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CALCULATION OF WAVE HYDROPHYSICAL CHARACTERISTICS FOR INLAND FRESHWATER RESERVOIRS OF SOUTHERN RUSSIA*

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An important role in the management of water resources is played by inland freshwater reservoirs, the main uses of which are: meeting the needs of the population in fresh water, irrigation, hydroenergy, shipping, fish farming, etc. At the same time, undesirable and inevitable disturbances of the natural environment and the natural balance of the ecosystem are increasingly observed. water bodies. A serious problem is a significant change in the bottom relief, the destruction of the shores, the accumulation of bottom sediments. The results presented in this article are aimed at creating a modern basis for forecasting trends in the development of inland freshwater reservoirs in the South of Russia, based on calculations of the hydrophysical characteristics of the wave regime. Mathematical models of three-dimensional wave hydrodynamics have been constructed and adapted to natural and climatic conditions and geographical features on the example of the Tsimlyansk reservoir. Based on the developed experimental set of programs, prognostic calculations were performed for its coast, the nearby village of Sarkel, named after the historical Khazar fortress city of Sarkel (flooded by a reservoir). For the selected local site, studies of the hydrodynamic characteristics of the wave impact on the coastal recreational zone, including wave profiles and velocity vector fields at different values of wind speed, were carried out.

Keywords: inland reservoirs, freshwater reservoirs, coastal zone, wave processes, modeling of hydrodynamic processes, parallel algorithms.

Introduction. The problem of studying and rational use of water bodies and water resources, their monitoring, protection and restoration are one of the most important tasks of the development of the state [1-4]. Especially great attention of state organizations, specialists and scientists in many countries of the world is attracted by the issues of creation and integrated use of inland freshwater reservoirs. Among their diversity, artificially constructed water bodies - reservoirs - play a major role in the development of the economy of many countries.

When planning the development of the coastal territories of reservoirs, accurate information about the hydrometeorological features of the regions is required, based on the features of wave processes [5].

The processes occurring in the coastal zone of the reservoir are markedly different from the wave fields in its open part. The proximity of the bottom begins to strongly influence the characteristics of the waves. When a group of waves enters shallow waters, long waves are the first to experience this effect. In shallow areas, the speed of wave propagation decreases and the wavelength decreases. This leads to the fact that due to the change in the speed of movement, there is a rapid increase in the height of waves in shallow areas, the waves become steeper and, eventually,

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collapse. Wave refraction is also characteristic for shallow water. The refraction of waves is caused by a decrease in the velocity of their propagation and is accompanied by the transformation of wave fronts, in which the fronts turn in such a way as to become parallel to the shore. Longer waves are subject to greater refraction. Short waves are more affected when they enter the currents, which entails a significant change in their characteristics such as speed, length and height. Short waves in the oncoming current are destroyed faster than long ones, in turn, long waves can pass through the flow area without breaking with minor changes.

In connection with the above, it is important to adapt and apply to the coastal zone the theoretical concepts and practical methods of calculating and forecasting the wave regime developed to date.

Currently, the most effective way to perform any calculations and forecasts related to the parameters of the wave is numerical modeling with the assimilation of instrumental observations of the wave and calibration of numerical models based on them [6 - 10]. When modeling, it is possible to take into account the features of natural processes characteristic of reservoirs, such as their significant spatial and temporal variability, multidimensionality, nonlinearity of processes and the diversity of dynamic phenomena.

Currently, there are several options for using modern wave models to study the wave climate and predict the waves of inland reservoirs [10 – 15]. However, they are primarily focused on the description of waves in the open part of the reservoir, and at the same time, calibration and verification of models based on coastal experimental data is rarely performed. This is due to the weak development of instrumental data for measuring waves off the coast.

This paper describes the results of using a 3D wave model for regional forecasting of waves in the coastal zone of the Tsimlian reservoir and similar water bodies located in the South of Russia. A private object of modeling is the coast of the reservoir, located near the village of Sarkel. This choice is not accidental, since Sarkel is a unique region with a rich history and traditions, a place to attract tourists and vacationers (Sarkel is a Khazar, later an ancient Russian fortress city on the left bank of the Don River, built between 834-837; flooded during the construction of the reservoir). Currently, the best beach on the Tsimlyansk reservoir with snow-white sands and warm water is located here. Despite the importance of maintaining the optimal mode of functioning of these territories, in order to maximize the use of positive and limiting or eliminating negative consequences, today there are quite a few environmental and economic problems that require a comprehensive solution and, in particular, forecasting the transformation of the coastal zone.

For the selected "local" area, including the territory of the reservoir, studies of hydrodynamic characteristics, such as the pressure field, the velocity vector field of the aquatic medium in different phases of the wave, and also wave profiles were constructed at different values of wind speed.

2. Description of the model and input data. 3D hydrodynamic model was used to solve the problem. Thy model includes:

– the equations of motion in three coordinate directions (Navier–Stokes equations)

$$\frac{\partial u}{\partial t}+u\cdot\frac{\partial u}{\partial x}+v\cdot\frac{\partial u}{\partial y}+w\cdot\frac{\partial u}{\partial z}+\frac{\partial(u^2)}{\partial x}+\frac{\partial(u\cdot v)}{\partial y}+\frac{\partial(u\cdot w)}{\partial z}= -\frac{1}{\rho}\cdot\frac{\partial P}{\partial x}+\mu_h\cdot\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(\mu_v\cdot\frac{\partial u}{\partial z}\right),\ (x,y,z)\in G, 0<t\le t_{fin}, \tag{1}$$

$$\frac{\partial v}{\partial t}+u\cdot\frac{\partial v}{\partial x}+v\cdot\frac{\partial v}{\partial y}+w\cdot\frac{\partial v}{\partial z}+\frac{\partial(u\cdot v)}{\partial x}+\frac{\partial(v^2)}{\partial y}+\frac{\partial(v\cdot w)}{\partial z}= -\frac{1}{\rho}\cdot\frac{\partial P}{\partial y}+\mu_h\cdot\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(\mu_v\cdot\frac{\partial v}{\partial z}\right),\ (x,y,z)\in G, 0<t\le t_{fin}, \tag{2}$$

$$\frac{\partial w}{\partial t}+u\cdot\frac{\partial w}{\partial x}+v\cdot\frac{\partial w}{\partial y}+w\cdot\frac{\partial w}{\partial z}+\frac{\partial(u\cdot w)}{\partial x}+\frac{\partial(v\cdot w)}{\partial y}+\frac{\partial(w^2)}{\partial z}=$$
$$=-\frac{1}{\rho}\cdot\frac{\partial P}{\partial z}+\mu_h\cdot\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(\mu_v\cdot\frac{\partial w}{\partial z}\right)+g,(x,y,z)\in G,0<t\le t_{fin}, \quad (3)$$

– continuity equation (law of conservation of mass)

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho\cdot u)}{\partial x}+\frac{\partial(\rho\cdot v)}{\partial y}+\frac{\partial(\rho\cdot w)}{\partial z}=0,(x,y,z)\in G,0<t\le t_{fin}, \quad (4)$$

– heat transport equation

$$\frac{\partial T}{\partial t}+\frac{1}{2}\cdot\left(u\cdot\frac{\partial T}{\partial x}+v\cdot\frac{\partial T}{\partial y}+w\cdot\frac{\partial T}{\partial z}+\frac{\partial(u\cdot T)}{\partial x}+\frac{\partial(v\cdot T)}{\partial y}+\frac{\partial(w\cdot T)}{\partial z}\right)=$$
$$=\mu_h\cdot\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{\partial}{\partial z}\left(\mu_v\cdot\frac{\partial T}{\partial z}\right),(x,y,z)\in G,0<t\le t_{fin}, \quad (5)$$

– equation of state for density

$$\rho_0=\rho(T_0),(x,y,z)\in G,0<t\le t_{fin}, \quad (6)$$

where $\bar{V}=\{u,v,w\}$ are components of the velocity vector, P is the pressure, g is the acceleration of gravity, ρ is the density, μ_h,μ_v are the horizontal and vertical components of the coefficient of turbulent exchange, T is the temperature at a specific point in the region, T_0 is the temperature at which the density is maximum..

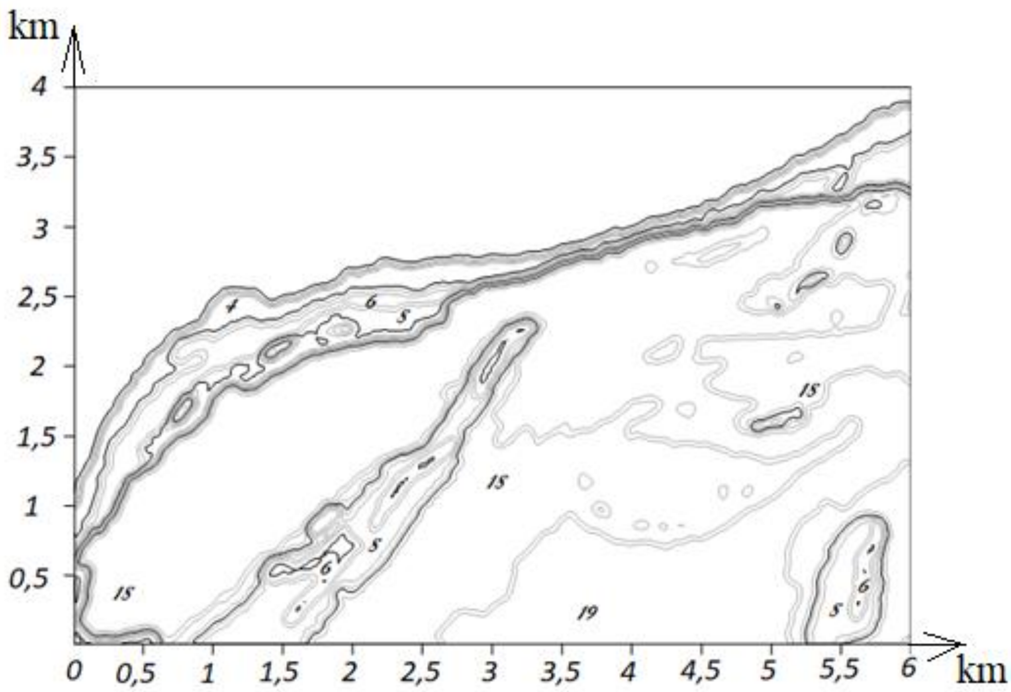

Fig. 1. Isolines of the depths of the computational domain

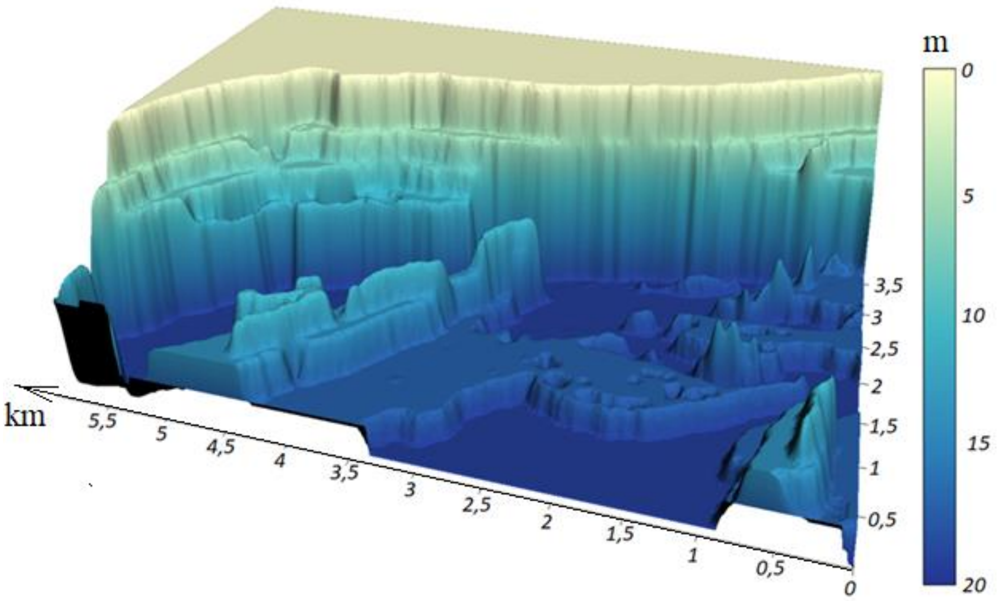

Fig. 2. Depth map of the calculated area

The description of the initial and boundary conditions supplementing equations (1) – (6), as well as the construction of a discrete analogue of the proposed model can be seen in detail in [16-21]. Since the purpose of this article is to describe the results of using the software package and the numerical experiment conducted, the authors suggest that the reader get acquainted in more detail with the information about the construction of a mathematical and specific 3D wave model in the link proposed above.

The local simulation area has dimensions of $6{\cdot}10^3 \times 4{\cdot}10^3$ m and a maximum depth of 19 m, the peak point rises 2 m above sea level. The source of disturbances is set at some distance from the shore line. At the initial moment of time, the liquid is at rest.

In order to prepare the input data, a digital model area was constructed, displaying a depth map of the calculated area and the contour of the function of the depths of the bottom surface and the coastline (Fig. 1, 2). The model area is characterized by a geometrically complex configuration of the coastline.

A uniform grid with dimensions of 200 × 200 × 240 was used as the calculated grid, which corresponds to the size of cells of the order of 30 m × 20 m in horizontal directions and 0.1 m in vertical directions. Input data on the depth readings of the water body were interpolated to this grid. The total number of grid nodes is 9600000.

To simplify the interpretation of the simulation results, the wind was set to be uniform in space and constant in time. Calculations were carried out for the north-west direction at different speed values - from 3 to 7 m/s.

It should be noted that when implementing the wave model, there is considerable arbitrariness in the selection and adjustment of several calibration coefficients. The reason for this situation is the imperfection of the physical description of wave energy dissipation, bottom friction, etc. Therefore, calibration coefficients are selected based on comparison with instrumental and other experimental data and may vary in a certain range.

Results. Numerical results are obtained based on the use of the created modern software package, which is adapted for modeling wave processes for inland freshwater reservoirs of the South of Russia. This software package is used in a wide range of parameters to calculate the velocity and pressure fields of the aquatic environment, and to assess the hydrodynamic impact on the shore in the presence of surface waves.

To obtain a representation of the velocity field, various sections of the calculated area are made by the *Oxz* plane. Fig. 3 shows the profiles of the horizontal velocity of the water medium in the constructed sections.

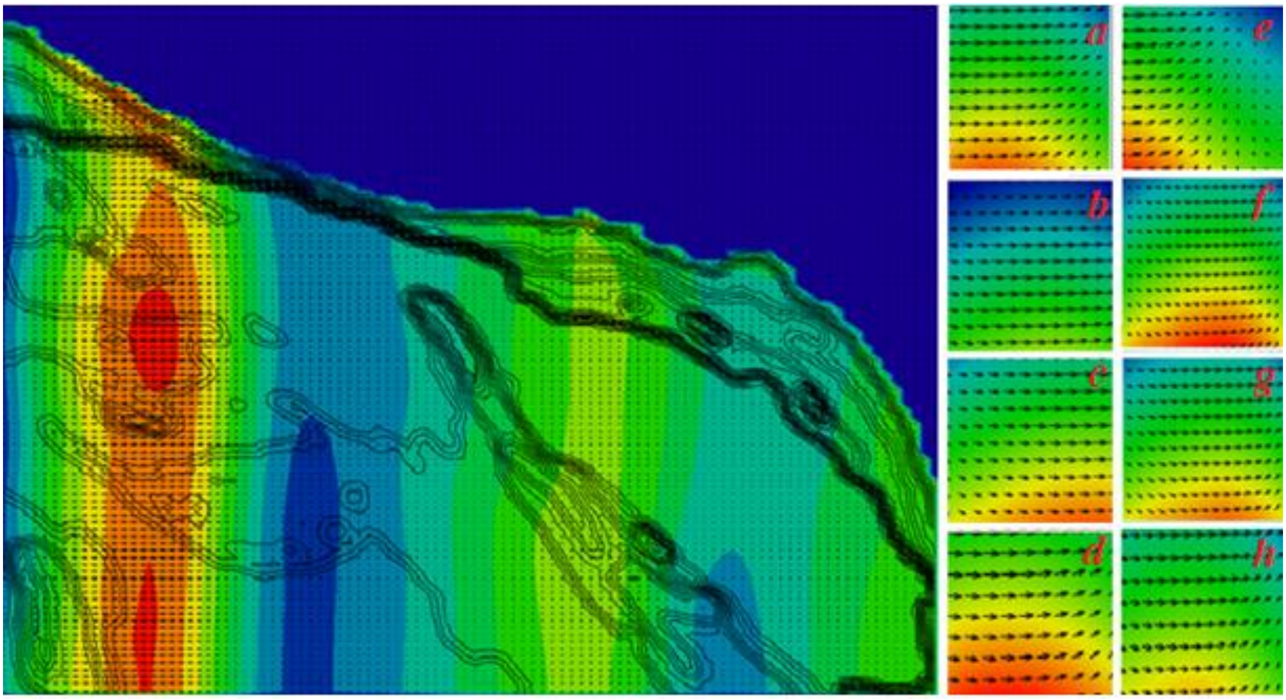

Fig. 3. The pressure field and the velocity vector field of the aqueous medium in different phases of agitation

The image of the velocity vector field of the aqueous medium, fragmentally presented in the left part of Figure 3 in the notation a, d, e, f, g, h, demonstrates the formation of small turbulent vortex structures with vertical movement.

One of the factors affecting the magnitude and direction of vortices is the unevenness of the bottom surface. In the studied area, significant differences in depth are observed, caused, among other things, by the «flooded forest» located in the western and central part of its territory (Fig. 4). Here, the sandy bottom of the site is mainly changing: there are areas of silt, deposits of snag, areas of flooded forest and shrubs.

For a more visual representation, Figure 5 shows an image of a formed turbulent vortex, in the physical region corresponding to the area adjacent to the territory of the «flooded forest».

The results of numerical experiments on modeling the wave profile and the velocity vector field taking into account the geometry of the bottom at different values of wind speed are presented (Fig. 6).

With a change in wind speed in the range from 3 m/s to 7 m/ s, a significant transformation of waves occurs. At first, shorter, well-defined waves are observed, the maximum height of which reaches 0.9 m (Fig. 6 a-c). As the wind speed increases, the waves lengthen. Their height first reaches 1.2 m (Fig. 6 d), and then 1.4 m (Fig. 6 e). Gradually, the waves become well developed in length, but not large. The maximum wave height reaches 1.5 m (Fig. 6 f), and then 1.7 m (Fig. 6 g).

Fig. 4. Map of the flooded floodplain forest of the Don River
(compiled from navigation maps of the Tsimlyansk reservoir). Comp. SSC RAS [22].

Numerical experiments make it possible to identify the areas of the studied area that are most susceptible to wind-wave effects. With the indicated wind direction and speeds, significant changes in the level rise function can be observed in this coastal section of the Tsimlyansk reservoir, flooding and shallowing zones can form.

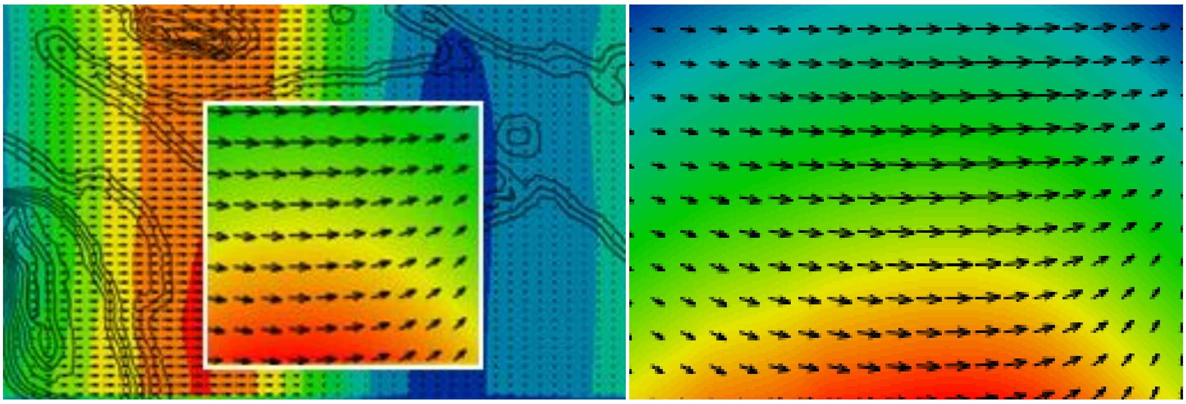

Fig. 5. Image of the formed vortex structures

Discussion and conclusions. The spatial-three-dimensional problem of wave hydrodynamics is solved. For the proposed model adapted for inland freshwater reservoirs, including reservoirs, numerical algorithms and a set of programs implementing them were developed, which made it possible to calculate the hydrodynamic characteristics of wave processes in the coastal zone. The results of numerical experiments obtained for the "local" section of the Tsimlyansk reservoir located near the village of Sarkel are presented. Numerical simulation allowed us to obtain the pressure field and the velocity vector field of the water medium in different phases of the wave, to observe the dynamics of changes in the wave profile with increasing wind speed.

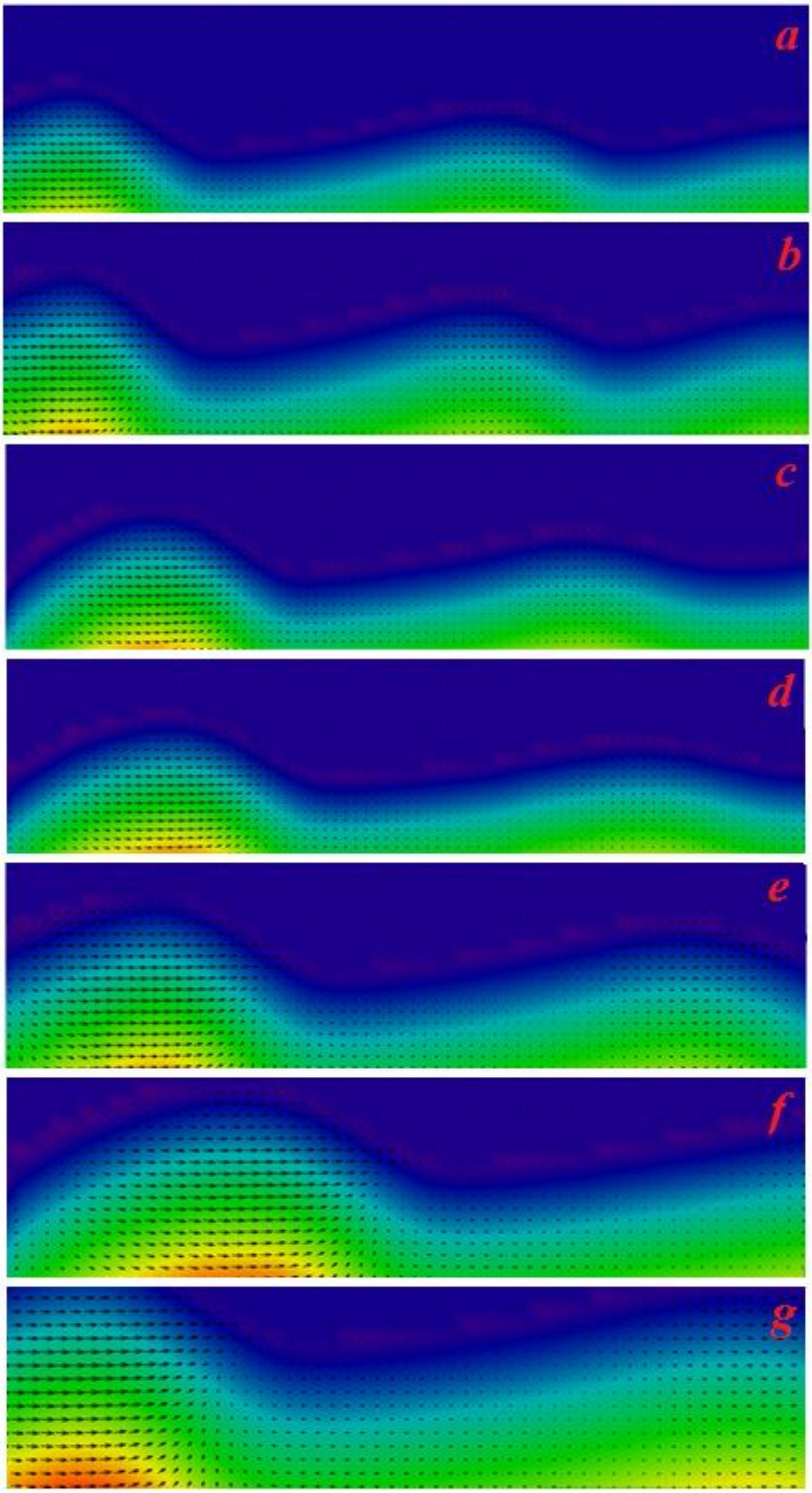

Fig. 6. Wave profiles and velocity vector fields at different values of wind speed

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РАСЧЕТ ГИДРОФИЗИЧЕСКИХ ХАРАКТЕРИСТИК ВОЛНОВОГО РЕЖИМА ДЛЯ ВНУТРЕННИХ ПРЕСНОВОДНЫХ ВОДОЕМОВ ЮГА РОССИИ *

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Важную роль в управлении водными ресурсами играют внутренние пресноводные водоемы, основными видами использования которых являются: удовлетворение потребностей населения в пресной воде, ирригация, гидроэнергетика, судоходство, рыборазведение и т.п. Вместе с тем все чаще наблюдаются нежелательные и неизбежные нарушения природной среды и природного баланса экосистемы данных водных объектов. Серьезную проблему представляют существенное изменение рельефа дна, разрушение берегов, накопление донных отложений. Представленные в настоящей статье результаты направлены на создание современной основы для прогноза тенденций развития внутренних пресноводных водоемов Юга России, базирующихся на расчеты гидрофизических характеристик волнового режима. На примере Цимлянского водохранилища построены и адаптированы к природно-климатическим условиям и географическим особенностям математические модели трехмерной волновой гидродинамики. На основе разработанного экспериментального комплекса программ выполнены прогностические расчеты для его побережья, расположенного поблизости посёлка Саркел, названного именем исторического хазарского города-крепости Саркел (затоплен водохранилищем). Для выбранного «локального» участка проведены исследования гидродинамических характеристик волнового воздействия на прибрежную рекреационную зону, в том числе, профили волн и поля вектора скорости при различных значениях скорости ветра.

Ключевые слова: внутренние водоемы, пресноводные водоемы, прибрежная зона, волновые процессы, моделирование гидродинамических процессов, параллельные алгоритмы.

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