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Análisis y seguimiento del impacto ecológico del temporal extremo de Sant Esteve (26/12/08) sobre los ecosistemas litorales del norte del levante español

Informe Final

Assessment of the ecological impact of the extreme storm of Sant Esteve's Day (26 December 2008) on the littoral ecosystems of the north Mediterranean Spanish coasts.

Final Report

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EXECUTIVE SUMMARY

The presence of a shallow depression over the Balearic Sea with a minimum pressure of 1012 hPa and a high pressure centre over northern Europe (1047hPa) around the 26 December 2008 (Sant Esteve's Day in Catalonia), originated an extreme storm that hit the Catalan coast with maximum wave heights of 14.4 m coming from the east. This event is the largest ever recorded in the area and probably the most virulent one in the last 61 years. The unprecedented swell originated caused three casualties and extensive damage in harbors, waterfront esplanades, strands, and other coastal infrastructures worth millions of Euros. No attention, however, was paid to the potential damage caused to the nearshore marine resources.

Many conspicuous evidences pointed to a possible relevant damage to the coastal marine biota (e.g., hundreds of fish stranded in the Costa Brava, the displacement of heavy boulders at depths down to 20m, or totally denuded photophilic algal communities). Owing to these evidences and to some rash talk to the press by some scientists, a debate was raised about possible catastrophic consequences to the natural heritage and to the aesthetic value of some submarine seascapes of the Catalan Coast. In response to this uncertainty, the Research Group "Diversity and ecology of the marine benthos: from molecules to ecosystems", of the Centre for Advanced Studies of Blanes (CEAB-CSIC), elaborated an action plan to make a rigorous assessment of the impact caused by the storm on the natural coastal populations and communities. The plan included experts in benthic ecology of the Ecology Department of the University of Barcelona and of the Institute of Marine Sciences (ICM-CSIC), hydraulic engineers from the Polytechnic University of Barcelona (Laboratory of Marine Engineering) and from the University of Cantabria (Institute of Environmental Hydraulics), and experts of the "Parc Natural del Montgrí, les Illes Medes i el Baix Ter (Generalitat de Catalunya)". The overall initiative was supported by around 50 participants (tenured, PhD students, technicians, and naturalists), and involved associations of professional fishermen and underwater sportsmen (spear fishermen and divers).

The physical analysis of the storm allowed to establish three different areas: (i) the northernmost part of the Catalan coast (Costa Brava) – characterized by the Roses and Palamós buoys – where the greatest wave power, the largest wave heights, and the longest storm duration were recorded, and where the storm first began. Following the storm classification of Mendoza and Jiménez (2008), the storm in this area can be classified as "extreme". This storm was also the largest ever recorded by those two buoys. Maximum shear stress was above 70 Nm^{-2} at 5 m depth; (ii) the

central coast – characterised by the Tordera and Llobregat buoys – where the wave power decreased down to about half of that in the northern area, with smaller wave heights (although still large), a slightly shorter duration and slightly later impact. Maximum shear stress was between ca. 50 and 70 Nm^{-2} at 5 m depth; and (iii) the southernmost area (the rest of the Catalan coast), where the wave power was only one third of that of the Costa Brava, with relatively small wave heights. Maximum shear stress below ca. 50 Nm^{-2} at 5 m depth. The average shear stress was of 78.2 Nm^{-2} for the whole coast, with a maximum value of 233.5 Nm^{-2} estimated for the area of Portlligat Bay (to the North of the Bay of Roses) at 5 m of depth (see Figure 1).

Against intuition, the most important agent of damage was not the direct effect of the hydrodynamic shear stress, but the impact and abrasion caused by the relative movement of the substrate particles surrounding the organisms. An appropriate analogy is that represented by a firearm or a bomb without or with bullets or shrapnel. A shot or a moderate explosion generates a shock wave that may case some damage, but normally only in the very vicinity of the explosion source. However, when that wave carries hard particles with it, the effect can be highly destructive. Those organisms growing on stable rocky substrates resulted virtually unaffected by the storm (algae, sponges) while sessile organisms growing among boulders or on the sand suffered the highest damage due to abrasion, burial, dislodgement or uprooting. The main factors modulating the damage were exposure to wave action (latitude, orientation and depth), the type of surrounding substrate (continuous rock, boulders, sand), and the morphological traits of the organism. The abundance of highly targeted fish species (including those accessible to artisanal nets and bottom long-lines) was not altered by the storm or the changes observed were small and/or not conclusive. For a number of commercial species the catch rate patterns changed significantly. For those for which catch rate increased (e.g., *Palinurus elephas*, *Phycis phycis*), an increase in the catchability, not in the abundance, seemed to be the most plausible reason. For these species, a higher vulnerability is predicted and a medium- to long-term negative effect hypothesised.

Among the hundreds of species monitored in the ca. 200 stations along the Catalan coast, only around 20 species and 1 community in the northern-most area suffered moderate to high impacts owing to their delicate body structure, mobility of the surrounding substrate, and exposure to wave energy. This was the case for some algal communities (0% to 94% biomass loss from shallow environments to down to 24 m depth), and some populations of the seagrass *Posidonia oceanica* (5% and 23% area loss below and above 10m depth, respectively), the sea urchin *Paracentrotus lividus* (up to 80% loss of individuals), the fan mussel *Pinna*

nobilis (from 0% to 100% of the shallow populations), and the soft coral *Paramuricea clavata* (average loss of 13.4% of the individuals). Because of their low recruitment capacity and turnover, the loss of individuals of *P. oceanica*, *P. nobilis*, and *P. clavata* (all three protected species in the Mediterranean) is to be considered the most critical and potentially permanent one (Table 1).

Observations and surveys conducted in 2010 and 2011, confirmed the slow (algal cover, sea urchins) or very slow or null recovery (seagrass meadows, gorgonians, fan mussels) predicted for those populations and communities that were severely impacted by the storm. The seagrass meadows and the algal communities are key for the spatial and trophic structuring of the ecosystems. While the first ones will take decades to slowly begin to recover, the algal cover lost from large areas of rocky bottom have been largely recolonized by pioneering seasonal species. The recovery of the original mature algal community, however, will not take place but in several years time.

The robustness and universality of the conclusions from some of the studies compiled in this project are affected by a number of limitations related to the timing of the sampling, the time range of the monitoring before and after the storm, or the methodological approach used. In spite of this, the information examined provided sound evidence supporting that **the majority of nearshore natural populations and communities of the Catalan coasts resisted well the effects of the extreme storm of 26 December 2008. With very few exceptions, no critical ecological or economical damage has been caused to the coastal ecosystem**. It remains unclear, however, to which extent may have the overall resilience of the coastal ecosystem been eroded. The monitoring programmes may be able to answer this question in the coming years.

In any case, the damages caused by this natural meteorological event are to be considered insignificant if compared to those derived from the anthropization of the coastal zone, namely, overfishing (species collapse), pollution and eutrophication (drastic diversity decrease, ecosystem state change), or trawling and coastal development (mechanical benthos destruction). This contrast, vividly evidences that human activities are far more unexpected and extreme for the natural evolutionary mechanisms than any storm recorded so far.

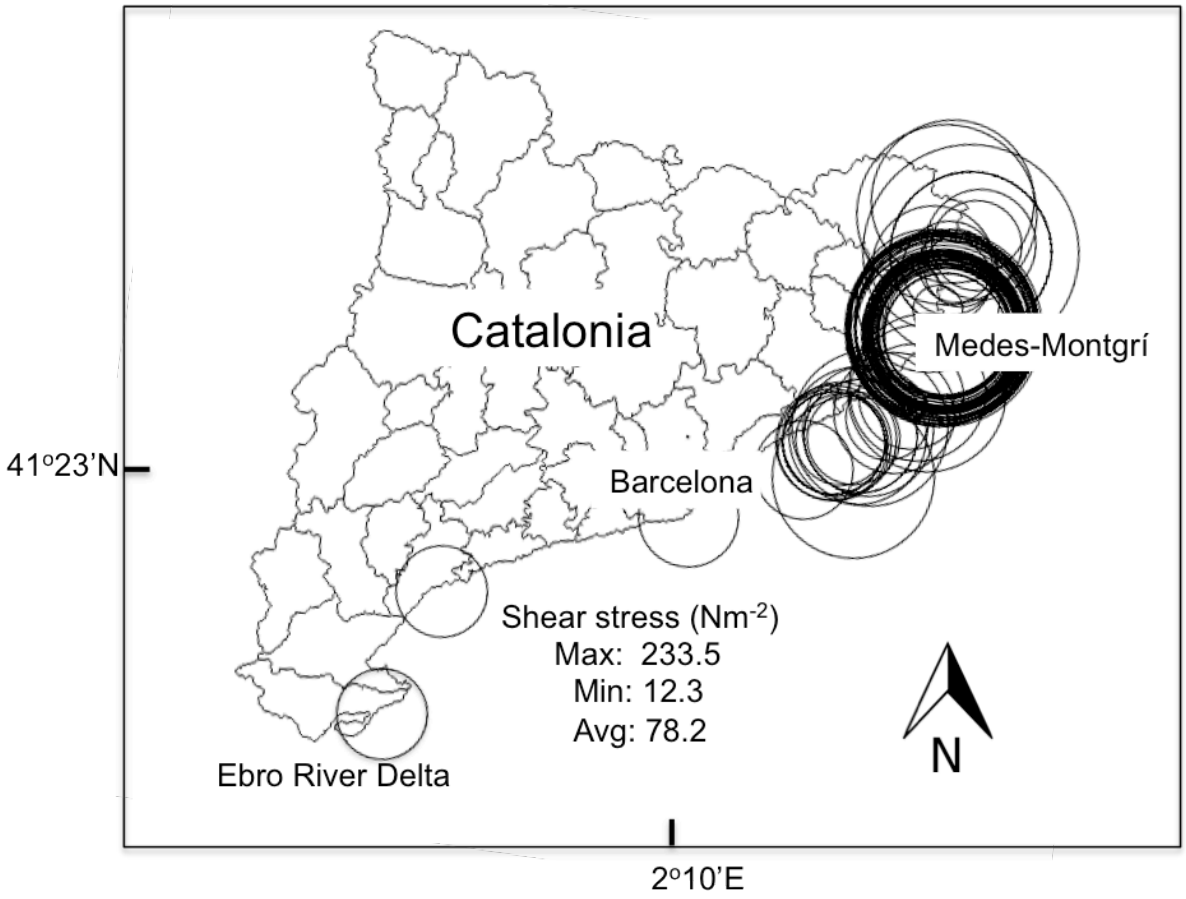

Figure 1. Preliminary representation of the distribution of the shear stress applied, during Sant Esteve's Day 2008 (26 December) in some of the stations sampled in this project. The image encompasses all depths, from 3 to 25 m. The higher intensity of the storm and the larger sampling effort made in the Costa Brava (in the area of Medes Islands and Montgrí coasts, in particular) is made evident (circle diameter is proportional to the shear stress). See Chapter 2 for details on the estimates of the shear stress.

Table 1. Summary of the species, groups or communities studied and the changes experienced. Observed change % may refer to number of individuals, biomass, cover, observation frequency (upper infralittoral algal community), or catching efficiency (littoral fisheries resources). Impact scale used: positive, none; negative: low, moderate, high, extreme. 'va', 'a', and 'r' stand for zones where *Cystoseira mediterranea* was very abundant, abundant or rare, respectively. 'ns' stands for no significant. Notice that a 'positive' impact assessment refers to the effect of the storm on the concrete species. The effect of such change on the ecosystem/community functioning could be different.

Species/group/community	Depth (m)	Observed change (%)	Recovery time	Impact assessment*	Chapter
Upper infralittoral algal community					
Corallina elongata	0 - 1	-50.7	months	low	8
Cystoseira mediterranea (va)	0 - 1	-39.5	months	low	8
Cystoseira mediterranea (a)	0 - 1	+19.2	months	positive	8
Cystoseira mediterranea (r)	0 - 1	+63.2	months	positive	8
Lithophyllum incrustans	0 - 1	+20	months	positive	8
Shallow rocky communities					
Algae	5 - 10	0 to -94	months/years	none/moderate	7, 9
Hydrozoans	5 - 10	+80	months	positive	7
Ascidians	5 - 10	ns	months	none	7
Cystoseira zosteroides	20 - 24	-15 to -78.5	months/years	moderate	10
Posidonia oceanica	< 5	-23	decades	**high**	11
	> 5	-5	decades	moderate	11
Pinna nobilis	5 - 15	0 to -100	decades	**high**	12
Paracentrotus lividus	6 - 25	-46 to -89	years	moderate	3, 11
Paramuricea clavata	16 - 20	-6.1 to -20.6	decades	**high**	4
Soft-bottom macroinvertebrates	8 - 14	ns	months	none	13
Sponges	4 - 20	0 to -6.6	months	none/low	5, 7
Targeted rocky fish populations					
Epinephelus marginatus	15 - 20	ns	years	moderate	14
Dentex dentex	15 - 20	ns	years	none	14
Dicentrarchus labrax	15 - 20	-72	years	moderate	14
Diplodus cervinus	15 - 20	ns	years	moderate	14
Sciaena umbra	15 - 20	ns	years	none	14
Sparus aurata	15 - 20	ns	years	none	14
Other rocky fish populations					
Serranus cabrilla	5 - 10	-33	years	moderate	15
Chromis chromis	5 - 10	-99	years	**high**	15
Coris julis	5 - 10	-50 to -87	years	**high**	15
Symphodus spp.	5 - 10	-50 to -91	years	**high**	15
Diplodus sargus	5 - 10	0 to -67	years	moderate	15
Cryptobenthic community	0 - 1.5	ns	years	none	16
Littoral fisheries resources (artisanal)					
Palinurus elephas	3 - 116	+267	years	**high**	17
Phycis phycis	3 - 116	+400	years	**high**	17
Other species	3 - 116	Significant variations have been observed in other species after the storm but did not seem to be 'retained' by the system but punctually.			17
Deep sea fauna (swimmers)	1200		weeks	low	18

*Impact assessment integrates several factors (damage extent, turnover of the species, ecosystem services provided, dynamics, expert knowledge) and not the observed change alone. For example, the catching efficiency of *Palinurus elephas* (Spiny lobster) and *Phycis phycis* (Forkbeard) increased 267% and 400%, respectively. Changes in the spatial distribution of these species and not in their abundance caused the higher catching efficiencies. We proposed a 'high' impact for them as they may become highly vulnerable to overfishing. Some algae from the upper infralittoral (*C. elongata* and *C. mediterranea*) were almost wiped out in many locations, yet we propose a 'low' impact because recolonization was expected within months. Finally, *P. clavata* lost around 13% of the individuals on average. The impact, however, was considered 'high' because, if any, recovery will take decades. See the corresponding chapter(s) for a more accurate interpretation of the values presented in this table.

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CONCLUSIONS

Main conclusion

With very few exceptions, the extreme easterly storm that hit the Catalan coasts the 26 December 2008, did not have critical consequences from the ecological or economical points of view on the marine nearshore natural resources.

Overall conclusions

The storm of 26 December 2008 that hit the Catalan coasts was caused by a shallow depression over the Balearic Sea with a minimum pressure of 1012 hPa and a high pressure centre over Northern Europe of 1047hPa. This event was **the largest ever recorded** at the locations of Roses and Palamós (Costa Brava, Spain). The average shear stress was of 78.2 Nm^{-2} with a maximum value of 233.5 Nm^{-2} estimated for the area of Portlligat Bay (to the North of the Bay of Roses) at 5 m of depth. The previous comparable storm in the Catalan coast was probably that of 1947, i.e., 61 years before the extreme event of Sant Esteve 2008. No temporal patterns or correlations with global atmospheric events have been found to be associated with these type of events, making them **unpredictable**.

Although the robustness and universality of the conclusions from some of the studies compiled in this project are affected by a number of limitations related to the timing of the sampling, the time range of the monitoring, or the methodological approach used, the information examined strongly suggests that the majority of **nearshore natural communities of the Catalan coasts resisted well the effects of the extreme storm** of 26 December 2008. Exceptions were some species and communities in the northern-most coasts which, owing to their delicate body structure, mobility of the surrounding substrate, and exposure to wave energy, suffered moderate to high impacts. This was the case for some algal communities (0% to 94% biomass loss from shallow environments to down to 24 m), and some populations of *Posidonia oceanica* (5% and 23% area loss below and above 10m depth, respectively), *Paracentrotus lividus* (up to 80% loss of individuals), *Pinna nobilis* (from 0% to 100% of the shallow populations), and *Paramuricea clavata* (average loss of 13.4% of the individuals). Because of their low recruitment capacity and turnover, the loss of individuals of *P. oceanica*, *P. nobilis*, and *P. clavata* (all three protected species in the Mediterranean) is to be considered the most critical and potentially permanent.

Against intuition, the most important **agent of damage** was not a direct consequence of the hydrodynamic shear stress, but of the **impact and abrasion** caused by the relative movement of the substrate particles surrounding the organisms. Those growing on stable rocky substrates resisted quite well the impact, while sessile organisms growing among boulders or on the sand suffered the

highest damage due to **abrasion, burial, dislodgement or uprooting**. The main factors modulating the damage were **exposure** to wave action (latitude, orientation, and depth), the type of surrounding **substrate**, and the **morphological traits** of the organism. Thus, the delicate algal community of the exposed shallow photophilic mobile environments underwent the most severe damage.

Observations and surveys carried on in 2010 and 2011, confirm the **slow** (algal cover, sea urchins), **very slow** or **null recovery** (seagrass meadows, gorgonians, fan mussels) predicted for those populations and communities that were severely impacted by the storm. The s**eagrass meadows** and the **algal communities** are key for the spatial and trophic structuring of the ecosystems. While the first ones will take decades to slowly begin to recover, the algal cover lost from large areas of rocky bottom, have been largely recolonized by **pioneering seasonal species**, not by the original more climax ones. The recovery of this crucial **mature algal community** will not take place but in several years time.

Specific conclusions

The populations of the sea urchin ***Paracentrotus lividus*** experienced the highest massive mortality ever recorded in the Mediterranean with a **loss of up to 80% of the individuals and 90% of the biomass** in the area Medes-Montgrí. In the various *Posidonia oceanica* meadows studied, the average loss recorded was of 46% of the individuals in meadows growing in Fenals Cove at 8 m. A continuation of the monitoring programme of this population is needed to follow its evolution and the interactions with its predators and with the algal cover. It will provide invaluable and unprecedented ecological information on **complex interactions in these benthic populations** in the Mediterranean.

Wave action was responsible of the overall loss of 13.4% of the ***Paramuricea clavata*** colonies in the Medes-Montgrí area. This value was found to be 8 times greater than the natural mortality rate due to detachment (1.5% y^{-1}). The effects of the storm in this species has to be considered as very severe because in this long-lived organisms, with a very low recruitment rate, even a small increase in the mortality rate **may produce unsustainable long-term effects** on the population.

The overall mortality of tagged **sponges populations** in the Costa Brava was low (6.6%). Collectively, the results suggest that most of the sponge species studied have evolved **effective anchoring mechanisms, shapes, and textures** to withstand the forces generated during heavy, periodic, and even extreme storm events. The effects of the storm have been found to be potentially beneficial to the bioeroding sponge ***Cliona viridis***. The elimination of a major part of the algal cover may have increased light availability for these photosymbionts-bearing sponges.

The deep-water, slow-growing Fucal ***Cystoseira zosteroides*** lost up to 80% of its biomass in some of the studied locations, being the highest ever recorded. One of these populations was found to be quickly recovered owing to a very high rate of recruitment. Differential traits of the two sites studied has allowed to hypothesise that catastrophic events such an exceptional storm can be **determinant for the structure and long-term dynamics** of *C. zosteroides* populations. However, the combination of these events and smaller scale, short-term factors, make it almost impossible to predict the distribution and size structure of this stands.

A thorough study before and after the storm using detailed cartography along the Catalan coast showed that the **upper sub-littoral macroalgal communities were not significantly affected**. The emblematic macroalga *Cystoseira Mediterranea*, in particular, far from being affected seemed to have experienced a certain progression in some areas, probably at the expense of a decline in *Corallina elongata*. In some areas of Medes-Montgrí, the results are suggestive of small changes in the organization of the shallow benthic communities, where the benthic per cent cover of bare rock and hydrozoans significantly increased after the storm at the expense of foliose algae. In contrast, **some deeper algal communities**, from 5 m to up to 25 m, **have been devastated by the storm**. While exposure was not determinant for upper sub-littoral communities, it was critical for those algal communities living on a mobile substrate. Wave action combined with lose medium to big-sized boulders had a high destructive effect on the photophilic algal community of Medes-Montgrí, resulting in cover loss from 0% to 94%.

Around 23% and 5% of the area of the ***Posidonia oceanica*** **meadows** above and below 10 m surveyed in this project, respectively, were found covered with more than 10 cm of sediment. As deleterious effects on this seagrass have been observed starting with only 4 cm of sediment, a much higher mortality is suspected. Moreover, as the effect of uprooting was not addressed in this project, an even larger mortality for *P. oceanica* meadows is hypothesised. Owing to the extent of the disturbance, the low recruitment rate of this species, and its key role as ecosystem services provider, the impact on *P. oceanica* meadows is categorized as severe. Other emblematic sandy bottom dwellers such as the endangered **fan mussel *Pinna nobilis*** resulted untouched or devastated depending on the degree of exposure. In the leeward zone of the Meda Gran in Medes Islands, all the population censed before the storm was found intact. Conversely, all the individuals of the population growing in Salpatxot area, largely exposed to the storm, disappeared. An intermediate impact was observed in Giverola Cove, where the population slightly sheltered by the north end of the cove was reduced in 16%, contrasting with the loss of 33% of the individuals in the more exposed

area. As for the seagrass *P.* oceanica, the main mechanism of damage was burial.

In contrast, the **macroinvertebrates of soft-bottom** environments (Mediterranean well calibrated fine sand community) from 8 to 14 m depth resulted unaffected.

A significant **decrease in the mean species richness, abundance and total biomass** of **littoral rocky reef fish assemblages** was observed when compared to counts from previous years (1999, 2002, 2005). The most conspicuous effects were: 1) a decrease of the abundance and biomass of *Chromis chromis, Coris Julis* and *Diplodus sargus* (to, at most, 50%) and 2) a decrease of biomass, but not of the total abundance, which was counterbalanced by a very high recruitment after the storm in *Serranus cabrilla*, *Symphodus tinca* and small *Symphodus spp*. (to, at most, 50%). The rest of the species studied, including the populations of cryptobenthic fishes from the upper sublittoral zone, resulted unaffected by the storm.

Dusky groupers (*Epinephelus marginatus*) were undoubtedly affected by the storm as evidenced by the 30 specimens found on the beach of l'Estartit the day after the storm. However, from the results obtained here **it cannot be concluded that the storm had a significant impact** on them and other **highly targeted species** in Medes-Montgrí. There are, at best, some indications of possible effects, such as the reduction in dusky groupers in the totally protected area of Medes Islands, along with the increase in this species in the partially protected area of El Molinet. Such a reduction, however, falls within the range of normal interannual variations. The **sea bass** *Dicentrarchus labrax* showed a sharp decline from 2008 to 2009 that may have been caused by the storm, and which led to the minimum values for this species since 1992. However, the poor statistical quality of the density and biomass data of for this species, prevents from obtaining a sound conclusion.

This project has provided unprecedented information suggesting that the abundance of most of the **species accessible to artisanal nets and bottom long-lines** was not altered by the extreme storm. However, **the catch rate patterns of a significant number of species (up to 18) changed substantially**. Most of these species showed an increase in catch rates. This phenomenon might be due to an increase in the spatial aggregation of the species, which increased their fishing availability. If this proved true, the observed changes would be **suggestive of an increase in species vulnerability** and, therefore of a negative effect on the populations in the medium term.

Results suggest that the storm had a stronger effect on the **Blanes submarine Canyon** than at the open slope as showed by the **collapse of swimmers** abundance after the extreme event. Inside the canyon **significant differences were recorded on taxa composition of swimmers** be-

tween samples collected before and after the storm. The results also highlight the role of the Blanes Canyon as **preferential conduit for matter and energy** exchange between shelf and deep basin. Although the effect has to be considered occasional, further studies are needed in order to understand its potential impact for the ecosystem.

Of the 42 individuals, including **artisanal fishermen, spear fishermen, and SCUBA divers**, inquired in this project about their perception on the effects of the storm on the marine biota, around 70% reported moderate to severe effects in some populations of both the benthos and the fish assemblages in the Costa Brava. The **high degree of detail and skill in their observations** was remarkable, showing a **good agreement with the results obtained by the research groups** of this project. Factors like latitude, type of substrate, or depth were neatly identified by underwater sportsmen. It has to be concluded that these three groups have to be regarded as a valuable source of information of changes in the marine benthos both for monitoring purposes and for assessing impacts after rare extreme events.

RESULTS DISSEMINATION

This report has been elaborated as a comprehensive compilation of independent studies carried out during the project using the format of scientific publications. A volume has been edited and hardcopies distributed among the participants, including professional fishermen and underwater sports associations. The report can also be consulted and downloaded from the project Internet website. Volumes are available at the library of the CEAB.

The preliminary results of the project were presented as a poster in the 11th International Plinius Conference on Mediterranean Storms held in Barcelona the 7-11 September 2009. The poster can also be downloaded from the website. The final results will be presented in the next Plinius edition and or other equivalent meeting.

The preliminary results of project have also been present in the local and national written media (La Vanguardia, El País, La Vanguardia de Girona, El Diari de Girona, Cel Obert de Blanes) and on TV (TV3 Comarques and Telenoticies, autonomous Catalan television). Some of the articles can be downloaded from the website of the project. The executive summary of this report will be made available to the CSIC Press Department and to the main national, regional, and local written and spoken media.

A scientific publication condensing the highlights of the project is under elaboration. Also, a special issue of an international SCI journal to publish the whole report is being considered.

A number of independent papers deepening in the results presented in this report, are being elaborated or have been submitted (Chapters 2, 3, 4, 7, 9, 10, 12, 14, 15, 17, and 18).

FINAL COMMENTS

This project has allowed, for the first time, to obtain a comprehensive vision of the overall effect of an infrequent extreme meteorological event on some of the most representative components of the coastal marine biota. It has evidenced the enormous benefits derived from putting efforts, ideas and results in common. Without it, every researcher, not to mention the managers, policy makers or the society in general, would have kept a fragmentary vision of the effects of the storm on the populations or communities they have studied or heard about.

This project has also reinforced the extraordinary value of the monitoring programmes. Without them, no references of the 'before-the-storm' state of the ecosystems would have been available and therefore any attempt at assessing the loss of ecosystems services or their resilience would not have been possible. This adds a very strong argument in support of the need to continue funding the monitoring programmes of the most relevant components of the benthos along the Catalan coast.

Finally, the creation of an **Observatory of the Benthos** of the Catalan Coasts has been proposed and is being discussed within the working group. The Observatory would benefit from the already extant logistics and from the precedent established by this project. Its ultimate aim should be to provide an integrated vision and specific answers and tools to scientists and managers interested in studying the natural dynamics or assessing the response of nearshore ecosystems affected by both natural and human perturbations.

More specifically, this Observatory should aim at:

1. Serving as a forum for all specialist involved in the study of the nearshore benthic ecosystems (meetings).

2. Providing a global, permanent, rigorous and up-to-date vision of any issue related with the research and management of the coastal natural benthic resources. This includes providing information and criteria to help decision makers in the elaboration of management policies and during environmental crisis (ad hoc reports; scientific publications; protocols).

3. Proposing a set of standard methodologies to adequately and consistently assess the state and evolution of the coastal ecosystems.

4. Helping in the dissemination of the information both at the scientific and popular levels to enhance interaction between researchers and awareness in the society.

5. Collaborating with other homologous organizations worldwide.

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