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The Problem of Safe Evacuation of Large Floodplains Population During Flooding

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Abstract: The natural conditions of the floodplains of regulated large rivers are attractive for the urbanization of such regions. However, severe floods on flat terrain pose a threat of extensive flooding of such areas. Therefore, the effective organization of the population evacuation is an urgent problem for such lowland floodplains. The spatial and temporal distribution of the flooding threat of large floodplains makes it possible to organize the population evacuation using a limited number of vehicles in the presence of a high-quality forecast of the hydrological regime. We study the problem of organizing the safe evacuation of all floodplain residents using fairly accurate forecasts of the flooding time points of settlements and evacuation routes based on high-performance hydrodynamic numerical experiments. The use of empirical algorithms makes it possible to minimize the number of evacuation vehicles on the set of safe schedules. The result is an empirical function of the dependence of the minimum number of vehicles that ensure the safe evacuation of the given territory population on the values of the hydrograph and the beginning moments of the evacuation. As an example, we construct this function for the Northern part of the Volga-Akhtuba Floodplain.

Keywords: evacuation, flooding, schedule, optimization problem, simulations, Volga-Akhtuba Floodplain

1. INTRODUCTION

The construction of hydroelectric power plants on large rivers makes it possible to regulate the hydrological regime and develop floodplains, accelerating the process of urbanization of such regions. However, the presence of a hydroelectric dam does not exclude the threat of catastrophic events during the spring floods and/or heavy rainfall when the safe values of the hydrograph (water discharge Q) are exceeded. The large flat relief of the floodplain determines the specific features of flood hazards. Even a relatively small (10–15 percent) excess of the average annual flood level can cause catastrophic events, when a significant part of the territory is flooded (up to 50 percent) with the formation of dangerous areas of hundreds of square kilometers [4, 23]. On the other hand, the flooding of urbanized large floodplains occurs relatively slowly, which makes it possible to solve the task of organizing effective evacuation of the population in conditions of limited resources.

The problem of organizing the population evacuation during floods has a high degree of objective and subjective uncertainty, and therefore it belongs to the field of decision-making research. These uncertainties are the reason for a wide variety of models of the evacuation situation, criteria for the effectiveness of the evacuation organization, modeling methods and technologies. The objective functions of this problem are, for example, the

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time and risk [1, 11, 18], the number of evacuated people [13], the various types of damage [6, 25, 27], the cost of evacuation and assistance to the population [12], the optimal shelter locations [10], the personnel resettlement points [24], the comprehensive safety criteria [5]. This requires the use of a wide range of models and methods, such as flood dynamics [11], road network and traffic flow [5, 11], game theory [1, 10], scenario [6, 11, 27], multi-agent [1, 27], econometric [6], dynamic [1, 5], stochastic [1] models, integer and linear programming [12, 24], heuristic methods optimization and decision making [1, 10, 12, 24], models of hydrotechnical projects [25]. Consideration of unorganized evacuation may require traffic control [20].

A wide variety of approaches to evacuation modeling does not change the main problem of its organization, which is to ensure safety for specific terrain conditions and hydrological regime dynamics. Therefore, we emphasize that the criterion for the effectiveness of the organization of evacuation directly affects its safety. For example, minimizing evacuation time can lead to traffic accidents when evacuation routes are overloaded using private vehicles for self-evacuation. The maximization of the number of organized evacuation of the population by ground transport with a lack of resources leads to high danger for a small part of those remaining in the flood zone in difficult conditions.

The most universal criterion for the effectiveness of the evacuation organization is in our opinion the aggregate risk of loss of health and life of the population in the flooded area. The mathematical model of risk management in the evacuation organization has the following form

$$F(E, \mathcal{S}) \longrightarrow \min_{\mathcal{S}}, \tag{1.1}$$

where F is the human life risk, $E = E(t) = \langle K_{fl}(t, Q), \vec{P}, \vec{L}(\mathcal{G}), t^{(0)}, M\rangle$ is the tuple of the evacuation situation, $K_{fl}(t, Q)$ is the dynamic digital map of the flooded area, t [hours] is the time after the flood start, $Q = Q(t)$ is the river hydrograph (water discharge or volume of water through the dam per unit of time), $\vec{P}$ is the vector of the number of inhabitants of settlements (n is the number of such settlements), $\mathcal{G}$ is the graph of the road network, $\vec{L}$ is the lengths vector of evacuation routes (the shortest paths from settlements to evacuation points in the graph $\mathcal{G}$), $t^{(0)}$ is the start time of evacuation in the floodplain, M is the number of evacuation vehicles, $\mathcal{S}$ is the schedule of evacuation transport (the number of buses on each route at each moment of time).

All components of the evacuation situation E have uncertainty, since part of the population leaves the danger zone ourselves, some refuse to evacuate, and so on. The accuracy of determining the flooding time of settlements and sections of the road network is determined by the errors of the hydrograph, the digital elevation model (DEM), and the adequacy of the computational hydrodynamic model. Estimating the number of vehicles involved is also inaccurate. Since floods can have a multifactorial negative impact on human health, the mathematical definitions of the objective function F can be different [16]. Simulation modeling and solving optimization problems can reduce a significant part of these uncertainties.

The solution (1.1) may exceed the valid risk level for large Q, $t^{(0)}$ and small M. Therefore, the urgent problem is to find situations E and schedules $\mathcal{S}$ that do not allow this excess. We will assume that the valid risk corresponds to the timely evacuation of the inhabitants of the flooded part of the territory without specifying the form of the function F. Such a safe evacuation is provided by the schedule $\mathcal{S}^{(sec)}$.

The optimization problem solution

$$M(K_{fl}(t, Q), \vec{P}, t^{(0)}, \mathcal{S}^{(sec)}) \longrightarrow \min_{\mathcal{S}^{(sec)}} \tag{1.2}$$

defines the boundary of the domain valid risk. Task (1.2) is a variant of the resource investment problem or a mirror copy of the extension of the classical RCPSP (Resource Constrained Project Scheduling Problem) with time windows (deadline) [2, 14, 15, 17, 26].

The purpose of this article is to create a algorithm for the approximate solution of the problem (1.2) and its implementation using the results of simulation modeling of flood dynamics in the Northern part of the Volga-Akhtuba Floodplain (VAF) as an example application.

2. RESEARCH METHODS AND TECHNOLOGIES

The proposed method for the approximate solution of the problem (1.2) is based on reducing the uncertainty of the parameters values of the evacuation situation using a series of computational experiments with our model of the development of an emergency situation. This allows us to reduce the problem of parametric optimization of a renewable resource (1.2), which is solved approximately by heuristic methods with an estimate of the effectiveness of the result and the use of upper and lower parameter estimates.

Our emergency development model consists of the numerical hydrodynamic flood model combined with the digital elevation model (DEM), which calculates the time of water arrival at specific floodplain points. This model allows us to reduce the evacuation situation $E(K_{fl}(t,Q),\mathcal{G},M)$ to the form $E(t,Q,P,M)$, since the hydrodynamic model instead of the flooding map and the graph of the road network $\mathcal{G}$ gives us the dependence $\vec{\tau}(Q)$ ($\vec{\tau}$ is the vector of the beginning times of flooding of settlements and sections of evacuation routes on the graph $\mathcal{G}$). The hydrodynamic model allows one to pass from $\vec{P}$ to the vector $\vec{P}^{(sh)}$, in which the components for non-floodable habitats are equal to zero.

2.1. Development Model of Emergency Situation

The calculation of flood wave propagation is based on numerical hydrodynamic model in the shallow water approximation [4, 8, 9]:

$$\frac{\partial H}{\partial t} + \nabla\left(H\vec{u}\right) = q(x,y,t)\,, \tag{2.3}$$

$$\frac{\partial H\vec{u}}{\partial t} + \nabla\ \left((H\,\vec{u})\otimes\vec{u}\right) = -gH(\nabla\,H) - gH(\nabla\,b) + H\vec{f}, \tag{2.4}$$

where $H(x,y,t)$ is the depth of the liquid, $\vec{u}$ is the velocity vector of the fluid, averaged over the vertical coordinate (z), q is the function of sources $(q>0)$ or drains $(q<0)$ of water, ∇ is the nabla operator in the plane (x,y), g is the gravitational acceleration, $b(x,y)$ is the bottom topography, $\vec{f}$ is the specific external total force, including the contribution of bottom and viscous turbulent friction, wind stress, Coriolis force, etc.

The topography is given by DEM on a fixed grid with a step $\Delta\ell$: $x_{i+1}=x_i+\Delta\ell$, $x_{j+1}=x_j+\Delta\ell$, $i=0,1,\ldots,N_x$, $j=0,1,\ldots,N_y$. The number of cells in two directions (N_x and N_y) is determined by the sizes of the simulated area $L_x=\Delta\ell\cdot N_x$ and $L_y=\Delta\ell\cdot N_y$. We neglect the processes of infiltration and interaction with groundwater in the model (2.3), (2.4) [8], since the duration of the emergency situation at the stage of evacuation is only a few hours. The effect of sediment transport together with water movement can be more significant and depends both on the properties of the underlying surface and, to a greater extent, on the features of the terrain. Then the system of equations (2.3), (2.4) must include an additional non-stationary equation for the function $b(x,y,t)$ [9, 19].

The developed evacuation method is applicable to any complex large floodplains. An example of such a natural object is the Volga-Akhtuba Floodplain (VAF) in the Lower Volga River (Figure 2.1). We restrict ourselves to the Northern part of the VAF (See inset on the right), which is the most urbanized area of the floodplain.

The calculation of the hydrological regime dynamics requires a high-quality digital elevation model (DEM) [3, 4, 9], and the non-stationarity of the flooding process imposes

Fig. 2.1. The location of the Northern part of the Volga-Akhtuba Floodplain is highlighted in the inset (BestMaps Aggregator Image)

special requirements on the accuracy of modeling. The spatial resolution of DEM is limited not only by topographic data, but also by the availability of computing resources. For example, halving the cell size increases the number of cells by a factor of 4 for a fixed area. There is an additional restriction of about two times on the integration step ($\Delta t \to \Delta t/2$) due to the stability requirement for the explicit numerical scheme [9]. However, parallelization increases the load on GPU, which increases the efficiency of computing. The total increase in computation time turns out to be less than 8 times when $\Delta x \to \Delta x/2$ is passed.

The cell size Δx is determined by the specific conditions of the study area. We will consider below the algorithms for organizing evacuation using the example of the Volga-Akhtuba Floodplain (See Figure 2.1), a characteristic feature of which is a developed hierarchical system of large and small channels (Figure 2.2). VAF is a very large floodplain and we use $\Delta x = 15$ m as the base DEM, which is built from a combination of various topographic data [7]. For example, the acceptable accuracy of flood modeling is provided by $\Delta x = 15$ m for lower Manhattan in New York City, which has an area of only about 15 sq km [3]. Small water systems require a more detailed grid with $\Delta x \sim 2 - 5$ m.

The basis of the hydrodynamic flooding model for a specific area is the Digital Hydrological Landscape Model (DHLM), which includes the DEM and other characteristics of the earth's surface and soil. First of all, it is the roughness coefficient (or the so-called manning's resistance coefficient) $n_M(x, y)$, which determines the intensity of the interaction between the water flow and the bottom as part of the force $\vec{f}$ in (2.4). The study of the hydrological regime over long time intervals requires additional spatial characteristics, such as the hydraulic conductivity K, the bottom porosity ψ, the groundwater bottom $b^{(gw)}$ [4,8,9]. All these parameters are specified in the cells of our grid (x_i, y_j) and form the DHLM as a set of spatial matrices $\langle b, n_M, K, \psi, b^{(gw)} \rangle$.

The distribution heterogeneity of $n_M(x, y)$ is due to changes in the roughness of the earth's surface (sand, gravel, arable land, etc.), various types of vegetation (meadow, shrub, sparse or dense forest, etc.) (Table 2.1). Hydrological resistance to surface water flow is one of the most important factors that changes the dynamics of water movement. Figure 2.3 shows the difference in flooding of the VAF for the two calculations. The first takes into account the real inhomogeneity of the surface properties ($n_M(x, y)$), the second is based on a constant roughness coefficient.

The emergency situation development model is multilayer geoinformation model of the certain territory, including DHLM, layers of the road network (the topological structure is determined by the graph $\mathcal{G}$), the settlements with data on the number of inhabitants, as well as a large number of layers of the dynamics of catastrophic floods that are built based on

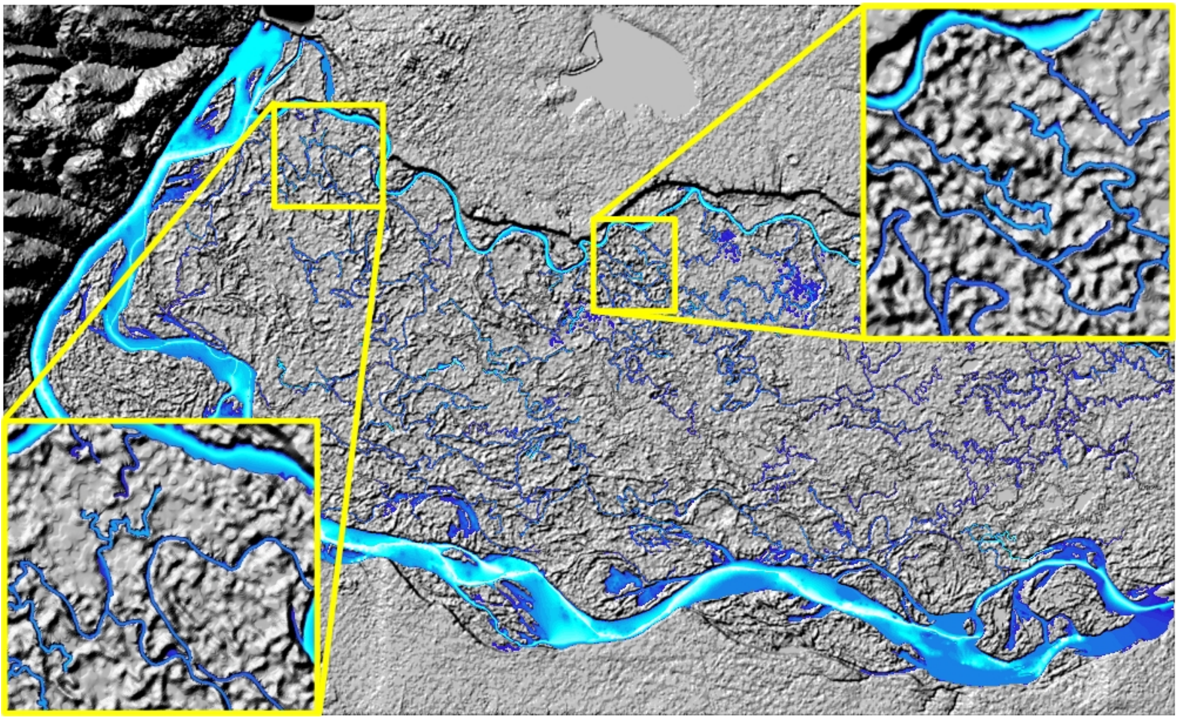

Fig. 2.2. The result of numerical hydrodynamic simulation on the grid with cell of 15 meters. The hydrological situation in the VAF corresponds approximately to the low-water level, when large channels contain water without flooding the flat part of the floodplain

Table 2.1. Roughness coefficient for different types of underlying surface in our model

Type of underlying surface	Roughness coefficient (n_M)
Riverbed	0.02
Sand	0.02
Bush	0.05
Sparse Forest	0.07
Dense Forest	0.09
Cultivated Land (Arable Land)	0.05
Meadow without Shrubs	0.04

hydrodynamic model (2.3), (2.4). Direct hydrodynamic modeling gives a table of flooding times for settlements and evacuation routes for their population for a given catastrophic hydrograph $Q(t)$ with a maximum level Q for the rectangular hydrograph model.

2.2. Algorithm for finding safe evacuation schedule

The evacuation schedule is determined by the matrix $\mathcal{S} = \|m_{tj}\|$, $t = 1, ..., T$, $j = 1, ..., n$, $T = \max\limits_{j}(\tau_j - t^{(0)})$, where m_{tj} is the number of vehicles to evacuate from point j at time step t, τ_j is the components of $\vec{\tau}$ vector. We call schedule $\mathcal{S}^{(sec)}$ a valid (safe) schedule if it

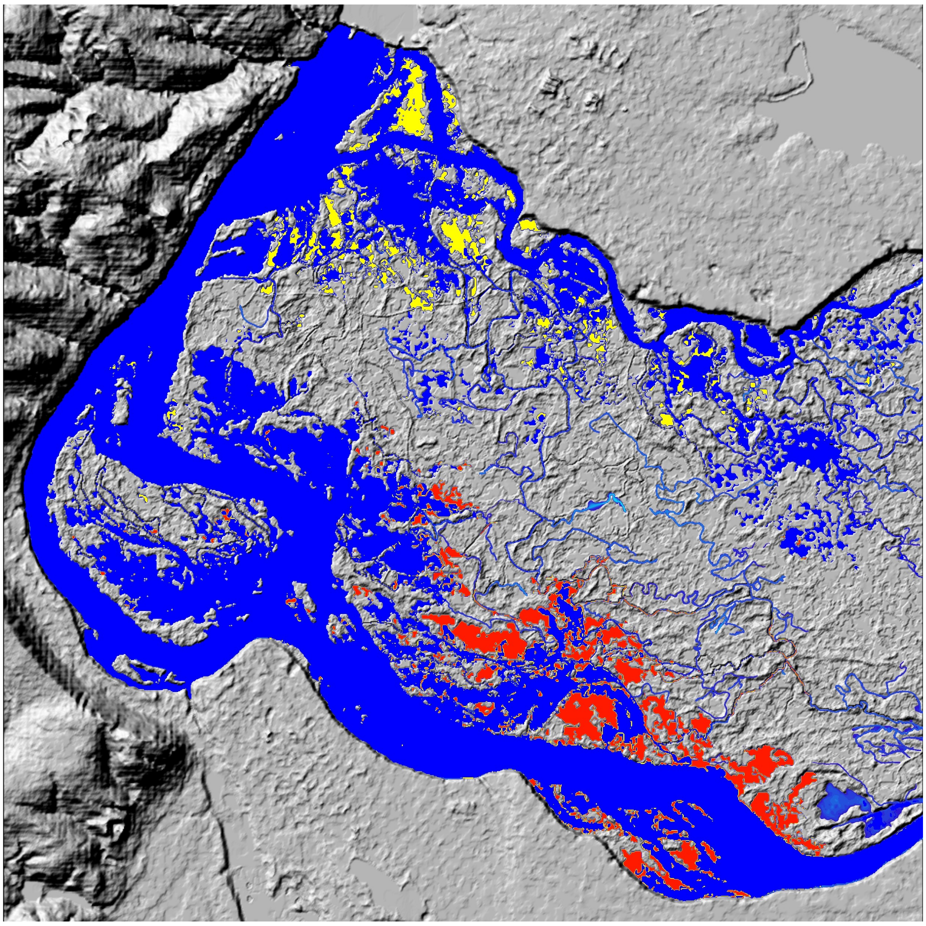

Fig. 2.3. Simulation results of the flooding of the Northern part of the VAF at $Q = 45000\,\mathrm{m}^3/\mathrm{sec}$ at the time $t = 15$ hr. Areas that are flooded at the non-uniform roughness coefficient ($n_M(x, y)$), but remain flooded at the constant $n_M = 0.045$, are highlighted in red. Yellow color shows areas flooded at $n_M = \mathrm{const}$, but not flooded at $n_M(x, y)$. Blue areas are flooded in both models

satisfies the condition

$$\tilde{M}_j \geq 1 + \left[\frac{P_j^{(sh)}}{a}\right] \ (j = 1, ..., n), \ \tilde{M}_j = \sum_{p_j=1}^{p_j^{max}} \tilde{m}_{p_i j}\,, \ m_{tj} = m_{tj}^{(0)},$$
$$m_{tj}^{(p_j)} = m_{tj}^{(p_j-1)} - \tilde{m}_{p_j,j}, \ \tilde{m}_{p_j,j} = \min\left(m_{p_j,j}^{(p_j-1)}, ..., m_{p_j+\theta_j,j}^{(p_j-1)}\right)\ , \ \ p_j = 1, ..., p_j^{max}\,,$$
$$p_j^{max} = \tau_j - t^{(0)} - \theta_j + 1, \ \ t = p_j, ..., p_j - t^{(0)} + \tau_j - 1, \ \ j = 1, ..., n\,, \tag{2.5}$$

where a is the evacuation bus capacity, $P_j^{(sh)}$ is the number of inhabitants in the settlement j subject to organized evacuation, θ_j is the stage duration of population evacuation from the settlement j.

Thus, the problem (1.2) reduces to minimizing the number of vehicles M on the set of safe schedules (2.5):

$$M = \max_t(M_t) \to \min_{S^{(sec)}}, \quad M_t = \sum_{j=1}^{n} m_{tj}, \quad t = 1, ..., T\,, \tag{2.6}$$

where the time t is measured in hours. The heuristic algorithm for solving the problem (2.5) – (2.6) is a multi-step process of redistributing vehicles between evacuation routes. Each redeployment results in a new valid evacuation schedule. The initial valid schedule $\mathcal{S}_0^{(sec)}$ is one that realizes the evacuation of the inhabitants number $P_j^{(sh)}$ along each route j in a time not exceeding $\tau_j - t^{(0)}$. This schedule requires M_0 buses, and each of them travels along a single route. Such a schedule is compiled by an elementary calculation. The first part of the algorithm implements the multiple distribution of the reserve of vehicles formed at the end of the evacuation on some routes to other routes.

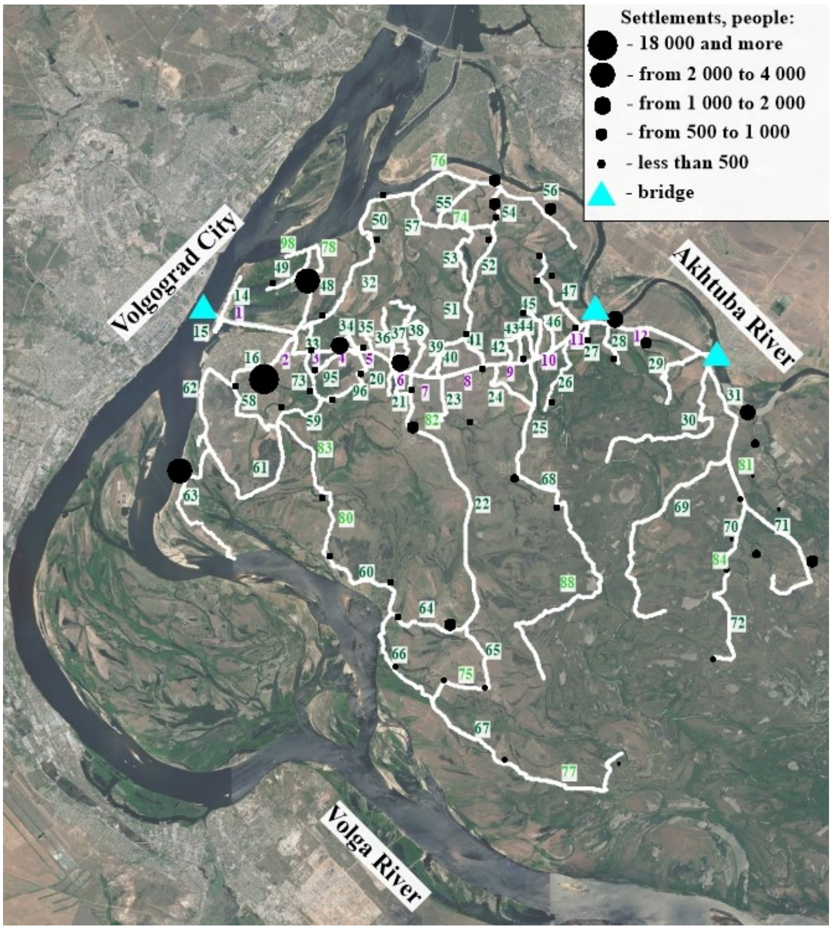

Fig. 2.4. Digital model of the road network of the VAF with the settlements locations and road numbers

The appearance of a reserve on one or several routes at step k (time θ_k, $k = 1, 2, ..., n-1$) leads to its assignment to one of the evacuation routes or to distribution over parts on several evacuation routes. A valid scheduling with a decrease in the number of machines in the initial schedule is generated for each possible reserve assignment. If the maximum of this reduction is reached on a single route, then the corresponding assignment is accepted. If the maximum is reached on several routes (in the amount of J_k), then a new valid evacuation schedule for each of them is calculated together with the moment of appearance of the first reserve θ_{kj} and its value m_{kj} ($j = 1, 2, ..., J_k$). The assignment is made to the route with the maximum value m_{kj}/θ_{kj}. If the maximum of this value is reached on several routes, then the reserve is assigned to the route with the minimum value of θ_{kj}. The equality of these values for several routes allows you to assign to any of them. The distribution of the reserve of buses on several routes is carried out in case of its redundancy for one route. After assigning a reserve, the algorithm step is considered completed and the schedule $\mathcal{S}_k^{(sec)}$ with $M_k \leq M_{k-1}$ is compiled. The algorithm ends when $k = n - 1$.

The second part of the algorithm is the sequence of constructing valid schedules $\mathcal{S}_w^{(sec)}$ $(w = n, n+1, \ldots)$ while decreasing M_{n-1} by one at each step of the sequence. Each valid schedule is constructed by sequential distribution of vehicles between evacuation routes at each time $t = T, T-1, \ldots, 1$ in the direction from the end of the evacuation period to its beginning. Higher priority is given to routes with the longest allowable evacuation period. Thus, the algorithm maximizes the reserve of vehicles for their use on routes with the minimum allowable evacuation periods. The algorithm stops at some step W if it is impossible to construct an valid schedule with the available number of buses M_W. The final schedule is the schedule $\tilde{\mathcal{S}}^{(sec)} = \mathcal{S}_{W+1}^{(sec)}$ at the minimum of vehicles number $\tilde{M} = M_{W+1}$. The efficiency of the two-stage algorithm is estimated by the vehicles load factor $\eta = (\tilde{M}\, T^{(act)})^{-1} \sum_{t=1}^{T^{(act)}} M_t$, where $T^{(act)} \leq T$ is the actual evacuation time in the generated schedule.

3. MODEL OF POPULATION EVACUATION IN THE NORTHERN PART OF THE VOLGA-AKHTUBA FLOODPLAIN

The VAF is located between the Volga and Akhtuba rivers (See Figure 2.1). The water flow of the Volga River is regulated by the passage of water through the dam of the Volga Hydroelectric Power Plant (VHPP). The development of the road network in the Northern part of the VAF in recent decades has been a powerful driver of population growth, which now exceeds 35,000 people. Figure 2.4 shows the road network map of the floodplain with the numbers of its local sections (edges of the G graph) and the settlements location. The final evacuation points are the bridges over the Volga River and the Akhtuba River marked with triangles. Table 3.2 shows the evacuation routes (ERs) of the $\vec{L}$-vector components.

The calculation of the parameters of the evacuation situation $E(t, Q, \vec{P}^{(sh)}, M)$ in the floodplain is based on a series of computational experiments on the study of the flooding dynamics of settlements and evacuation routes of the VAF for $Q = \{30, 35, 40, 45\}$ thousands $\mathrm{m}^3/\mathrm{sec}$ with flood map every hour. The modeling results show that the flooding of settlements can occur at maximum hydrographs greater than $29\,000$ $\mathrm{m}^3/\mathrm{sec}$, and the territory flooding occurs during the first 4 days. Figures 3.5, 3.6 a show floods maps and time dependences of the inhabitants' number of flooded settlements, respectively, for several values of emergency situation parameters. Table 3.2 contains the times of settlements flooding and local sections of evacuation routes for different hydrograph maxima. Bold type highlights situations where the escape route is flooded before the settlement.

Figure 3.6 b shows the dynamics of the distribution of the settlements number into groups with different durations of safe evacuation periods for several values of Q. Dependences of the flooded settlements number and their evacuation routes on the maximum value of hydrograph are shown in Figure 3.7. We classified all settlements into three groups: 1) the settlement is not flooded; 2) the settlement is flooded later than the evacuation route; 3) the settlement is flooded earlier than the evacuation route.

Approximate solutions of the problem (2.5), (2.6) are constructed for two series of schedules for the VAF territory with an estimate of the efficiency factor η. The first series of safe schedules $\mathcal{S}_0^{sec}(t^{(0)}, Q)$ with average efficiency $\eta(\mathcal{S}_0^{sec}) = 44\%$ describes safe evacuation from potentially floodable settlements during the entire safe period without reassignment of transport between settlements.

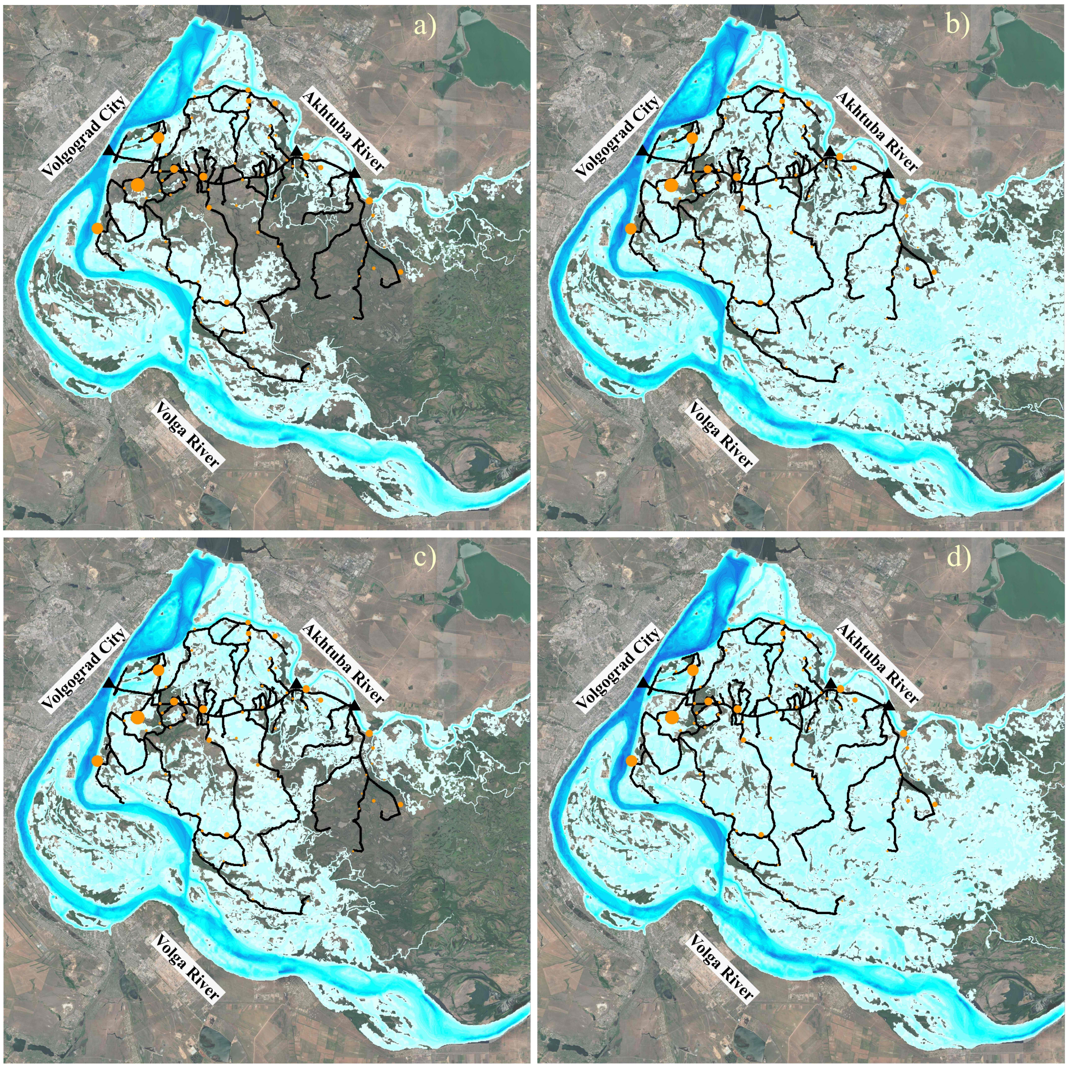

Fig. 3.5. Flood maps of the VAF and hazard levels of settlements at $Q = 35\,000$ m^3/sec, $t = 32$ hr and $t = 72$ hr (a, b); at $Q = 45\,000$ m^3/sec, $t = 32$ hr and $t = 48$ hr (c, d).

The heuristic algorithm described above underlies the constructed series of schedules $\tilde{\mathcal{S}}^{(sec)}(t^{(0)}, Q)$ with average efficiency $\eta(\tilde{\mathcal{S}}^{(sec)}) = 72\%$ and the corresponding approximate function of the minimum transport support for the safe evacuation of the VAF population $\tilde{M}(t^{(0)}, Q)$ (Figure 3.8). The function $M_0(t^{(0)}, Q)$ corresponds to the initial schedules $\mathcal{S}_0^{(sec)}$.

4. DISCUSSIONS AND CONCLUSION

A feature of flood development in floodplains is the high frequency of earlier flooding of evacuation routes than settlements. For example, the number of such cases is 5 times higher than the number of opposite cases in the territory of the Volga-Akhtuba Floodplain (Figure 3.7). This causes the high sensitivity of the transport support for safe evacuation ($\tilde{M}$) to the start time of evacuation $t^{(0)}$.

Solution of the considered problem (2.5), (2.6) at 30000 m^3/sec $\leq Q \leq$ 45000 m^3/sec exists only at $t^{(0)} \leq 4$ hours. Evacuation by vehicles at $t^{(0)} > 4$ hours can only be considered

Table 3.2. Parameters of settlements evacuation: N is the settlement number, P_i is the component of vector $\vec{P}$, N_{ER} is the escape route (ER) number, L_i is the components of vector $\vec{L}$ (km), "–" is the no flood sign, t_p is the beginning time of the settlement flooding (hours), t_r is the time the escape route flooded after the flood started (hours), N_{fp} is the local section flooded number. The numbers of settlements for which evacuation routes are flooded before the settlement are in bold.

N	P_i	N_{ER}	List of evacuation roads	L_i	$Q = 30\,000$ m^3/sec			$Q = 40\,000$ m^3/sec		
					t_p	t_r	N_{fp}	t_p	t_r	N_{fp}
1	1330	1	66,75,26	16	-	-	-	**52**	**48**	**66**
2	100	2	75,26	6	-	-	-	-	**50**	**75**
3	2000	3	26	5	-	-	-	-	-	-
4	1500	4	10	2	33	-	-	20	-	-
5	200	5	55,74,77,54,68,1,0	**21**	**54**	**11**	**55**	**26**	**9**	**55**
...										
15	18000	15	14,0	10	17	-	-	13	35	14
16	200	16	44,73,43,0	**13**	**17**	**5**	**44**	**13**	**5**	**44**
17	170	17	45,27,0	15	**-**	**6**	**45**	**-**	**6**	**45**
18	480	18	69,48,46,36,7,8,9,10	22	**45**	**18**	**69**	**23**	**14**	**69**
19	300	19	27,0	12	**-**	**31**	**27**	**52**	**19**	**27**
20	180	20	46,36,7,8,9,10	13	**-**	**50**	**46**	**30**	**28**	**46**
21	80	21	42,10	7	**-**	**42**	**42**	**29**	**27**	**42**
22	100	21	42,10	7	**-**	**42**	**42**	**32**	**27**	**42**
23	100	12	51,49,47,46,36,7,8,9,10	21	**-**	**32**	**47**	**-**	**20**	**51**
24	300	22	41,9,10	6	-	-	-	**42**	**39**	**41**
25	345	23	22,10	3	-	-	-	-	-	-
...										
50	185	2	75,26	6	-	-	-	**-**	**50**	**75**
51	100	27	38,8,9,10	15	**67**	**63**	**65**	**43**	**42**	**65**
52	100	44	78,65,75,26	16	**-**	**63**	**65**	**52**	**42**	**65**
53	200	45	29,3,2,1,0	14	-	-	-	-	-	-
54	460	46	25	10	**63**	**38**	**25**	**31**	**29**	**25**
55	10	47	35,6,5,4,3,2,1,0	19	-	-	-	31	52	35
56	20	48	33,5,4,3,2,1,0	19	**50**	**46**	**33**	**30**	**28**	**33**

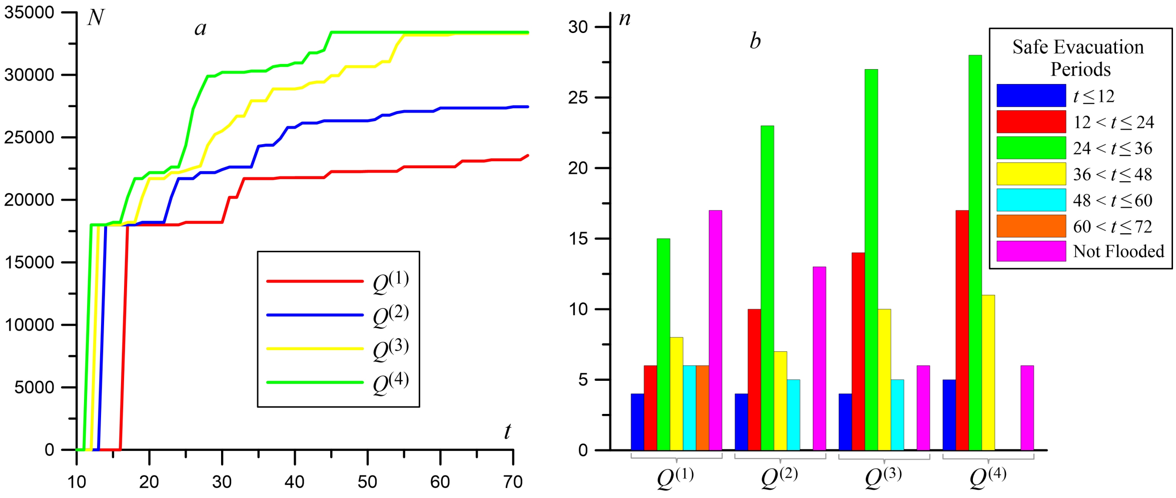

Fig. 3.6. *a* — Dependences of the inhabitants number of flooded settlements of the VAF on time for different hydrographs with maximum values: $Q^{(1)} = 30\,000\,\text{m}^3/\text{sec}$, $Q^{(2)} = 35\,000\,\text{m}^3/\text{sec}$, $Q^{(3)} = 40\,000\,\text{m}^3/\text{sec}$, $Q^{(4)} = 45\,000\,\text{m}^3/\text{sec}$. *b* — Diagram of the distribution of the settlements number into groups with different durations of safe evacuation periods for different maximum values of the hydrograph.

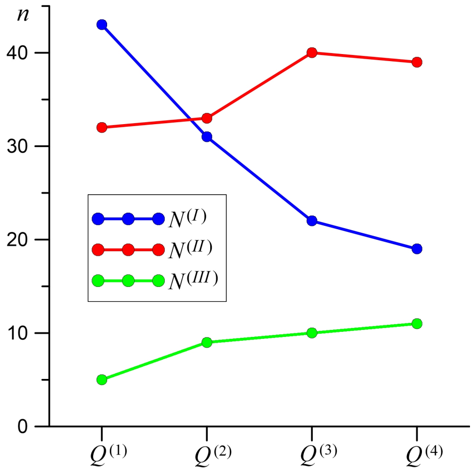

Fig. 3.7. Dependences of the number of settlements in three groups (See text) on the maximum value of the hydrograph for the next situations: I — non-flooded settlements ($N^{(I)}$), II — the evacuation route is flooded before the settlement ($N^{(II)}$), III — the settlement is flooded before its evacuation route ($N^{(III)}$). The results are shown for the four maximum hydrograph values Q (See caption in Figure 3.6)

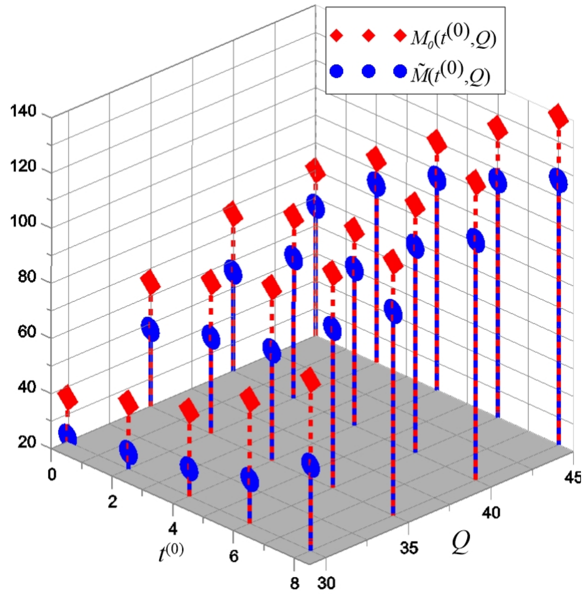

Fig. 3.8. Functions $M_0(t^{(0)}, Q)$ and $\tilde{M}(t^{(0)}, Q)$).

conditionally safe, since residents of some settlements (N 16 and N 17, See Table 3.2) can no longer be evacuated along the road network. Thus, the constructed functions in Figure 3.8 for $t^{(0)} > 4$ hours provide only a conditionally safe evacuation of the VAF population. Analysis of Figure 3.8 for $t^{(0)} \leq 4$ hours shows that the ratio $\tilde{M}(t^{(0)}, Q)$ to $M_0(t^{(0)}, Q)$ varies from 0.59 to 0.88.

An important feature of flood development in a large flat floodplain is the spatial and temporal distribution of threats. The possibility of sufficiently accurate forecasting of the hydrological situation based on numerical simulation allows reducing the problem of hydrological risk minimization to a more deterministic and simple problem of finding a valid (safe) evacuation schedule with the available stock of vehicles for evacuation. The uncertainty of this reserve is overcome by solving the problem of minimizing the number of vehicles on the set of safe evacuation schedules. Our results on the example of the Volga-Akhtuba Floodplain show that the construction of the function of the minimum resource support for safe evacuation provides effective management of its organization for various hydrographs. The practical implementation of safe schedule for organized evacuation requires the advance compilation of a directory of safe schedules for each territory in a wide range of hydrographs for various moments of the evacuation beginning.

The variety of tasks for effective evacuation of the population during floods is primarily due to the variability of the components of the evacuation situation E. The main factor in the evacuation situation is a catastrophic hydrograph. The nature of the flooding events is determined by the inflow rate and the total volume of water, the duration of high water, etc. These parameters depend both on the type of floods (snowmelt, rains, accidents at hydraulic structures) and on the nature of the river system (plain or mountain area, lowland rivers with mountain tributaries). It is necessary to take into account the factors that determine the disaster development: the relief height of the flooded area, the territorial compactness or low population density, the capacity of the road network and the quality of the roadway, the temporary and transport resources. Various combinations of these factors lead to varying degrees of severity of the evacuation situation.

The considered problem of finding the minimum resource support for the safe evacuation of the large floodplains population during flooding (zero life risk) is a special case of the problem of minimizing life risk under uncertainty. The effectiveness of its solution is provided by objective and subjective groups of factors. The first group includes the specificity of the conditions for the development of the disaster: a relatively small excess of the safe threshold of the hydrograph and the territorial distribution of settlements. Subjective factors are the possibility of a fairly accurate forecast of the flooding moments of settlements and sections of evacuation routes, as well as solving the problem of minimizing the number of vehicles on a set of safe schedules. The absence of at least one of the listed factors greatly reduces the efficiency of solving our problem or makes the solution impossible. Indeed, the compactness of the residents distribution in a big city or a catastrophic hydrograph lead to the rapid flooding of places where people live. This and the lack of forecast of the flooding of settlements do not allow for the safe evacuation of the entire population. In these cases, the evacuation effectiveness is measured by its speed and the number of residents evacuated.

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