# Experimental Study of the Ecological Impact of Hot Water / High Pressure Cleaning on Rocky Shores

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## Abstract

Cleaning up oiled shorelines is a paradox in that the most efficient methods are often the most detrimental from an ecological point of view. According to most literature, such is often the case when using high pressure, hot water to clean up oiled rocky shores. The goal of this ongoing study is to define values of water temperature and pressure which remain effective and minimize ecological effects, with the aim of providing operational recommendations.

The first step was to determine effective combinations of temperature, pressure and duration of treatments; these combinations were then applied *in situ*, without oil, on several biological communities among the most common on temperate rocky shores.

The results show that pressure, higher than 170 g/m² on the substratum, has the most harmful effects whereas temperature, between 25 and 53°C, has only minor effects. The most sensitive taxa are the foliaceous lichens and the barnacles. Crustose lichens and algae, brown algae: *Pelvetia* and fucoids, are found to be tolerant to both pressure and temperature. Moreover, the seaweeds protect the underneath epifauna.

## 1.0 Introduction

When an oil spill occurs on rocky shores, high pressure / hot water cleaning is commonly used to remove the oil. However, from an ecological point of view, this technique is said to induce more detrimental short term effects than the oil itself (Broman *et al.*, 1983; Houghton *et al.*, 1991; Lees *et al.*, 1993). Moreover, due to these acute short terms effects, cleanup does not enhance recovery and, in worst cases, even delays it (Houghton *et al.*, 1993; Houghton and Gilmour, 1995; Houghton *et al.*, 1997; Stekoll *et al.*, 1993). After exhaustive screening of literature dealing with ecological impacts of oil spills and subsequent cleanup operations on rocky shores, Sell *et al.* (1995) concluded that, in most cases, there were no scientific justifications for shore treatment. However, it is admitted that cleanup might be justified by socioeconomic factors for example, but also by the necessity to eliminate a potential source of pollution susceptible to affect a nearby clean sensitive area. When removal of oil is necessary, a trade-off has to be found between cleanup and ecology. For such cases however, operational recommendations on how to minimize ecological impact largely remained to be defined.

This problem has already been tackled by Mauseth *et al.* (1996), about optimization of hydraulic cleaning of rocky shores. They concluded that, with regards to temperature, seaweed (*Fucus* sp) and barnacles (*Chthamalus dalli* and *Balanus balanoides*) death rates increased significantly between 40°C and 60°C and that, with regards to pressure, only barnacles were sensitive. Hydraulic cleaning is attractive from an operational point of view insofar as it offers flexible ways of use: the

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temperature to be used can be adjusted on the cleaner and pressure could be easily controlled via variation of distance between nozzle and substratum. Therefore, an experiment was conducted by *Cedre* on efficiency and biological effects of various combinations of water temperature and pressure.

The first step of this study was to determine the efficiency of treatments. It is known, according to Mauseth *et al.* (1996), that the lethal temperature for rocky shore organisms is comprised between 40°C and 60°C; therefore, the maximal temperature used did not exceed 50°C. The second step of the experiment was the application of treatments on organisms. This was made *in situ*, but without oil, on four different communities characteristic of temperate sheltered rocky habitats. Nine combinations of three values of temperature and three values of pressure were applied on each community in order to test potential effects of synergy between temperature and pressure.

## 2.0 Effective Combinations of Temperature / Pressure and Duration of Treatments

### 2.1 Pressure on the substrata

The hot water pressure cleaner used in this study was a Karcher HSD 1000, the maximal theoretical values of temperature and pressure delivered by this unit are respectively: 150°C and 100 bars. The pressure exerted by water on the substratum was measured by application of the water jet on a steel sheet of 2 $cm^2$ which was linked to a weighing machine by means of a stick. The variation of pressure was obtained by varying the distance between nozzle and substratum; the distance between the cleaner's nozzle and the sheet ranging from 2 to 30 cm. Two measures were recorded for each test. The results are given in g/$cm^2$ (Table 1).

Table 1. Relation Between Distance and Pressure on the Substrata

| Distance nozzle/sheet (in cm) | mean pressure (in g/$cm^2$) |
|---|---|
| 1 | 1330 |
| 2 | 1040 |
| 3 | 720 |
| 4 | 600 |
| 5 | 530 |
| 10 | 230 |
| 15 | 160 |
| 20 | 120 |
| 30 | 70 |

### 2.2 Water temperature

The temperature of the water delivered by the cleaner was recorded directly at the outlet of the nozzle according to the values given by the thermostat of the cleaner. Theoretical temperatures ranged from ambient temperature to 150°C, real ones

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ranged from 23°C (without heating and for an ambient temperature of 17.5°C) to 70°C. A stable temperature could only be obtained for maximal temperature.

### 2.3 Efficiency

Tests were carried out on an upright concrete wall. Four experimental plots of 80x70 cm were polluted with Fuel Oil n°6 (Bunker C) at a rate of 0.5 l/m$^2$. Washing was done one week after oil application. The first plot was cleaned using maximal values of temperature and pressure and was used as a reference. The three other plots were divided in 5 strips of 12.5 cm high, each strip receiving a defined treatment (Figure 1). Water temperature should have been comprised between 40°C and 60°C so a theoretical maximal temperature of 50°C was used (the real one ranged between 40 and 54°C). The minimal temperature used was the minimal hot temperature delivered by the cleaner: 30°C on thermostat and a real temperature ranging from 30 to 44°C. In order to control the distance between nozzle and substratum, a sliding guide was fitted out at the end of the nozzle. Before each treatment, water temperature was recorded at nozzle contact and at guide end.

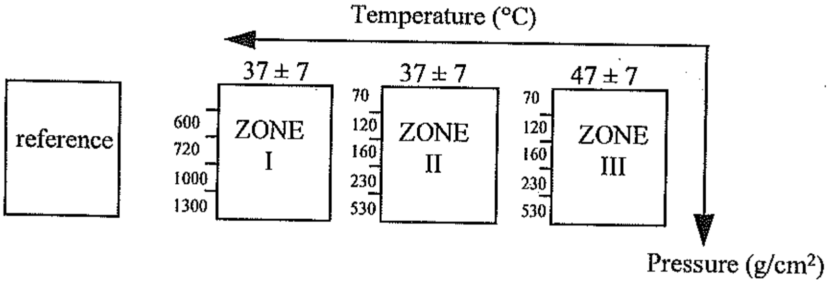

Figure 1. Combinations of Temperature and Pressure Values Tested for Efficiency

For each treatment, cleanup was stopped when the washed strip had visually the same color than the reference. The time needed for cleanup was recorded. The first criterion for efficiency was therefore the color. After treatment, some strips, even if they had the same color than reference, remained greasy; therefore the greasiness of substratum was retained as second criterion of efficiency. For some combinations of temperature and pressure values, it was not possible to obtain the same color as the reference for washed strip during a realistic time of flushing. Finally, 3 qualitative ranks of efficiency have been defined to characterize treatments:

- rank 1: color as the reference, not greasy = efficient treatment,
- rank 2: color as the reference but grey = moderately efficient treatment,
- rank 3: color different from the reference = inefficient treatment.

Cleanup efficiency decreased regularly with the decrease in pressure, down to a critical value for which flushing became inefficient whatever the duration of treatment (Figure 2). This critical value of pressure is related to water temperature, ranges from 230 g/m$^2$ to 160 g/m$^2$ (10 to 15 cm) for a mean temperature of 37°C and ranges from 160 g/m$^2$ to 120 g/m$^2$ (15 to 20 cm) for a mean temperature of 47°C.

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Duration of clean-up for efficient and moderately efficient treatments is around 125 seconds with a mean temperature of 35°C and 90 seconds for a mean temperature of 45°C, that is to say respectively 24 minutes/m$^2$ and 17 minutes/m$^2$.

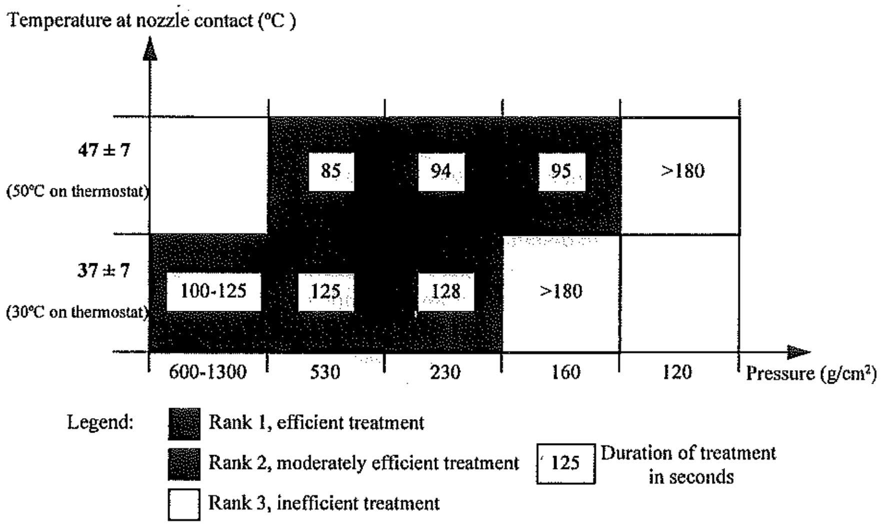

Figure 2. Efficiency of Treatments

## 3.0 Ecological Impact

### 3.1 Methods and materials

The ecological impact of water washing was tested *in situ*, in AUGUST 1997, for combinations of three values of temperature and three values of pressure. The duration of each treatment was inferred from previous results of efficiency.

The highest temperature to be used was determined from the thermal tolerance of species. According to Mauseth *et al.* (1996), the critical value for temperature is included between 40 and 60 °C. A theoretical value of 50°C was selected, real corresponding temperatures ranged from 38°C to 53°C. The minimal temperature was that delivered by the cleaner: 25°C. The intermediate one was the minimal hot temperature which could be delivered by the cleaner, the theoretical value was 30°C and the real one ranged from 30 to 45°C.

The values of pressure used were included between the effective margins. The distances between the nozzle and the substratum were 3.5, 7 and 14 cm that is to say respectively 670, 330 and 170 g/m$^2$ (these values were deduced from previous results).

The tests were carried out on surfaces of 600 cm$^2$. The duration of each treatment was inferred from previous results, taking into account the surface and the values of temperature: 120 seconds for minimal temperature, 90 seconds for

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intermediate temperature and 60 seconds for maximal temperature. The efficiency of each treatment was also deduced from previous results (Figure 2, Figure 3).

The combinations of temperature and pressure values represented 9 different treatments, each of them was tested for ecological impact on 4 rocky shore communities. The following communities were chosen among the most common on the middle and upper parts of the intertidal zone:

- the lichen-dominated zone, mainly composed of 6 species: *Caloplaca marina, Verrucaria maura, Ramalina siliquosa, Xantoria* sp (2 species) and *Lecanora atra*;
- the *Pelvetia canaliculata*-dominated zone, occupied by *Pelvetia* and some barnacles;
- the barnacle-dominated zone, made up of 4 species: *Chthamalus stellatus, Chthamalus montagui, Elminius modestus* and *Balanus balanoides*;
- the rockweed-dominated zone, mainly made up of *Fucus spiralis, Fucus vesiculosus, Ascophyllum nodosum* and *Fucus serratus*, with a diversified flora and fauna.

During a first survey, one week before treatment, 9 squares of 600 cm$^2$ were marked permanently in each zone and the cover or density of macrobiota was estimated in each square. Pictures of each square were also taken. The treatments lasted 1 day, during August 1997. The water temperature was measured before application of each treatment. Visual effects noticed during flushing were noted down as qualitative information. Post-treatment estimation of cover or density of macrobiota was conducted 3 weeks later in order to take into account differed mortality. At that time, pictures were taken.

### 3.2 Results

The results are expressed in terms of survival rates (Figure 4) and are represented under the same form as efficiency (Figure 3). Effects of temperature are figured on the X-axis and effects of pressure are figured on the Y-axis. The mean density or mean cover before treatment is given for each of the major taxa.

### 3.2.1 Lichen-dominated zone

The lichen was well developed with two dominant species, *Caloplaca marina* and *Verrucaria maura*. Two groups of species can be distinguished according to their sensitivity to treatments. The first one includes *Verrucaria maura* and *Lecanora atra* which are resistant to both temperature and pressure. The second one includes *Ramalina siliquosa, Xanthoria sp* and *Caloplaca marina* which are very sensitive to treatments. Individuals only survived lowest pressures but even in this case, they were all damaged. Effects of pressure overcome any effects of temperature.

### 3.2.2 *Pelvetia*-dominated zone

The mean cover rate of *Pelvetia canaliculata* was about one third. Sparse individuals of *Fucus spiralis* also occurred in the lower part of the zone. The associated epifauna was mainly composed of barnacles and a few individuals of *Littorina saxatilis*.

*Pelvetia canaliculata* and *Fucus spiralis* are both sensitive to maximal pressure and temperature values. The survival rates do not exceed 40% with the more efficient treatments. The moderately efficient treatments however induced little or no mortality.

The low survival rate for *P. canaliculata* with the combination of maximal temperature and medium pressure value is most certainly due to the nozzle angle to the substratum rather than to the increase in temperature. The square corresponding to this treatment was placed on an inclined plane which was not easily accessible and compelled us to work with a 45 degree nozzle angle. With this angle, the water jet clearly cut off the algal thallus. The mortality for barnacles is high, even with the less aggressive treatment in which case survival rate does not exceed 40%. Littorines were ejected from the squares during treatments but mortality is not obvious.

### 3.2.3 Barnacle-dominated zone

The mean density for barnacles was about 22000 individuals/m$^2$. The community was dominated by *Chthamalus stellatus*. *Patella vulgata* occurred in this zone with a mean density of 25 individuals/m$^2$ but individuals were not present in all the squares. The crustose red algae *Hildenbrandia rubra* was also present but sparse.

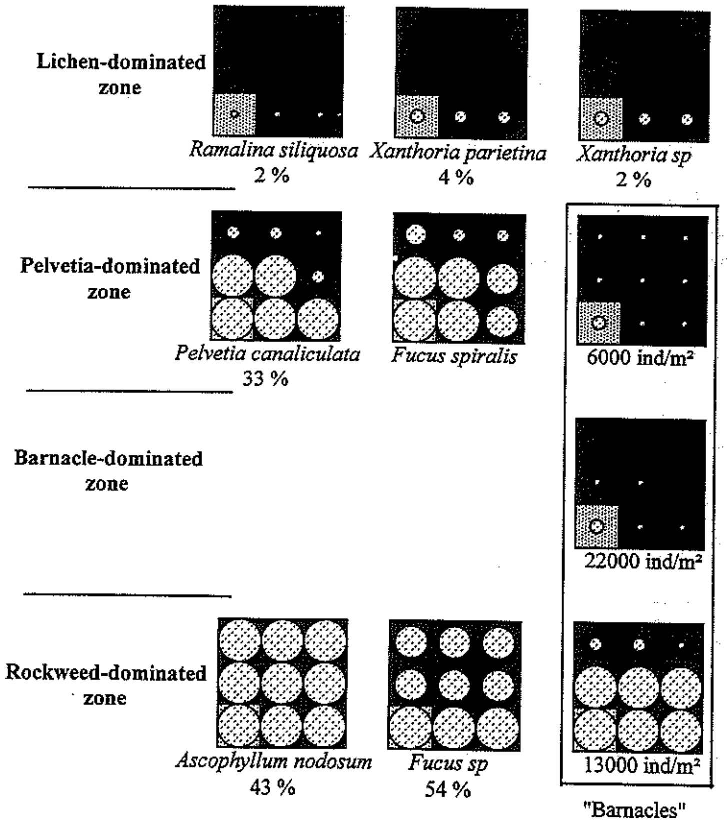
Whatever the species, barnacles are very sensitive to pressure. The survival rate does not exceed 40% for the lowest one. Individuals of *Patella vulgata* were not dislodged during treatments but some of them were absent three weeks after. *Hildenbrandia* occurred only on two squares which had received the following treatments: P=670 g/m$^2$, T= 38-53°C and P=170 g/m2, T=30-35°C. Both treatments seems to have little effect on this algae.

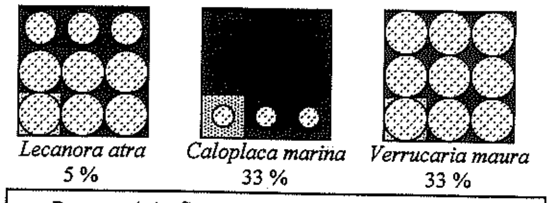
### 3.2.4 Rockweed-dominated zone

From the upper to the lower level of the zone, the dominant algae was respectively *Ascophyllum nodosum* or *Fucus vesiculosus*, the squares were mainly located at the fringe between these levels. Sparse individuals of *Fucus spiralis* occurred with *A. nodosum* and sparse individuals of *Fucus serratus* occurred with *F. vesiculosus*. In all the squares, the mean cover rate ranged from 90 to 100%. The associated flora and fauna were well diversified. The attached epifauna was dominated by barnacles, mainly *Elminius modestus* and *Chthamalus sp* plus *Balanus balanoides* which occurred only on the lower part of the zone.

*Ascophyllum nodosum* is resistant to both pressure and temperature, the survival rates range between 80 and 100%. Individuals of *Fucus* can be cut off with increasing pressure but mortality never exceeds 30%. The crustose algae (*Hildendrandia rubra, Ralfsia verrucosa*) survived even the most intrusive treatments. Inversely, the micro-algal cover was destroyed with highest pressures.

Survival rates for *E. modestus* and *Chthamalus* sp are high, especially when compared with results obtained in the barnacle-dominated zone. Only the highest pressure induced significant mortality. *Balanus perforatus*, a bigger species characteristic of the lower part of the zone, seems to be more sensitive, with survival rates that do not exceed 50% for the medium values of pressure. Individuals of *Patella vulgata* do not seem to have suffered either from pressure or from temperature. The mobile epifauna, mainly *Gibulla sp* and *Littorina sp* was ejected





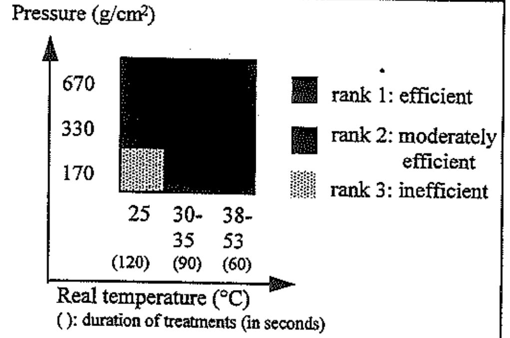


Figure 3. Relationship Between Intensity of Treatments and Efficiency

**Survival rates:**

◎ 81-100 %
◎ 61-80 %
◎ 41-60 %
◎ 21-40 %
∘ 1-20 %

no symbol: 0 %

**% ; ind/m²** : mean density or mean cover before treatment

Figure 4. Suvival Rates of Main Taxa as a Function of Treatment Efficiency

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during treatments but densities 3 weeks after treatments did not differ from those recorded before treatment.

### 3.3 Discussion

As Mauseth *et al.* (1996) showed that lethal temperature for rocky shore organisms ranges from 40 to 60°C, the maximal temperature used was chosen to be between these margins; nevertheless, because of the running thresholds of the cleaner's boiler, maximal temperature ranged between 38 and 53°C. Our results show that this temperature has minor or no effects. Therefore, major detrimental effects are all due to pressure. The lethal temperature value for organisms is related to tolerance of molecular and physiological mechanisms, so the lethal temperature is more or less the same for all temperate intertidal rocky shore organisms. That is not the case for pressure which impact varies from a species to another. A quantitative survey was done for 11 taxa in 4 different communities, among them, 2 species *Ascophyllum nodosum* and *Verrucaria maura* have a good resistance to maximal pressure. In most cases, other brown seaweeds resist to medium pressure and have mean survival rates of 70% for maximal pressure. Inversely, the lichens *Ramalina siliquosa* and *Xanthoria* sp and the barnacles in the barnacle-dominated zone have low survival rates even for the lowest pressure. Among lichens, sensitivity to pressure depends on individual morphology. The crustose species *Verrucaria maura* and *Lecanora atra* have high survival rates whereas the leaflike form of other species exposes them to pressure impact. Brown seaweed sensitivity to pressure seems to depend on coverage, related to individual size and morphology. *Ascophyllum nodosum* has a lashlike morphology and is settled in dense tuft, and so covers all the substratum. The upper lash protects the lower ones, therefore, even if some lashes are damaged, coverage remains the same and individuals are safe. Algae belonging to the genus *Fucus* are smaller, with a leaflike morphology and are less dense than *A. nodosum*. However, *Fucus vesiculosus* and *Fucus serratus* can cover all the substratum and partially overlap. Therefore some individuals can be damaged by pressure and others can be protected. *Pelvetia canaliculata* and *Fucus spiralis* in the upper levels are more sparse, no intraspecific protection is possible and their sensitivity to pressure is higher.

The algal cover also protects the underneath fauna and flora. Medium pressure induced almost no mortality on barnacles settled in the rockweed-dominated zone, whereas the same species suffered 70 to 90% mortality with lowest pressure when settled in the barnacle-dominated zone devoid of seaweed. The rockweed-dominated zone is the most diversified one, among all present species, only the Sponges *Hymeniacidon* sp and *Halichondria* sp missed on treated squares. Among others species that do not seem to have suffered, at least to mean pressure values, the main ones are: *Hildenbrandia prototypus* and *Lithothamnium normandii* (crustose red algae), *Ralfsia verrucosa* (crustose brown algae), *Dynamena pumila* (Hydozoa), *Actinia* sp (sea anemone), *Spirobis* sp (Polychaeta) and *Mytilus edulis*.

Gastropods belonging to genera *Gibbula* and *Littorina* had fallen off the substratum during flushing but no mortality could be recorded. Pressure might have pushed them over but it could also be the expression of a protective behavior (Shanks *et al.*, 1986 ; Wright & Shanks, 1995).

Comparison of pictures taken before and after treatments showed that some limpets were missing from the treated squares of the barnacle-dominated zone. However, limpets did not seem to have suffered during treatments. Mauseth *et al.* (1996) reported that death rates of limpets were significant for temperatures over 60°C and that pressure had no significant effects. As the biofilm was destroyed by treatments without the protection of algal cover, it is assumed that limpets had migrated because of lack of food.

## 4.0 Conclusion

High pressure / hot water washing is a very efficient technique for cleaning oiled rocky shores. It is generally used on rocky substrate not -or poorly- colonized by macrobiota. Indeed, there is no point in using this technique for washing seaweeds; however, sometimes such an operation is implemented on rocks even highly covered with seaweeds or lichens, mainly because of a bad knowledge of its potential harmful impacts.

When comparing efficiency to survival rates, only two species survived an efficient flushing, *Ascophyllum nodosum* and *Verrucaria maura*. However, in the lichen-dominated zone, all species except *V. maura* and *L. atra* suffer even from inefficient treatment. Oiled lichens had higher survival rates than when they had to withstand high pressure / hot water flushing (Broman *et al.*, 1983). These species have a mainly vegetative way of growth so, when individuals survive oiling, the single treatment to be applied from an ecological point of view is low pressure / cold water flushing (Lallemant and Van Haluwyn, 1981). Lichens, however, occurred mainly on the fringe between intertidal and supratidal zones where natural cleanup rate is low. Therefore, sites where the lichen-dominated zone is well diversified with foliaceous species and where individuals survive oiling, a trade-off between ecological constraints and cleanup necessity will be difficult to define.

Barnacles can survive oiling up to a certain level but not high pressure. As for lichens, a choice will have to be made between cleanup and ecology in barnacle-dominated zones, nevertheless these species contrary to lichens can recover quickly.

Finally, brown seaweeds are the more resistant species and, according to coverage, they can protect the underneath flora and fauna, notably in case of moderate surface coating. In this study, a pressure of 330 g/m$^2$ appeared to be moderately efficient and ecologically sustainable. During cleanup operations, the pressure could be adjusted visually: when seaweeds are cut-off by water jet, the pressure is too high.

The assumption of this study was that a trade-off could be defined, the first ecological constraint imposed for the experiments being the maximal temperature value which should not exceed 50°C. Even if an efficient or a moderately efficient treatment can be applied without inducing drastic short term depopulation, the first constraint to be accepted is to reduce water temperature when carrying out high pressure / hot water flushing and therefore to spend more time for cleanup.

The study highlights the level of tolerance towards high pressure / hot-water of different intertidal biota and proposes some operational recommendations for using this technique in regards with the biota sensitivity range. The study also underlines the necessity to flush as soon as possible the oiled rocky shores by using low pressure/ cold water jets in the aim of (i) moving free oil towards a collecting site, leaving thus only thin layers of oil on substrate that will not require further harmful cleanup technique (ii) preventing the on-site weathering/sticking of oil deposits that will afterwards require more strength (in terms of pressure and temperature) to be removed.

## 5.0 Acknowledgments

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