ABSTRACT: During massive cleanup of a heavily oiled saltmarsh, much of the surface sediment was removed to a depth of about 50 centimeters (cm), exposing in places the underlying granitic basement. This has resulted in a marked increase in the marsh cross-sectional area, in its tidal prism, and in the current velocities through the marsh. As a result, the marsh is undergoing increased erosion and invasion of sand from offshore stocks. Observations of sand transport 1 year after the cleanup, as well as the formation of megaripple and sheet-flow characteristics 2 years after the cleanup, indicate an increase in current velocities from a pre-spill average of 0.5 meters per second (m/s) to 1 m/s, and exceeding 1.7 m/s in the main channel of the marsh.

A 2-year study of geomorphological changes in the marsh has shown that the normal pre-spill colonization rate of the marsh (28 to 90 cm/yr) has changed to a net erosion (6.5 to 17 m/yr). Increased current velocities have resulted in erosion of the exposed marsh surfaces and undercutting of the secondary and tertiary marsh tidal channels.

Residual oil, left behind from the cleanup, is being trapped under sandbars. Pockets of such oil-permeated sand deposits represent potential long-term storage reservoirs available for later release.

Marsh recovery to pre-spill state depends critically on the reduction of its tidal prism and of the current flow through the marsh. Based on the depositional rates for this marsh and others, this is expected to be a very slow process, unless perhaps it is enhanced by replanting saltmarsh vegetation in denuded areas.

Introduction

The Ile Grande saltmarsh, located on the north shore of Brittany, France, was heavily oiled following the breakup of the supertanker Amoco Cadiz in March 1978. The marsh lies at the northern tip of the Lannion peninsula, and because of its northwesterly exposure lay directly in the path of oil slicks moving easterly along the north Brittany coastline (Figure 1). During the first month after the breakup, oil slicks drifted into the marsh entrance more or less continuously, and eventually oil
covered the marsh to a depth of 5 to 20 cm. In some pools, the oil reached depths of 50 cm.

Because of the extreme oiling, and because previous experience had demonstrated the futility to attempt recovery of such an extremely heavily oiled marsh, the decision was made to remove the oil using heavy machinery (Hann et al., 1978). In the process, a considerable quantity of the marsh vegetation and underlying sediments was removed, resulting in a sharp change in the marsh cross-section and in the velocities of currents through some parts of the marsh. These changes have been described in a preliminary note (Long and Vandermeulen, 1979). The following sections provide greater detail on the marsh sedimentology and on the changes in the marsh ecosystem, including the formation of sandbars and the burial of residual oil. The expected recovery rate and potential terms of the changed sedimentary system is also discussed.

**Observations**

**Pre-oiling geomorphology.** The saltmarsh of Ile Grande is one-half of a two-bay system, in which the saltmarsh occupies the western half (Figure 1). The two bays are connected by a narrow, shallow neck, which forms the roadway from the mainland to the island. The channel effectively divides the system into two parts, with the channel functioning only at high tide.

The western part of the system, the Ile Grande marsh, is about 1.2 kilometer (km) long by 1 km wide, and covers an area of about 120 hectares (ha). Its western entrance (250 m) lies directly exposed to the dominant westerly wave and wind action of the Channel. The eastern half of the system is slightly larger (2 x 1.5 km), and has its entrance to the northeast (100 m). Thus the saltmarsh in the strictest sense of the word is not a true marsh in that it has two entrances—one to the west near Pointe de Tomot, and the second to the east through the narrow channel into the second bay—with potential water flow in both directions through the entire system. However, because of the shallow constriction at the roadway to the island, the main tidal wave passes into the marsh from the western entrance near Pointe de Tomot, whereas the eastern entrance functions only infrequently, during Spring tides.

The tidal current in the marsh before the oiling was generally less than 0.5 m/s, with peak velocities in the main channel up to 1 m/s during maximum flow periods. The marsh system is a low wave-energy system, with wave energy highest at the Pointe de Tomot entrance and decreasing from west to east. Wave action for the marsh becomes important only for the short period during the high tides.

Geologically, the Ile Grande saltmarsh is a typical marsh system, including normal development through a series of low-energy depositional stages (Figure 2). Following sand deposition and sand-flat formation during the Holocene transgression, the marsh was formed by a combination of vegetative colonization and silt entrapment. The bedrock is Hercynian granite, overlain by a layer of detritic material formed in situ (kaolin and cobble/sand). Overlying this granitic detritus layer is a layer of sand, brought in during the sea-level changes (Figure 2B). The resulting sand-flat in turn formed the basis for colonization by vegetation, with the vegetation playing a major role in entrapping and holding finer sediments (Figure 2C). Sedimentation rates during this period were low, calculated at less than 2 millimeters per year (mm/yr) (Long, 1975). With time, the water flow decreased and the sedimentation rates increased correspondingly. The rate of coloni-

**Post-cleanup geomorphology.** During the days immediately following the spill, a barricade was built across the narrow channel connecting the marsh with the eastern half of the bay system. Though this measure did help in keeping the oil from entering the back half of the system, it also resulted in a buildup of oil in the marsh proper. Eventually much of the oil was deposited onto the vegetation lining the various marsh channels; in the end most of the marsh up to the limit of the high-tide line became oiled.

Cleanup efforts consisted of a combination of manual and mechanized efforts, including front-end loaders and crawler-equipped machinery (Hann et al., 1978). Secondary and tertiary marsh tidal channels were deepened to promote oil drainage from the grassy regions of the marsh. Pits and trenches were dug to collect the oil. The net result was that, together with the removal of oil and oiled vegetative matter, the top sediment layer was also removed from either side of the main marsh channel, in some places down to 75 cm or more. With this removal of the surficial mud layer, and in many places the underlying sand layer as well, the granitic basement has become the new erosion surface for much of the schorre-part of the marsh (Figures 2D, 4).
During 1979, one year after the cleanup, initial study of the effects showed erosion of the deepened secondary channels, together with a deposition of sand in the primary channel and onto the bordering tidal flat. There was the beginning of formation of a ripple-zone in the main marsh channel, and of a sandbar in the large open middle section of the marsh.

In 1980, erosion of the new vertical channel walls had increased considerably, with undercutting of the walls as much as 10 cm in many instances (Figure 5). Mapping of the July 1980 erosion line for the entire marsh showed a regression of the erosion line along its entire length since 1978 (Figure 3), with maximum regression in the schorre-part of the marsh. Prior to 1978, the colonization rate for the schorre-part was about 90 cm/yr for its north shore and 28 cm/yr for the south shore (Figure 3). However, in the period 1978 to November 1980, this changed to a net erosion of 17 m/yr for the north shore and 6.5 m/yr for the south shore.

In July 1980, sand was found deposited throughout the marsh, both within the deepened channels and up onto the vegetative parts of the marsh (Figure 5). New sandbars were formed in the entrance to the schorre-part of the marsh (Figures 6, 7) and an extensive megaripple area has been mapped, with individual megaripples averaging 2.5 m in length by 10 cm in height. Sand movement in the main channel was marked by sheet-flow.

In several places throughout the marsh, and especially in the main channel, quantities of oil have become entrapped within and under these new sand deposits (Figure 8). This buried oil is quite liquid and appears little changed from the oil that came ashore in the marsh in March and April of 1978.

**Discussion**

Probably the most important factor that determined the fate of this saltmarsh was the bulldozing of the main tidal area, and the deepening of the secondary and tertiary channels. While these actions no doubt aided in draining off the spilled oil, they also drastically increased the water flow through the marsh and encouraged marked erosion of the remaining vegetative areas.

With the removal of much of the surface sediment, the cross-sectional area and the tidal prism of the marsh were increased, resulting in current velocities exceeding those normally found in these low-energy, low-velocity systems. This is evidenced by the
period 1979–1980 increased considerably, as shown by the formation of megaripples and sheet-flow in the main channel. The former requires currents of 1 m/s, whereas sheet-flow occurs at velocities of 1.5 to 1.7 m/s (Komar and Miller, 1974). These velocities far exceed the threshold limits of the marsh depositional process, and will continue to function in the ongoing erosion of the marsh surface.

The problem is compounded by the deepening and instability of the drainage channels. In most cases after the deepening, the walls of the channels consisted of vertical walls, which tended to erode more rapidly than more sloping channel walls. Furthermore, in the deepening process the surface mud layer was removed and the underlying sand layer became exposed. Thus oil draining from these channels had ready entrance into the sand layers lining the channels. Further, the increased currents through these drainage channels (throughout the marsh the bottom of the channels, because of the deepening, came to lie below the terrain of the marsh) have generally added to the erosion of the marsh, and particularly to the erosion of the peripheral vegetated areas.

Since the original terrain of the marsh was a direct function of the vegetative cover, it is likely that with the removal of this cover a new depositional regime will be created in which the equilibrium of the new system will be very close to that of the stage of the sand-flat (Figure 2b).

Probably the crucial factor in the natural recovery of the marsh—that is a return to a pre-spill state—is the reduction of the tidal prism (i.e., reduction of the current velocity through the marsh). This could be done by damming the marsh, but that would bring with it other problems and other changes in the marsh. Probably the best natural way to effect recovery is by mass planting of marsh vegetation, taking into consideration the various current regimes within the marsh. Thus revegetation of the tidal flats directly adjoining the main channel is likely to be unsuccessful because of the higher currents. But a massive replanting effort would in time result in the necessary entrapment of the finer sediments, with, in the long term, a slow but positive reduction of the marsh cross-sectional area. (It may well be that the present influx of sand masses is already aiding in this reduction to some degree.) If the marsh is left untouched, spontaneous recovery may require centuries.
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References


