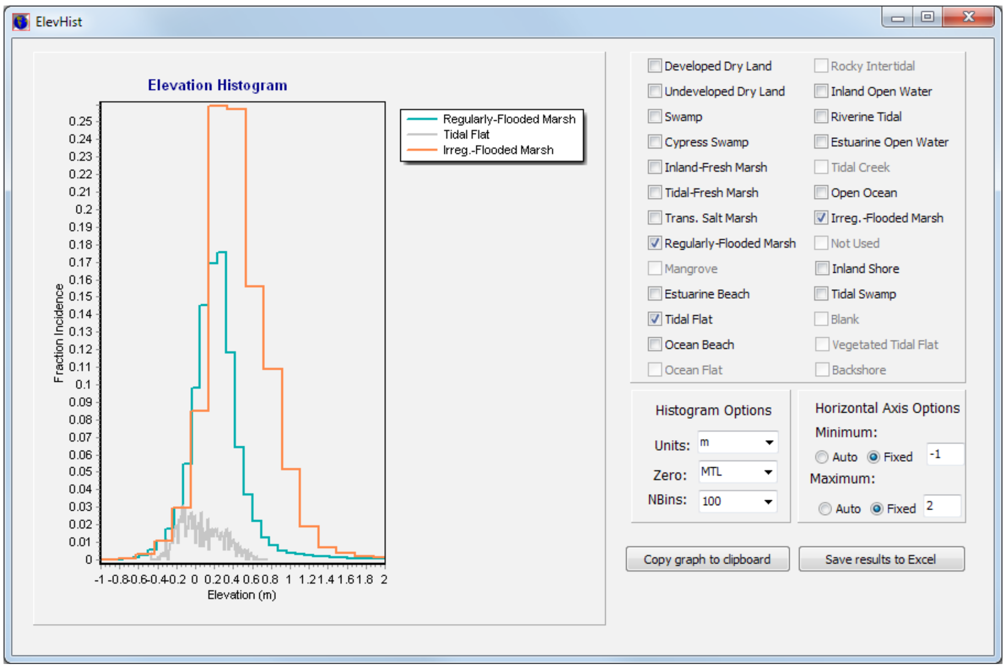


Figure 4. Histograms of the elevations of wetland categories provide visual information to support adjustments to the SLAMM conceptual model.

SLAMM and Land Acquisition Planning Perhaps the clearest use for SLAMM is in land acquisition planning. To facilitate this use, refuge-specific SLAMM analyses include appendices with wetland projection maps that cover large areas inland and upland of coastal refuges and surrounding locale (Figure 6). In the context of comprehensive conservation planning, land acquisition is addressed primarily in the Land Protection Plan (LPP), which often appears as an appendix to the CCP but may also constitute a stand-alone NEPA document (e.g., FWS 2011). For coastal refuges where land acquisition is proposed within or close to the tidal range, the LPP should reflect sea-level rise considerations as informed by SLAMM analysis (Figure 6).

Land acquisition planning activity takes place before or outside of the comprehensive conservation planning process, too. For example, the Land Acquisition Priority System is used to rank land acquisition proposals for Land and Water Conservation Fund appropriations (FWS 2012). A sea-level rise component has been proposed for the Land Acquisition Priority System such that, all else being equal, land acquisition proposals are ranked higher if wetland losses are projected to be less severe.

SLAMM and Landscape Conservation Design A recent development in FWS is the formal adoption of landscape-level planning through the use of landscape conservation designs (LCDs). LCDs are intended to "effectively serve as 'pre-planning' umbrella documents for the wide variety of plans written by the Service" (FWS 2013:3). The LCDs will be produced through Landscape Conservation Cooperatives (LCCs), which comprise "a network of public-private partnerships that provide shared science to ensure the sustainability of America's land, water, wildlife and cultural resources" (http://www.doi.gov/lcc/index.cfm). LCDs are well-suited to planning for climate change and sea-level rise. As climates and habitats shift across the landscape, the periodic preparation of LCDs and their revisions provides an iterative approach to determining where to refocus conservation efforts for long-lasting results.

Combining the range-shifting effects of climate change with the wetland-loss effects of sea-level rise, pre-planning in a coastal LCD will entail identifying coastal wetlands further north and further inland for protection to maintain populations of particular species. SLAMM analyses will be useful for such pre-planning, with maps and tables fit for LCDs. Some efforts to integrate SLAMM analysis into LCDs are already underway. For example, the Gulf Coast Prairie LCC is working with its partners to coordinate a Gulf Coast-wide SLAMM analysis for use by the four LCCs in the region - Gulf Coast Prairie, Gulf Coastal Plains and Ozarks, Peninsular Florida, and South Atlantic (B. Bartush, Gulf Coast Prairie LCC, personal communication). This precedent-setting landscape project will leverage multi-LCC funding to identify potential wetland migration corridors in the context of sea-level rise.

"Re-SLAMMing" Most refuge-specific SLAMM analysis in the foreseeable future will take the form of "re-SLAMMing" - reapplication of the model. Re-SLAMMing may be appropriate when: 1) better input data (e.g., elevation, accretion, tidal range, and upgraded NWI data) become available, 2) when SLAMM is upgraded, 3) when the factors affecting relative sea-level rise (e.g., subsidence) have changed significantly, or 4) when wetland conditions have been altered dramatically (e.g., by a hurricane). Re-SLAMMing is sometimes called for when managers want to investigate the projected effects of additional sea-level rise scenarios, different inputs such as accretion rates (which in some cases can be managed), or new infrastructure such as dikes. Major new land acquisition proposals near existing refuges may also serve as rationale for re-SLAMMing. Often the decision for re-SLAMMing is based on multiple factors, such as the availability of new data simultaneously with a new land acquisition proposal.

Re-SLAMMing of refuges commenced in 2011 and twenty refuges have been re-SLAMMed (Table 1), primarily due to recent availability of relatively high-resolution LiDAR data. All refuges where SLAMM 4 or an earlier version was applied have been re-SLAMMed. As of July 15, 2012, SLAMM 5 has been applied to 62 refuges and SLAMM 6 to 74 refuges (Table 1).

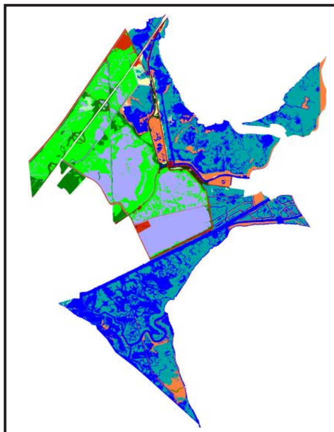
SUGGESTIONS FOR IMPROVING SLAMM AND ITS APPLICATION

Model Improvement SLAMM improvement has been ongoing for most of the past decade and is expected to continue for the foreseeable future. The most recent substantial improvement (completed during the writing of this manuscript) was conversion from a 32-bit to a 64-bit program. This conversion allows for greater memory utilization and therefore modeling of larger areas and/or with higher resolution. Many additional improvements have been identified and several are described below.

One increasingly obvious limitation of SLAMM is the failure to address the formation, development or “migration” of seagrasses and other submerged aquatic vegetation (SAV). Because low-lying coastal habitats over many and large areas are submerging, what transpires in the areas of submergence is vital for fish and wildlife resources and nearshore ecology. Given bathymetric data and sound assumptions pertaining to seagrass ecology, a useful SAV module is feasible for development. Indeed, while this article was in preparation, a SAV module was developed and is now undergoing testing by the U.S. Geological Survey (D. Reusser, USGS, personal communication).

The value of coastal ecosystem services is also of increasing interest to scientists, managers, and policy-makers. Craft et al. (2009) set a precedent by using SLAMM to assess threats of sea-level rise to ecosystem services. However, the assessment was exogenous - performed outside the model per se. For certain ecosystem services (e.g., freshwater provision, carbon sequestration, and fisheries production), economic estimates of the impact of sea-level rise should become endogenous to the model – at least as an optional module for use when economic data are available – if SLAMM is to be widely used in ecological economics.

Existing SLAMM modules pertaining to dikes, erosion, soil saturation, and barrier island overwash are other likely candidates for improvement. These modules are based on relatively coarse assumptions. For example, while dike heights may accounted for, dike failure is assumed only when sea levels cause inundation once per 30 days or more frequently. This is a “conservative” approach in the sense that habitats currently protected by dikes are modeled to remain as they are for unreasonably long periods. In reality, dikes are often compromised in stages (e.g., leakage or partial breaching) and as a function of dike age, condition, and construction specifications. The dike module should be



	Initial	2025	2050	2075	2100
Regularly-flooded Marsh	3964	3244	1579	377	178
Estuarine Open Water	3243	3997	4938	6784	8465
Inland Open Water	2204	2203	2202	2202	2202
Inland Fresh Marsh	2148	2144	2121	2117	1614
Irregularly-flooded Marsh	768	563	297	198	142
Swamp	533	511	442	395	331
Undeveloped Dry Land	358	335	320	300	256
Developed Dry Land	98	98	98	98	98
Tidal Swamp	89	81	66	59	51
Estuarine Beach	79	68	47	45	32
Tidal Fresh Marsh	60	59	57	55	38
Tidal Flat	15	259	1390	925	141
Transitional Salt Marsh	11	8	13	15	22
Total (incl. water)	**13571**	**13571**	**13571**	**13571**	**13571**

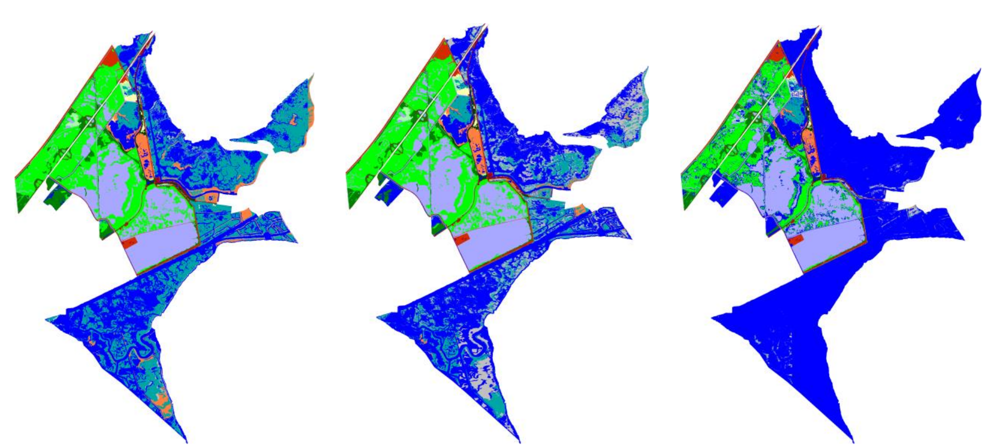


Figure 5. SLAMM results for Bayou Sauvage National Wildlife Refuge, Louisiana. Initial wetland distribution (upper left) and SLAMM output table (upper right) with results in hectares. Projections of wetland distributions are mapped for 2025, 2050, and 2100 (lower row, left to right). These projections are based on a sea-level rise schedule of 1 m from 1990-2100.

improved to incorporate such factors because information on these factors is often readily available. As with the dike module, ideas for improving the erosion, soil saturation, and barrier island overwash modules are already conceived. The limiting factor for module improvement is funding. For each of the variables involved, background research must be conducted to support module refinement. SLAMM must then be tested for smooth integration of module refinements, and ideally tested for performance with hindcasting (see e.g., Geselbracht et al. 2011).

A different type of model improvement would be the integration of a flexible wetland transformation flowchart. This would allow users to add and remove wetland categories and to reconfigure how categories are converted to others. A flexible flowchart would allow expert users to tailor the model to diverse types of coastal ecosystems from Gulf of Mexico Chenier Plains to Alaskan coastal wetlands.

Improving Data Inputs Re-SLAMMing should occur in all instances where SLAMM was applied in the absence of high-quality LiDAR data, especially if the original SLAMM analysis raised concerns about maintaining refuge purposes. SLAMM users should invest in LiDAR coverage in cases where none is forthcoming from other sources.

In many circumstances, the accretion rate is a key variable in determining the future of marshes. The most reliable data for accretion rates in specific areas come from the use of SETs (Cahoon et al. 2002). Approximately 20-30 refuges have functional SETs that are monitored periodically. All else being equal, more SETs are better, and ideally distinctive wetland units within a refuge are equipped with SETs. In the absence of SETs, well-communicated insights from field personnel and modelers are required for estimating appropriate accretion rates.

One more variable closely related to accretion is noteworthy. To capitalize on research pertaining to the relationship between inundation and sediment deposition, data sets on suspended sediment concentrations (SSC) are needed. In modeling threshold rates of sea-level rise, "above which marshes are replaced by subtidal environments," SSC is a key variable (Kirwan et al. 2010:3). Especially in cases where SLAMM has been run and where SSC is thought to be substantial and not already accounted for in the SLAMM analysis, re-SLAMMing may be appropriate based on the procurement of SSC data. The SLAMM accretion module may be tailored on a case-by-case basis to account for SSC.

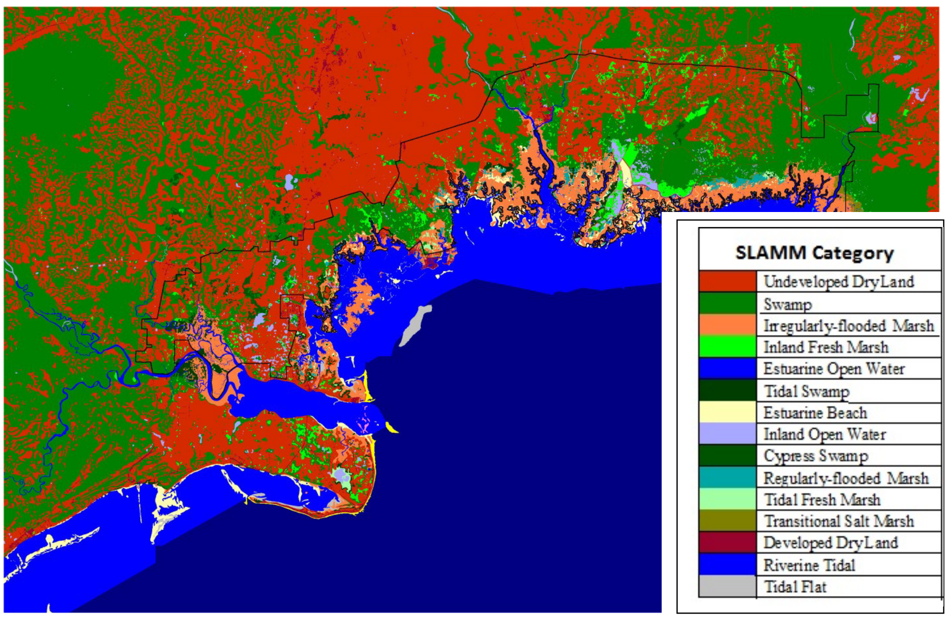
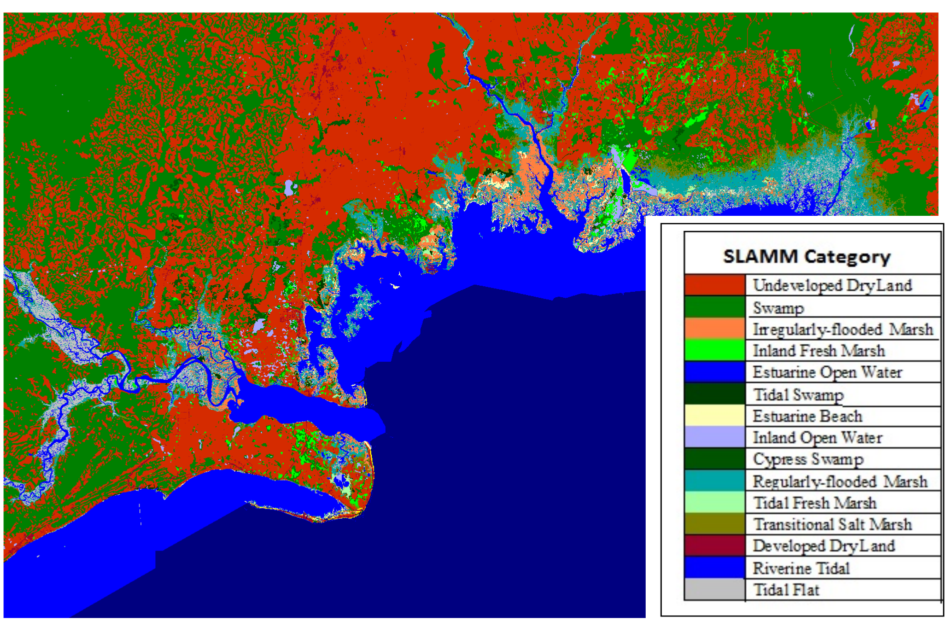


Figure 6. SLAMM contextual maps for St. Marks National Wildlife Refuge, Florida. Initial conditions are mapped above, with refuge boundary indicated by fine black line. Projections of wetland distributions are mapped for 2100 below based on the 1 m sea-level rise scenario.



CONCLUSION

As with most models, SLAMM will never be viewed as completed or perfect. It will be improved as wetland and sea-level rise science produces findings that clarify relationships among the numerous input variables. SLAMM will also change with the needs of coastal managers and the resources available for modeling. The need for adding processing capability, addressing additional issues, and developing more detailed algorithms must be balanced with the need to keep SLAMM transparent, wieldy, flexible, and affordable at the refuge, landscape, Regional, and Washington Office levels.

Despite the challenging uncertainties associated with sea-level rise, and even with SLAMM's limitations, this much appears certain: SLAMM is a useful tool in assessing the implications of sea-level rise on the Refuge System and meeting the mandates for climate change planning on coastal refuges. ■

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DISCLAIMER

The use of trade names and reference to proprietary software is for informational purposes only and does not constitute endorsement by the U.S. Fish and Wildlife Service.

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