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Towards improving the representation of beaching in oil spill models: A case study

Achilleas G. Samaras [a,*], Michela De Dominicis [b], Renata Archetti [c], Alberto Lamberti [c], Nadia Pinardi [d]

[a] CIRI – EC, Fluid Dynamics Research Unit, University of Bologna, Via del Lazzaretto 15/5, Bologna 40131, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Viale Aldo Moro 44, Bologna 40127, Italy
[c] Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale Risorgimento 2, Bologna 40136, Italy
[d] Corso di Scienze Ambientali, University of Bologna, Via S. Alberto 163, Ravenna 48123, Italy

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ABSTRACT

Oil–shoreline interaction (or "beaching" as commonly referred to in literature) is an issue of major concern in oil spill modeling, due to the significant environmental, social and economic importance of coastal areas. The present work studies the improvement of the representation of beaching brought by the introduction of the Oil Holding Capacity approach to estimate oil concentration on coast, along with new approaches for coast type assignment to shoreline segments and the calculation of permanent oil attachment to the coast. The above were tested for the Lebanon oil spill of 2006, using a modified version of the open-source oil spill model MEDSLIK-II. The modified model results were found to be in good agreement with field observations for the specific case study, and their comparison with the original model results denote the significant improvement in the fate of beached oil brought by the proposed changes.

1. Introduction

A general image on the processes and respective drivers controlling the fate of oil spilled in the sea, can be drawn from Fig. 1. Focusing on coastal areas, oil behavior at the shoreline depends on a number of interrelated factors that can be summed up to three categories: (a) oil properties, (b) coast type and beach properties, and (c) coastal hydrodynamics.

Oil–shoreline interaction – or "beaching" (the term that prevails in literature) – is an essential part of oil spill impact assessment, as it regards the definition of the location and extent of oiled shorelines, the amount of oil that reaches and stays at the shore, as well as the temporal characteristics of the processes in action. These processes (that follow oil attachment to the coast) are far too complicated and – still – not deeply understood, due to the great amount of parameters and uncertainties involved in the physical problem. Wave and tide action on the foreshore, combined with the complex two-phase flow (water–oil) and ongoing oil weathering, seem to create an insurmountable obstacle for the detailed representation of the phenomenon. Accordingly, research attempts to describe it until now follow the approach of parametrizing the behavior of "beached" oil based on available field data, laboratory experiments and approximations adopted from groundwater hydraulics.

Gundlach and Hayes (1978) set the basis for coast type dependent parametrization of beaching, proposing a method for classifying shorelines according to their vulnerability. The classification, expressed by the "Vulnerability Index", was to reflect the sensitivity of each coast type to oil pollution. Based on the same notion, Torgrimson (1980) suggested the use of half-life values to describe the rate of oil re-entrainment after its attachment to the shoreline; the specific approach has become one of the most widely used in oil spill modeling (see details in Section 2.4). Equally widespread is the approach to use a limiting value for the total amount of oil than can be accumulated on shore, commonly referred to as Oil Holding Capacity (henceforth denoted by OHC).

OHC is defined as the maximum oil volume the beach can actually hold. A series of different methods to estimate OHC have been proposed over the years. Gundlach (1987) developed OHC and oil removal coefficients for different shoreline types, based on field data from the Amoco Cadiz, Ixtoc I and Urquiola spills. Owens and Teal (1990) proposed an organized set of activities for data collection after shoreline impact (see Section 2.3 for details), resulting in OHC estimates appropriate to be used as case-independent values in the absence of better data. Cheng et al. (2000) proposed an empirical formula for the calculation of OHC, based on field data from Gundlach (1987) and Reed et al. (1989), and the notion that the maximum loading expressed by OHC can be divided in a sur-

* Corresponding author. Tel.: +39 051 2090551; fax: +39 051 2090550.
E-mail address: achilleas.samaras@unibo.it (A.G. Samaras).

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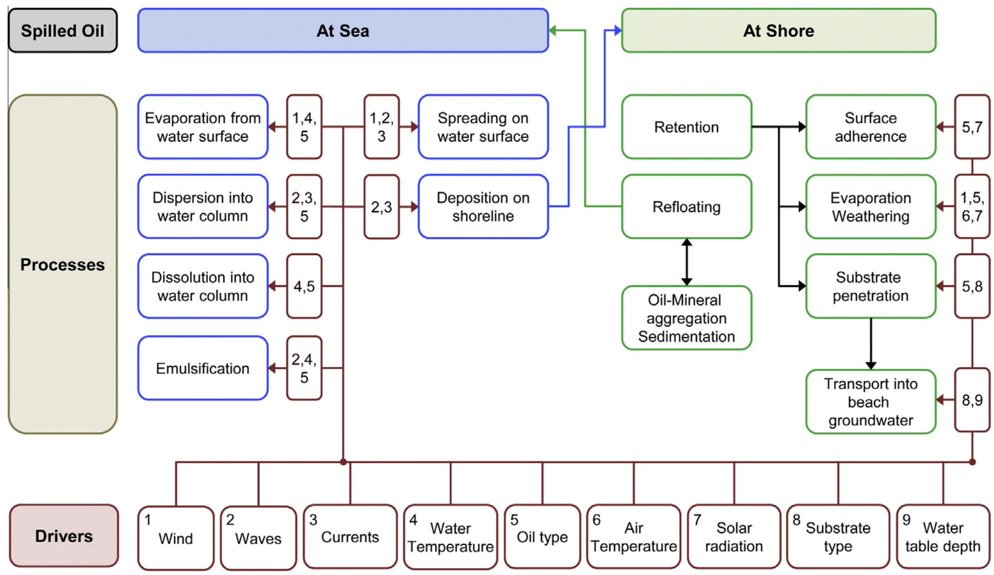

Fig. 1. Schematic representation of interrelated oil fate processes and drivers (figure redrawn and modified after Etkin et al., 2007).

face and a subsurface component. Humphrey et al. (1993) suggested the calculation of OHC based on fundamental hydraulic modeling, proposing a formula including geometric properties of the beach (length, width, depth) and its effective porosity to represent the volume fraction that "entraps" oil. Based on the aforementioned approach, Boufadel (2000) proposed a methodology to calculate OHC incorporating the response to tide of the water table in the beach. Useful insights in the described processes, or even direct estimates of OHC, can be extracted from extensive field trial data as well (e.g. the Svalbard Shoreline Field Trials; Sergy and Goodman, 2003).

The use of approaches described in the previous paragraph can be found in a series of models and respective case studies. Indicative reference can be made to the work of Shen et al. (1987), Cheng et al. (2000), Chao et al. (2001), Wang et al. (2005), Guo and Wang (2009), and Danchuk and Willson (2010).

A separate case is that of the coastal oil spill model COZOIL (Reed et al., 1989), which includes explicit representations of the active processes that affect the fate of an oil spill in the nearshore, foreshore and backshore. However, the model aims to simulate mainly nearshore spills, and its conceptual/structural differences from typical operational spill models (based on the Eulerian–Lagrangian approach) restrain its use to smaller-scale applications.

The present work studies the improvement of the representation of beaching brought by the introduction of coast type- specific Oil Holding Capacity estimates, along with a new algorithm for coast type assignment to shoreline segments and a new approach for the calculation of permanent oil attachment to the coast based on the half-life approximation. The above are tested for the Lebanon oil spill of 2006, using a modified version of the open-source oil spill model MEDSLIK-II (De Dominicis et al., 2013a). The modified model results are found to be in good agreement with field observations for the specific case study (OSOCC, 2006); their comparison with the original model results denote the significant improvement in the fate of beached oil brought by the proposed changes.

2. Materials and methods

2.1. MEDSLIK-II: A Lagrangian oil spill model

MEDSLIK-II (De Dominicis et al., 2013a) is an oil spill model for surface oil slicks in the marine environment. The processes of transport and weathering of oil are simulated using a Lagrangian model formalism coupled with an Eulerian circulation model. The system is identified by structural, oil slick and particle state variables. Structural state variables, i.e. the components of oil concentration (at coast – surface – dispersed – at the bottom), are obtained based on the definition of the other two sets of variables. Oil slick state variables are used for the representation of the transformation processes (evaporation, spreading and dispersion), which are considered to act on the bulk slick volume based on the fate algorithms of Mackay et al. (1980); these variables regard the definition of the surface and dispersed volumes of the slick. The Lagrangian particle formalism is then applied decomposing the bulk volume into N constituent particles, each of them characterized by a number of particle state variables (i.e. particle volume, particle status index identifying the classes correspondent to the four structural state variables, and particle position vector). Oil concentration is calculated afterwards by assembling the Lagrangian particles together, along with their associated properties. The processes of interest in the present work will be further discussed in Sections 2.2, 2.3 and 2.4; a detailed description of MEDSLIK-II in the framework of Lagrangian oil spill modeling can be found in De Dominicis et al. (2013a) and the model validation in De Dominicis et al. (2013b).

2.2. Coast type data and assignment to shoreline segments

A sound mathematical formulation of oil–shoreline interactions is by itself not enough to improve the representation of beaching in oil spill models, especially since the involved processes are largely affected by coast type, beach properties and their variation in the area of interest. Accordingly, the availability of field data and their correct assignment to the segments used to reconstruct the shoreline is essential for operational oil spill models. This intuitively deduced claim can be supported by any respective sensitivity analysis, as was done for MEDSLIK-II in this work before the final model applications.

Regarding coast type data, the improvement for the Lebanon oil spill that is studied in the present work (see Section 2.5) was based on the Oil Spill Operations and Coordination Centre Report (OSOCC, 2006). The report identified 30 points of known coast type (Fig. 2a); this dataset was extended with the addition of 163 additional points (Fig. 2b), identified on the basis of their proximity to

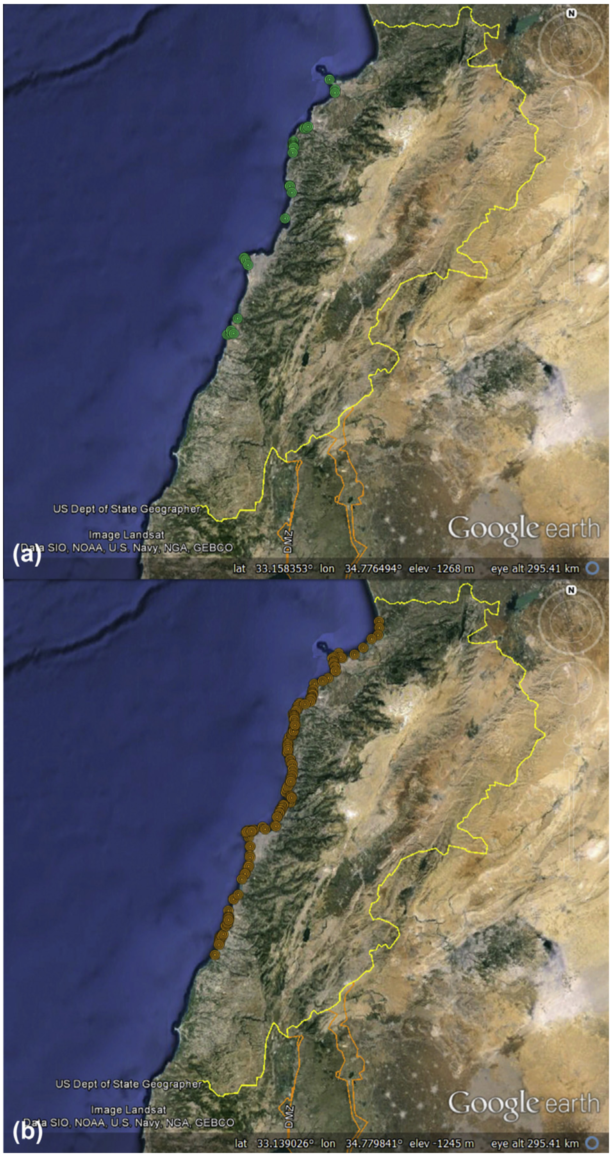

Fig. 2. Points of known coast type: (a) initial dataset based on the Oil Spill Operations and Coordination Centre Report (OSOCC, 2006); (b) extended dataset for the Lebanon spill case (Google Earth, 2013; privately processed).

Table 1
Coast types and respective half-lives for release (T_W) and permanent attachment (T_S) of beached particles in MEDSLIK-II.

Coastal type	T_W	T_S
Sand beach	24	24
Sand and gravel beach	24	36
Cobble beach	24	48
Rocky shore	18	96
Seawall, Concrete wall etc.	0	96
Exposed headland	1	96
Sheltered sand or gravel beach	120	24
Sheltered rocky shore	120	96
Sheltered marsh or mud flats	120	24

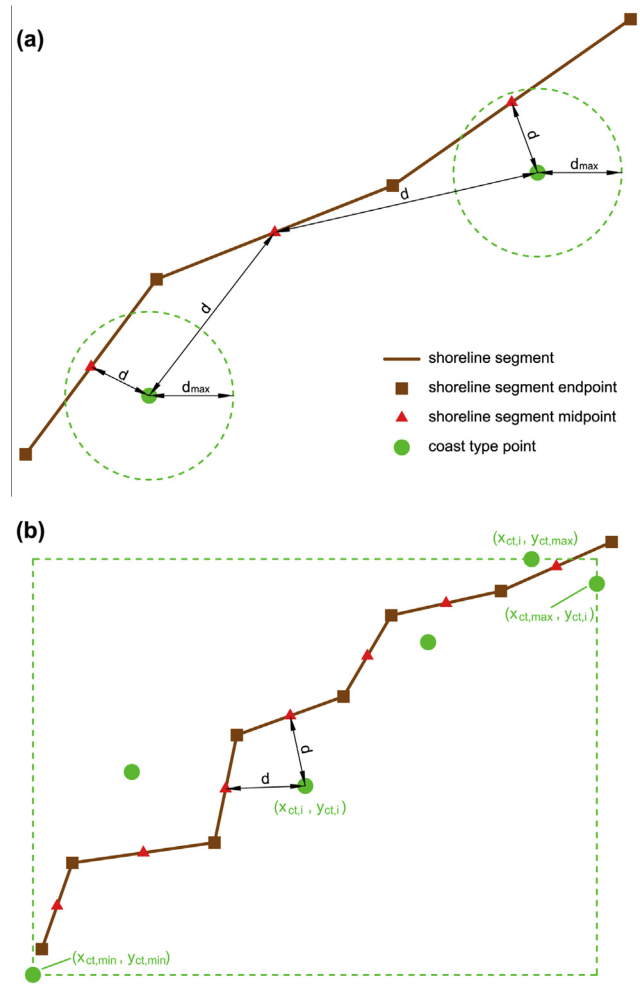

Fig. 3. Schematic representation of: (a) the original MEDSLIK-II algorithm and (b) the new proposed algorithm for coast type assignment to shoreline segments.

the OSOCC Report points and visual pattern recognition. It should be noted that the focus was given on coast types with significantly different behavior regarding the processes of interest (e.g. structures and artificial shorelines as opposed to different types of beaches). The total of 193 coastal-type data points were used to create the appropriate file used in the model applications.

For the assignment of coast type data to shoreline segments, the improvement presented in this work regards the revision of the respective algorithm used in MEDSLIK-II. To begin with, such an algorithm is needed because shoreline and coast type discretizations differ; the first depends on the modeling approach and the numerical solution scheme, while the second depends on available data of coastal morphology. In MEDSLIK-II the shoreline is discretized to segments of variable length, ranging up to a few hundred meters for an almost straight segment, while the coast type file consists of the respective information for specific locations (geographical points) categorized into nine representative coast types (see Table 1).

The original algorithm is schematically represented in Fig. 3a and is based on the definition of a uniform maximum distance (d_{max}) for coast type assignment. The algorithm implies, conceptually, the creation of a circular "zone of influence" centered to the points of known coast type. After the calculation of the positions of the shoreline segment midpoints and their distance from coast type points (d), shoreline segments are assigned the coast type of the closest coast type point, on the condition that their midpoints fall within this specific coast type point's zone of influence (i.e. $d < d_{max}$); elsewise, a default coast type is assigned. Fig. 4 shows the schematic representation of the main shortcomings from applying the original algorithm, with three cases where relevant coast type information would be neglected. Fig. 4a represents a case where d marginally exceeds d_{max}; Fig. 4b represents a case

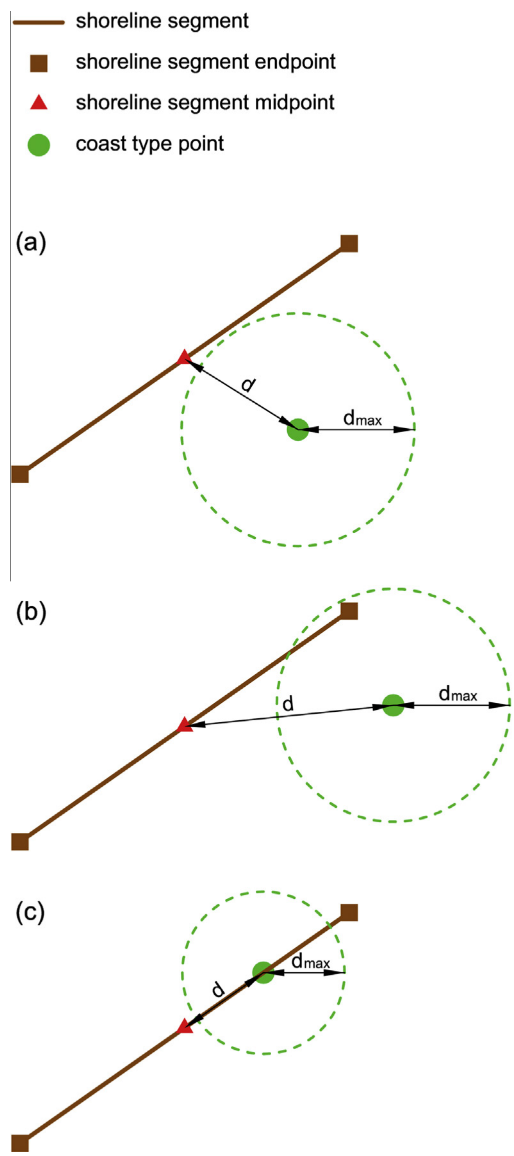

Fig. 4. Schematic representation of the main shortcomings of the original MEDSLIK-II algorithm for coast type assignment to shoreline segments.

where d exceeds d_{max}, but since d is calculated from the segment midpoint, part of the specific shoreline segment still falls within the maximum distance buffer; Fig. 4c represents a case in long shoreline segments or small d_{max} values, where although the coastal type point is practically on the shoreline, the segment midpoint does not fall within the maximum distance buffer. Furthermore, an approach based on the "zone of influence" concept, as implied by the definition of d_{max}, would require varying and not uniform d_{max} values dependent on coast type and local morphodynamics, information only rarely available. Accordingly, a new approach was adopted, leading to the algorithm schematically represented in Fig. 3b. The new algorithm implies, conceptually, the creation of an outline for the area of known coast types, so that:

$$x_{ct,\min} \leqslant x_{ct,i} \leqslant x_{ct,\max} \tag{1}$$

$$y_{ct,\min} \leqslant y_{ct,i} \leqslant y_{ct,\max} \tag{2}$$

where (x_{ct}, y_{ct}) are the coast type point coordinates and the subscript i refers to the i-th point in the respective file. After the identification of the closest such point to each shoreline segment, the respective coast type is assigned to shoreline segments that fall within the aforementioned outline without any constraints imposed by a maximum distance. And, although coast type assignment would always depend primarily on the quantity and quality of the available data, the proposed approach ensures that within the area covered by that data no relevant information will be neglected. The latter was confirmed by sensitivity analyses and preliminary test-runs for the Lebanon case study, in which the original algorithm neglected coast type information for a significant number of shoreline segments (thus significant shoreline length as well), while the new algorithm did assign the nearby coast types correctly. The effect of this correct coast type assignment extends to the results presented in Figs. 8–10 (although admittedly not clearly identifiable), as in the particular approach used in MEDSLIK-II coast type is associated with the essential T_W and T_S parameters for the half-lives of release and permanent attachment, respectively (see Section 2.4).

2.3. Oil concentration on coast

Regarding the oil concentration on coast, the original MEDSLIK-II formulation assumes, by default, a uniform limiting oil concentration of 5000 bbl/km (*bbl* = barrel). This approach lacks dependence on coast type, along with the fact that the aforementioned value is high, especially considering that it was uniformly set to all shoreline segments.

After extensive literature review (Gundlach and Reed, 1986; Gundlach, 1987; Reed et al., 1989, 1999; Lee et al., 2003; Owens and Lee, 2003; Johnson et al., 2005; Etkin et al., 2007 among others) and taking into consideration the points noted in Section 1, it was decided the improvement regarding oil concentration on coast to be based on Oil Holding Capacity (OHC), parametrized for different coast types. The detailed review of Etkin et al. (2007) on oil–shoreline interaction and its simulation by oil spill models, suggests a combination of: (a) the Boufadel (2000) methodology (hydraulic oil-holding capacity model) for light oils, and (b) the SCAT (Shoreline Cleanup Assessment Team) methodology for medium-heavy oils. Of the two, the Boufadel (2000) methodology requires more detailed field data to be implemented, regarding beach sediment properties (porosity, hydraulic conductivity) and groundwater properties (existence or not of groundwater flow from inland areas). Given the general scarcity of such data for large coastal stretches, this can be considered as a shortcoming of the specific approach. In the present work, for the specific case study of the Lebanon spill (oil with an API gravity identified equal to 26 °API; *API gravity* = American Petroleum Institute gravity = *141.5/SG – 131.5*, where *SG* is the specific gravity at 60 °F) and in the absence of case specific data, the improvement was based on SCAT data for the Exxon Valdez spill.

SCAT is the acronym of "Shoreline Cleanup Assessment Team" ("Shoreline Cleanup Assessment Techniques" also found in literature), a term first developed during the Exxon Valdez oil spill impact assessment (Owens and Teal, 1990; see also Owens and Sergy, 2003). It refers to an organized set of activities for data collection after oil spills that affect shorelines and shoreline habitats. SCAT surveys are intended to provide a rich array of data in order to develop a shoreline cleanup plan that maximizes the recovery of oiled habitats and resources, while minimizing the risk of injury from cleanup efforts (NOAA, 2000).

As also mentioned above, in the absence of a case-specific SCAT survey for the Lebanon oil spill, the results of the respective one for the "Exxon Valdez" spill were used as presented in Table 2 (adopted by Etkin et al., 2007). The specific data regard a series of extensive surveys conducted on 5221 km of shoreline of eight major types, in Prince William Sound, Alaska. The SCAT data coast types were matched to the ones of MEDSLIK-II (Table 1) and the total oil volume units (defining OHC) were properly transformed.

Table 2
Exxon Valdez oil spill shoreline oiling 1989 – Total volume of oil per area (SCAT survey data; adopted by Etkin et al., 2007).

Shoreline type	N	Total volume of oil per area (m^3/m^2)		
		Max	Mean	St. Dev.
Cliff	23	0.0395	0.00810	0.01250
Boulder	235	0.0529	0.01090	0.01420
Rocky	399	0.0603	0.00660	0.01230
Cobble	163	0.1140	0.01100	0.01740
Pebble	104	0.0525	0.00760	0.01280
Gravel	71	0.0326	0.00260	0.00740
Sandy	62	0.0403	0.00200	0.00610
Mudflat	3	0.0281	0.00950	0.01610

In the improved model version there are user-defined options about: (a) the selection between mean and max OHC values to be used, (b) the tidal range TR and (c) the representative beach slope sl. Tidal range and beach slope are used to define the width of the impacted coastal zone W_{imp}, by $W_{imp} = TR/sin(atan(sl))$.

2.4. Release and permanent attachment of beached particles

Once attached to the shoreline, oil fate can be roughly broken down into two scenarios: (a) being washed-off/released and re-entrained into the nearshore, and (b) being deposited on the beach surface (usually the backshore – protected by wave and tidal action) and/or seep into the beach structure.

Regarding the first of the aforementioned scenarios, as also mentioned in Section 1, Torgrimson (1980) suggested the use of half-life values to describe the rate of oil re-entrainment after its attachment to the shoreline; the approach proposed the use of different half-lives for different coast types based on their vulnerability. Previously, Gundlach and Hayes (1978) had proposed a method for classifying shorelines according to their vulnerability, expressed by the "Vulnerability Index". Based on the above, the volume of oil remaining on the beach can be related to its original volume by (Shen et al., 1987):

$$\Delta V_b/V_b = 1 - 0.5^{\Delta t/\lambda} \tag{3}$$

where ΔV_b is the volume of the beached oil re-entrained into the sea during each time step, V_b is the volume of oil on the beach, Δt is the modeling time step and λ is the half-life for release.

The representation of beaching in MEDSLIK-II is based on the same approach. The change of any oil particle's status index from "on surface" to "on coast/beached" is decided by checking whether its trajectory between two consecutive time instances intersects any shoreline segment. The release of beached oil particles is based on the half-life approximation to calculate their probability of release $P^{(C)}$, assigning different half-lives for the release of beached particles for different coast types (T_W parameter in Table 1). By calling a random number r between 0.0 and 1.0 and projecting the particle position in the next time step (thus using hydrodynamics information from the nearest gridpoint to the shoreline segment), the algorithm releases beached particles if $r < P^{(C)}$ and the position projection is to be "off-shore". The formulation for the probability of release is expressed by:

$$P^{(C)} = 1 - e^{(-t^* \ln 2/T_W)} \tag{4}$$

where t^* is the time since deposition.

The improvement presented in this work regards the revision of the release criteria, using as a sole condition for release the one expressed by $r < P^{(C)}$ as described above. The criterion based on the particle position projection was omitted, due to the dependence of the specific projection on values at the nearest grid point for the particle displacements, combined with the field discretization and the inherent shortcomings brought by it in oil spill models (see also the discretization issue raised in Section 3).

Regarding the second scenario for the fate of beached oil, the permanent attachment of beached oil particles to the coast (through seepage and/or other process) in the original MEDSLIK-II formulation is again based on the half-life approximation. By assigning different half-lives to particles of different coast types (T_S parameter in Table 1), the formulation calculates the fraction of oil attached permanently to the coast after deposition, defined by:

$$pf = 1 - e^{(-t^* \ln 2/T_S)} \tag{5}$$

with the total volume of the permanently attached oil limited by the holding capacity of the coast.

The improvement presented in this work regards the re-evaluation of the suitability of Eq. (5) to describe the permanent attachment of beached particles, following the notion that the probability of release and the fraction pf are based on processes that are conceptually opposite. And, although the probability of release is expected to be higher as time goes by, seepage and/or other processes of permanent attachment are expected to be higher after deposition (when the beach surface and structure are "oil-free") and get slower with time as more oil stays on-coast, eventually limited by the Oil Holding Capacity of the respective coast type. Accordingly, instead of using Eq. (5) to calculate pf, the modified

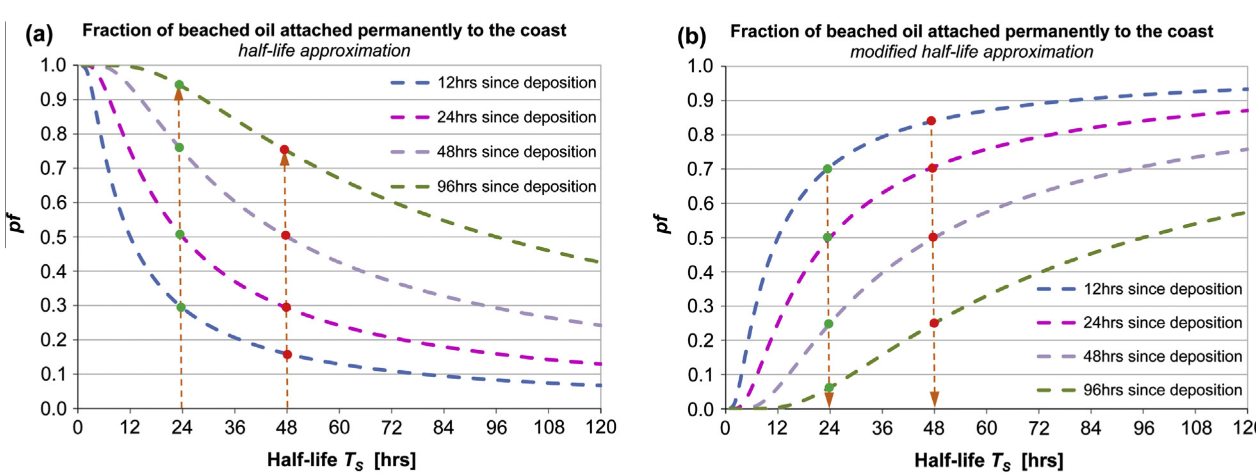

Fig. 5. Fraction of beached oil attached permanently to the coast (pf) for various instances after deposition, based on: (a) the half-life approximation used in the original MEDSLIK-II formulation (Eq. (5)), and (b) the modified half-life approximation (Eq. (6)).

formulation expressed by Eq. (6) was selected, still based on the exponential half-life approximation.

$$pf = e^{(-t^{*}\ln 2/T_S)} \tag{6}$$

Fig. 5b, based on Eq. (6), presents how the fraction of permanently attached oil – for a given half-life – decreases with time since deposition, instead of increasing as the original formulation dictates (Fig. 5a based on Eq. (5)).

2.5. The Lebanon oil spill

On July 13 and 15, 2006, the Jiyeh power station located about 30 km South of Beirut and directly on the Lebanese coastline (Fig. 6) was hit during hostility events. Some of the impacted storage tanks caught on fire, with the oil not consumed in the fire being spilled into the Mediterranean Sea. Estimates on the total amount of oil spilled (API gravity identified equal to 26 °API) range from 10,000 to 15,000 tonnes (OSOCC, 2006). Fig. 7a shows the observations of floating oil (classified as light and heavy) as drawn from OSOCC (2006); Fig. 7b shows the respective results for beached oil on different coast types.

2.6. MEDSLIK-II applications

MEDSLIK-II was used to simulate the fate of the spilled oil for 27 days (648 hrs) after the accident. Applications were performed using the original model version, as well as versions at various stages of the implementation of the improvements presented in Sections 2.2–2.4. The tidal range of the study area resulted from OTIS (Egbert and Erofeeva, 2002) runs for the specific period. The objective was to evaluate the proposed improvements and to validate – through intercomparison with the original model results – their suitability for a new formulation of MEDSLIK-II.

The results presented in the following will be indexed as Version I, II, III or IV results. Ver. I refers to the original MEDSLIK-II version, while Ver. II, III, and IV refer to the various stages of the implementation of the improvements of Sections 2.2–2.4, as presented in Table 3. It should be noted that the improved Versions of MEDSLIK-II presented in this work were intentionally focused on Oil Holding Capacity and release/permanent attachment of beached particles; the importance of the improvements presented in Section 2.2 was validated during sensitivity analyses and preliminary test-runs.

Fig. 6. The wider study area, Lebanon and the location of Jiyeh power station (Google Earth, 2013; privately processed).

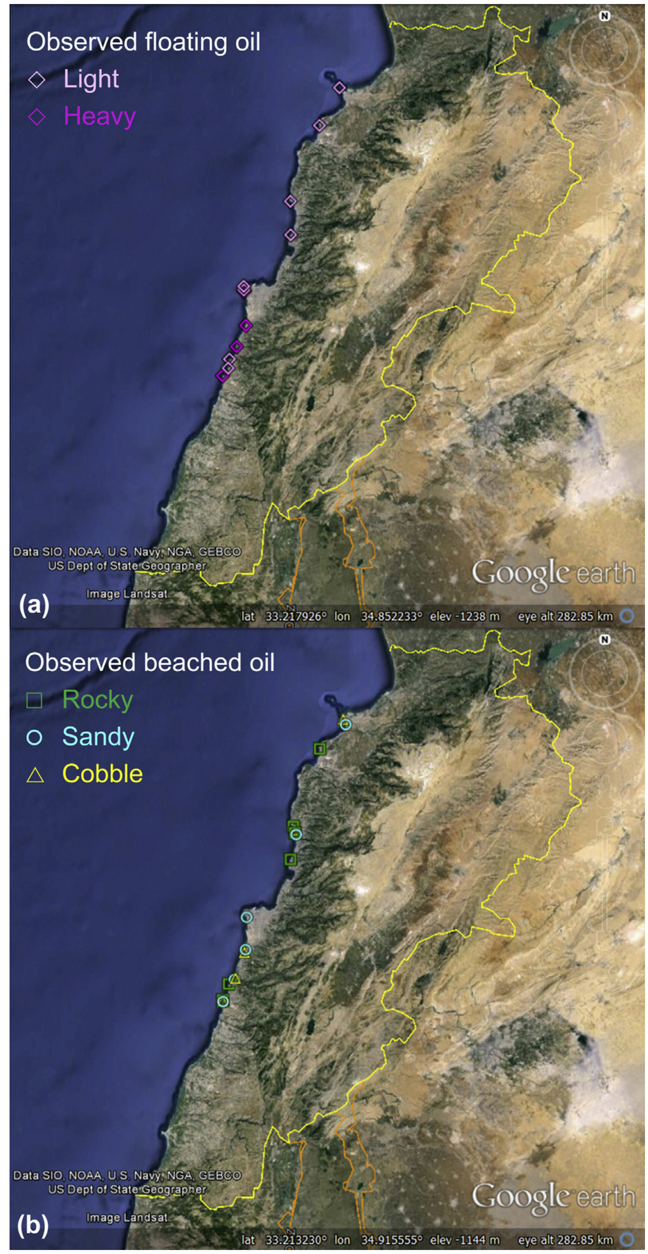

Fig. 7. Observations of: (a) floating oil (classified as light and heavy) and (b) beached oil on different coast types, as drawn from the OSOCC (2006) Report (Google Earth, 2013; privately processed).

3. Results and discussion

MEDSLIK-II output divides beached oil into two categories: (a) "fixed", i.e. oil permanently attached to the coast with no probability of release, and (b) "total", i.e. the total amount of oil that is beached at any given time, comprising both "fixed" oil and oil located on coast but free to be released according to the formulation presented in Section 2.4. In order to clarify any ambiguity that may arise from the use of the aforementioned terminology, "fixed" oil will be henceforth denoted as "permanent" (abbreviation: *perm*) and the amount of oil that is located on coast but is free to be released will be denoted as "free". It is intuitively deduced that

Table 3
Annotation on MEDSLIK-II versions based on the included improvements.

Improvement	Version			
	I	II	III	IV
Updated coastal type data	Original model version	✓	✓	✓
New algorithm for coastal type assignment		✓	✓	✓
Oil Holding Capacity approach for concentration on coast		✓	✓	✓
Change in release criteria			✓	✓
Modified calculation of *pf*[a]				✓

[a] *pf* is the fraction of beached oil attached permanently to the coast after deposition (see Eqs. (5) and (6)).

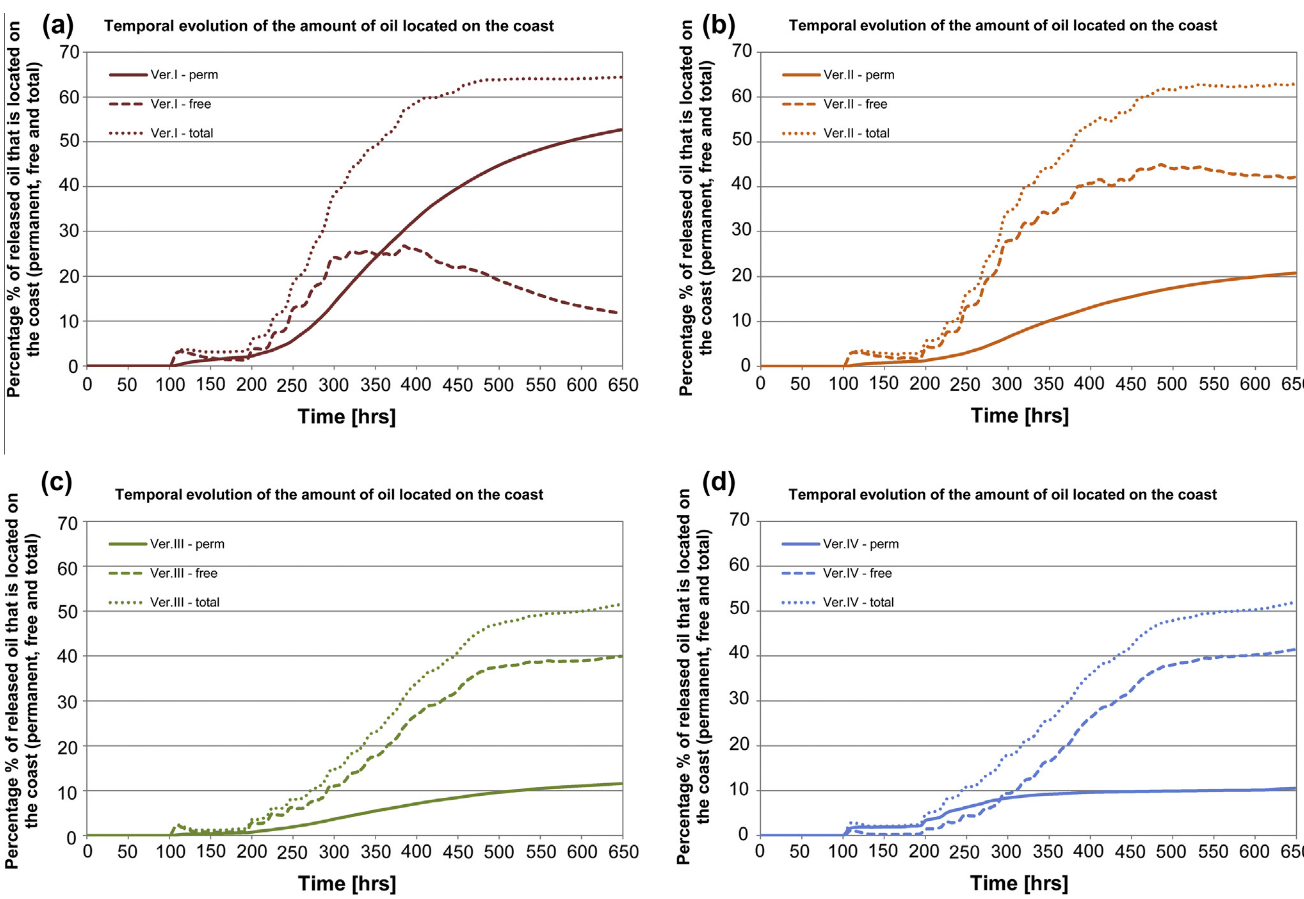

Fig. 8. Temporal evolution of permanent (*perm*), free and total oil located on coast for the MEDSLIK-II (a) Ver. I, (b) Ver. II, (c) Ver. III and (d) Ver. IV runs.

the total amount of oil located on coast at any given time is the sum of *perm* and *free* oil.

Fig. 8a–d present the temporal evolution of the above quantities for the MEDSLIK-II Ver. I, Ver. II, Ver. III and Ver. IV runs, respectively, for the Lebanon oil spill. Fig. 9 presents the temporal evolution of the *perm* and *total* oil on coast. Fig. 10 presents the temporal evolution of the *free* and *total* oil on coast.

Ver. I results denote the significantly different model behavior regarding the simulation of beaching before and after the implementation of the improvements presented in this work. The differences are evident, not only in the quantitative comparison of Ver. I and other Versions' results, but in the qualitative evolution of the modeled processes as well.

The improvement brought by the introduction of the coast type specific Oil Holding Capacity (OHC) approach (along with the updated coast type data and the assignment algorithm) in the representation of oil concentration on coast (see also Table 3 and Sections 2.2 and 2.3) is clearly identified in Fig. 8 and the comparative graphs of Figs. 9 and 10. Significant differences are identified between Ver. I and the other Versions' results. Specifically, in Ver. I the amount of permanent oil on coast follows the increase of the total amount, with the free oil reaching its maximum (to a relatively low quantity) shortly after the shoreline impact, and decreasing after that. To further elaborate, this means that the original formulation led the majority of beached oil particles to be practically "trapped" in the beach structure, leaving only a small amount of particles with the probability of being released back to the water column. On the contrary, Ver. II, Ver. III and Ver. IV results show permanent oil being constrained by the OHC of the various coast types, with a trend of reaching a maximum over time. Consequently, the respective amount of free oil particles is larger and follows the evolution of the total oil on the coast.

The improvement brought by the change in the beached particle release criterion (see also Table 3 and Section 2.4) is identified

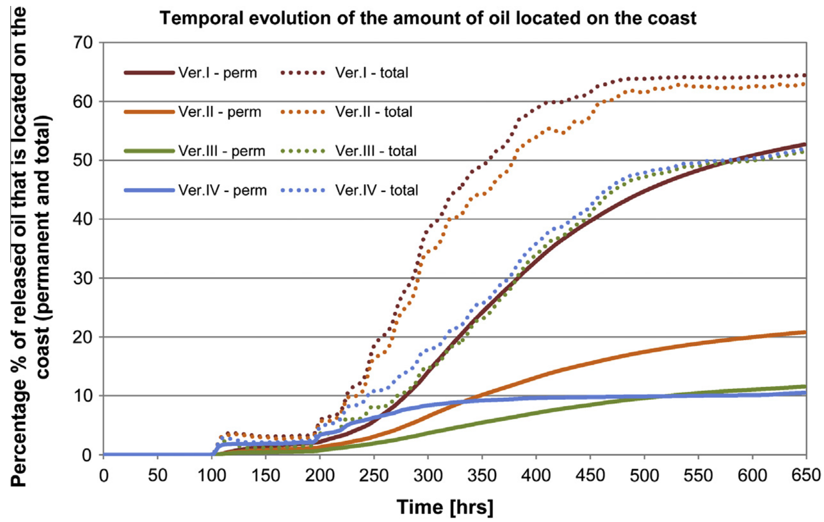

Fig. 9. Temporal evolution of permanent (*perm*) and total oil located on coast for all MEDSLIK-II versions' runs.

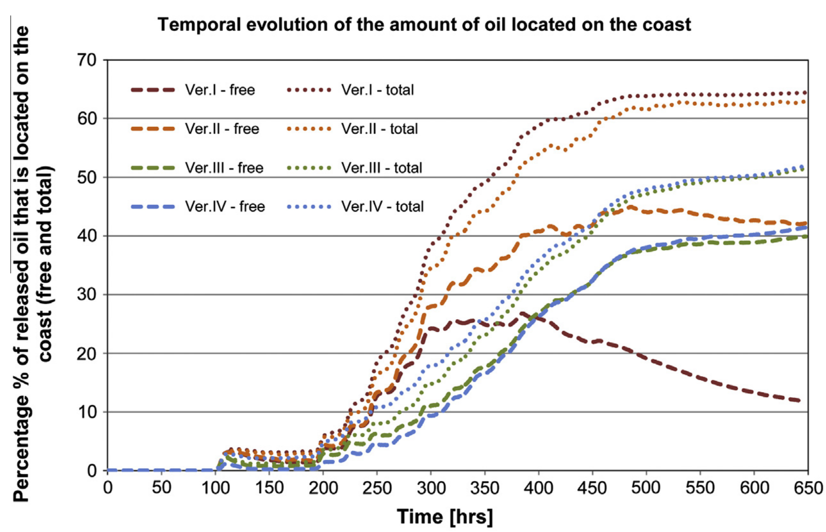

Fig. 10. Temporal evolution of free and total oil located on coast for all MEDSLIK-II versions' runs.

between Ver. II and Ver. III/Ver. IV results, and can be seen in Figs. 8–10. The original model formulation (still present in Ver. II) resulted in particles with high probabilities of release (i.e. $P^{(C)}$) not being "allowed" to return into the water column, due to the impact of the coarse grid resolution on their projected position (see also discussion in the following). The specific change allowed free beached particles to be released more easily, leading to a decrease of the total amount of oil located on coast by approximately 15% (see also discussion on Fig. 11 in the following).

Finally, the improvement brought by the introduction of the modified calculation of the fraction of oil attached permanently to the coast *pf* (see also Table 3 and Section 2.4) is identified between Ver. II/Ver. III and Ver. IV results, and can be seen in Figs. 8–10. The focus should be given to the temporal evolution of the amount of permanent oil located on coast. Ver. II and Ver. III results show a mild but continuous increasing trend of this amount, as dictated by the original half-life approximation used for *pf*. However, the modified half-life approximation in Ver. IV results in a more representative evolution of the process, with permanent oil rapidly increasing towards its high value shortly after the attachment to the shoreline and then remaining almost stable as OHC was reached.

Fig. 11 shows the plots of oil concentration on coast at the end of the of the 648hr (27d) MEDSLIK-II runs for all Versions (see also Table 3); Fig. 12 shows the comparison between the respective plot for the Ver. IV run (i.e. the Version comprising all the improvements presented in Sections 2.2, 2.3 and 2.4) and the field observations of beached oil (OSOCC, 2006). The results presented in Fig. 11 denote the improvement brought by the change in the beached particle release criterion on the simulated extent of the oiled shoreline. The change in the release criterion (included in Ver. III and Ver. IV) allows more beached oil particles to be released and the slick to travel farther to the North. Ver. I (Fig. 11a) and Ver. II (Fig. 11b) runs using the release criterion of the original formulation, show the impacted shoreline limited up to the area of Batroun (approx. 25 km S-SW of Tripoli and 45 km N-NE of Beirut). On the other hand, Ver. III (Fig. 11c) and Ver. IV (Fig. 11d) runs show oiled shoreline to be extended up to the area of Tripoli. The change in the extent of the oiled shoreline between Ver. I/Ver. II and Ver. III/Ver. IV runs is more than significant and reaches 40%. Furthermore and

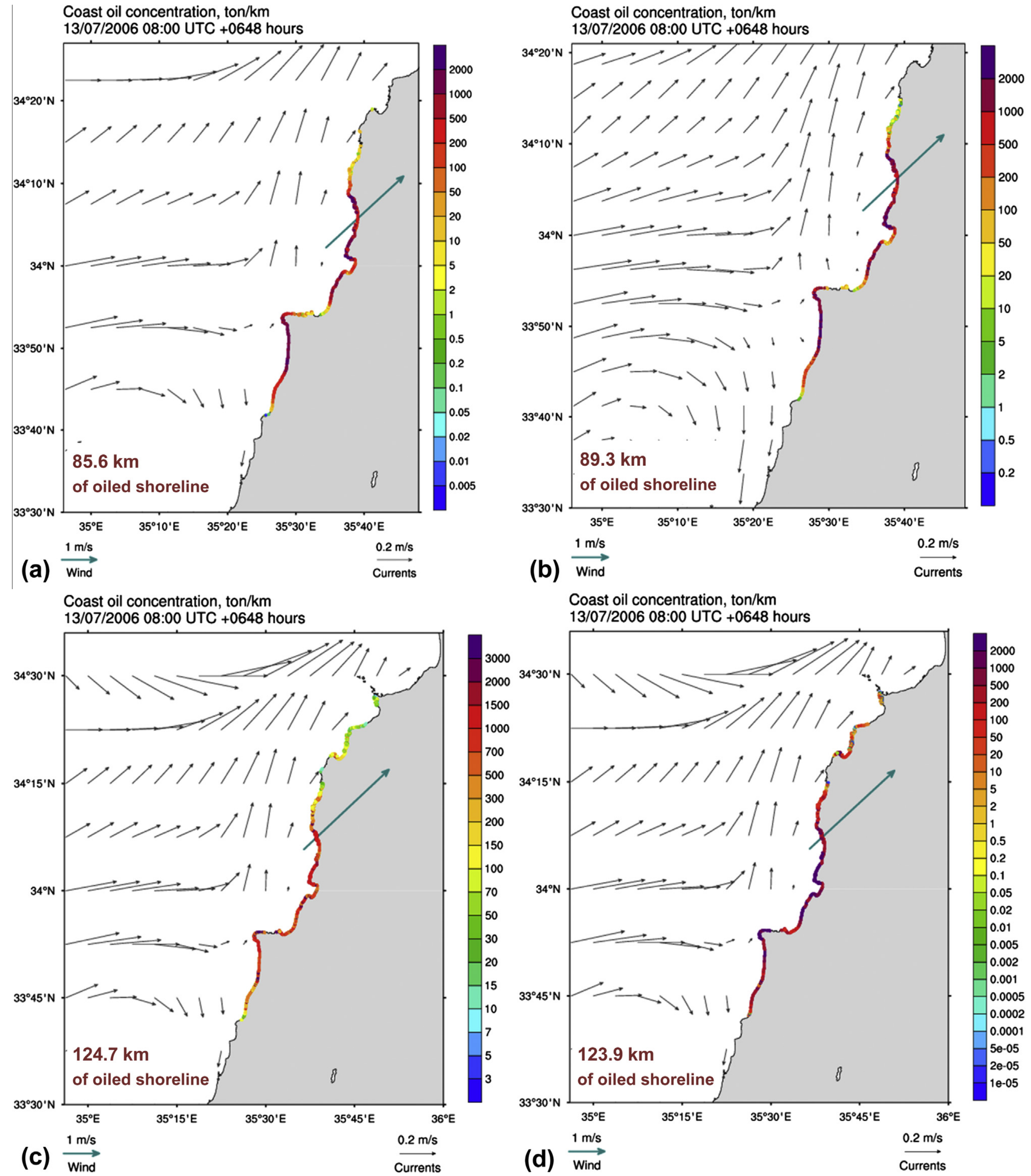

Fig. 11. On coast oil concentration plots and oiled shoreline extent at the end of the 648 h (27d) MEDSLIK-II (a) Ver. I, (b) Ver. II, (c) Ver. III and (d) Ver. IV runs.

most importantly, Fig. 12 shows that the improved model version manages to capture entirely the extent of the oiled shoreline as drawn from the OSOCC (2006) Report. Results do not show the oil slick traveling past the Lebanese-Syrian border, as indicated by satellite images of the wider area in the period after the accident (Coppini et al., 2011; El-Fadel et al., 2012). The lack of detail on the nearshore wave climate (see discussion in the following) could be the explanation for this shortcoming, as – for example – longshore currents due to braking waves would significantly contribute to the slick transport.

Elaborating on the last comment, it should be noted that a basic modeling problem identified in most operational oil spill models, arises from the fact that they aim to simulate mainly offshore spills, thus using relatively coarse spatial grids. Due to that, they cannot adequately represent the zone defined as "nearshore", where the decrease of water-depth and the consequent dependence on bathymetry entirely change coastal hydrodynamics.

However, even apart from the above consideration, from a wider perspective the main issue for all modeling attempts remains, and can be summed up to the question: "What should

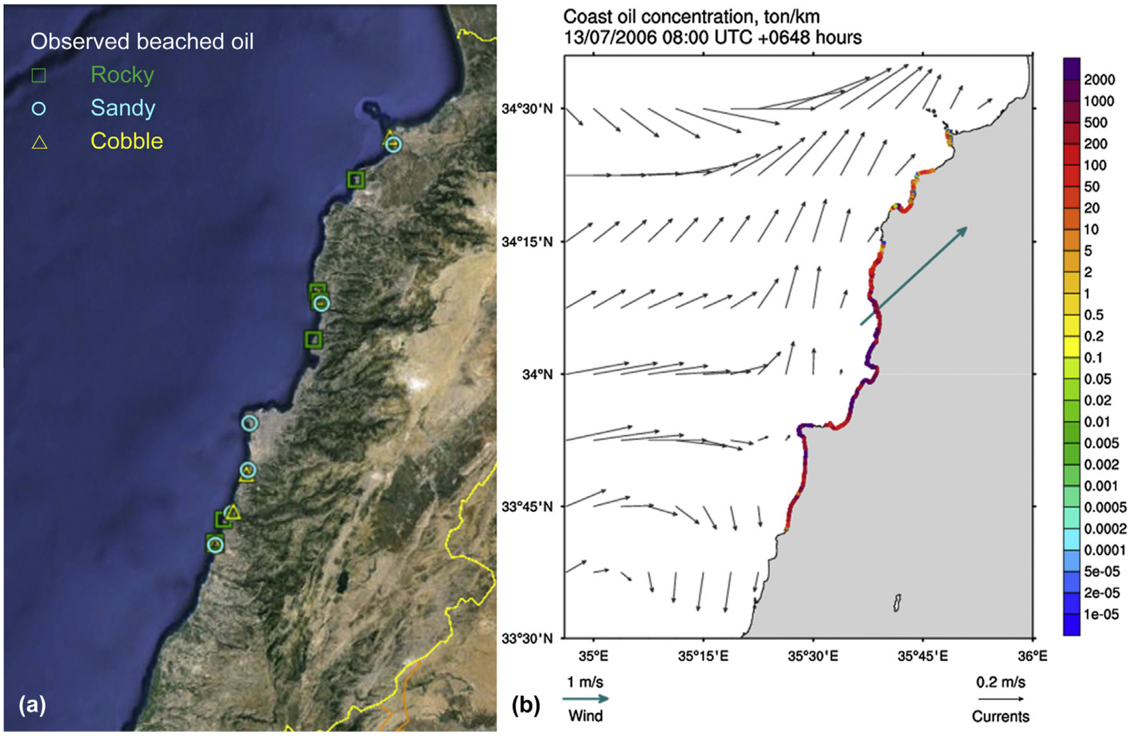

Fig. 12. (a) Observations of beached oil on different coast types, as drawn from the OSOCC (2006) Report (Google Earth, 2013; privately processed), and (b) on coast oil concentration plot at the end of the 648 h (27 d) MEDSLIK-II Ver. IV run.

be considered as effective representation of beaching for operational oil spill models?". The answer to that conceptually depends on the modeling objectives, but it is also largely affected by data availability of coast types, beach properties and oil concentration evolution on-coast (surface and subsurface). The argument that the increasing computational capacity and model-coupling will allow high-resolution representations of nearshore hydrodynamics (maybe at some point even two-phase oil-water dynamics on the foreshore), can only be valid to a certain extent without detailed field data to validate the expected improvement. All in all, considering the current capabilities of operational oil spill models, the present scarcity of field data, and the fact that oil spill response for impacted coastal areas is primarily a remediation and not a sampling process, the representation of beaching and the respective model results (location/extent of oiled shorelines, oil concentration on coast, temporal characteristics of acting processes) should be evaluated accordingly.

4. Conclusions

The present work studies the improvement of the representation of beaching in oil spill models. In particular, it investigates the effect of the introduction of the Oil Holding Capacity approach to estimate oil concentration on coast, along with a new approach for coast type assignment to shoreline segments, the revision of the release criteria for beached particles and a revised formula for the calculation of permanent oil attachment to the coast based on the half-life approximation. The above were tested for the Lebanon oil spill of 2006, using a modified version of the open-source oil spill model MEDSLIK-II (De Dominicis et al., 2013a); the coast type database for the specific study was also reconstructed for the new model runs.

The modified MEDSLIK-II Version has brought significant improvements in the representation of beaching in the model. The final version's run (Ver. IV – comprising all the aforementioned improvements) was based on case-specific coast type data for the Lebanon oil spill of 2006, a new algorithm for coast type assignment to shoreline segments and a coast type- dependent representation of the oil concentration on coast based on the Oil Holding Capacity approach. The revised criteria for the release of beached particles circumvented shortcomings imposed by the lack of detail in nearshore hydrodynamics, while the modified version of the half-life approximation for the calculation of permanent oil attachment to the coast lead to an overall better representation of the process. Furthermore, results showed a close agreement with field observations, capturing entirely the extent of the oiled shoreline as drawn from the OSOCC (2006) Report.

Given the inherent uncertainties in the understanding and modeling of the processes following oil attachment to the coast, the alterations presented in this work are considered as a significant step towards the overall improvement of the representation of beaching in oil spill models. Accordingly, their implementation to a real case study using an open-source model is deemed to serve as a useful example for researchers involved in oil spill modeling, setting the basis for future attempts on the same path.

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References

Boufadel, M.C., 2000. A mechanistic study of nonlinear solute transport in a groundwater–surface water system under steady state and transient hydraulic conditions. Water Resour. Res. 36, 2549–2565.

Chao, X., Shankar, N.J., Cheong, H.F., 2001. Two- and three-dimensional oil spill model for coastal waters. Ocean Eng. 28, 1557–1573.

Cheng, N.S., Law, A.W.K., Findikakis, A.N., 2000. Oil transport in surf zone. J. Hydraul. Eng. 126, 803–809.

Coppini, G., De Dominicis, M., Zodiatis, G., Lardner, R., Pinardi, N., Santoleri, R., Colella, S., Bignami, F., Hayes, D.R., Soloviev, D., Georgiou, G., Kallos, G., 2011. Hindcast of oil-spill pollution during the Lebanon crisis in the Eastern Mediterranean, July-August 2006. Mar. Pollut. Bull. 62, 140–153.

Danchuk, S., Willson, C.S., 2010. Effects of shoreline sensitivity on oil spill trajectory modelling of the Lower Mississippi River. Environ. Sci. Pollut. Res. 17, 331–340.

De Dominicis, M., Pinardi, N., Zodiatis, G., Lardner, R., 2013a. MEDSLIK-II, a Lagrangian marine surface oil spill model for short-term forecasting – Part 1: Theory. Geosci. Model Develop. 6, 1851–1869.

De Dominicis, M., Pinardi, N., Zodiatis, G., Archetti, R., 2013b. MEDSLIK-II, a Lagrangian marine surface oil spill model for short-term forecasting – Part 2: Numerical simulations and validations. Geosci. Model Develop. 6, 1871–1888.

Egbert, G.D., Erofeeva, S.Y., 2002. Efficient inverse modelling of barotropic ocean tides. J. Atmos. Ocean. Technol. 19, 183–204.

El-Fadel, M., Abdallah, R., Rachid, G., 2012. A modelling approach toward oil spill management along the Eastern Mediterranean. J. Environ. Manage. 113, 93–102.

Etkin, D.S., French-McCay, D., Michel, J., 2007. Review of the State-of-the-Art on Modelling Interactions between Spilled Oil and Shorelines for the Development of Algorithms for Oil Spill Risk Analysis Modelling. Cortlandt Manor, New York, p. 157.

Google Earth, 2013. Map of Lebanon. © 2013 ORION-ME, US Dept. of State Geographer, Image Landsat, Data SIO, NOAA, U.S. Navy, NGA, GEBCO.

Gundlach, E.R., 1987. Oil-holding capacities and removal coefficients for different shoreline types to computer simulate spills in coastal waters, 1987 International Oil Spill Conference. Baltimore, Maryland, USA, pp. 451–457.

Gundlach, E.R., Hayes, M.D., 1978. Vulnerability of coastal environments to oil spill impacts. Mar. Technol. Soc. J. 12, 18–27.

Gundlach, E.R., Reed, M., 1986. Quantification of oil deposition and removal rates for a shoreline/oil spill interaction model. In: 14th Arctic and Marine Oil Spill Program Technical Seminar, pp. 65–76.

Guo, W.J., Wang, Y.X., 2009. A numerical oil spill model based on a hybrid method. Mar. Pollut. Bull. 58, 726–734.

Humphrey, B., Owens, E.H., Sergy, G., 1993. Development of a stranded oil in coarse sediment (SOCS) model. In: 1993 International Oil Spill Conference, Tampa, Florida, USA, pp. 575–582.

Johnson, W.R., Ji, Z.-G., Marshall, C.F., 2005. Statistical estimates of shoreline oil contact in the Gulf of Mexico, 2005 International Oil Spill Conference. Florida, USA, Miami, pp. 547–551.

Lee, K., Stoffyn-Egli, P., Tremblay, G.H., Owens, E.H., Sergy, G.A., Guénette, C.C., Prince, R.C., 2003. Oil-mineral aggregate formation on oiled beaches: natural attenuation and sediment relocation. Spill Sci. Technol. Bull. 8, 285–296.

Mackay, D., Paterson, S., Trudel, B., 1980. A mathematical model of oil spill behaviour. Report to Research and Development Division, Environment Emergency Branch, Environmental Impact Control Directorate, Environmental Protection Service, Environment Canada, Ottawa, Canada.

NOAA – National Oceanic and Atmospheric Administration,, 2000. Shoreline Assessment Manual. National Oceanic and Atmospheric Administration, Office of Response and Restoration, Seattle, USA, p. 54.

OSOCC – Oil Spill Operations and Coordination Centre, 2006. Lebanon Marine and Coastal Oil Pollution International Assistance Action Plan. Ministry of Environment, Lebanon.

Owens, E.H., Lee, K., 2003. Interaction of oil and mineral fines on shorelines: review and assessment. Mar. Pollut. Bull. 47, 397–405.

Owens, E.H., Sergy, G.A., 2003. The development of the SCAT process for the assessment of oiled shorelines. Mar. Pollut. Bull. 47, 415–422.

Owens, E.H., Teal, A.R., 1990. Shoreline cleanup following the "Exxon Valdez" oil spill – field data collection within the SCAT program. In: 13th Arctic and Marine Oil spill Program (AMOP) Technical Seminar. Environment Canada, Ottawa, Canada, pp. 411–421.

Reed, M., Gundlach, E., Kana, T., 1989. A coastal zone oil spill model: development and sensitivity studies. Oil Chem. Poll. 5, 411–449.

Reed, M., Johansen, O., Brandvik, P.J., Daling, P., Lewis, A., Fiocco, R., MacKay, D., Prentki, R., 1999. Oil spill modelling towards the close of the 20th century: overview of the state of the art. Spill Sci. Technol. Bull. 5, 3–16.

Sergy, G., Goodman, R., 2003. In situ treatment and fate of oil stranded on coarse-sediment shorelines: the Svalbard shoreline field trials. Spill Sci. Technol. Bull. 8, 229.

Shen, H.T., Yapa, P.D., Petroski, M.E., 1987. A simulation model for oil slick transport in lakes. Water Resour. Res. 23, 1949–1957.

Torgrimson, G.M., 1980. The On-Scene Spill Model: A User's Guide. Hazardous Materials Response Branch, National Oceanic and Atmospheric Administration, Seattle, Washington.

Wang, S.D., Shen, Y.M., Zheng, Y.H., 2005. Two-dimensional numerical simulation for transport and fate of oil spills in seas. Ocean Eng. 32, 1556–1571.