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Modeling oil pollution of the Caspian Sea resulting from the Ural and Volga rivers input

Abstract. A 2D transport model has been developed to predict the oil pollution resulting from river discharges. The transport module of the model computes two-dimensional Reynolds averaged Navier-Stokes equations (RANS) and uses scalar transport equation to predict the motion of the oil slick. The basic processes affecting the fate of the oil spill are taken into account and parameterized in the transport model. The model is used to simulate a continuous oil release from the Volga and Ural rivers into the coastal waters of the north part of the Caspian Sea. Oil slick movement and risk of contamination of the coastline by beaching oil spills are illustrated for different wind conditions.
Key words: Caspian Sea, oil spill, river discharge, mathematical modeling.

Introduction

The Caspian Sea is the largest inland sea on the planet and located at the Caspian lowland (fig. 1). Sea surface area is about 384 thousands km2., volume is 78 thousand km3. and coastline is more than 7 thousands km. Five countries share the Caspian sea coastline. They are – Kazakhstan, Russia, Azerbaydzhan, Turkmenistan and Iran [1]. The Caspian is divided into three distinct physical regions: the Northern, Middle, and Southern Caspian. The Northern Caspian only includes the Caspian shelf, and is very shallow, it accounts for less than 1% of the total water volume with an average depth of only 5–6 meters. The sea noticeably drops off towards the Middle Caspian, where the average depth is 190 meters. The Southern Caspian is the deepest, with oceanic depths of over 1000 meters. Hydro-dynamical conditions on the Caspian Sea are defined by large longitudinal extension of the sea, high depth difference between northern and southern parts and irregular coastline geometry. The Caspian Sea is fed by numerous rivers, but the Volga and Ural rivers contributes about 85 % of the annual input [2, 3].

Development of the oil production and transportation industry led to the increase of the sea pollution. The Volga and Ural are major conduits of pollutants to the Caspian Sea including oil pollution. The estimated amount of the pollution input is given in Table 1 [4]. Most part of the river input pollution comes from the Volga and Ural.

Oil discharged to the sea surface is transported by convection and influenced by various processes, such as evaporation, emulsification, dissolution, photolysis, biodegradation, etc. These processes are characterized by different time scales at which they interact with the environment. Winds and surface currents are the main sources of energy for the oil slick movement. Several authors summarized such dynamics for water-oil interaction [5-7].

At the moment two most popular universal frameworks for ocean and sea water flow modeling are POM and FVCOM. POM – Princeton Ocean Model [8] computes hybrid 2D-3D dynamics of the sea on a structured grid. FVCOM mostly deals with the same model as POM, but numerical method uses finite volume method with coastline following triangular mesh [9].

This paper is structured as follows: In Section 2 mathematical model and boundary conditions for oil spill transportation and its implementation for the Caspian Sea are described. Numerical method is described in Section 3. Results of simulations of oil slick resulting from the Volga river discharge for different wind conditions are analyzed in Section 4. A short summary is given in Section 5.

Mathematical model

Transport model is based on numerical solution of the RANS equations (1-3) [10]. The model is used to simulate a continuous oil release from the Volga and Ural rivers into the coastal waters of the north part of the Caspian Sea.

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$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv = -\frac{1}{\rho_0}\frac{\partial(p)}{dx} + \nu_{eff}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + F_u \quad (1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu = -\frac{1}{\rho_0}\frac{\partial(p)}{dy} + \nu_{eff}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + F_v \quad (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = E \quad (3)$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = \alpha_{eff}\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) + F_C \quad (4)$$

$$\frac{\partial S}{\partial z} = 0, \text{ at } z = \zeta(x, y, t) \quad (5)$$

Table 1 – Oil pollution load to the Caspian sea

Source	Amount (tons/year)
Rivers	75000
Municipalities	19000
Industries	28000
Atmosphere	350
Total	122350

Figure 1 – The Caspian Sea (source: https://commons.wikimedia.org)

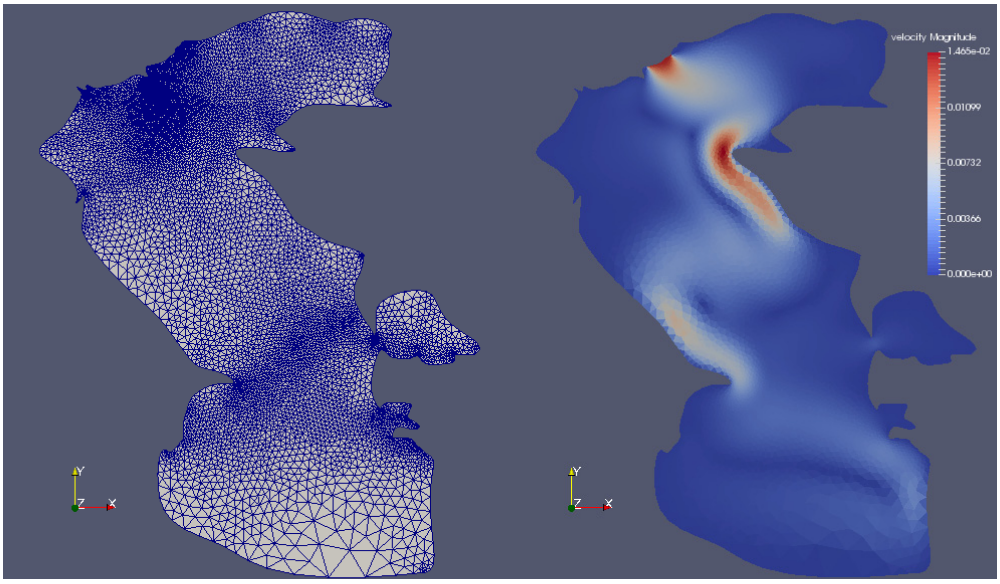
Numerical method

Coastline following unstructured finite volume mesh was generated from the free access World coastline vector map layer [11] with the Gmsh[12] mesh generator (fig. 2). Sharp borders of the mesh were smoothed by several Jacobi relaxation procedures. The equation set is solved numerically with a finite volume Navier–Stokes solver using unstructured two-dimensional non-orthogonal grid, with Cartesian vector and tensor components and collocated variable arrangement [13]. The second order accurate central difference scheme (CDS) is applied for discretization of diffusive terms. For the convective terms, the second-order accurate linear upwind (LUDS) is applied by using a deferred correction.

The SIMPLE algorithm is used for the treatment of the pressure fields. Underrelaxation parameters (w) were used for the velocity (w=0.8) and pressure (w=0.2). For unsteady simulations, a fully implicit second order three-time-level marching scheme is used.

Results

According to the main question: will pollution from the Ural and Volga reach Kazakhstan part of the Caspian, and how much time it will take ?, following case was considered. Constant 5m/s east directed wind. Constant sea surface temperature was 20 C. Total oil pollution release intensity was 8.5 tons per hour. It is obvious that such case is most dangerous meteorological condition for Kazakhstan. Simulation results are depicted in fig. 2-6. The Volga and Ural rivers starts to introduce continuous pollution at the initial time (fig. 3a). Oil slick movement affected by wind and surface stress leads to the pollution of the middle sea part and the coastal region. Numerical simulations show that low speed wind (<2-3 m/s) does not affect marine flow much. On the other hand large longitudinal extend of the Caspian makes Coriolis force more significant. According to the simulation data continuous pollution sources from the Ural and Volga may reach Kazakhstan part of the coastline in about 20-25 days.



a b

Figure 2 – a) Computational mesh, b) Flow pattern on the Caspian Sea.

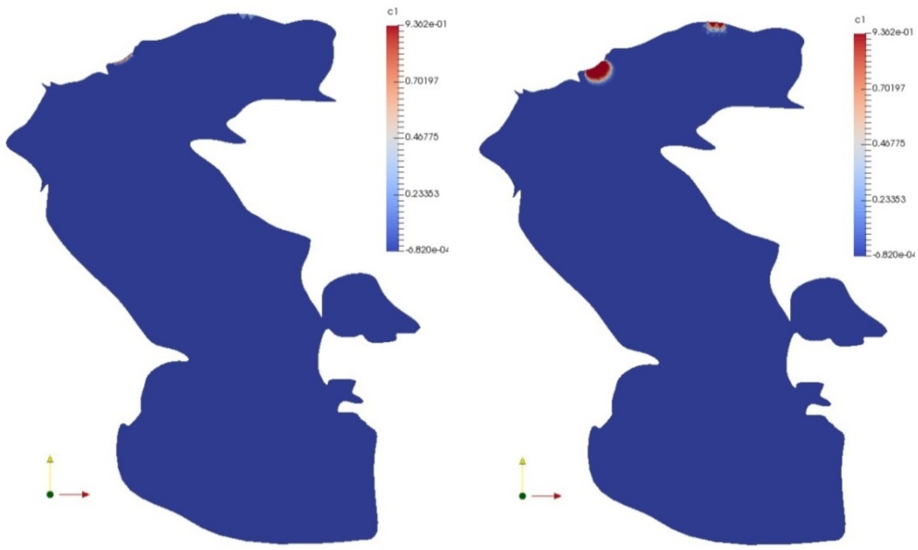


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Figure 3 – Pollution transport on the Caspian Sea, a) –t=0 min, b) –t=1728 min.

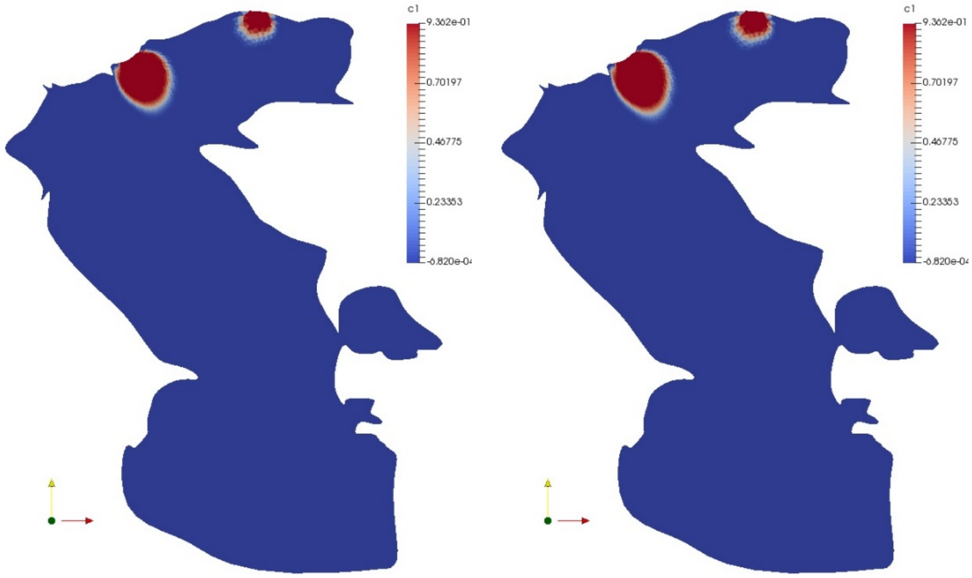

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Figure 4 – Pollution transport on the Caspian Sea, a) –t=10368 min, b) –t=12096 min.

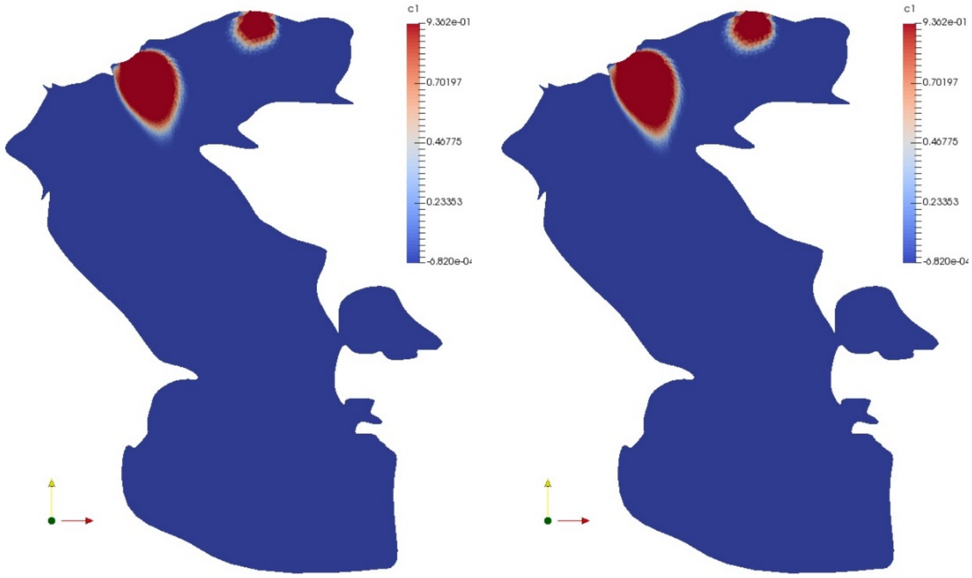

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Figure 5 – Pollution transport on the Caspian Sea, a) –t=17280 min, b) –t=19008 min.

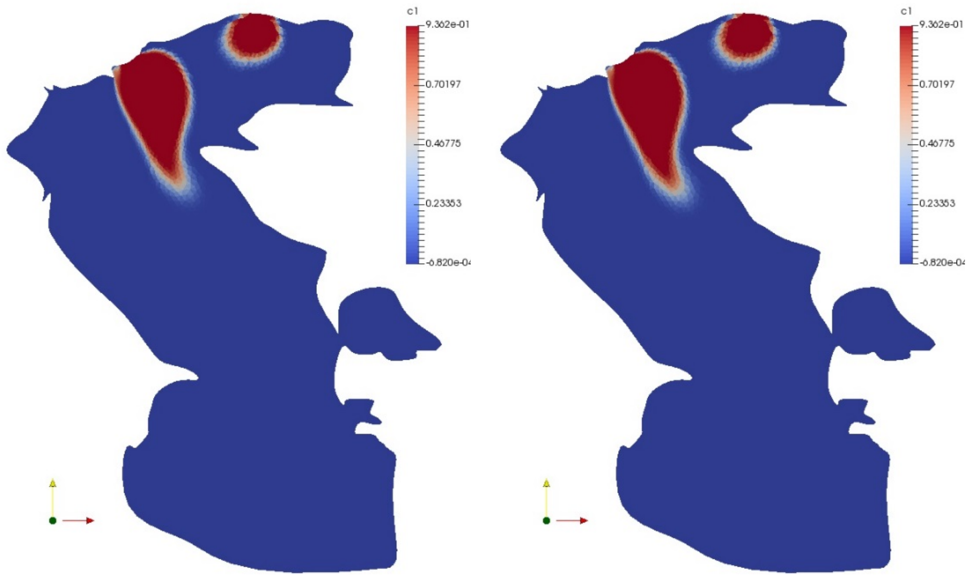

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Figure 6 – Pollution transport on the Caspian Sea, a) –t=31104 min, b) –t=32832 min.

Conclusion

A 2D transport model has been developed to predict the oil pollution resulting from river discharges in an in-house CFD code CFVM. The transport module of the model computes two-dimensional Reynolds averaged Navier-Stokes equations (RANS) using k-epsilon turbulence model. Oil slick movement is governed by scalar transport equation. Among the processes affecting the fate of oil, advection, turbulent diffusion, evaporation, and decay are included; the decay is modeled as the combined effect of all the biochemical and physical mechanisms that decompose oil.

The transport model has been implemented for the Caspian Sea to predict oil slick movement and the area covered by the oil. Coastline pollution by the oil slick illustrated on artificial meteorological case. Numerical experiments with 25-day scenarios of the possible oil input resulting from the Volga and Ural rivers discharge show the potential threat caused by beaching and cross-boundary transport of the oil pollution in the northern part of the Caspian Sea.

Further modifications to the model and its implementation are related to the introduction of the bathymetry (sea depth), wave-oil slick interaction and usage of finer grids on high performance computing systems. First two modifications have to be supported by significant model modification, third is highly related to efficient domain decomposition and parallel computations.

References

1. Kireev M.A. Reshenie gidrometeorologicheskih problem v ramkah Kaspijskojj ekologicheskoj programmy. // Problemy gidrometeorologii i ekologii: Materialy Mezhdunar. nauch.-prakt. konf., posvjashhennoj 50-letiju KazNIIMOSK. – Almaty: KazNIIMOSK, – 2001. – P. 114-115.

2. Sydykov Zh.S., Golubcov V.V., Kuandykov B.M. Kaspijskoe more i ego pribrezhnaja zona (prirodnye uslovija i ekologicheskoe sostojanie). Almaty, – 1995. – P. 211.

3. Budyko M.I. Izmenenie klimata. // L. Gidrometeo izdat. – 1974. – P. 280.

4. Korotenko K. A. et al. Particle tracking method in the approach for prediction of oil slick transport in the sea: modelling oil pollution resulting from river input // Journal of Marine Systems. – 2004. – Vol. 48. – No 1. – P. 159-170.

5. Mackay D., McAuliffe C. D. Fate of hydrocarbons discharged at sea // Oil and Chemical Pollution. – 1989. – Vol. 5. – No 1. – P. 1-20.

6. Spaulding M. L. A state-of-the-art review of oil spill trajectory and fate modeling // Oil and

Chemical Pollution. – 1988. – Vol. 4. – No 1. – P. 39-55.

7. Korotenko K.A., Mamedov R.M., Mooers C. N. K. Prediction of the transport and dispersal of oil in the south Caspian Sea resulting from blowouts // Environmental Fluid Mechanics. – 2001. – Vol. 1. No 4. – P. 383-414.

8. Giunta G. et al. pPOM: A nested, scalable, parallel and Fortran 90 implementation of the Princeton Ocean Model //Environmental Modelling & Software. – 2007. – Vol. 22. – No 1. – P. 117-122.

9. Cowles G.W. Parallelization of the FVCOM coastal ocean model //International Journal of High Performance Computing Applications. – 2008. – Vol. 22. – No 2. – P. 177-193.

10. Razrabotka geoinformatsionnoy sistemy modelirovaniya avariynykh razlivov nefti na kaspiyskom more dlya planirovaniya deystviy v usloviyakh chrezvychaynykh situatsiy // Projectreport / DGPSSIMM, proj. leader. A.K. Khikmetov. Almaty. – 2015.

11. http://www.naturalearthdata.com/downloads /10m-physical-vectors/10m-coastline/

12. Geuzaine C., Remacle J. F. Gmsh: A 3-D finite element mesh generator with built-in pre-and post-processing facilities // International Journal for Numerical Methods in Engineering. – 2009. – Vol. 79. – No 11. – P. 1309-1331.

13. Hanjalić K., Kenjeres S., Jonker H.J.J. Analysis and modelling of physical transport phenomena. – 2007.