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OIL POLLUTION CONTROL. A COOPERATIVE EFFORT

ENVIRONMENTAL ASSESSMENT AND RESTORATION RECOMMENDATIONS FOR A MANGROVE FOREST AFFECTED BY JET FUEL

Thomas G. Ballou[1]
RPI International
P.O. Box 328
Columbia, South Carolina 29201

Roy R. Lewis, III
Mangrove Systems
P.O. Box 290197
Tampa, Florida 33687

ABSTRACT: *A jet fuel spill in Ensenada Honda, Naval Station Roosevelt Roads, Puerto Rico, was investigated to determine impacts on mangrove communities and to develop a mitigation plan to reverse the damage. The spill caused rapid, widespread damage to mangroves, killing almost six hectares of forest. Residual contamination of water and sediments was very low.*

Mitigation recommendations were developed for this incident and other mangrove forests affected by oil spills. The recommendations place primary emphasis on natural recovery, with additional actions to increase colonization and/or survival of propagules as needed.

On November 27, 1986, a spill of jet propulsion fuel (JP-5) was discovered in Ensenada Honda, Naval Station Roosevelt Roads, Puerto Rico (Figure 1). The spill was traced to Tank 85, which had a capacity of over 900,000 gallons. Fuel had leaked through a newly installed tank bottom and out a drain pipe, flooding an adjacent catchment depression and eventually flowing into Ensenada Honda. Winds then carried the spilled fuel across the bay, where approximately 59,000 gallons collected against the Coast Guard pier and an adjacent mangrove forest.

Two areas were affected by the spill. The northernmost area is a red mangrove *(Rhizophora mangle)* forest drained by a tidal creek. The trees here are moderate-sized and grow in thick, soft sediments. The second area is located north of and immediately adjacent to the Coast Guard pier. The mangrove forest here consisted of a mixed species assembly of moderate-sized red mangroves, white mangroves *(Laguncularia racemosa)*, and black mangroves *(Avicennia germinans)*. The forest in this area has several species assemblages and growth forms. The landward edge of the forest is dominated almost exclusively by large black mangroves, with moderate understory development. Just seaward of this black mangrove area is an extremely dense, mixed-species zone; the forest here has a very dense canopy and understory and the general appearance of a relatively young forest. The edge of the affected area (defined by total defoliation of adult trees) passes through this mixed-species zone, which is relatively narrow compared to the black mangrove forest and the next seaward zone, the red mangrove-dominated zone.

The red mangrove-dominated zone is composed of small- to medium-sized trees, almost all of which were killed by the JP-5 spill. Located in the middle of this zone are two large and several very small lagoons. The lagoons are very shallow and have thick, soft mud sediments. They appear to be persistent features of this area, judging by their areal extent both north and south of the Peri Road, and by the scarcity of any trees or seedlings colonizing the bare mud surface.

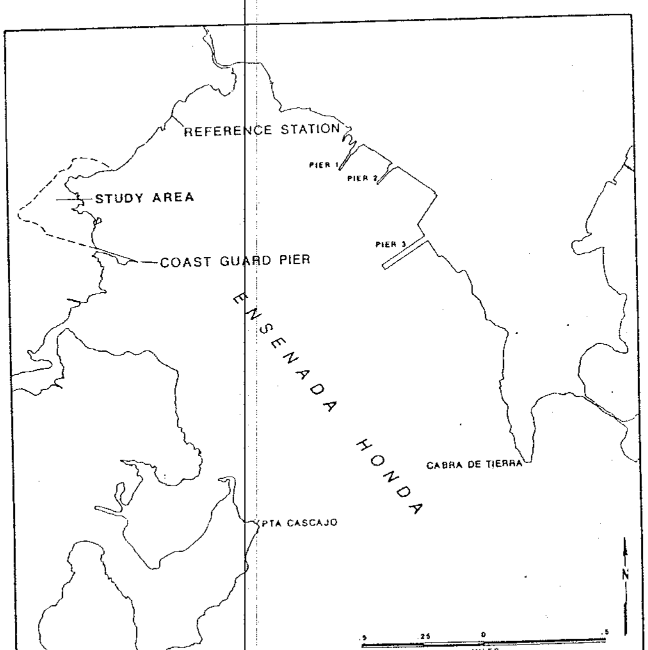

Figure 1. Map of Ensenada Honda, Puerto Rico, showing the study area and reference station

1. Current address: Wilbur Smith Associates, P.O. Box 92, Columbia, South Carolina 29201

Several species of wading birds were observed feeding in these lagoons. The most common was the black-necked stilt *(himantopus mexicanus)*, which was observed feeding every day during the two site visits, and which was observed nesting in April 1987 at two locations near the edges of the large lagoons.

The most seaward zone of the study area was a fringing mixed forest. Red mangroves tended to dominate this zone in tree height, but white mangroves were also abundant here.

Methods

The affected mangrove forest north of the Coast Guard pier was surveyed twice, from April 28 to May 2, 1987 (152 days post-spill), and then again from October 21 to October 24, 1987 (328 days post-spill). Three transects were established through the forest (Figure 2), and a number of detailed biological measurements were taken at stations located on each transect. A detailed characterization of the mangrove forest was developed from data collected on Transect 1 only. This transect was determined to represent the entire affected area based on visual observations of the affected area.

Six stations were established on Transect 1. Four of these stations were selected for detailed study (Stations 1, 3, 4, and 6). At each of these stations, a 10 × 10 m^2 plot was measured and marked. Within this plot, all adult trees were identified, by species and as dead or alive, and then were measured to determine their height and diameter at breast height (DBH). DBH is measured at 1.3 m above the forest floor. Measurements were also taken to determine the amount of open canopy.

Tree height was measured using an optical range finder (Opti-meter Ranging, Inc., Rochester, N.Y.). DBH was measured using a DBH tape measure that converts circumference directly to diameter. Canopy coverage was measured using a spherical densiometer, a hand-held device that uses a convex mirror over which a grid pattern is etched. The amount of open space in the tree canopy observed on the mirror surface is then converted to percent open canopy.

All seedlings present in the study plots were counted and marked using surveyor's flagging tape. Measurements of the density of mangrove fauna (crabs, snails, and other organisms present on the forest floor or on the mangrove roots) were taken using a 0.5 × 0.5 m^2 quadrat. This quadrat was placed in five randomly selected locations within the study plot, and the number of animals inside it were counted.

At all of other sites in the affected area (Transects 2 and 3), measurements were made of canopy coverage, tree height, seedling density, and animal density only.

On the central transect (Transect 2), sediment and water samples were taken at four stations located at approximately equal intervals along the transect. Four additional water samples were taken at various locations in the study site.

A fourth transect was established in a neaby unaffected mangrove forest located approximately 1 mile north of the Coast Guard pier. On this transect, two detailed stations were established. All measurements conducted at the detailed stations on Transect 1 were made at the 2 stations on Transect 4. In addition, a set of water and sediment samples were taken at one station on this transect, and an additional water sample was taken at the outer fringe of the forest.

Each sediment sample was taken using a 2-inch-diameter aluminum core that had been washed with soap and water and rinsed in hexane. Each core sample was divided into 2 subsamples (0–10 cm and 30–50 cm intervals). The subsamples were then placed in hexane-rinsed glass jars with aluminum-foil-lined lids. Water samples were taken by scooping water directly into hexane-rinsed glass jars. All samples were stored on ice until analyses were conducted.

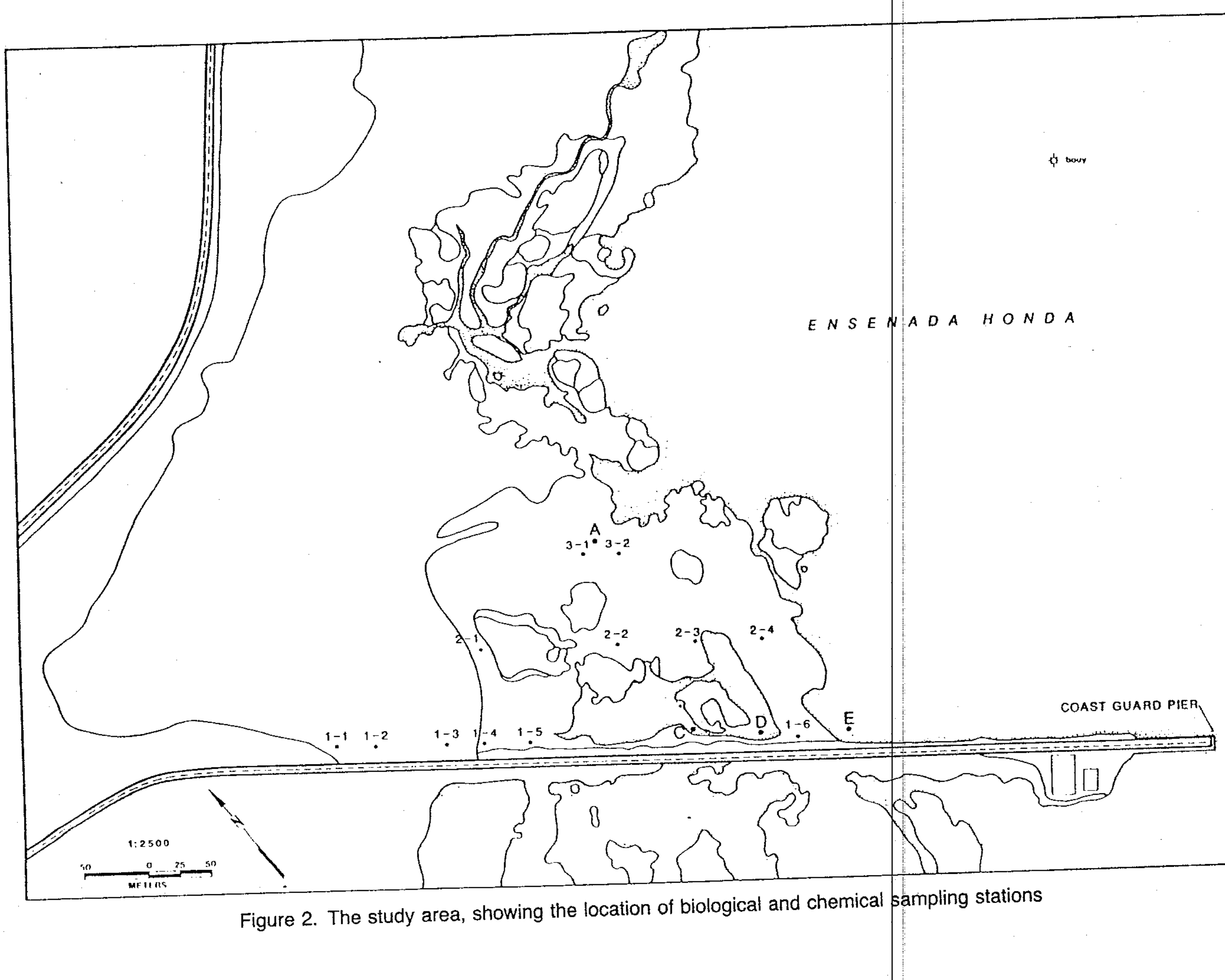

Figure 2. The study area, showing the location of biological and chemical sampling stations

In June 1987, a false-color infrared aerial photograph of the affected area was taken of the study area. This photograph was analyzed to identify unaffected areas, partially defoliated areas, and completely defoliated areas.

During the second site survey (October 21 to 24, 1987), all measurements (except adult tree density and DBH) were repeated, and a second set of chemistry samples was taken and analyzed. At this time, a brief site inspection was made of the affected tidal creek forest located north of the main affected area. Visual observations were made of the forest type, species composition, sediment characteristics, and level seedling colonization.

Investigations were also conducted on the physical and chemical properties of JP-5, to relate these properties to the observed toxic effects.

Restoration and mitigation actions were evaluated to identify the most cost-effective and environmentally acceptable approach to reversing the impacts caused by the spill.

Results

Chemical and physical properties of JP-5. Aviation turbine fuel, grade JP-5, is a high flashpoint, kerosene-type, refined petroleum product. It is composed of a variety of petroleum hydrocarbons, including alkanes, cycloalkanes, and aromatics, most of which are C_{10} to C_{16} molecules. The relative proportion of each varies slightly, but the aromatic fraction is generally about 20 percent by volume, and the alkanes and cycloalkanes make up the remainder. The military specification for JP-5 requires that it have a maximum of 25 percent aromatic hydrocarbons.

JP-5 is a relatively light refined oil that has low viscosity. Military specifications require viscosity less than 8.5 centistokes at −20°C or 16.5 centistokes at −34.5°C. Thus, JP-5 is very thin and tends to spread rapidly on the water surface when spilled. JP-5 is also highly volatile and tends to evaporate very rapidly. Estimates made by the National Oceanographic and Atmospheric Administration Hazardous Materials Response Branch during the spill on November 29, 1986, indicated that approximately 70 percent of the spilled JP-5 would evaporate within 24 hours.

The fuel in this spill had been treated with icing inhibitor (ethylene glycol monomethyl ether, 0.15 percent by volume). No other additives were present in this fuel when spilled.

Biological investigations. The field surveys and aerial photograph revealed widespread damage to the mangrove forest north of the Coast Guard pier. Figure 3 shows the distribution of unaffected, partially defoliated, and completely defoliated forest. A total of 5.5 hectares (ha) (13.7 acres) of mangroves were completely defoliated, and 0.8 ha (2.0 acres) were partially defoliated.

Tables 1 and 2 summarize measurements of adult and juvenile mangroves at each station. Stations 1-1 and 1-2 were located in the black mangrove *(Avicennia)* forest immediately adjacent to the affected area. No impacts to the forest at these stations were observed.

Station 1-3 is located in a mixed-species zone with red mangroves, white mangroves, and black mangroves present in approximately equal abundance. The forest at this station was extremely dense, with many small- to medium-sized trees. Basal area (15.98 m^2/ha) and density (2.62 trees/m^2) were high, indicating a dense, thick stand of trees. Canopy coverage also was very high, with only a small percentage of the canopy open. Seedling density was relatively low (0.25 and 0.77 seedlings/m^2 in May and October 1987 respectively).

Stations 1-4 and 1-5 are located in the central area of the affected forest. These stations were dominated by red mangroves, Adult density, basal area, and height were somewhat lower than at Station 1-3.

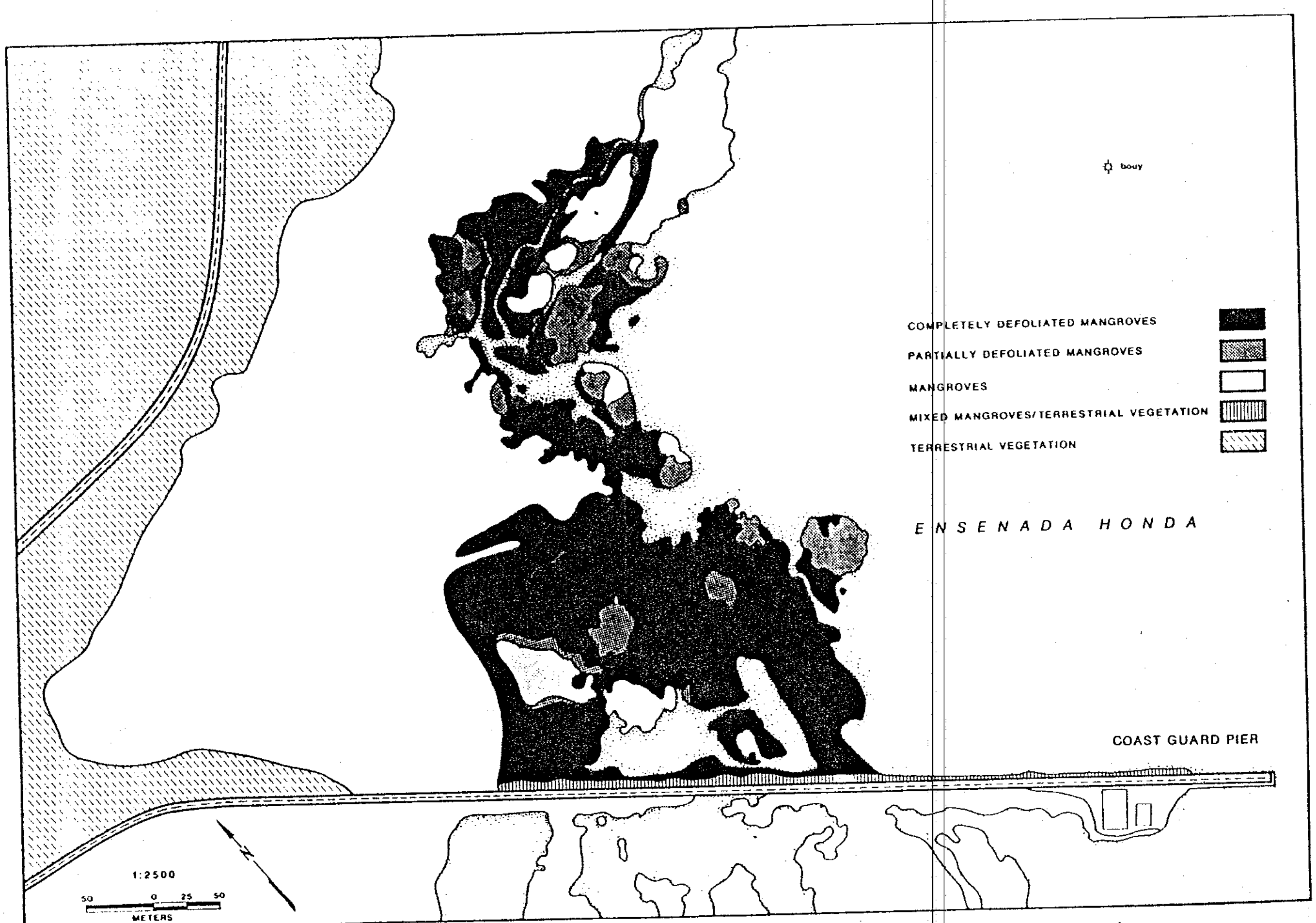

Figure 3. Distribution of completely defoliated, partially defoliated, and unaffected mangroves in the study area

Table 1. Results of measurements at stations on Transects 1 and 4 taken in April–May 1987[1]

Transect-station	Adult density (number/m²)	Basal area[2] (m²/ha)	Height (m)	Species composition (percent)	
1–1	0.18	10.15	8.5	*Avicennia*	(100)
1–2	NM	NM	8.2	NM	
1–3	2.62	15.98	7.0	*Laguncularia* *Rhizophora* *Avicennia*	(40.8) (32.4) (26.8)
1–4[3]	1.74	7.81	4.8	*Rhizophora* Other	(71.8) (28.2)
1–5[3]	NM	NM	4.3	NM	
1–6[3]	1.70	13.53	5.5	Other *Rhizophora*	(62.3) (37.7)
4–1	3.11	12.71	4.0	*Laguncularia* *Rhizophora* *Avicennia*	(74.6) (23.6) (1.8)
4–2	0.38	16.87	7.9	*Rhizophora*	(100)

1. NM = not measured.
2. Basal area was determined using measurements from trees with DBH greater than or equal to 2.5 cm.
3. All trees present at these stations were dead.

Seedling densities were about the same at Stations 1-3, 1-4, and 1-5. All of the adult trees at Stations 1-4 and 1-5 were completely defoliated.

Station 1-6 is located on the outer fringe of the affected area. The forest here was also a mixed-species forest, but it was not possible to determine the relative proportion of white and black mangroves because all the trees here were dead, and these two species are very difficult to distinguish in this condition. Adult density and basal area were very similar to that measured at Stations 1-3 and 1-4. The most striking feature of Station 1-6 was the high number of seedlings present (4.77/m² and 4.65/m² in May and October 1987 respectively). This high value undoubtedly owes to close proximity to the open water of Ensenada Honda. Proximity to the ocean allows much higher rates of colonization from other areas, and it creates a more favorable growing environment for mangroves.

The results of on-site investigations at the remaining stations in the affected area are summarized in Table 2. These results basically mirror those for Stations 1-4 to 1-6, with all adults being dead and completely defoliated, and seedling density being low to moderate in the interior portions of the site and very high on the outer, exposed portions.

Visual inspection of the affected tidal creek forest north of the main affected area in October 1987 also indicated severe damage to the mangroves there. The tidal creek channel apparently acted as a conduit for the spill, as the forest on both sides of the creek was completely defoliated. Large numbers of newly sprouted seedlings were evident throughout the area inspected.

Stations 4-1 and 4-2, located north of the Coast Guard pier in an unaffected mangrove forest, show many of the same trends as seen in the affected area, except almost all of the adult trees were alive and healthy. Station 4-1 is a mixed forest dominated by white and red mangroves. Values for adult density and basal area are high. The forest here appears to be growing on a fill area, becuse the sediments are overlain by a layer of carbonate mud and sand. Station 4-2 is a typical, mature, fringing red mangrove forest with moderate adult density and basal area, a very dense canopy, and high seedling density.

As part of the biological investigations conducted at each station, a number of red mangrove seedlings were marked in May 1987 and then reexamined in October 1987 to determine mortality rates. These data are summarized in Table 2. Seedling mortality was highly variable among stations, but appears to be correlated with the degree of exposure to the open ocean. Seedlings at Stations 1-6, 3-2, and 4-2 (located on the edges of the study area) all had relatively high survival rates, although seedlings at Stations 2-2 and 3-2 also showed high survival, and seedlings at Station 2-4 somewhat lower survival. In any case, the observed overall mortality rates of seedlings in the affected area did not appear to be exceptionally high.

Chemical investigations

Sediment samples. Figure 2 shows the location of each sampling station in the study area. The results indicate that there was a very low level of residual contamination by petroleum hydrocarbons. The highest concentration of any individual hydrocarbon compound measured was 247 parts per billion (ppb) toluene at Station 2-2 (30-50 cm depth interval). All other concentrations were much lower and, in many cases, below detection limits (less than 10 ppb). Total volatile hydrocarbon concentrations were also very low (100.0–423.4 ppb).

Station 4-2 is located at the reference site, approximately 1 mile northeast of the Coast Guard pier. This site was not affected by the JP-5 spill. Sediment samples taken at Station 4-2 show evidence of contamination by petroleum hydrocarbons from an unidentified source (Table 3). Previous investigations into chemical contamination of terrestrial and aquatic habitats at U.S. Naval Station Roosevelt Roads include several reports of previous oil spills, including the release of approximately 210,000 gallons of diesel fuel from the tanker ship *Arco Prestige* in 1981, a diesel spill from Tank 1080 in 1978, and a Bunker C oil spill in 1958 from Tank 82. All of these spills contaminated mangroves in Ensenada Honda, although it is not clear from reports whether measurable impacts (beyond contamination of sediments) occurred to these mangroves. This pattern of successive, large spills is typical of many port facilities. Combined with much more frequent releases of gasoline and lube oil from small craft operating at the marina, petroleum hydrocarbons would be expected to be ubiquitous in this area.

Visual observations at various locations in the study area indicated that there was some residual contamination of sediments, as indicated by the release of oil sheen at a few locations. Although no sediment samples were taken in the affected tidal creek forest, there was clear evidence of previous oil contamination there. Disturbance of bottom sediments at this location resulted in release of small blobs of thick, black oil that floated to the water surface and then slowly spread out into sheen. This oil appeared to be Bunker C fuel oil judging from its dark color and high viscosity. The source of this oil is possibly the 1958 Tank 82 spill.

Water samples. The concentration of volatile aromatic hydrocarbons in all water samples analyzed was below detection limits (less than 10 ppb). The other water-quality parameters measured were highly variable among stations and are indicative of relatively poor water quality resulting from restricted water circulation, high evaporation rates, and high levels of organic materials in the water and sediments.

The analytical data reported here and observations made in the

Table 2. Summary of data on additional biological parameters from the study sites[1]

Transect-station	Canopy coverage (percent open canopy) May 1987	Canopy coverage (percent open canopy) October 1987	Seedling density (number/m^2) May 1987	Seedling density (number/m^2) October 1987	Seedling mortality (percent)
1–1	15.6	15.4	114[3]	116[3]	NM
1–2	15.8	2.4	66[3]	146[3]	NM
1–3	7.2	3.4	0.25	0.77	48
1–4	100.0	100.0	0.55	0.33	48
1–5	100.0	100.0	1.03	0.53	61
1–6	100.0	100.0	4.77	4.65	3
2–1	96.6	97.8	0.57	0.41	33
2–2	100.0	100.0	5.53	3.23	2
2–3	100.0	100.0	2.82	2.60	22
2–4	100.0	100.0	11.19	12.76	40
3–1	95.4	100.0	0.38	0.75	23
3–2	100.0	100.0	16.93	13.83	14
4–1	18.4	18.8	0.62	0.73	44
4–2	3.4	3.8	5.65	5.11	22

1. NM = not measured.
2. Mortality of marked *Rhizophora* seedlings between May and October 1987.
3. These seedlings were all *Avicennia*; at all other sites, all seedlings were *Rhizophora*.

field indicate that the residual concentrations of JP-5 in sediments and water are very low and equivalent to those measured at a nearby unaffected mangrove forest. This result is probably due to the local climate and the physical characteristics of JP-5, which tend to promote very rapid removal of hydrocarbons through evaporation. Residual levels present probably represent a combination of the JP-5 and low-level input from nearby marina operations.

Discussion

Given the relatively high proportion of low-molecular-weight hydrocarbons in JP-5, its low viscosity, and high evaporation rate, the primary mode of toxicity of JP-5 to the mangroves in Ensenada Honda appears to be direct toxic poisoning. There was little or no physical smothering effect, as has occurred at mangrove forests exposed to heavy petroleum products. The rapid onset of defoliation and death of adult mangroves and the low concentration of residual hydrocarbons in the sediments tend to support this view. On-site observations by local spill response personnel indicated that visible effects on adult trees occurred within 10 days, but numerous seedling mangroves appeared to have survived the spill. These results together suggest that fuel was absorbed into the exposed pneumatophores (aerial gas exchange organs in white and black mangroves) and into the prop roots of the red mangroves, resulting in toxic effects to the adult trees. The seedlings had higher survival rates, possibly because their root systems were buried in the sediments and thereby able to avoid direct toxic exposure. It is likely that some of the seedlings were killed by the fuel, but no detailed measurements of survival during and immediately after the spill were made. Observations during our on-site surveys in April and May 1987 did show that a considerable number of seedlings survived the spill.

Recovery of damaged mangrove forests depends on two factors: adequate supply of mangrove seeds and acceptable growing conditions for these seeds. Seeds may either be produced locally within the forest or come from nearby forests. There are a few small patches of healthy mangroves located in the middle of the study area, many of which were observed with flowers and seeds in October 1987, the first major new recruitment period for seeds since the spill. These trees, combined with the relatively large mangrove forest present elsewhere in Ensenada Honda, probably will be able to supply enough seeds to recolonize the entire study area. Measurements of seedling density in October 1987 indicate that most of the new colonization is probably occurring from seeds produced outside of the study area, because of the very high seedling densities measured on the outer fringes of the area. Seedling densities were much lower in the central portion of the study area but are probably sufficiently high to allow adequate regrowth.

Growing conditions are affected by several factors, especially residual contamination and the amount of flushing by clean seawater. Residual contamination can kill mangrove seedlings if levels are too high. Analyses of sediment and water samples indicate that residual levels of jet fuel are very low and not appreciably different than those measured at the reference station that appears completely normal. It is safe to conclude that residual contamination from the spill will have no long-term effects on recovery.

Degree of flushing is an important factor because it affects local growing conditions within the forest. Adequate flushing and circulation of surface waters stabilize surface and interstitial water salinities, bring in nutrients, and increase colonization rates. The tidal cycle in Puerto Rico is semidiurnal (two high and two low tides daily), with a diurnal inequality and a maximum range of 0.2 m (0.8 feet). High tides less than about 0.3 m (0.9 feet) above mean sea level (MSL) are unlikely to result in significant flushing of the intertidal portion of the study area. Because of seasonal fluctuations in tidal height, high tides are greater than 0.3 m (0.9 feet) MSL only 4 to 8 times per month during January to June, but during July to December the higher high tide exceeds this height almost every day, and the lower high tide is close to this height several days per month. As a result, there are extended periods of time when there is relatively little flushing, expecially in the central portions of the study area, where there is no direct access to the ocean.

Because of the relatively low flushing rates in the central portion of the study area, newly sprouted seedlings there may experience less than optimal survival and growth rates, thereby slowing recovery of the mangrove forest. Current colonization and survival rates there are within acceptable ranges but are well below rates measured on the outer edges of the area.

Measurements of seedling density, seedling mortality, residual sediment contamination, and local tidal conditions were evaluated to determine mitigation actions for affected mangrove forests. General recommendations were developed for the particular situation described above, but they also applicable to a wide range of other situations involving mangrove forests affected by oil spills.

Restoration and mitigation actions. A number of possible restoration and mitigation actions were considered to reverse the adverse impacts of the spill. The use of any cleanup technique, such as low-pressure flushing, was not necessary in light of the very low residual contamination levels present in the sediments in the main affected area adjacent to the pier. Removal of dead mangroves also was not recommended. The only benefit of this action would be esthetic improvement of the area, and at a high economic and environmental price. Removal of dead trees would result in damage to thousands of live mangrove seedlings, would eliminate the existing functional fish and invertebrate habitat, and would result in no improvement in recovery.

The actions discussed below were developed as separate options that represent a series of restoration actions: they may be taken successively, depending on the success of the previous operation. Each option may be carried out independently of the others, but the mitigation plan was designed with the idea that Option 1 be tried before Option 2, and so forth, with primary emphasis on natural recovery, followed by more intrusive and expensive actions only if natural recovery were in some way impeded.

Option 1. No action. Option 1 would allow natural recovery to occur, with periodic (annual) monitoring of the area to evaluate the progress of natural colonization and seedling growth. The affected area probably would recover (in the absence of future spills) within about 10 years. Our assessment of the area indicated that this process is already occurring, although there is a significant difference between the inner and outer portions of the area in the rate of colonization by new mangroves. The main negative aspect of this alternative is that recovery probably would proceed at an unequal pace, with the central portion of the area lagging considerably behind the outer portions. The complete recovery of the area would probably be delayed by several years.

Option 2. Selected replanting. Replanting of those areas determined to be deficient in naturally colonizing seedlings would help to equalize the recovery rate of the entire area. This operation would be conducted manually, using locally collected seeds. It would focus on those portions of the study area where seedling density is less than 1 seedling/m^2. This option is recommended only when the primary impediment to recovery is seed availability. When the primary impediment is seedling survival, Option 3 is recommended.

Option 3. Opening of channels. Option 3 would increase the level of flushing in the central portion of the affected area, thereby improving growing conditions and increasing the survival and colonization rates of seedlings. Some benefit might be gained in reducing sediment contamination levels (that are already very low), but the primary benefit would be in improving growing conditions by increasing flushing and circulation within the study area. As discussed above, the interior of the study area is poorly flushed much of the year; excavation of a channel into the most sheltered portion of the area would increase flushing and natural invasion of seeds and, as a result, would improve density, survival, and growth rates of mangroves there.

Excavation of channels into the area would be a relatively expensive and complex task compared to the other alternatives. The optimal location for a channel based on environmental and economic considerations would depend on local conditions, including access, location of live and dead mangroves, and nearby subtidal communities. Additionally, though Option 3 offers the potential for increasing flushing and circulation within the study area, it may also result in some undesirable changes. The primary concern is alteration of the natural hydrologic conditions. Significant increases in flushing could result in changes in the pattern of colonization by mangrove seedlings and ultimately in changes in the species composition of the various zones described above. Implementation of Option 3 thus presents a potential environmental trade-off that must be evaluated, in addition to the obvious economic considerations.

The options described above, when considered as a whole, represent a series of increasingly intrusive and expensive actions that could be pursued sequentially as the situation warrants. The first step would be to exercise Option 1 and allow natural recovery to proceed. If monitoring indicated that recovery was not occurring at an acceptable rate, Option 2 or 3 then could be exercised, depending on the reason for slow recovery. Option 2 would be exercised if recovery was impeded by lack of seeds in certain areas. Option 3 would be exercised if natural colonization was adequate, but survival of seedlings was low. This course of action is recommended because it poses the least additional disturbance and the lowest costs appropriate for the situation.

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