The modelling of a spring-time flood streams on the Vyatka River to the forecast extreme situations

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Abstract. There are presented results of modelling of a spring-time flood run evolving on a river floodplain. The model is used to forecast contamination transfer processes during spring floods running on Kirovo-Chepetsk floodplain of Vyatka River. The model verification was made with satellite photoshots of the flood propagation area and with monitoring data for contamination concentrations obtained by ecological services both of Kirovo-Chepetsk chemical plant and of Kirov region’s administration. The digital implementation of the model can allow to simulate action of various defensive hydrotechnical structures that might be designed and to evaluate their influence on the redirection of the flood streams.

1. Introduction
Kirovo-Chepetsk floodplain presents a specific interest in terms of view of some outcomes of spring floods on Vyatka River. “Kirovo-Chepetsk chemical plant named after B.P. Konstantinov” is situated in close vicinity of Kirovo-Chepetsk floodplain. The products decision to built it was taken still in the year 1938. Its industrial waste was damped and is being damped into the sanitary control zone of Kirov urban water intake from the start of working of this enterprise. The identical problems had been investigated in the articles [1-5]. One of the substantial contaminating constituents of this industrial waste is ammonia nitrate. The total volume of contaminated underground waters, on a number of assessments, amounts 500,000 m³. It is necessary to add that a chain of floodplain lakes is disposed on the way by which the located underground waters contamination is migrating toward Vyatka’s riverbed. There are Bobrovoyes, Berezovoye lakes and sand pits next the last one between these ponds. These pools are appears to be peculiar accumulators and traps for polluting substances that are supplied with contaminated underground waters. These accumulators discharge during spring flood times when they are being flooded with high water. By the way some kind of volley ejection is forming being the cause of interruptions in the urban water supply of Kirov that lays down the river. An overview scheme of Vyatka’s floodplain vulnerable flooded with high water is presented on figure 1.
2. Materials and methods

The hydrodynamics model of the riverbed-floodplain streams flow is presented in terms of Navier-Stokes-Saint-Venant shallow water equations. These are a system of the 2D fluid hydrodynamics equations written for water in riverbed with taking into account some boundary conditions on air-water and water-bottom surfaces, on open inlet-outlet boundaries and on firm riverside banks. The mathematical description of the model and the equations derivation had been given in the works [6-9].

The explicit finite difference scheme has being used for the numerical solution on the rectangular grid with number of nodes 2122x2320. The differential equations have been approximated on the grid with the second order of accuracy. The algorithm for solving the problem takes automatically into account the “dry” and “wet” spots of the computational domain by comparison the water levels in each cell with the relief heights on the specified digital 3D topographical map of the terrain [10-12]. Because of the great number of nodes, the necessity to provide stability of the computational process on the explicit scheme and the algorithm complications as well, the calculations were being performed in the cluster supercomputer of the Vyatka State University. The calculation program has been realized in Intel Fortran 12 in Intel Cluster Studio for Linux Open MP [12].

Figure 1. Topographical map of Kirovo-Chepetsk floodplain.
3. Results
The development of flooding processes on the simulated area (and, as a consequence of, “draining” processes of the floodplain pools) is strongly dependent on scenarios of the temporal development of a flood. And so it is strongly dependent on the boundary conditions as well in which one should be included the flood development regime on Prosnitsa River. It is obviously, of course, any mechanism of “draining” of the floodplain ponds must be dependent on the way how the considered area is being flooded. One should recognize the time dependency of water height levels in the inlet of the modelled domain as the main factor predicting the scenario of the oncoming flood. Thus specifying the time profile of water level in the riverbed of Vyatka specifies the regime of evolving flood. Luckily there are lots of statistical hydrometeorology data in this domain. The plots of distribution of stream velocities, flood depths and contaminants concentrations are presented on the figures 2, 3 at the end of the first phase of a typical spring-time flood of a higher-than-mean intensity.

On the following figure 4 we will consider evolution of transfer of contamination concentrations during a flood at the confluence of the Voloshka River with the main streams of the Vyatka River.
Filling of the floodplain stretch with high water is occurring during the first phase of a flood, the flooded area is broadening, the process being steady. We shall estimate the contaminants level on the piece immediately next to Vyatka riverbed near to Voloshka river outlet into the last one. We mark four specific points in the riverbeds of Voloshka and of Vyatka after the Voloshka outlet. The point 1 describes the concentration near the right riverbank, the point 2 – in the middle of the riverbed, the point 3 – near the left riverbank of Voloshka, the point 4 – in the middle of Vyatka riverbed immediately after Voloshka outlet. The peculiarity of the considered scenario is the substantial increase of ammonia nitrate concentration in the third phase of the evolving flood (21th-26th days) comparing with its onset. By the way the maximal concentration is achieved at the end of the computing time (25th day). The contamination concentration is rising during the first phase (1st-9th days) from 0.007953 mg/dm$^3$ up to maximal value 12.11 mg/dm$^3$. Then during a week (9th-16th days) the concentration is going down to mean value in Voloshka 1.29 mg/dm$^3$. From the 17th day again the rise of concentration is on having a steady rate (18th-23th days) and then sharp jumping (23th-25th days). Thus the contamination concentration distributions in the outlet of Voloshka have two distinct local extremums 12.11 mg/dm$^3$ (8th day) and 14.3 mg/dm$^3$ (25th day). The plots of the concentration distributions are presented on figure 4.
4. Discussion

There is shown the water velocities field at the flood peak on figure 2. Prominent here are the streams with the relatively high velocities in the chain: Ivanovskaya channel, Beryozovoye Lake, Bobrovoye lakes. The contamination source has been assigned according to [13]. There are presented the results of the concentration distribution calculations with the contamination sources located in Beryozovoye lake, sand pits and Bobrovoye lakes on figure 3. The provided illustration distinctly demonstrates the arrival channel of contamination substances into Vyatka. Thus, on the one hand the obtained results of the modelling give some information for environmental monitoring, on the other hand they prompt the sites for arrangement some artificial constructions which might block this trace and diminish the
contaminations arriving to the water supply intake in Kirov. The discussed hydrodynamical model has allowed to undertake a series of computational experiments on virtual modelling of action of some hydrotechnical constructions.

5. Conclusion
As it appears to be, the most effective solution would be digging of a long intercepting canal from the north part of Ivanovskoye lake to the main riverbed of Vyatka. One should note, such bypass canal would have a length of order 2500 m, a width from 50 to 100 m and a depth of 4-5 m. The canal substantially changes the flow regime and constrains the downstream on the main way of water arrival into the chain of lakes: Beryozovoye, Bobrovoye, Prosnoye - until a flood peak. In addition, one has been simulated erection of two chevron-like dykes next before Beryozovoye and 1st Bobrovoye lakes, which would shield the contaminated lakes of water streams at the flood peak. Distributing of hydrodynamical parameters and contamination concentrations in such circumstances are presented on figures 5 and 6.

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References
[1] Van Rijn L C 1990 Principles of fluid flow and surface waves in rivers, estuaries, seas and oceans Aqua Publications [The Netherlands] p 392
[2] Van Rijn L C 1984 Sediment transport part II: suspended load transport. J of Hydraulic Engineering 110 11 pp 1613-1641
[3] Van Rijn L C 1984 Sediment transport, part III: bed forms and alluvial rouges. J of Hydraulic Engineering 110 12 pp 1733-1754
[4] Van Rijn L C. 1987 Sedimentation of dredged channels by currents and waves. J of Waterway Port Coastal and Ocean Engineering 112 5 ASCE Paper No 20883
[5] Van Rijn LC 1989 Mathematical modeling of morphological processes in case of suspended sediment transpor. Diss of Degree Dr Tech University of Delft (Emmeloard Netherlands) p 160
[6] Peeters F, Wuest A and Piepke G 1996 Imboden D.M. Horizontal mixed in lakes J of Geophysical Research 101 C8 pp 361-375
[7] Van Rijn LC 2007 Uniforms of sediment transport by currents and waves I: Invitation of motion, bed roughness and bed-load transport J of Hydraulic Engineering 133 6 pp 649-667
[8] Mazda Y and Wolanski E 2009 Hydrodynamics and Modeling of Water Flow in Mangrove Areas. In: Gerardo M E Perillo, Eric Wolanski, Donald R Cahoon, Mark M Brinson, editors, Coastal Wetlands: An Integrated Ecosystem Approach (Elsevier) p 231
[9] Le Minor M, Bartzke G, Zimmer M, Gillis L, Helfer V, and Huhn K 2018 Numerical modelling of hydraulics and sediment dynamics around mangrove seedlings: Implications for mangrove establishment and reforestation (Estuarine, Coastal and Shelf Science) 217 5 pp 81-95 (doi: 10.1016/j.ecss.2018.10.019
[10] Sutherland J, Walstra D J R, Chesher T J, Van Rijn L C and Southgate H N 2004 Evaluation of coastal area modelling systems at an estuary mouth Coastal Engineering 51 2 pp 119-142
[11] Arkhipov B V, Solbakov V V, Shapochkin D A 2010 Modelirovanie hydrodynamicheskikh protsessov v pribrezhnoy zone I ekologicheskie raschyoty [Modeling of hydrodynamic processes in a coastal zone and ecological calculations] (Moscow: Computing Center RAS) p 97 (In Russian)
[12] Arkhipov B V, Solbakov V V, Soloviev M B and Shapochkin D A Ekologicheskiye modelirovaniye i lagranzhevyy podkhod 2013 [The Ecological Modeling and Lagrangian...
Approach] – Matematicheskoye modelirovaniye [The Mathematical Modeling] 25 pp 47-61
(In Russian)

[13] Rychkov S L and Shatrov A V 2013 Gidrodinamicheskaya model pavodkovykh navodneniy na r. Vyatka 2013 [The Hydrodynamics Model of a Spring-Time Flood Streams on Vyatka River] II Vserossiyskaya nauchnaya konferentsiya “Okruzhayushchaya sreda i uстойчивое развитие регионов” Tezisy dokladov 23.09-27.09 sentyabrya 2013 [II All-Russian Scientific Environment Conference and Sustainable Development of Regions] (Kazan: Russia, Kazan Federal University Press) (In Russian)