The use of Computational Fluid Dynamics analysis (CFD) in studying river-type systems

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Abstract - This paper discusses the use of the CFD technique in studying river-type systems. The problem of water quality is addressed. The advantages of using CFD to determine the spatial-temporal evolution of transport and dispersion of pollutants are analyzed. A case study of accidental pollution on the sector of the Prut River from the Giurgiulesti locality is presented. The results of numerical simulation are discussed.

Key-Words - river, water quality, Computational Fluid Dynamics (CFD) simulation, software packages, transport and dispersion of pollutants.

I. Introduction

WATER quality is a primary problem for the sustainable development of the countries. As a result of human activities, water quality has strongly diminished. The evaluation of several water bodies from the Europe, according to the requirements of the Water Framework Directive, shows a satisfactory or unsatisfactory ecological status. There is a strong necessity of a thorough analysis of the aquatic systems to maintain them in a "very good" state [1].

In many regions of the world, there is a fierce competition for water, and the overuse and pollution of the environment contribute to reducing the available resources. Approximately 80% of all diseases in the developing countries are related to water, which causes 1.7 million deaths each year [2].

In the majority of cases, for human necessities, water from rivers is used. Its quality is more frequently influenced by various chemical, physical and biological substances, which cause pollution [3, 4].

To model various processes of fluid flow, including turbulent flow, and to determine the parameters of the flow, Computational Fluid Dynamics (CFD), analysis is widely used. This method uses techniques of approximate numerical computation. The advantage of using CFD is the possibility to obtain detailed information, with a high precision, about the studied system.

Solving a problem using CFD involves the following steps: modeling the geometry of the studied domain, meshing the domain, defining the model, setting the properties, establishing the initial and limit conditions, solving, analysing the results [5, 6, 7, 8, 9].

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II. Problem Formulation

To study water quality, in present are used informational systems consisting of two components – mathematical modeling of the studied sector of the river and evaluation of water quality using numerical models obtained [10, 11].

The flow in the river-type systems is turbulent. It can be described by the Naveier-Stokes system of equations - composed of Navier-Stokes equations (1, 2) and the continuity equation (3).

$$h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}-\frac{h}{\rho}\left(E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right)+gh\left(\frac{\partial H}{\partial x}+\frac{\partial h}{\partial x}\right)+$$
$$+\frac{gun^2}{\left(h^{1/6}\right)^2}\times\left(u^2+v^2\right)^{1/2}-\varsigma V_a^2\sin\psi+2h\omega v\sin\phi=0 \tag{1}$$

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0 \tag{2}$$

$$h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}-\frac{h}{\rho}\left(E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right)+gh\left(\frac{\partial H}{\partial y}+\frac{\partial h}{\partial y}\right)+$$
$$+\frac{gvn^2}{\left(h^{1/6}\right)^2}\times\left(u^2+v^2\right)^{1/2}-\varsigma V_a^2\sin\omega+2h\omega v\sin\phi=0 \tag{3}$$

To approximate the Navier-Stokes equations, the most frequently used are the following numerical methods: Direct Numerical Simulation (DNS), Reynolds-averaged Navier–Stokes equations (or RANS), Large Eddy Simulation (LES), Detached Eddy Simulation (DES) [5, 6].

Rivers are complex aquatic systems, therefore their modeling requires a detailed study for each case particularly. Proceeding from this fact, it was formulated the problem of obtaining numerical models using CFD technologies to determine parameters characteristic to pollutant transportation and water quality.

III. Problem Solution

Mathematical and numerical modelling of the spatial-temporal evolution of river-type systems in order to estimate the parameters of water quality is a decisive factor for determination of water quality with a higher precision [7, 11, 24].

To describe the evolution of the studied sector in an adequate manner, the mathematical model is transformed into a numerical model by means of numerical methods. The numerical modeling is done using CFD techniques, by which partial differential equations are transformed into systems of algebraic equations, whose solutions are approximations of state quantities in the defined nodes of the computing field [5, 6, 14].

The study of the hydrodynamic processes and the processes that influence parameters of water quality is presented in the papers [13, 14, 8, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 11]. The mathematical model was developed using the Navier-Stokes equations and the advection-dispersion equation. On the basis of CFD technologies, the hydrodynamics of the transport and dispersion processes of pollutants were simulated. The meshing of the studied domain was done using different methods, such as: finite volume method, finite element and finite difference methods. The numerical modelling was done using various software packages: WASP (Water Quality Analysis Simulation Program), QUAL2E, ANSYS CFX (Computational Fluid Dynamics Software), GWLF (Generalised Watershed Loading Function), MONERIS (Modelling Nutrient Emissions in River Systems), WQRRS (Water Quality for River Reservoir Systems), WMS (Watershed Modelling System), SMS (Surface-water Modelling System), HEC-RAS (Hydrological Engineering Centres River Analysis System), CE-QUAL-W2, COMSOL Multiphysics Delft3D-FLOW, FlexPDE, CARMEL [13, 14, 8, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 11].

In this paper is presented a scenario of numerical simulation of transport and dispersion processes of pollutants on a sector of the Prut River from the Giurgiulesti locality from the Republic of Moldova. As a result of the study, it was found that the greatest exceedances of Maximum Admisible Value (MAC) in the period 2008-2013 were recorded for petroleum products [28] (figure 1):

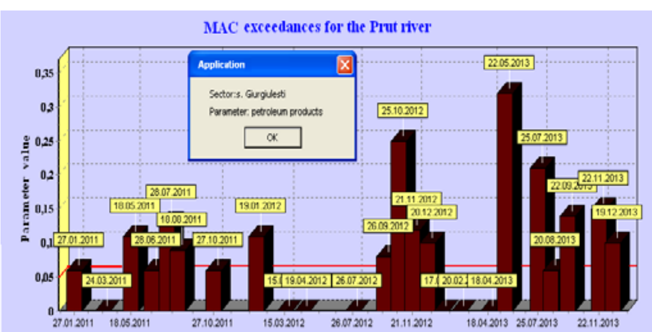

Fig. 1. Exceedances of MAC for petroleum products

Based on this fact, a scenario of accidental pollution with the concentration of petroleum products of 0,7 mg/L, that exceeded the MAC value 14 times, was simulated. The confluence of the pollutant with water occured in the middle of the studied sector (figure 2):

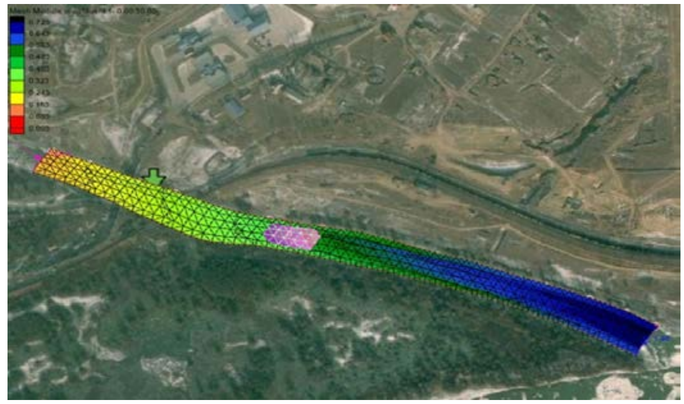

Fig. 2. Confluence of the pollutant with water.

To obtain the numerical models, Surface-water Modelling System (SMS) was used. The hydrodynamics of the studied sector was obtained using RMA2 module, and the spatial-temporal evolution of pollutants – using RMA4 module.

The simulations were performed in a dynamic regime, for 12 hours. The following boundary conditions were established: upstream - flow rate Q = 260 m^3/s, downstream – geodesic share H = 3,32 m.

The results obtained for the hydrodynamics of the studies sector are presented in the figures 3-5:

Name	velocity mag
Number of time steps	25
Beginning time	0 00:00:00
Ending time	0 12:00:00
All time steps	
->Minimum	0.792914
->Maximum	1.99866

Fig. 3. Resultant velocity

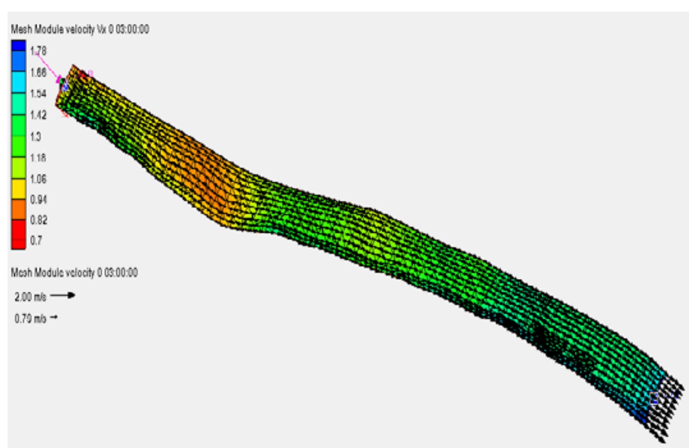

Fig. 4. Local velocities field in the *x* direction

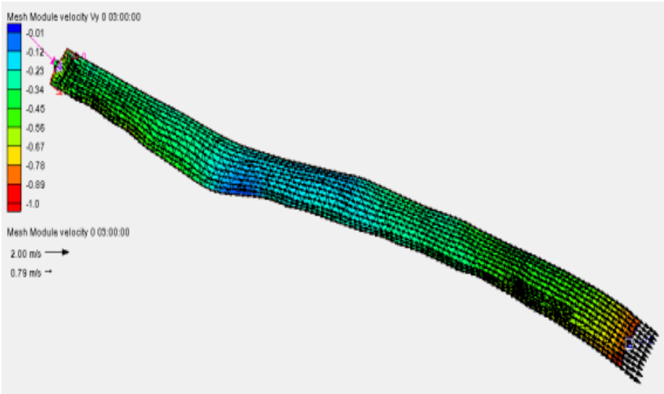

Fig. 5. Local velocities field in the *y* direction

It has been found that in the *x* direction the velocity of the particles motion is greater than in the *y* direction.

Numerical results obtained for the transport and dispersion of petroleum products are presented in the figures 6-8:

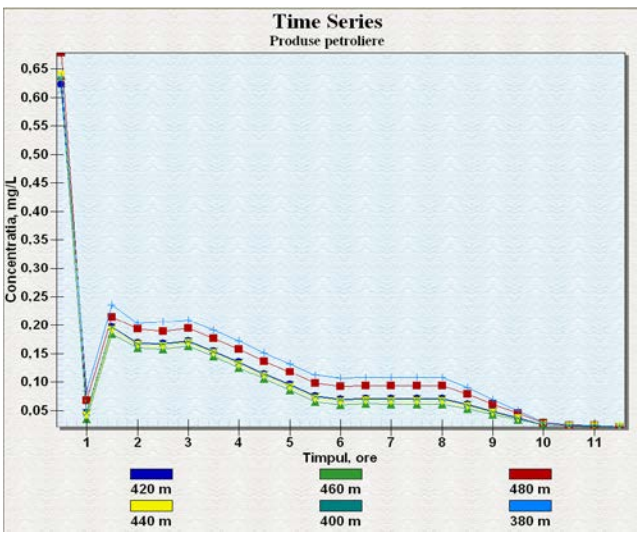

Fig. 6. Spatial-temporal evolution of the concentration of the pollutant downstream of the confluence area in the middle of the river

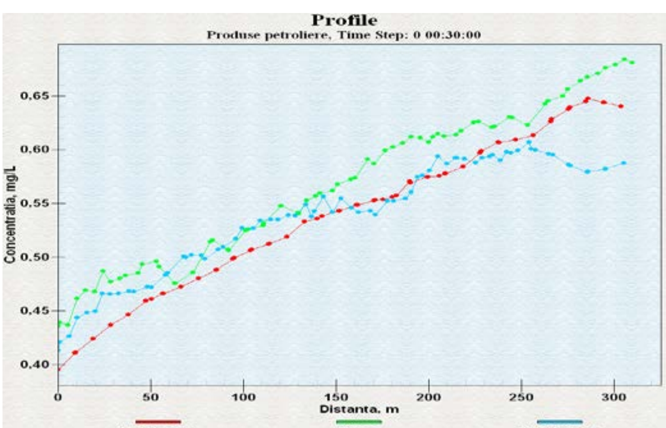

Fig. 7. Concentration of the pollutant downstream of the confluence area after 0,30 hours

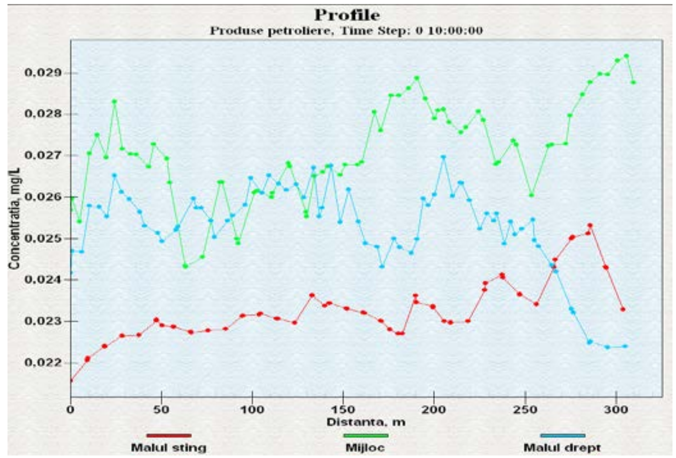

Fig. 8. Concentration of the pollutant downstream of the confluence area after 10 hours

Based on the numerical simulations of water movement and processes of transport and dispersion of pollutants in the sector of the Prut River from the Giurgiulesti locality, were determined:

- Variation of water depth;
- Variation of resultant velocity;
- The field of velocities in the *x* and *y* directions;
- The field of concentrations in time and space.

The concentration of petroleum products in time and space was estimated, as following:

- After 4 hours from the moment of confluence with water the concentration of pollutant with the value of 0,7 mg/L in the confluence area changed its value to 0,16 mg/L; after 7 hours - 0,09 mg/L; after 9 hours - 0,06 mg/L; after 10 hours – 0,03 mg/L;
- Concentration of the pollutant remains high during 9 hours downstream of the confluence area;
- After 10 hours from the moment of confluence with water the value of concentration of petroleum products became smaller than MAC on the entire sector studied.

IV. Conclusion

As a result of the bibliographical study, it is concluded that CFD is a powerful tool for the determination of water quality and prediction of emergency situations.

The obtained models make it possible to determine water quality in each of the finite element of the studied sector, not only in the sampling point. This ensures determination of water quality with a higher precision.

The numerical simulations proved a good capacity of the mathematical model to accurately reproduce real processes in river-type systems, as confirmed by comparing actual data, collected in situ, with data obtained by using developed numerical models.

Based on the results of numerical simulations, it was determined that the obtained numerical models, calibrated and validated, can be used directly for any scenario of pollution in the studied sectors, in emergent and accidental situations.

REFERENCES

[1] *** European Parliament and Council Directive EU 2000/60/EC establishing a framework for Community action in the field of water, 2000.

[2] OECD (2011), “Water security”. In: Better Policies for Development: Recommendations for Policy Coherence, OECD Publishing. 2011, pp. 40-42.
http://dx.doi.org/10.1787/9789264115958-15-en.

[3] R. J. Garde, River Morphology. Publisher: *New Age International (P)*, 2006. 502 p.

[4] O. Ionuş, Water quality index - assessment method of the Motru River water quality (Oltenia, Romania). In: *University of Craiova, Series Geography*, vol. 13, 2010, pp. 74-83.

[5] Anderson, *Computational Fluid Dynamics for Engineers*. Cambridge: University Press, 2012, 2012 p.

[6] T. J. Chung, *Computational Fluid Dynamics*, Second edition. Cambridge: University Press, 2010, 1058 p.

[7] D. Wilcox, *Turbulence Modeling for CFD*. California: DCW Industries, 1994, 456 p.

[8] V. Cristea, E. Bagiu, P. Agachi, Simulation and Control of Pollutant Propagation in Somes River Using Comsol Multiphysics. In: *Proceedings of the 20th European Symposium on Computer Aided Process Engineering– ESCAPE 20*, Italy, 2010, pp. 985-991.

[9] B. E. Launder, D. B. Spalding, The numerical computation of turbulent flows. In: *Computer Methods in Applied Mechanics and Engineering*, vol. 3, Issue 2, 1974, pp. 269–289.

[10] R. Găgescu, M. Tertişco, P. Junie, C. Eremia, Ensuring sustainable use of water on Earth by computerized environmental monitoring, *Romanian Journal of Information and Automation*, vol. 21, No. 3, 2011, pp. 5-12.

[11] G. Marusic, A study on the mathematical modeling of water quality in "river-type" aquatic systems. In: *Journal Wseas Transactions on Fluid Mechanics*, Issue 2, Volume 8, 2013, pp. 80 – 89.

[12] J. Ferziger, M. Peric, *Computational Methods for Fluid Dynamics,* Springer Berlin, 2002, 431 p.

[13] C. Fan, W. Wang, K. Liu, T. Yang, Sensitivity Analysis and Water Quality Modeling of a Tidal River Using a Modified Streeter-Phelps Equation with HEC-RAS-Calculated Hydraulic Characteristics. In: *Environmental Modeling & Assessment*, Vol. 17, Issue 6, 2012, pp. 639-651.

[14] P. Iu. Puşistov, K. S. Alsînbaiev et all, Numerical modeling of spatial and temporal structure of hydrodynamics and water quality characteristics of the river Severnaia Sosiva. *Journal of Atmospheric and Oceanic Optics*, No. 11, 2006, pag. 956 – 960.

[15] A. E. Cisteacov, Approximation of boundary conditions of three-dimensional model of movement of water environment, *Proceedings of the Southern Federal University*, Russia, No. 6, 2010, pp. 66 – 77.

[16] V. Petrescu, O. Sumbasacu, Comparison between numerical simulation and measurements of the pollutant dispersion in a river. Case study. In: *U.P.B. Sci. Bull., Series D*, vol. 72, Issue 3, 2010, pp. 157-164.

[17] A. Sarfaraz, A. Matin M., Application of 2D morphological model to assess theresponse of Karnafuli River due to capital dredging. In: *Journal of Water Resources and Ocean Science*, Vol. 2, Issue 3, 2013, pp. 40-48.

[18] B. O. Tsydenov, A. V. Starchenko, Numerical model of river-lake interaction in the case of a Spring thermal bar in Kamloops Lake. Tomsk State University. *Journal of Mathematics and Mechanics*, №5 (25), 2013, pp. 102-115.

[19] A. B. Usov, Finite-Difference Method for the Navier–Stokes Equations in a Variable Domain with Curved Boundaries. In: *Computational Mathematics and Mathematical Physics*, Vol. 48, no. 3, 2008, pp. 464–476.

[20] M. Amara Capatina-Papaghiuc, D. Trujillo, Hydrodynamic modelling and multidimensional approximation of estuarial river flows. In: *Computing and Visualization in Science*, Vol. 6, Issue 2-3, 2004, pp. 39-46.

[21] E. O. Iulaeva, K. O. Raznopolov, Iu. Suharev, Overview of WASP6 program applied to the problem of the aquatic ecosystem research "Argazi - Miass - Shershni"// *Proceedings of the Chelyabinsk Scientific Center*, No. 28, 2005, pp. 89 – 94.

[22] L. Andrei, Pollutant dispersion in natural flows. În: *Materials of the Annual Scientific Conference of the National Institute of Hydrology and Water Management*, Romania, 2011, pp. 417-430.

[23] E. Ania, S. Wallisc, A. Kraslawskia, P. Serban, Development, calibration and evaluation of two mathematical models for pollutant transport in a small river. In: *Environmental Modelling & Software*, Vol. 24, Issue 10, 2009, pp. 1139-1152.

[24] K. Kachiashvili, D. Gordeziani, R. Lazarov, D. Melikdzhanian, Modeling and simulation of pollutants transport in rivers. In: *Applied Mathematical Modelling*, vol. 31, Issue 7, 2007, pp. 1371-1396.

[25] G. Marusic, I. Sandu, C. Filote ş. a. Modeling of Spacio–temporal Evolution of Fluoride Dispersion in “River-type” Systems. In: *Revista de Chimie*, 66, Nr. 4, 2015, pp. 503-506.

[26] G. Marusic, C. Filote, C. Ciufudean, The spatial - temporal evolution of iron dispersion in "river-type" systems. In: *Proceedings of the 17th WSEAS International Conference on Applied Mathematics (AMATH '12*), Montreux, Switzerland December 29-31, 2012, pp. 95 – 98.

[27] G. Marusic, C. Ciufudean, Current state of research on water quality of Prut River, În: *Proceedings of the 11th International Conference on Environment, Ecosystems and Development (EED '13),* Romania, Brasov, June 1-3, 2013, pp. 177 – 180.

[28] ***http://www.meteo.md/