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Advances in operational oil spill modelling: Implications for the protection of the Black Sea Basin

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ABSTRACT. Oil spills pose a severe threat for the coastal and marine environment, due to their negative impact on ecosystems, habitats and human activities. Oil spill models simulate the processes that control the fate of oil spilled at sea and its interaction with different types of coasts (when attached to them), providing with estimates of the slick's trajectory, along with the spatial and temporal evolution of oil concentration. The operational applicability of the models is further extended by incorporating the representation of various response actions for the containment and removal of oil (e.g. deployment of booms, use of skimmers / dispersants / sorbents), as well as by coupling them with optimization modules for the optimal allocation of coastal oil slick combatting stations. In the above context, it is self-evident that operational models are nowadays essential in the process of mitigating the effects of oil spills, and do constitute the basis for the set of activities comprised in Oil Spill Response. The present work focuses on recent advances in operational oil spill modelling and analyzes their implications for the protection of the Black Sea Basin. The latter is examined through exemplary applications for the Sea of Azov, a main maritime transport route for ships moving from the Danube to the Caspian Sea and an area of significant environmental importance.

Key words: Oil spills; Modelling; Oil spill response; Black Sea; Sea of Azov

INTRODUCTION

Marine pollution is defined as the input of harmful or potentially harmful substances in the marine environment that affect water quality, marine habitats and human activities. The sources of oil input in the marine environment can be classified into three main categories: (a) natural, comprising natural seepage from fissures in the ocean seabed and eroding sedimentary rocks; (b) sea-based, further classified into operational, accidental and airborne discharges; and (c) land-based, comprising from accidental discharges to untreated sewage and wastewater ending up to the sea. Oil pollution has always been on the spotlight due to the severity of its impact on coastal and marine ecosystems, particularly attracting interest due to the visible effects of major accidental spills from sea- or land-based activities. Estimates about the quantity of oil released to the sea vary from 2 to 9 million tonnes per year, with the percentage attributed to spills from ships ranging from 12% to 24% (US National Research Council and GESAMP estimates respectively). And, although oil spills may not represent the single biggest source, the quick release of large amounts of (usually) crude oil multiplies their impact on the marine environment.

Oil Spill Response is a set of organized activities that aim to protect the safety and health of responders and the public, reduce the impact to the environment, and protect properties in the impacted coastal areas. These activities can be organized to a number of respective "steps" to be followed by the responsible authorities [***9***]: (1) activating of response operations; (2) obtainment and assessment of incident data; (3) surveillance and tracking of the spill; (4) containment and removal of the oil; (5) protection of threatened resources; (6) evaluation of wildlife rehabilitation options; (7) conduction of shoreline treatment; and (8) finalizing operations. The role of numerical modelling in the above is essential, as oil spill models – depending on their type and sophistication – are either the basis or an indispensable part of the activities comprised in steps 2, 3 and 4 listed above.

Fig. 1 presents a general schematic layout of oil spill models. The models' objective is to adequately represent physical processes, with their operational applicability being further extended by incorporating the representation of various response actions for the containment and removal of oil (e.g. deployment of booms, use of skimmers / dispersants / sorbents).

Oil spill models can be classified into five major types: (a) Oil weathering models, providing with spilled oil percentages affected by the various processes; (b) Trajectory / Particle-tracking models, used to estimate the slick trajectory and particle positions; (c) Stochastic or Probabilistic models, providing with estimates of the probability of where an oil spill may impact for defined time periods (used for risk assessment); (d) hindcast models, reversing the trajectory modelling process in order to estimate the spill origin (in case it is unknown); and (e) 3D / quasi-3D models, providing with detailed estimates of the slick's trajectory and spreading, as well as of the evolution of the various processes and oil concentration. The model used in this work falls into this last category.

The Black Sea in one of the most remarkable regional seas in the world, extending over an area of approx. 436,400 km^2 with a maximum depth of 2212 m. It is bordered by six countries (i.e. Romania, Ukraine, Russia, Georgia, Turkey and Bulgaria) and is connected to the Aegean Sea through the Bosphorus Strait (at the SW), the Sea of Marmara and the Dardanelles Strait. The basin is also connected to the N-NE with the Sea of Azov through the Strait of Kerch. The Black Sea has always been an area of major economic importance, hosting numerous maritime transport routes connecting the border countries, as well as the entire area to the Aegean Sea and the Mediterranean Sea. This significant economic importance and the increase of maritime transport have deteriorated – and do still endanger – the environmental quality of the entire Black Sea basin, which comprises a large amount of sensitive marine/coastal ecosystems and habitats ([***2***]; [***3***]).

The present work retains the viewpoint of environmental risk assessment for threats posed by oil spills to the marine and coastal environment, studying the improvements brought by advances in operational oil spill modelling. The study focuses on the Sea of Azov, a particular case of an enclosed basin of limited depth (below 15 m). The exemplary selected applications of an oil spill model coupled with a respective hydrodynamic model denote the importance of such results for operational planning and response to oil spills, while setting the basis for future work on the same path.

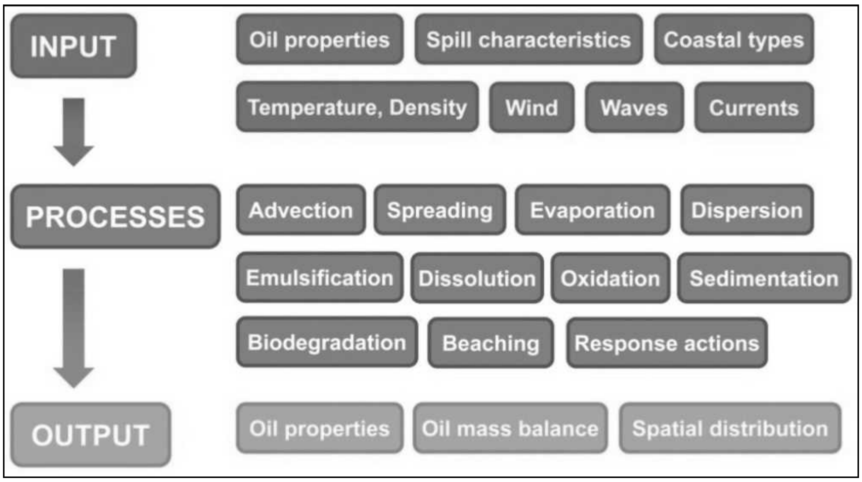

Fig. 1. Schematic layout of oil spill models.

MATERIALS AND METHODS

Study Area

As also mentioned above, the Sea of Azov is located N-NE of the Black Sea, and connected with it through the narrow (approx. 4 km of width) Strait of Kerch (see **Fig. 2**). It extends over an area of approx. 39,000 km^2 with a maximum depth of only 14 m, being considered as the shallowest sea in the world ([***4***]; see **Fig. 3**). Its total drainage basin is approx. 570,000 km^2, with the main fresh water source being the Don River at the NE. The Don was historically characterized by high seasonal fluctuations in flow, prior to the reservoirs constructed during the ’50s that significantly stabilized the respective regime to a mean annual discharge of approx. 900÷1000 m^3/sec [***1***].

Oil spill modelling

Oil slick evolution in the present work was modeled using an oil spill model based on the Lagrangian model formalism (representation of the spill as a number of passive particles), coupled with a 2DH hydrodynamic model to describe wind and river-inflow generated circulation. The models were properly adapted for the application to the Sea of Azov. The detailed description of the models and the modeled processes exceeds the scope of this work; one may refer to the previous works ([***5***]; [***7***]; [***8***]).

Applications to the Sea of Azov

The scope of this work was to investigate the implications of operational oil spill modelling for the protection of the Black Sea Basin. The contribution of such models to the set of activities described as Oil Spill Response was studied through exemplary applications to the Sea of Azov. Two accident locations were selected along the main maritime transport route connecting the Black Sea with the port of Rostov-on-Don; one near the Strait of Kerch and one at Taganrog Bay. The basin circulation regime was studied using as forcings NE and W winds (prevailing directions in the area) combined with the discharge from the Don.

RESULTS AND DISCUSSIONS

Fig. 4 shows the wind and river-inflow generated circulation in the Sea of Azov for a 5m/sec NE wind and 900m3/sec Don discharge; **Fig. 5** shows the respective results for a same intensity but different direction W wind. The depth averaged and surface currents depict the circulation patterns in the study area. The influence of the Don discharge can be identified more clearly in the part near its estuary, while the results for the case of the – statistically prevailing – NE wind show a clear outflow pattern through the Strait of Kerch. The higher current velocities are observed near the shallow N, S and SE (depending on wind direction) coasts of the enclosed basin, reaching, at maximum, 0.25m/sec (surface velocities).

Figs. 6 and **Fig. 7** show the modeled slick evolution 1, 3 and 7 days after the spill based on the first forcings scenario (5m/sec NE wind and 900m^3/sec Don discharge), for the two accident locations, respectively. The bottom parts of the figures present the impacted coastal segments and the respective beached oil quantities as well; the quantities are expressed as percentages of spilled oil. The results for the accident near the Strait of Kerch (**Fig. 6**) show the oil particles, constrained by local hydrodynamics, travelling near the adjacent coasts to the West and partially through the Strait. The spilled oil ends up almost entirely beached, affecting a shoreline of approx. 100km of length within a week. For the accident at Taganrog Bay (**Fig. 7**), the Don inflow along with the NE wind drive the oil slick outside of the Bay. Beached oil quantities are significantly lower than for the first accident location, with the impacted shoreline limited to Dolzhanskaya Spit and its immediate vicinity, measuring approx. 50km of length.

Figs. 8 and **Fig. 9** show the respective results based on the second forcings scenario (5m/sec W wind and 900m^3/sec Don discharge). For the accident near the Strait of Kerch (**Fig. 8**), the oil slick travels to the East, affecting on its way the S-SE part of the basin's coasts almost up to Primorsko-Akhtarsk.

And, although the beached oil quantities are kept below 5% of the spilled oil at individual coastal segments, the impacted shoreline measures approx. 120km of length within the week of the simulation. The accident at Taganrog Bay for this second forcings scenario (**Fig. 9**) is the one with the most extensive impact on the coasts of the Sea of Azov, as the wind-induced circulation drives the oil particles further inside the Bay, marginally reaching the Don estuary within the week of the simulation. The heavier impact is observed at the Yeysk and Glafirovsk Spits (beached oil percentages >10%); the total length of the impacted shoreline reaches 150km.

Fig. 2. Satellite image of the wider are of the Sea of Azov (base image [***10***]; privately processed]**.**

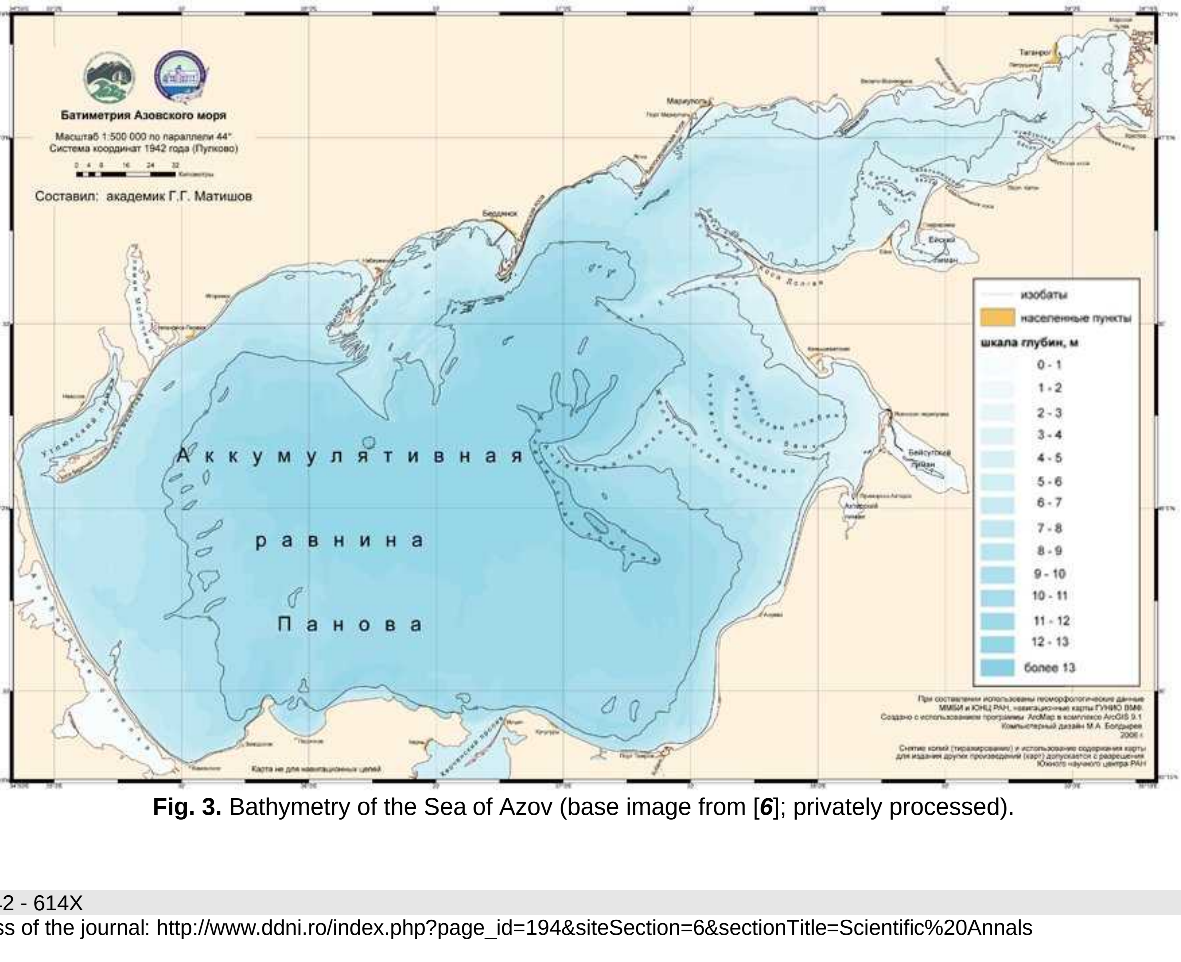

Fig. 3. Bathymetry of the Sea of Azov (base image from [***6***]; privately processed).

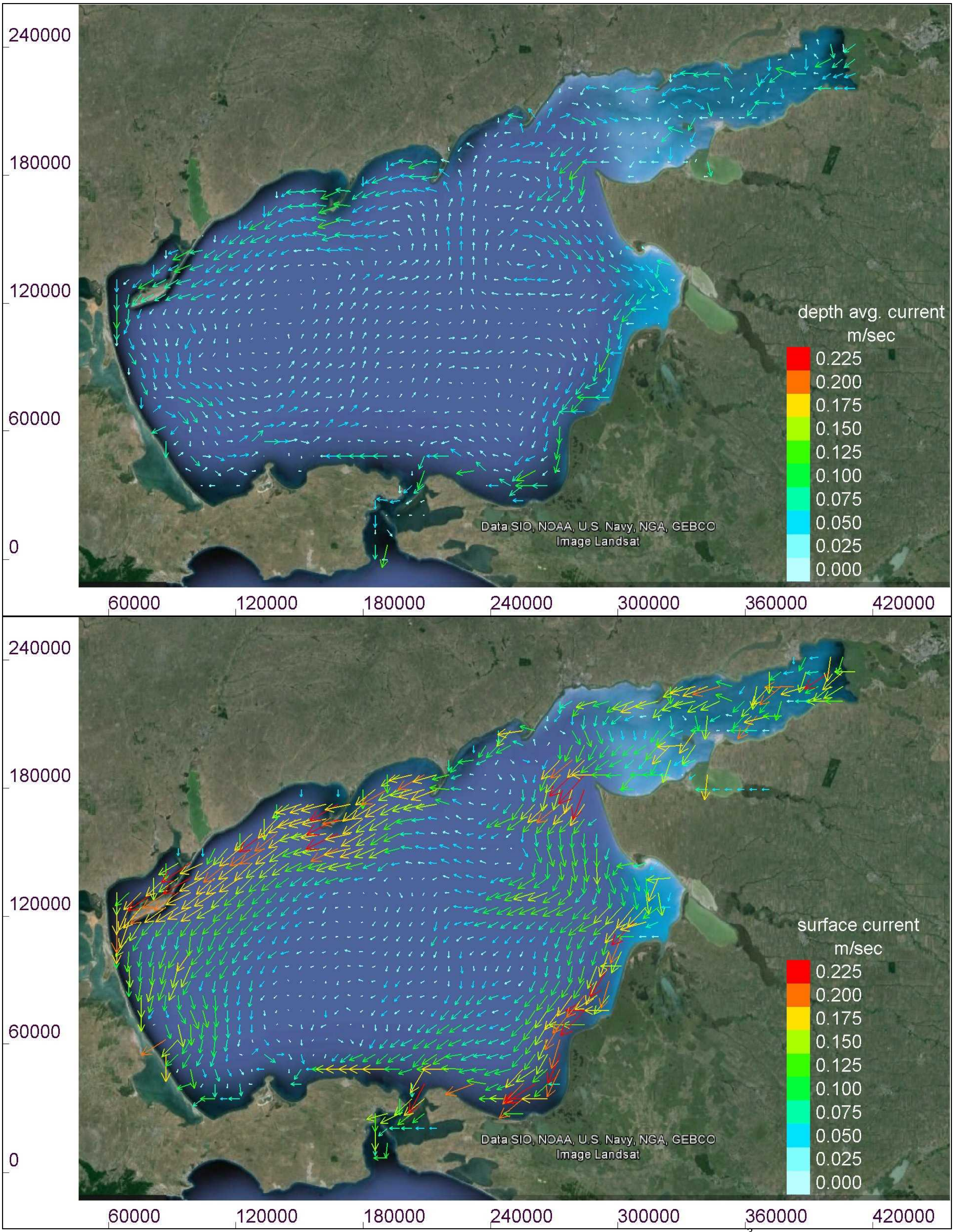

Fig. 4. Wind and river-inflow generated circulation in the Sea of Azov for a 5m/sec NE wind and 900m^3/sec Don discharge; depth averaged (top) and surface currents (bottom) as resulted from the hydrodynamic model.

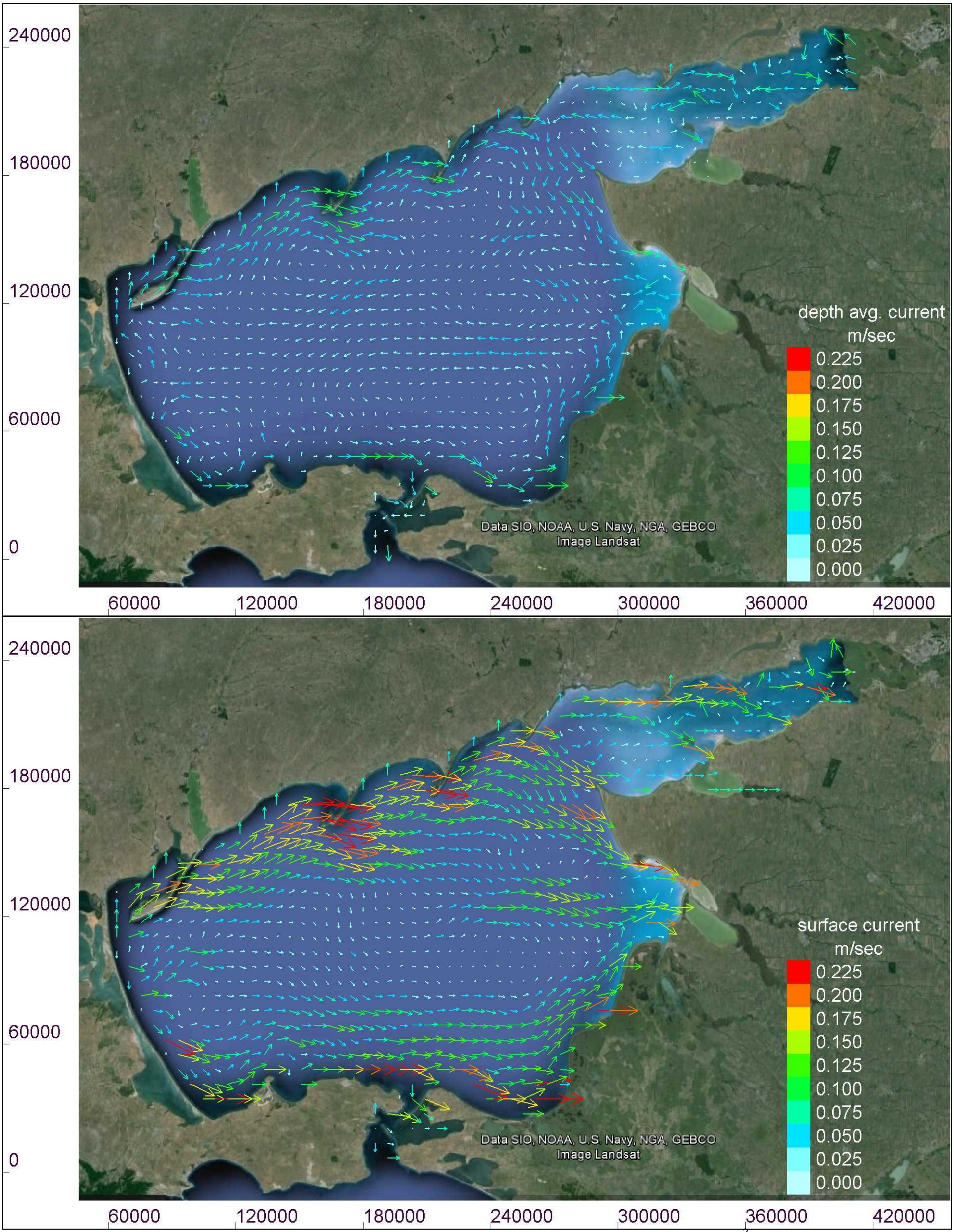

Fig. 5. Wind and river-inflow generated circulation in the Sea of Azov for a 5m/sec W wind and 900m^3/sec Don discharge; depth averaged (top) and surface currents (bottom) as resulted from the hydrodynamic model.

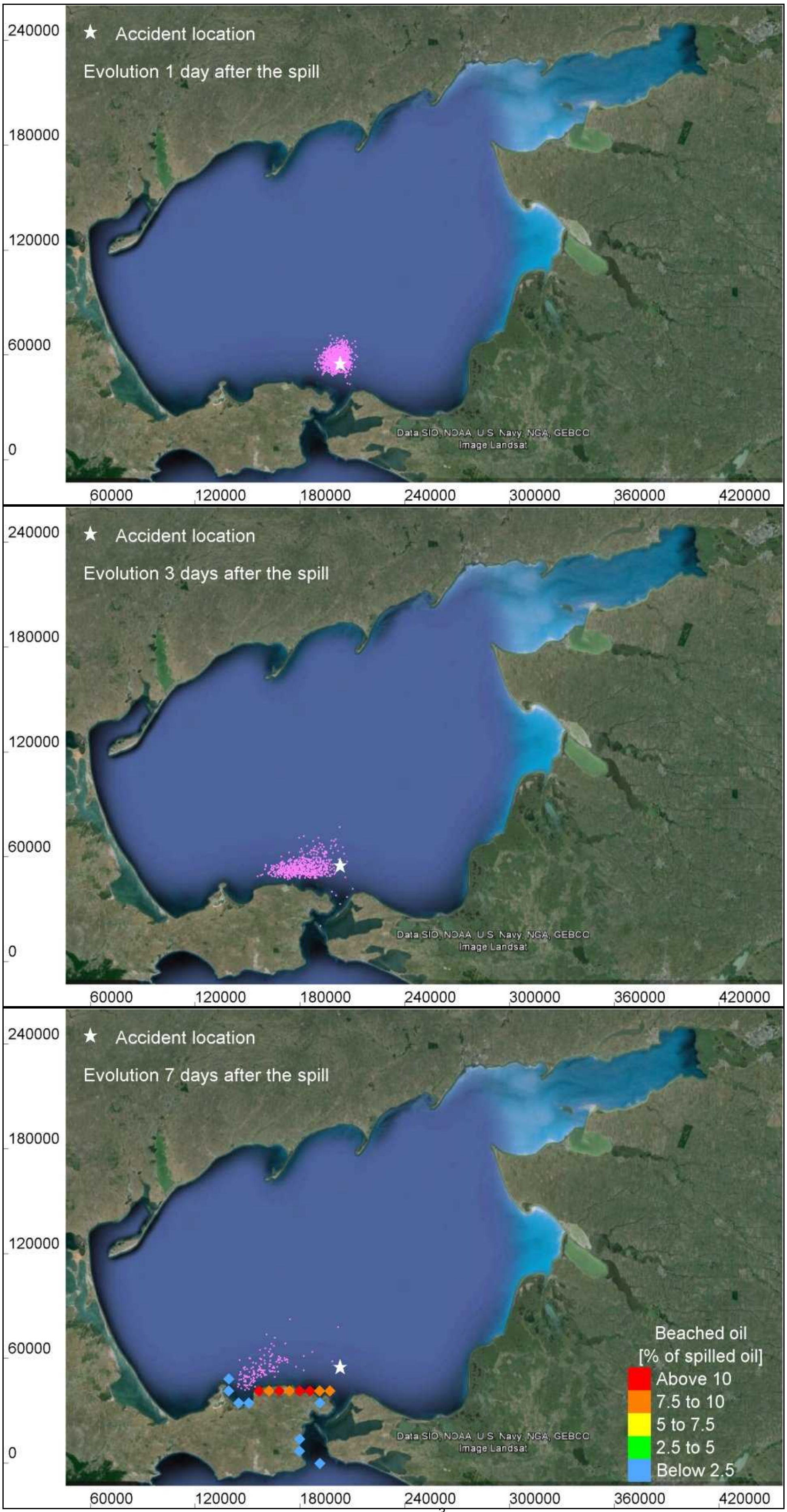

Fig. 6. Accident near the Strait of Kerch – 5m/sec NE wind and 900m^3/sec Don discharge; modeled slick evolution 1 day (top), 3 days (middle) and 7 days after the spill, along with the impacted coastal segments and the respective beached oil quantities (bottom).

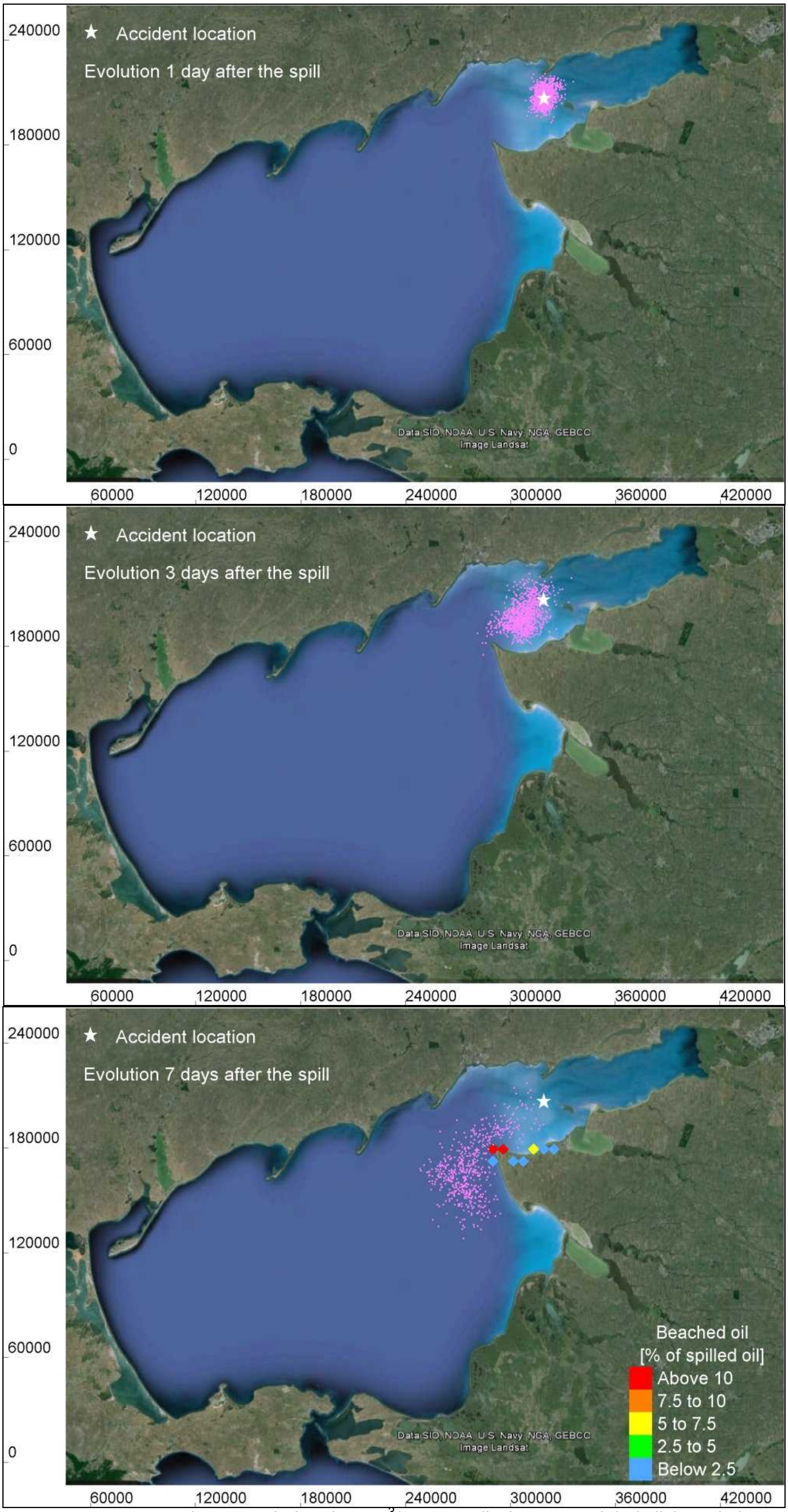

Fig. 7. Accident at Taganrog Bay – 5m/sec NE wind and 900m^3/sec Don discharge; modeled slick evolution 1 day (top), 3 days (middle) and 7 days after the spill, along with the impacted coastal segments and the respective beached oil quantities (bottom).

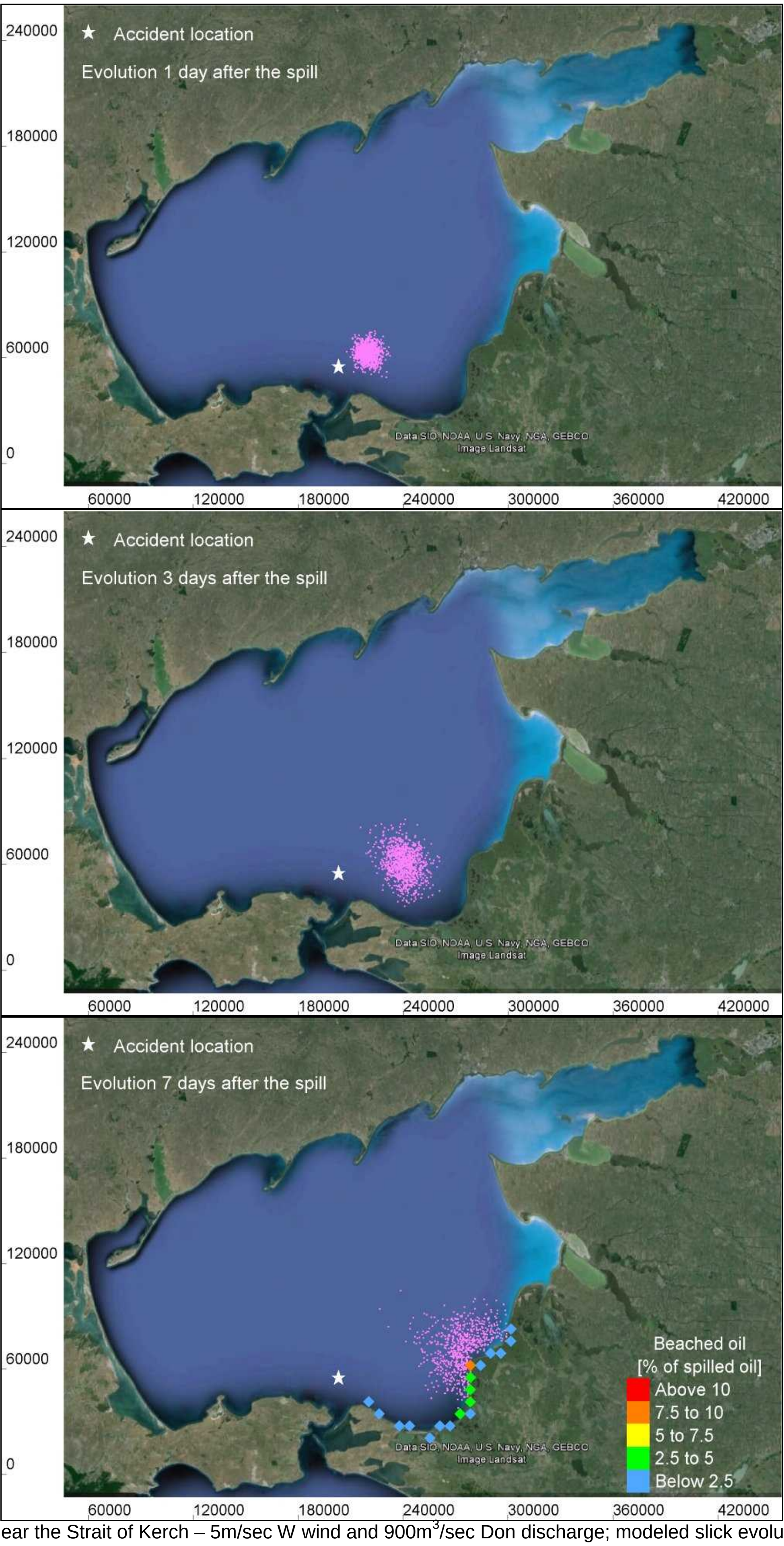

Fig. 8. Accident near the Strait of Kerch – 5m/sec W wind and 900m^3/sec Don discharge; modeled slick evolution 1 day (top), 3 days (middle) and 7 days after the spill, along with the impacted coastal segments and the respective beached oil quantities (bottom).

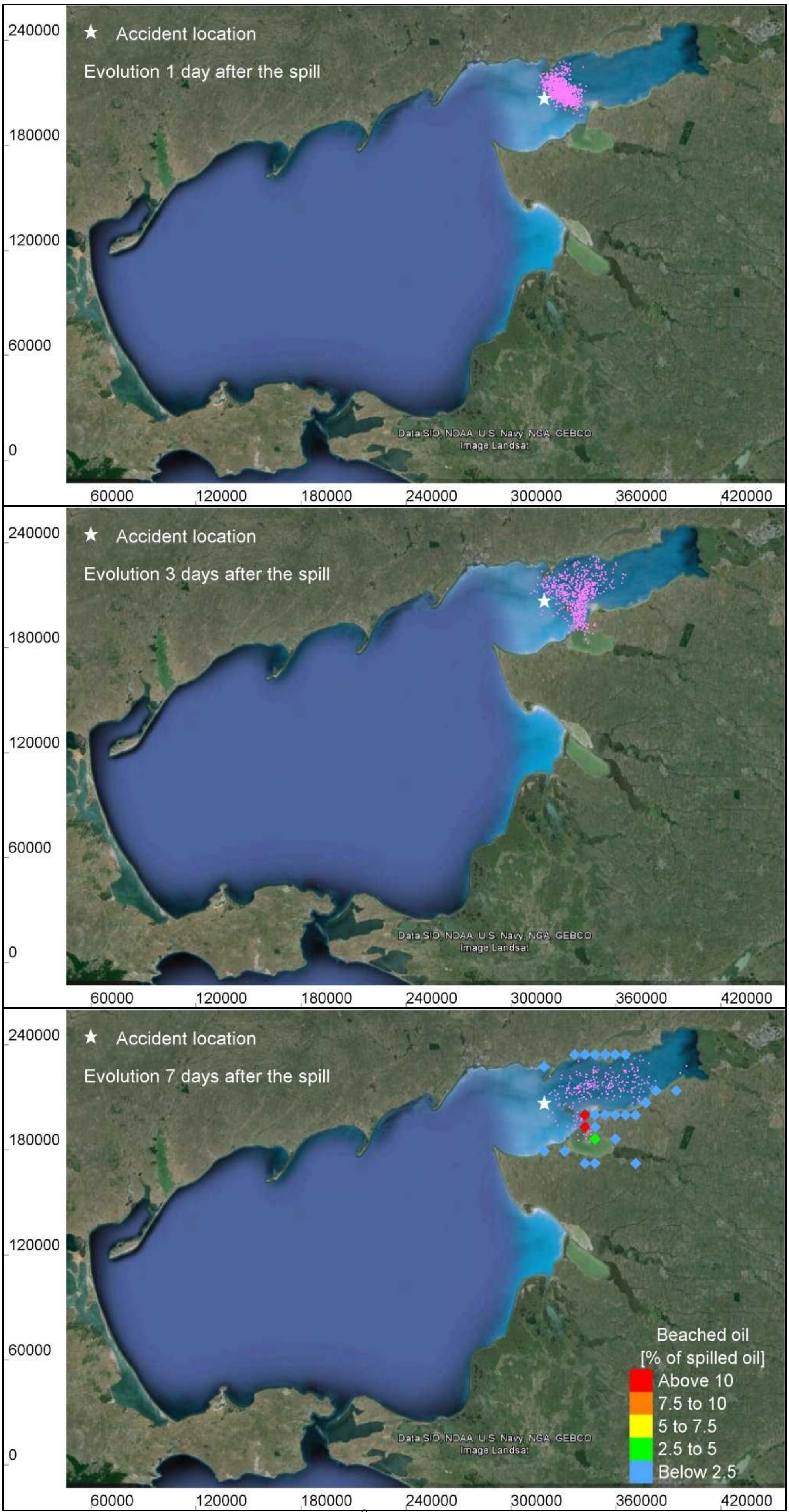

Fig. 9. Accident at Taganrog Bay – 5m/sec W wind and 900m^3/sec Don discharge; modeled slick evolution 1 day (top), 3 days (middle) and 7 days after the spill, along with the impacted coastal segments and the respective beached oil quantities (bottom).

CONCLUSIONS

The present work focuses on recent advances in operational oil spill modelling and analyzes their implications for the protection of the Black Sea Basin through exemplary applications for the Sea of Azov. The results presented in **Figs. 4 to 9** are indicative of how operational oil spill models can be used as the basis of essential Oil Spill Response activities, creating a database of diverse scenarios' results in order to evaluate and assess the risk from accidental oil spills in the Black Sea Region. Such knowledge can be used for the optimal allocation of oil slick combating stations (as in [***8***]), the coordination of the activities for the containment/removal of the spilled oil and the protection of endangered coastal areas, as well as for the identification of the spill origin in case of not reported accidents. Moreover, the oil spill model used in this work can be easily adapted to incorporate, through spatiotemporal oil removal coefficients, the representation of various response actions – should respective information on operational facilities and resources be readily available – further extending its applicability.

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