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Control Model of the Floodplain Territories Structure

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Abstract: We have developed a model of an integrated hydrological, environmental and socio-economic structure of the floodplain area, which is the subject of strategic control based on the observational data, the results of numerical hydrodynamic and geoinformation modeling. The state assessment of each structural element is determined by the degree of correspondence between the hydrological type and the socio-economic type of the floodplain area. The goal of control is to implement a territorial structure that maximizes the value of the aggregated criterion for a stable state of the system. The control mechanism is a complex of hydraulic engineering projects (multiproject) in various channels in the floodplain area. The simulations results of the implementation of the sustainable development strategy of the environmental and socio-economic system of the Volga-Akhtuba floodplain northern part are presented.

Keywords: simulations, development management, hydrological regime, environmental and socio-economic systems, hydraulic engineering projects, Volga-Akhtuba Floodplain

1. INTRODUCTION

The problem of sustainable development (SD), which until recently was in the focus of management/control theory and practice, has largely lost its popularity in the last decade. In our opinion, the reason for this is the existence of a difficult gap between existing conceptual and formal models, on the one hand, and the development management practice of real environmental and socio-economic systems (ESES), on the other. For example, in [1, 2] the authors developed the concept of SD control based on game-theoretic models and the active systems theory. The main parameters of these models are the “system compatibility indices” calculated on the basis of the objective functions of its actors and ecosystem sustainability criteria. However, justifying these values that underlie these and many other SD models is an almost insurmountable difficulty in most cases. Indeed, the shortest periods of degradation and, moreover, the restoration of regional ecosystems are decades, so the “compatibility indices” should characterize conflicts between generations to a greater extent than conflicts between its actors.

In the absolute majority of cases, the development of modern ESES occurs within the framework of the “weak sustainability” concept, according to which natural capital is exchanged for human and productive capital with varying degrees of efficiency. A possible transition to SD in a state of degrading ecosystems requires both a study of the conditions for their restoration and a readiness for the necessary self-restraint in the context of economic competition. In addition, the level of modern theoretical and empirical knowledge about real

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ecosystems at the regional level does not allow us to confidently identify the their stability thresholds and predict their dynamics.

The floodplains of regulated large rivers with a developed ESES are among the territories in which, on the one hand, this gap manifests itself in the most acute form, on the other, it can potentially be bridged more easily than on other areas. The high conditionality of their territorial structure by the unstable nature of floods is an objective factor of weak environmental sustainability, which, as a rule, is destroyed in the process of their socio-economic development. The development of high-performance supercomputers and effective methods of computational fluid dynamics in recent years makes it possible to effectively simulate a realistic flood regime, which is a system-forming factor in floodplain areas, allowing to significantly reduce the complexity of the constructed SD models.

An example of a model successful construction for sustainable development of a regional environmental system is the work [3] in which the authors created the model of ecological and economic control of the biological resources extraction of the Azov Sea with sustainable reproduction. Their complex numerical simulation model successfully combines models of hierarchical differential games, biological kinetics, hydrodynamics using high performance computational algorithms for supercomputers. However, we note that the ecological criterion in this model (the stability of the biosystem) essentially coincides with the long-term economic criterion (sustainable extraction of biological resources). The work [4] is aimed at creating computer technology for effectively assessing the reliability of meeting the demands of Volga water users and, in particular, for the Lower Volga including projects to improve environmental conditions. The model is based on the multicriteria analysis methods and the compromises theory. Integrated decision support systems (DSS) allow solving the problems of planning water resources management in river basins, scarcity of river water resources for socio-economic needs, rational balance between socio-economic and environmental needs. Let us point out some good examples of DSS for the Haihe River Basin [5, 6], the northern part of the Volga-Akhtuba floodplain [7], the Illinois River [8], the Pinhao River Basin [9], the Biosphere Reserve Elbe River Landscape in Lower Saxony [10], the Pecos River [11]. This work and our research use similar methods and technologies, such as interdisciplinary modeling, GIS technologies, multi-criteria assessments, peer review. Our research is distinguished by a more active use of direct numerical hydrodynamic modeling.

The objective of this study is to solve the problem of identification and realizability of the values of the territorial structure parameters, necessary for SD. Our model is based on a simplified version of the "indices of system compatibility" (See [1]), implemented as a vector for assessing the self-compatibility of the territorial structure of the ESES, the components of which are calculated by territorial aggregation of expert consistency indices between the hydrological (H) type and the environmental and socio-economic (ESE) type for each site of the territory. The practical implementation of the proposed research concept is the identification and study of the attainability of the target H-structure of the Northern part of the Volga-Akhtuba Floodplain within the Volgograd Region (hereinafter called VAF) in the context of the sustainable development of its ESES through hydrotechnical multiproject, based on the construction of hydraulic structures (canals and dams) with calculated characteristics. These characteristics should stabilize the H-structure of the floodplain area and thereby make it possible to implement the mechanisms of ecological and economic control by its economic entities, which is described in [12].

The set of software tools presented in this paper includes the Decision Support System (DSS), which is an extension of the DSS for river water resources distribution. This set of tools for control sustainable development of floodplain areas is an implementation of the general model of the SD information-analytical system proposed by the authors of works [1, 2].

2. RESEARCH METHODS, TOOLS AND TECHNOLOGIES

The hydrological regime of the floodplain area is determined by three main factors: the river hydrograph ($Q(t)$ is the volume of water flowing per unit of time or the variation of discharge), the channel structure and the area topography [13–15]. Natural changes in the last two factors, as a rule, are insignificant for several tens of years, and the first factor has high variability at short time intervals. If the distribution function of flooding volumes for the period $\mathcal{T}$ is determined, then the frequencies of flooding of interfluve fragments calculated for this period remain constant over time T ($T \gg \mathcal{T}$). In other words, the H-structure of the floodplain area $\mathcal{Z}^{(H)}$ exists stably during the time interval T. This structure is described as a set of maps territories $\langle \mathcal{M}_i^{(H)}\ (i = 1, ..., n)\rangle$, flooded by water with frequencies from the specified ranges, and the distribution function of the relative flooded area at the floods peak $\Psi(x) : P(S^{(H)}/S < x)$ gives the aggregated state of the system (S is the total area of the VAF). The time interval $\mathcal{T}$ is determined experimentally from the observations data of the parameters of flood river hydrographs over a long period $T \gg \mathcal{T}$. The choice of the value of $\mathcal{T}$ affects the existence conditions, the type and accuracy of determining the stable hydrological structure $\mathcal{Z}^{(H)}$.

In turn, the stability of the hydrological structure is the main factor in the formation of the territorial environmental and socio-economic (ESE) systems of the floodplain area $\mathcal{Z}^{(ESE)}$, characterizing the spatial sites distribution by functionally homogeneous ESE-types. The term "territorial natural structure" in this work means a biotopes system of the main structural elements of a floodplain ecosystem. ESE-structure can be built on the basis of the corresponding cadastral maps. H- and ESE- structures define the complex structure $\mathcal{Z}^{(C)} = \mathcal{Z}^{(H)} \cap \mathcal{Z}^{(ESE)}$, which is given by flood maps of functionally homogeneous territories or ESE maps of hydrologically homogeneous territories

$$\mathcal{M}^{(C)} = \cup_{ij}\mathcal{M}_{i,j}^{(C)}, \text{ where } \mathcal{M}_{i,j}^{(C)} = \mathcal{M}_i^{(H)} \cap \mathcal{M}_j^{(ESE)}(i = 1, ..., n;\ j = 1, ..., m), \quad (2.1)$$

where $\parallel S_{ij}^{(C)} \parallel, S_{ij}^{(C)} = S(\mathcal{M}_{ij}^{(C)})$ is the land area. The complex structure $\mathcal{Z}^{(C)}$ is also determined by the distribution functions of the relative area of the flooded terrain at the floods peak

$$\Psi_j(x) :\ P(S_j^{(H)}/S_j^{(C)} < x),\ \ S_j^{(C)} = \sum_{i=1}^{n} S_{ij}^{(C)}\,, \quad (2.2)$$

where the number of frequency intervals n and their sizes, the number of ESE-types m are determined by the purpose and accuracy of modeling.

The construction of a hydroelectric dam and / or abrupt climatic changes are often the reasons for the formation of a new H-structure and an adaptive transformation of the ESE-structure of the floodplain. But these factors can also be the reason for the activation of slow changes in rivers channel topography, disrupting the stability of the H-structure, and, as a result, causing a decrease in the degree of self-compatibility between the H- and ESE-structures, which leads to ESE-degradation.

ESE-degradation counteraction requires periodic fine tuning of H- and ESE-structures. Within the framework of the weak stability concept, the control task is the implementation of a constant or variable H-structure, which ensures high efficiency and safety of a constant or variable territorial ESE-structure. The objective H-structure should first of all ensure the sustainability of the ecosystem in the case of a sustainable development concept. This in turn requires the stabilization of the H-structure itself with parameters that ensure stable flooding of its biotope.

In the absence of a floodplain ESES model, we estimate the potential efficiency of $\mathcal{Z}^{(C)}$ based on the expertly constructed vector of "disharmony" $\delta = (\delta_1, ..., \delta_m),\ \delta_j = 1 -$

K_j $(j = 1, ..., m)$, in which the functions $K_j = K(\Psi_j) \in [0; 1]$ characterize the degree of correspondence between hydrological regime of functionally homogeneous territory and its ESE-type j.

The complete uncertainty of the K_j functions for some j, their exact coincidence for different j, the insensitivity of the functions $K(\Psi_j)$ for all j to certain ranges of flooding frequencies allow us to reduce the dimension of the actual structures $\mathcal{Z}^{(H)}, \mathcal{Z}^{(ESE)}, \mathcal{Z}^{(C)}$ and the dimension of the problem (2.3). We can rewrite the general control problem for the structure of the floodplain area as a multi-criteria optimization problem:

$$\delta_{\tau+\theta}(u) \longrightarrow \min_{u \in U\,,\ \mathcal{Z}^{(C)}_{\tau+\theta} \in \Omega_{\mathcal{Z}}}\,, \quad (\theta = 1, 2, ..., \Theta)\,, \tag{2.3}$$

where $\Omega_{\mathcal{Z}}$ is the set of admissible structures, depending on the chosen concept of development stability (weak or strong stability), U is the set of realizations of a hydraulic engineering multiproject, Θ is planning horizon, the τ index corresponds to the calculation of hydrological structures for the period $[\tau - \mathcal{T}, \tau]$. The lack of effective methods for solving inverse problems of hydrodynamics allows using only heuristic branch-and-bound methods to solve the problem (2.3), while the exact methods can be used at some stages in (2.3). Special particular problems of (2.3) and methods for their solution are described in the works [7, 16] using hydrodynamic, geoinformation and game-theoretic simulations.

3. TOOLS AND SIMULATIONS RESULTS FOR VOLGA-AKHTUBA FLOODPLAIN

VAF is located in the lower reaches of the Volga River (the area of the northern part of the floodplain is approximately 870 km^2, the number of small natural channels exceeds 200 with total length of about 1000 km). Figure 3.1 shows a diagram of the general hydrological system of VAF, which can be conditionally divided into the western part, which is flooded mainly from the Volga River. The hydrological regime in the eastern part is determined by the water dynamics in the Akhtuba River and in the large middle trunk water system of natural channels of the floodplain.

The structure of our software package for solving the problem (2.3) for ESES of VAF is shown in the Figure 3.2. Individual parts of this software are described in detail in [7, 16, 17]. The key component is a numerical hydrodynamic model of the area flooding, which takes into account all the main physical and meteorological factors [13, 17, 18]. This mathematical model is based on 2D shallow water equations, which has been successfully applied to similar problems, See, for example, [19, 20].

The existence, type and accuracy of determining the stable hydrological structure of the VAF under the condition of the stability of the channel system and topography in the period 1962–2018 are established as a result of computational experiments. We have generated sequences of all possible samples of fragments of the time series $V^{(t)}$ $(t = 5, 6, ..., 57)$, containing t data units, using the observations array of normalized volumes of V for flood hydrograph through the hydroelectric dam. For these fragments, we have constructed a set of experimental distribution functions $\Psi^{(t)}(x) : P(V^{(t)}/V_{\max} < x)$ ($V_{\max}$ is the maximum volume for the entire observation period). The performed analysis indicates that the error in determining the magnitude of the flood volume realized in the VAF with frequency of $n_{flood} \geq 0.85$ for $t \geq 20$ does not exceed 0.05.

Initial hydrological data are based on the official primary statistical information on the operation of the Volga hydroelectric power station (See also [21]). The regression model for describing the flow of flood waters into the Akhtuba River in the period 1962-2018 was built based on the results of measurements of flood water levels at the gauging station in the Volgograd City [7]. The modeling results and the constructed retrospective hydrological

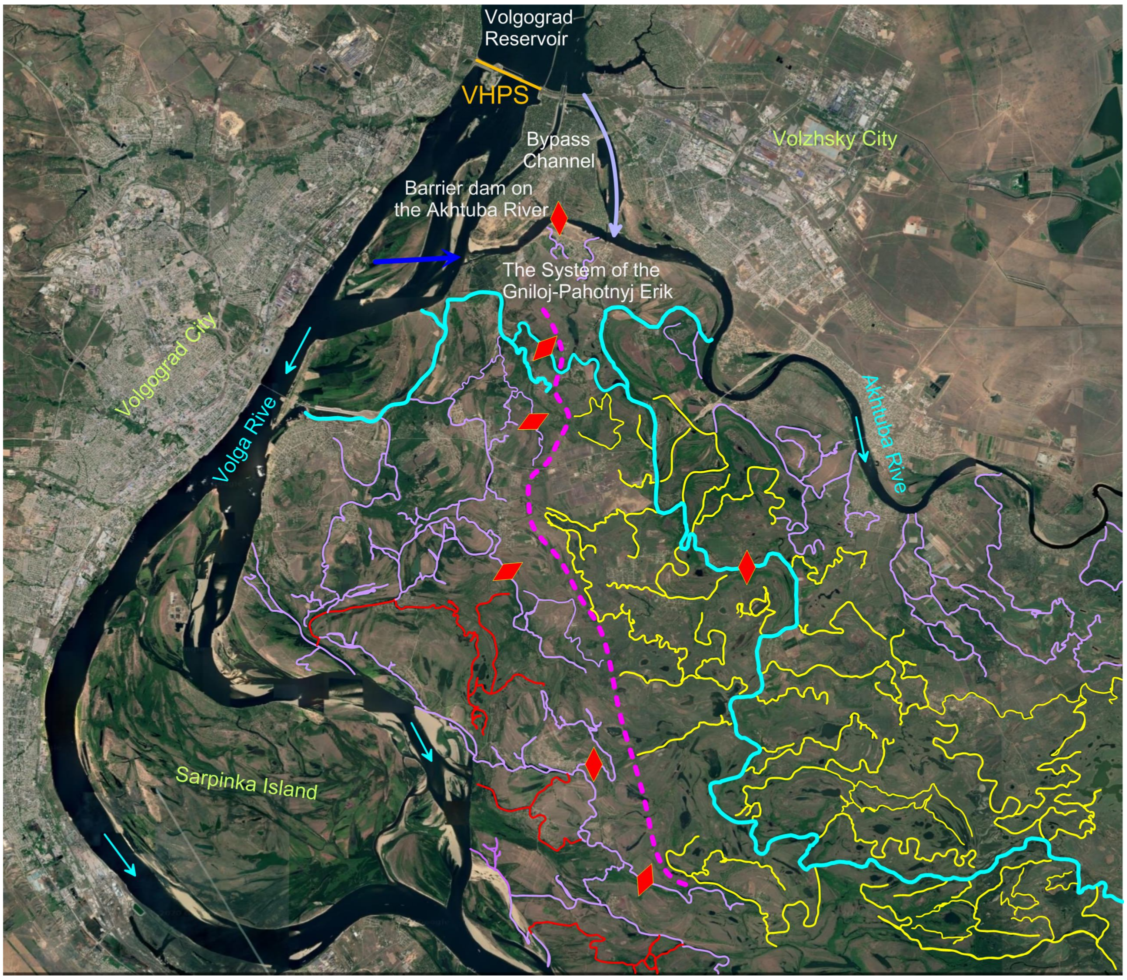

Fig. 3.1. Scheme of the complex of hydraulic engineering projects. The blue lines show the system formed by the Erik Gniloj and the Erik Pahotnyj in the northern part and by the Kashirskij water tract in the eastern part of the VAF. The yellow lines show only some of the small channels associated with this system. Light purple channels are filled directly from the Volga River. Red lines indicate canals from the Akhtuba River. Magenta diamonds show possible positions of dams of different types. Magenta dashed line delimits the conditional "western" zone from the "eastern" zone.

structure $\mathcal{Z}_{1982}^{(H)}$ show that the main factor of the loss of stability of this hydrological structure and the drying up of the interfluve is a gradual decrease in the average volume of low-flow and flood waters in the Akhtuba River due to the progressive degradation of the Volga riverbed after the construction of the Volga hydroelectric power station in 1962. Figure 3.3 shows the distribution functions $\Psi_{1982}(x)$ and $\Psi_{2018}(x)$. Comparative analysis of curves 1 and 2 shows both the general reduction of the flooded territory and the qualitative change in its structure. The share of sustainably flooded territory is reduced from 85 percent to 47 percent.

The northern territory of the VAF cadastral map contains 607 cadastral parcels that belong to 35 cadastral types. Moreover, cadastral types have not been established for 35 percent of the VAF. Such areas and recreational areas are not evaluated and the $K(\Psi_j)$ functions are undefined for them. We combine the remaining types into four groups based on the proximity of the estimated coefficients. The first two are wetlands ($j = 1$) and flood-meadows (type of farmland) ($j = 2$) and they collectively represent the floodplain ecosystem biotope for which non-flooding is damage. The other two are areas of residence of the population ($j = 3$) and forests + economic areas ($j = 4$), for which flooding is a damage. Very small floods

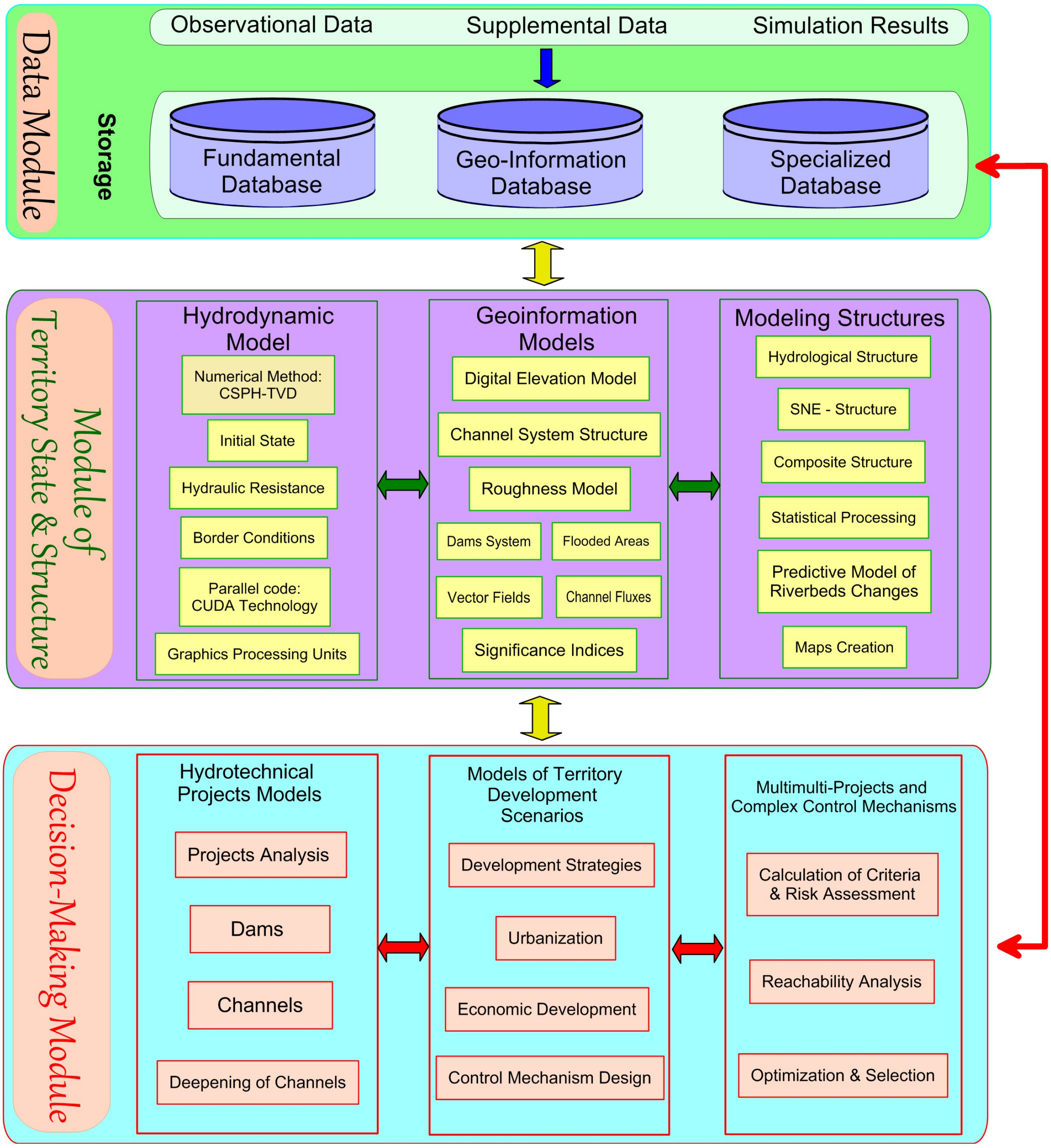

Fig. 3.2. The structure of the software package for our model of the floodplain territory control.

on the Volga River were observed every 10–15 years in the period 1880–1930 before the construction of the Volga system of hydroelectric power plants [21]. This allows us to relate the stability boundary of the floodplain ecosystem with the value of the threshold frequency of flooding of the floodplain biotope $n_{flood} = 0.85$.

Table 3.1. Evaluative coefficients of the efficiency of typical elements of the Volga-Akhtuba floodplain.

n_{flood}	0	$(0; 0.25]$	$(0.25; 0.50]$	$(0.50; 0.85)$	$[0.85; 1.0]$
$k_{i,1}$	0	0	0	0.25	1
$k_{i,2}$	0	0	0.25	0.5	1
$k_{i,3}$	1	0	0	0	0
$k_{i,4}$	1	0.1	0	0	0

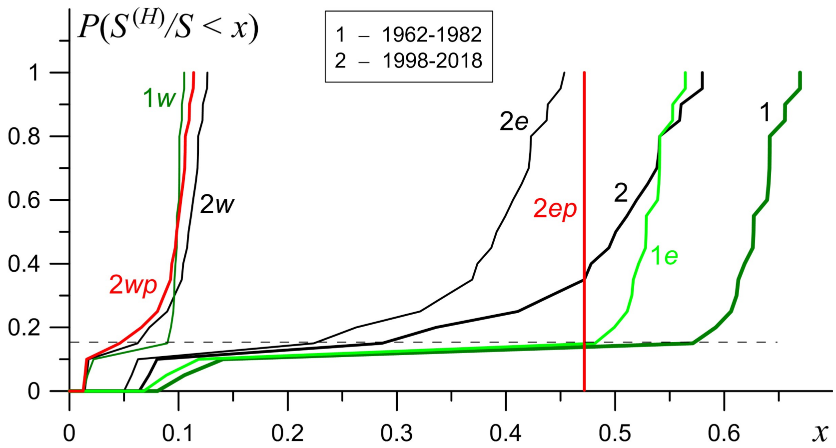

Fig. 3.3. Model integral distribution functions of the flood area are shown by the following curves: 1 — $\Psi_{1982}(x)$; 2 — $\Psi_{2018}(x)$; *1e* is eastern zone for 1962–1982; $1w$ is western zone for 1962–1982; $2e$ is eastern zone for 1998–2018; $2w$ is western zone for 1998–2018. The symbols $2wp$ and $2ep$ denote the corresponding curves, taking into account the implementation of hydraulic projects. The horizontal dashed line corresponds to flooding of the floodplain with a frequency of at least 0.85.

Evaluation of the effectiveness of the territorial structure of VAF is carried out using special functions of the form

$$K(\Psi_j) = \frac{1}{S_j} \sum_{i=1}^{n} k_{ij}(n_{flood})\, S_{ij} \quad (j = 1, ..., m)\,, \tag{3.4}$$

where $k_{ij}(n_{flood})$ are the dependencies of the coefficients on the flooding frequency (See Table 3.1). Thus, the current complex (integrated) structure of VAF is characterized by $n = 5$, $m = 4$.

The presence of a significant part of the territory with undefined evaluation functions $K(\Psi_j)$ is a source of great uncertainty in the task (2.3). The expert estimation of the threshold value of the area of the floodplain ecosystem biotope is approximately $0.5\,S$, which noticeably exceeds both the area of modern stable flooding ($0.3\,S$) and the value of $S_1 + S_2$. To remove this uncertainty, we included in the first group of ESE structures ($j = 1$) a part of the territory with indefinite evaluation functions $K(\Psi_j)$, which was steadily flooded in the period 1962–1982. We estimate the error in determining the this territory area as 0.02, while it is 0.07 for the period 1998-2018. The reason for this is the stable flooding in the past of all the plains, while the modern border of the stable flooded area is within the plains. Figure 3.4 shows both the target areas of stable flooding and areas where flooding causes damage. For the ESE structure $\mathcal{Z}^{(ESE)}_{2018}$ changed in this way, we calculated the "disharmony" vectors for the complex and virtual structures using a series of computational experiments.

$$\mathcal{Z}^{(C)}_{2018} = \mathcal{Z}^{(H)}_{2018} \cap \mathcal{Z}^{(ESE)}_{2018} \;: \qquad \delta_{2018} = (0.45;\; 0.53;\; 0;\; 0.11)\,,$$

$$\mathcal{Z}^{(C)}_{virt} = \mathcal{Z}^{(H)}_{1982} \cap \mathcal{Z}^{(ESE)}_{2018} \;: \qquad \delta_{virt} = (0;\; 0.06;\; 0.02;\; 0.17)\,.$$

The first vector shows a high level of disharmony of the VAF ESES due to catastrophic drying up of the interfluve, the second vector is the objective vector for solving the problem (2.3).

The main part of the multiproject is the channel from the Volgograd Reservoir to the Akhtuba River bypassing the Volga River and a dam that closes the entrance to Akhtuba from the Volga River (See "Barrier dam on the Akhtuba River" on the Figure 3.1). The parameter of the flood hydrograph is the maximum discharge through the canal (Q_{ch}). The product of Q_{ch} by the duration of the flooding τ_f (which is equal to 15 days in all experiments) gives

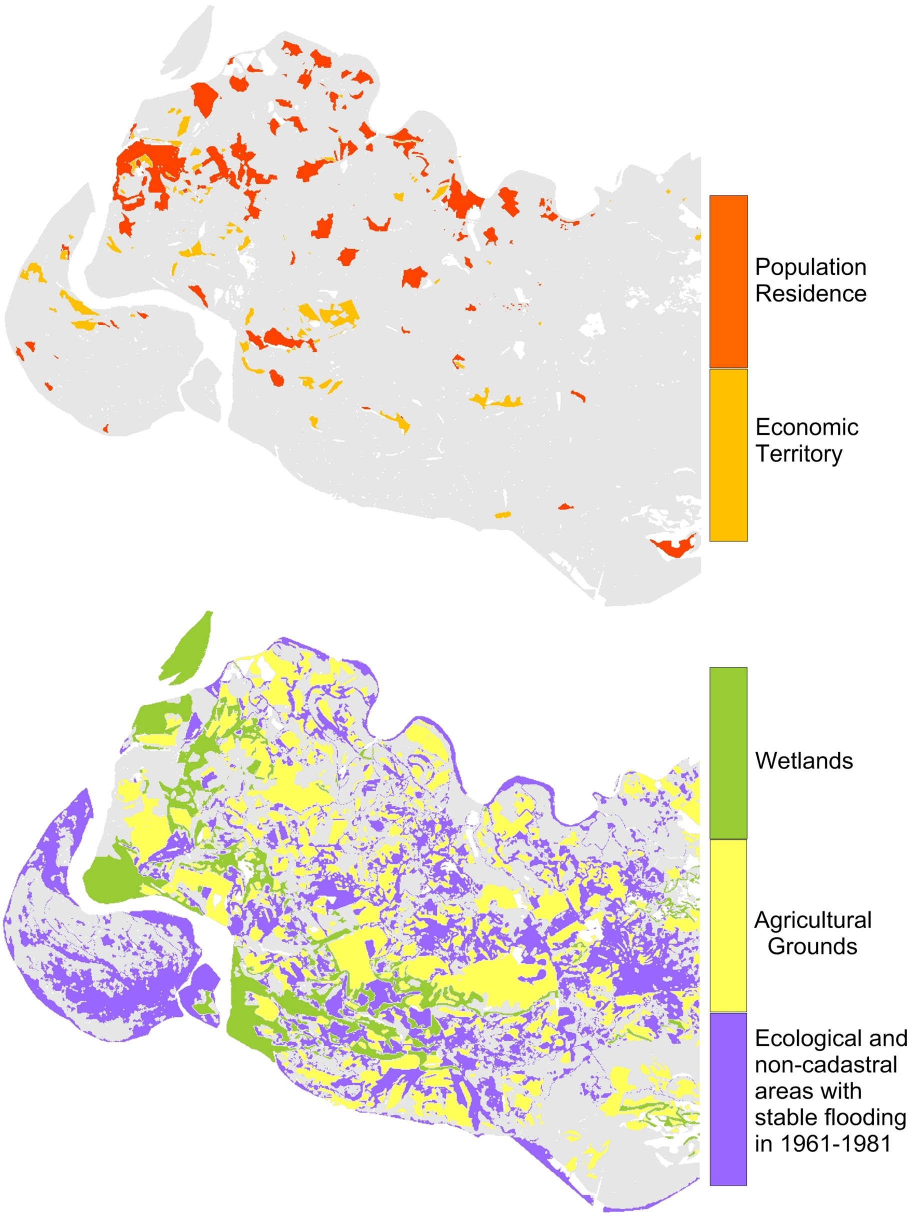

Fig. 3.4. Upper panel: the target area for stable flooding of the VAF. Bottom panel: areas where flooding causes damage.

the volume of flood waters that determine the flooded territory map and its area. Since the amount of flood water entering the Akhtuba River is less than 10 percent of the total spring water ($V_{tot}^{(flood)}$), the project allows for stable flooding of almost any target area in the eastern part of the VAF, limited by the condition of non-flooding of socio-economic territories (curve $2ep$ in Figure 3.3) even in conditions of high natural variability of $V_{tot}^{(flood)}$. Considering that Q_{ch} is a small value of the total water discharge in the River Volga during the flood period, we restrict ourselves to the case of a fixed Q_{ch}.

We determine the location of the dams by heuristic analysis of the directions of water flows across the boundary between the east and west zones (See dashed line in Figure 3.1) during the flooding stage. The designed dams in the channels should prevent the flow of water from the western zone to the eastern zone. Features of the real topography limit the number of

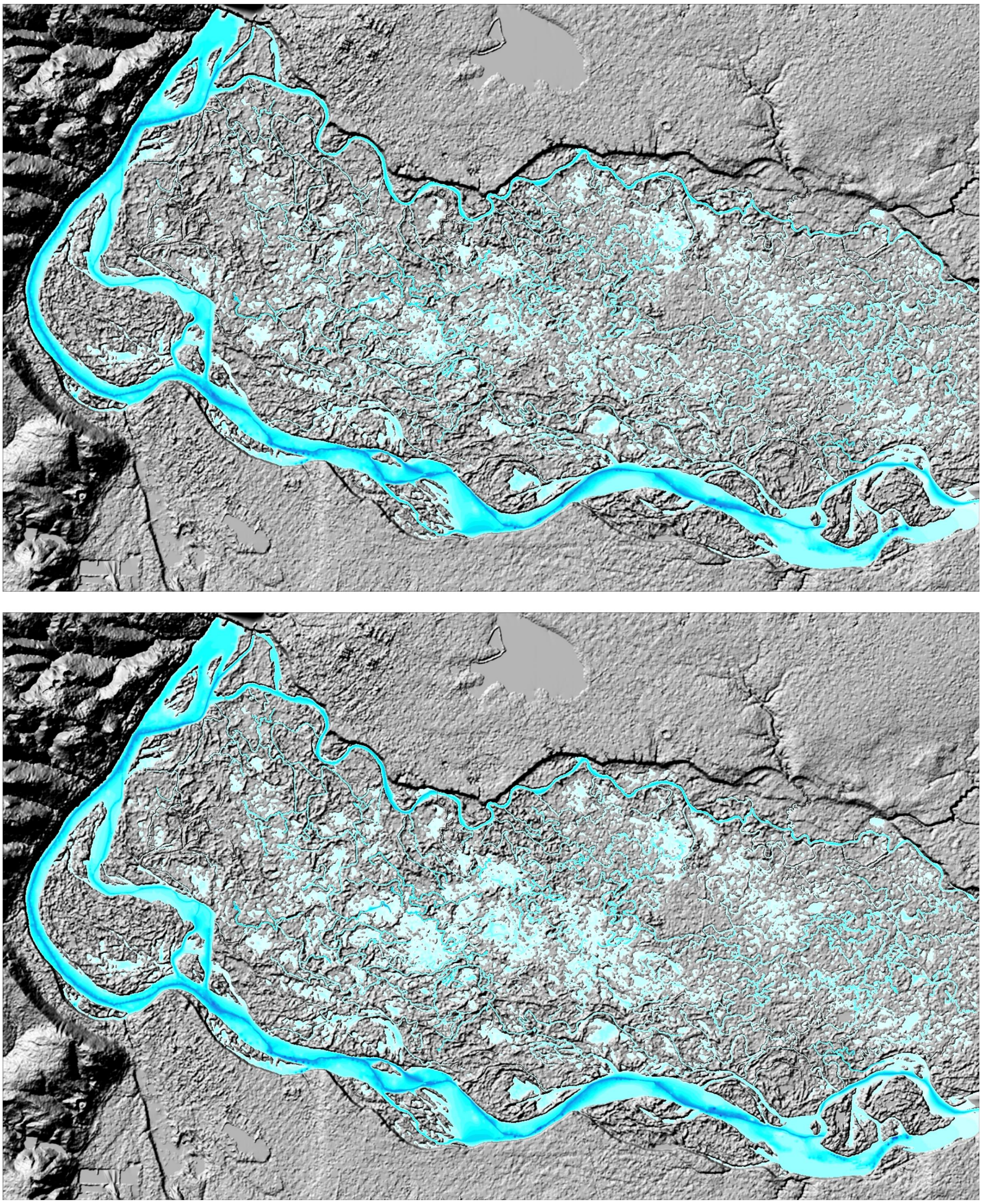

Fig. 3.5. Maps of the stably flooded area of the VAF in the period 1998-2018. Up panel: model without bypass channel with $Q_{ch} = 0$. Bottom panel: model with bypass channel $Q_{ch} = 2000$ m^3 sec^{-1}.

positions of such dams. We have found the dam locations that have a noticeable effect using hydrodynamic simulations.

The results of hydrodynamic modeling and optimization of projects for deepening small channels and installing additional dams on the VAF territory (See works [22–24]) showed the possibility of reducing the discussed negative effect by 8 percent. Figure 3.1 demonstrates the hydrological system of the floodplain and the complex of hydraulic projects. We distinguish the eastern zone ("e"), adjacent to the Akhtuba River, and the western zone ("w"), for which the hydrological regime is determined directly by the Volga River. We have highlighted in red small channels in the western part of the VAF, for which deepening of the channels is also advisable. The optimal locations of dams on small canals are marked by rhombuses in Figure 3.1.

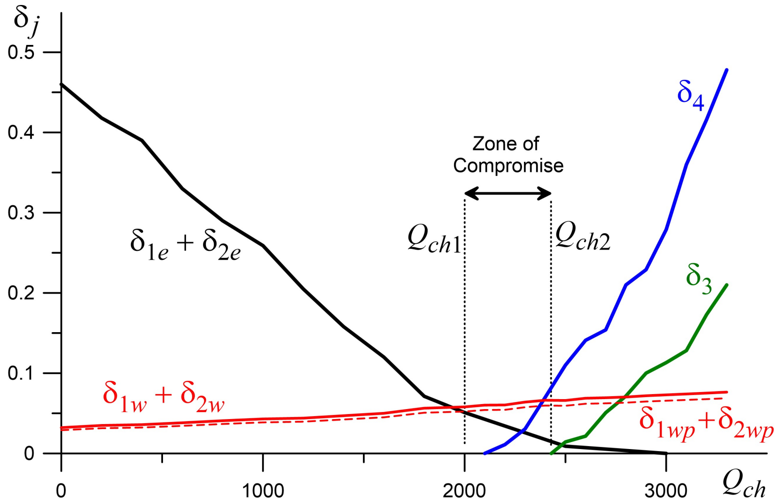

Fig. 3.6. Dependencies of the vector components of "disharmony" δ_m on Q_{ch} for the ESES.

Figure 3.3 shows the distribution functions of flooded areas for two time intervals (1962–1982 and 1996–2018) separately for the western zone (curves $1w$, $2w$, $2wp$) and for the eastern zone (curves $1e$, $2e$, $2ep$), which are highlighted in Figure 3.1. The horizontal dashed line corresponds to stable flooding of the interfluve. The post-design distribution function for the western zone is denoted as $2wp$. A comparison of the $2w$ and $2wp$ curves shows an approximately 25 percent reduction in stable flooded area. Distribution function $x = \text{const} = 0.47$ (See vertical line $2ep$) corresponds to the annual flooding with $Q_{ch} = 2000$ m^3 sec^{-1}.

The arrow in Figure 3.1 indicates the position of a possible large bypass channel from the Volgograd Reservoir to the Akhtuba River, the project of which is being discussed. Such construction should include a barrier dam on the Akhtuba River. Figure 3.5 shows the results of our spring flood simulations with and without such a bypass channel. The bypass canal can significantly improve the hydrological regime for the eastern area of the VAF. Small projects are based on the work to clear and deepen small channels (they are indicated in yellow, purple and red in Figure 3.1), as well as the use of special dams to regulate the water flow in the middle channels.

Figure 3.6 shows the curves $\delta_m(Q_{ch})$, which determine the dependence of the objective functions on the main project parameter Q_{ch}. The values $\delta_1^{(1)}$ and $\delta_2^{(1)}$ correspond to the project with a bypass canal and a barrier dam, and the values $\delta_1^{(2)}$ and $\delta_2^{(2)}$ additionally include hydraulic engineering projects on the territory of the VAF (deepening of channels, dams on small channels). The case $Q_{ch} = 0$ corresponds to the pre-design state and $\delta_{2018} = (0.45; 0.53; 0; 0.11)$.

The increasing sequence of Q_{ch} values determines the sequence of nested flood maps of the VAF at the peak of floods. There are two critical values of the parameter Q_{ch} that define the set of feasible solutions to problem (2.3). The value Q_{ch1} determines the largest value of Q_{ch}, at which the equalities $\delta_3 = \delta_4 = 0$ are satisfied. This value corresponds to the largest flood map for the peak of high water included in the stable flood target map. The value Q_{ch2} defines the largest flood map by inclusion, at which the equality $\delta_3 = 0$ is fulfilled. Thus, the segment $[Q_{ch1}; Q_{ch2}]$ is the "compromise zone" that contains the value of Q_{ch}. A decrease in the total disharmony index $\delta_1 + \delta_2 + \delta_4$ ($\delta_1 = \delta_{1e} + \delta_{1w}$, $\delta_2 = \delta_{2e} + \delta_{2w}$) in this segment is possible if some economic zones are added to the multiproject or if the target area of stable flooding is reduced.

4. CONCLUSION

We present an approach to the control of the spatial structure of the floodplain territory, which is the basis for creating strategies for their development. The consistency functions between the hydrological type of each spatial structural element and its ESE-type are used as objective functions. The hydrotechnical multiproject for the interfluve channels is a control tool. The implementation of this approach for the northern part of the Volga-Akhtuba floodplain makes it possible to determine the parameters of the hydraulic engineering multiproject, which provide the conditions for its sustainable development.

The analysis of expenses and ESE-effects of the implementation of the investigated multiproject are beyond the scope of our task. We also do not discuss here game-theoretic models of the environmental and economic control mechanisms of the economic entities of the VAF. Three such mechanisms (the control of the economic entity of the Volga hydroelectric power station, the control of the urbanization process, the mechanism of co-financing for the project of deepening small channels) were investigated in our previous works [16, 24, 25].

Modeling a complex of projects and mechanisms for sustainable development of the VAF territory, as well as a comparative analysis with a similar complex that implements the strategy of weak sustainability, are the subject of our future research. Undoubtedly, each floodplain territory has a unique structure, therefore, the combination of hydraulic projects and mechanisms of ecological and economic control in each of them is also individual. However, we believe that the proposed approach to the control of the territorial structure of floodplain environmental and socio-economic systems will be useful both for theoretical research and for the practical implementation of strategies for their sustainable development.

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