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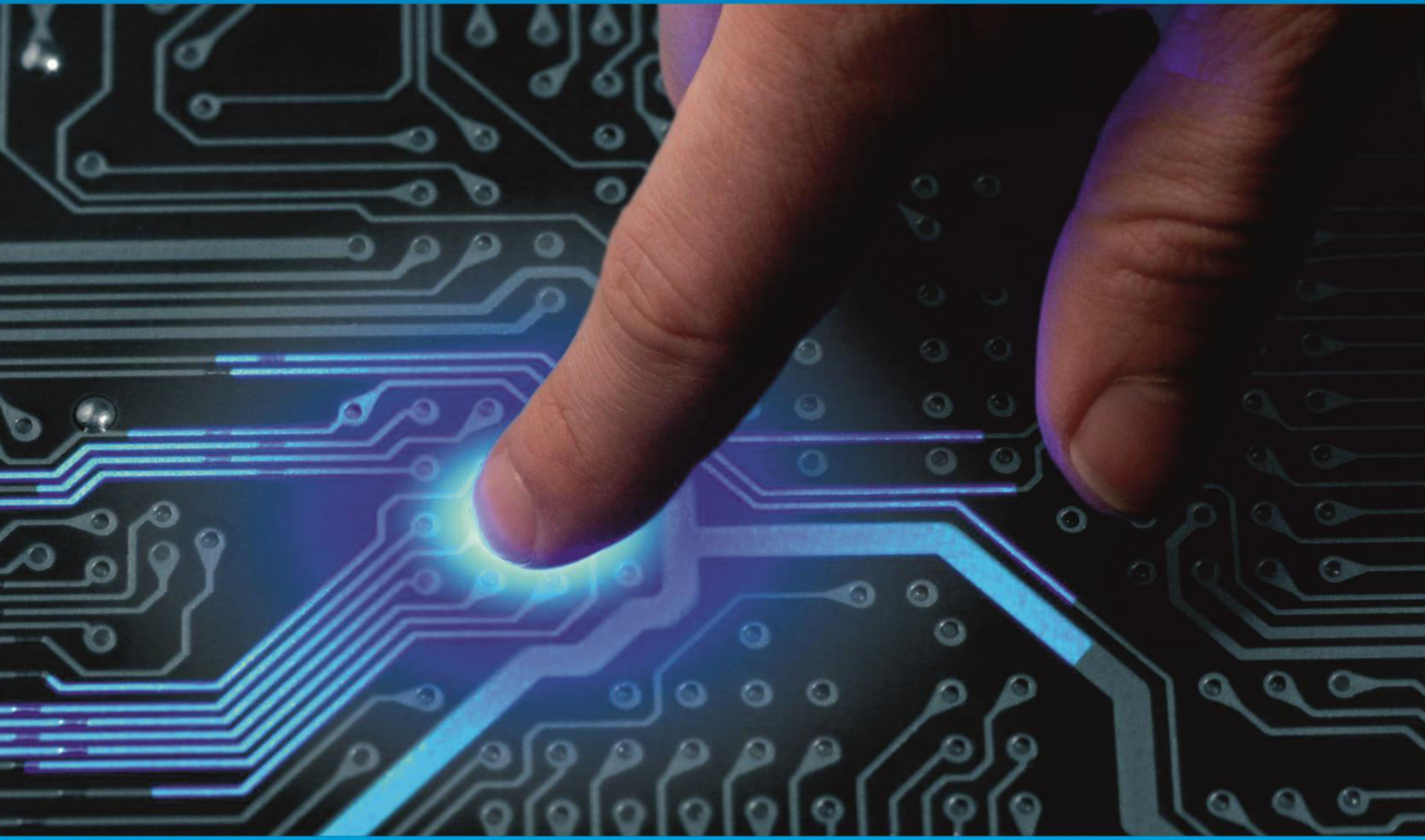

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Simulation of the Phytocenosis Evolution of the Dry Bottom of the Aral Sea

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ANNOTATION: The article discusses the issues of the simulation the evolution of the phytocenosis of the dry bottom of the Aral Sea. It is noted that in recent decades there have been negative changes affecting the growth of vegetation due to the drying up of the Aral Sea and the development of the oil and gas industry in the Aral Sea region. With the distance from the roads, the indicators of the projective vegetation cover change in a positive direction. It was also found that the specificity of slope processes determines relatively rapid desalinization of soils in 1-4 decades. A slowdown in desalinization processes with the appearance of sandy beaches adjacent to the Ustyurt Plateau is observed in 5-6 decades. The performed calculations of the mathematical simulation of the dynamics of the phytocenosis of the drained bottom of the Aral Sea made it possible to reveal the coefficient of reliability under the assumption that the only factor in the dynamics of the phytocenosis is soil salinity.

KEYWORDS: Aral Sea region, projective cover, vegetation, simulation, ecological factors, dynamics of phytocenoses.

Relevance. Because of environmental cataclysms, the international community,into the 21st century has developed sustainable development as a new paradigm of human economic activity on the Earth. It requires the activation of national and international environmental institutions and movements towards sustainable, environmentally smart nature management. Mathematical simulation is one of the most important methods of developing scientific foundations for effective planning of environmental management, choosing a strategy, and supporting of decision-making [1].

The drying of the Aral Sea is associated with many environmental, socio-economic, climatic, and other problems, and the problem of the removal of toxic salts from the drained bottom stands out. This process has a number of negative forcings, such as provoking pathologies of the respiratory tract (up to oncological) [2], soil salinization [3], degradation of vegetation [4], climate change [3]. The danger of salt removal is aggravated by its scale. Thus, the salt and dust storm that occurred on May 27-28, 2018 (Fig. 1) covered an area of 250 thousand km^2. At the same time, the one-time MPC for sulfates was exceeded tenfold. There were observed death of young shoots of plants, pathology, and mortality of livestock that were at that time on grazing.

Large experimental works with prevailing phytomelioration have been and are being carried out, in order to weaken the removal of salts [5, 6]. Therefore, the relevance of studies aimed at studying plants tolerant to soil salinity is undoubted.

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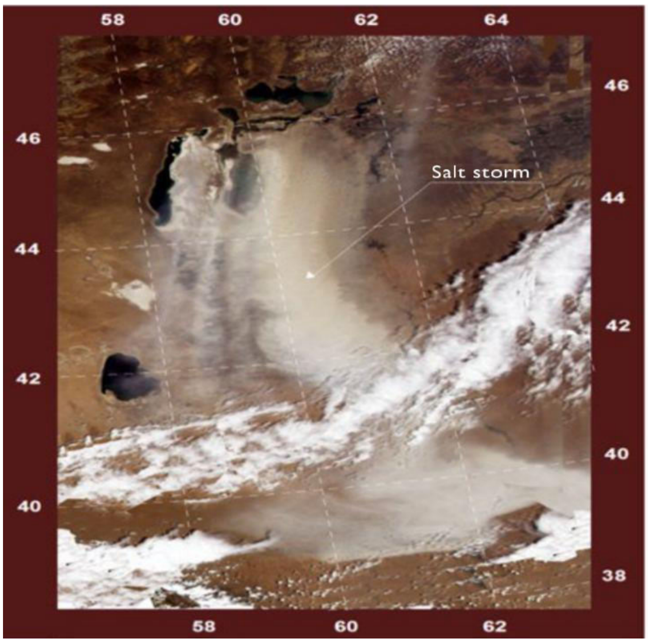


Fig. 1. Synthesized snapshotdust and salt storm 05/27/2018 (satellite NOAA-18)

Along with the experimental work of a local and episodic nature, an aggregated analysis of the long-term dynamics of the phytocenosis of the dried bottom of the Aral Sea is required. It provides information, verified over the years, and by the natural course of successions, on the mechanisms of plant adaptation to the extreme conditions of this territory. The work, carried out in this direction with the use of mathematical simulation, is aimed to identify the main regularities in the evolution of the phytocenosis of the dried bottom of the Aral Sea and its survival. The simulation period of 1968-2017 is divided into decades since this is the minimum time for significant natural transformations. The main emphasis is placed on such a parameter of the phytocenosis as the projective cover since it is the most indicative characteristic in terms of the protective function of vegetation against salt removal.

The simulation work in this work is carried out only for the western and eastern parts of the dried bottom of the Aral Sea (Fig.2) since the northern and southern parts of the dried bottom of the Aral Sea since the 90s have been subject to positive anthropogenic interventions (Kokaral dam and the system of delta reservoirs), with episodic drainages, and, accordingly, the natural dynamics of the phytocenosis is destabilized.

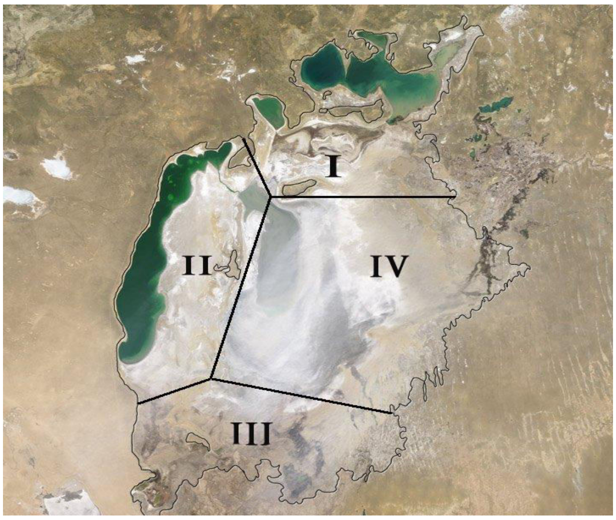
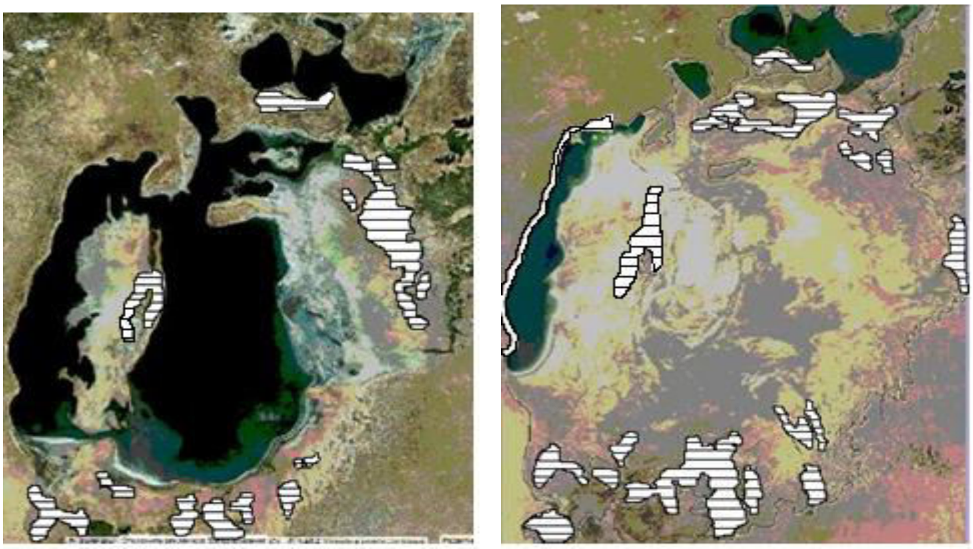


***Fig*. 2.** Model division of dried bottom of the Aral Sea into the northern (I), western (II), southern (III) and eastern parts (IV).

As for the simulation of the northern and southern parts of the dried bottom of the Aral Sea, there is a need for currently absent studies of the stochastic regime of spillways and the regularities of the influence of their volumes, frequency, and duration on the dynamics of phytocenosis.

Research methods. Simulation of the long-term dynamics of any natural process involves aggregation, simplification, alignment of data series, and approximation of the mathematical expectation trajectory by analytical functions. In this case, the aggregation consists of the statistical averaging of such characteristics as projective cover and salt tolerance over plant species. The average aggregation error for the whole simulation period was 13 and 27 %, respectively. The main simplification in simulation in this work is the assessment of the quantitative dynamics (total projective cover) of the phytocenosis without taking into account species differences. However, it should be noted that the proposed models can be implemented for individual species if there are representative data for these species. The adequacy of the real dynamics of the total projective cover was ratified by field research data and remote sensing data processed by the LpSquare program (Fig. 3).



1989 y. 2017y.

***Fig*. 3.** Areas of dried bottom of the Aral Sea occupied by vegetation with a total projective cover of more than 2% (shading).

Since the western and eastern parts of the post-aquatic land have significantly different geoclimatic and orographic features, the models developed for them also differ.

For the western part of the dried bottom of the Aral Sea (the cliff of Ustyurt), regression models, developed on the basis of field data obtained during expeditions with the participation of scientists from the IO RAS and authorsare used (Fig. 4)

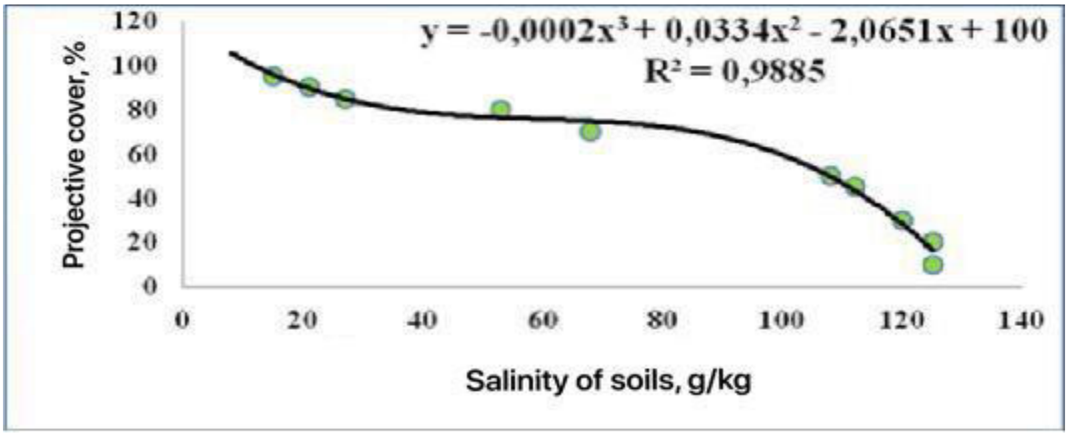


Fig. 4 Dependence of vegetation cover density from soil salinity.

The resulting equation for the long-term dynamics of phytocenosis in the western part of the dried bottom of the Aral Sea is a superposition of the function of the dependence of the total projective cover on soil salinity (f_1) and the function of the dependence of soil salinity on the drainage time (f_2):

$$\delta_f(t) = f_1(f_2(T)),$$
$$f_1(t) = -0{,}0002S^3+0{,}0334S^2-2{,}0651S+100, \quad (1)$$
$$f_2(T) = S = \begin{cases} -1{,}1 * T + 11, & 1961 - 1967 \text{ г.} \\ -2.37 * T + 38, & 1968 - 1977 \text{ г.} \\ -3.88 * T + 66, & 1978 - 1987 \text{ г.} \\ -5.22 * T + 94, & 1988 - 1997 \text{ г.} \\ -5.79 * T + 110, & 1998 - 2007 \text{ г.} \\ -6 * T + 120, & 2008 - 2017 \text{ г.} \end{cases} \quad (2)$$

where $\delta f(t)$- is the total projective vegetation cover, S is soil salinity (g / kg), and T- is the drying time.

Note that the drainage time is understood as the number of years that have passed since the time the given section of the former sea bottom came out onto the day surface. The degree of aggregation of the model allows for the homogeneity of the orography of the western coast, which justifies the applicability of the developed model for the entire western coast of the Aral.

For the eastern part of the dried bottom of the Aral Sea, it is used a complex system of regression models, obtained on the basis of the results of system simulation of the long-term (1966-2005) dynamics of the water-salt regime of the Aral Sea, the salinity of the post-aquatic land and the projective vegetation cover in [3]. In these equations, the factors of phytocenosis evolution are considered to be soil salinity and plant impulse formation with sulfates during dust storms on the dried bottom of the Aral Sea. The model is essentially nonlinear since it reflects the feedback that exists between soil salinity, salt carryover, and vegetation cover. The factor of soil moisture enters into the equations implicitly, being taken into account in the numerical model of the salinity of the post-aquatic land [3].

The dynamics of salinization of the dried bottom of the Aral Sea (t/ha/year) is calculated by the formula:

$$S_{IIC}(N) = S_{SDB}(N)+S_{SALT}(N)[1-\delta_f]-V_A(N)[1-0{,}01DV_f]-G_f(N) \quad (3)$$

where δ_f- is the projective cover, N - is the decade number in the simulation period, $S_{SDB} = 6{,}2547\exp(0{,}8499N)$- is the amount of salts remaining in the surface soil horizon when the coastline recedes, $V_A = -3{,}11N + 76{,}85$ - wind removal of salts, $DV_f = 166{,}43\delta_f - 13{,}28$- reduction of salt removal by vegetation, $G_f(N)$- absorption of salts by the roots of halophytes, S_{SALT} - salts evaporating from groundwater, are calculated by the formula:

$$S_{SALT}(t,T) = A(t)T^4+B(t)T^3+C(t)T^2+D(t)T+E(t), \quad (4)$$

where T = 1, 2, 3 ... is the time of drying of the reference point of the PS (years), t- is the time of transformation (drying out) of the Aral Sea (years), counted from 1961. For the coefficients with an average reliability score $R^2 = 0.911$, the following expressions are obtained:

$A(t)=-0{,}00001$, $B(T)=0{,}00002T + 0{,}0007$, $C(T)=-0{,}00069T - 0{,}01455$,
$D(T)= -0{,}0116T - 0{,}0434$, $E(T)=-0{,}0419T + 0{,}094$.

The dynamics of phytocenosis depending on the drying time T and the drying time of the Aral Sea t is expressed by the formula:

$$\delta_f(T,t) = -0{,}0002x^3+0{,}0334x^2-2{,}0651x+100 - C(N)/C_{cr} \quad (5)$$

where x= S_{SALT} , $C(N) = 3{,}3kV$ -is the average annual concentration of salts in the near-surface layer of the atmosphere (µg / m3), C- is the critical concentration of salts at which the plant dies.

Results and discussion. We present the simulation results only for the western part of the dried bottom of the Aral Sea since numerical experiments on the dynamics of the phytocenosis of the eastern part of the dried bottom of the Aral Sea have not yet been completed.

The western part of the dried bottom of the Aral Sea, as can be seen from Fig. 2, consists of the western coast of the western part of the large Aral and the exposed bottom adjacent to the former VozrojdeniyeIsland. The average slope of the western coast is 15°, while the slope of the dried-up areas of Vozrojdeniye Island is much less - 5°. Therefore, in the course of numerical experiments, it was found that the dynamics of soil salinity of Vozrojdeniye Island are more adequately described by equation (4). Thus, the results of the implementation of the model (1) presented below refer to the western coast of the western part of the large Aral Sea.

According to the model (1), two calculation options were performed:

1) on the assumption that the only factor in the dynamics of phytocenosis is soil salinity (Table 1);

2) taking into account the effect of the wind carryover of salts on the degradation of the vegetation cover by impulverization of the plant root with salt particles and an increase in soil salinity during the infiltration of salt particles with precipitation (Table 2). In this case, the corresponding term $C(N)$ / C_{cr} $C(N) = 3{,}3kV$ - is added to equation (1): is the average annual concentration of salts in the near-surface layer of the atmosphere (µg / m3), C - is the critical concentration of salts at which the plant dies.

Table 1

Spatial-temporal dynamics of phytocenosis of causal areas of the dry bottom depending on soil salinity

N	T=1	$\delta_f(t)$	T=5	$\delta_f(t)$	T=10	$\delta_f(t)$	T=20	$\delta_f(t)$
1	9,9	82,634	5,5	89,619	0	100	0	100
2	35,63	59,77	26,15	65,26	14,3	76,71	0	100
3	62,12	52,66	46,6	56,057	27,2	64,51	0	100
4	88,78	39,96	67,9	51,15	41,8	57,42	0	100
5	104,21	21,17	81,05	45,54	52,1	54,78	0	100
6	114	2,33	90	38,881	60	53,134	0	100

Table 2

Dynamics of phytocenosis of the cliff part of the drying bottom depending on soil salinity and wind carry-over of salts

N	T=1	$\delta_f(t)$	T=5	$\delta_f(t)$	T=10	$\delta_f(t)$	T=20	$\delta_f(t)$
1	9,9	81,54	5,5	88,53	0	100	0	100
2	35,63	58,68	26,15	64,17	14,3	75,62	0	100
3	62,12	51,57	46,6	54,96	27,2	63,42	0	100
4	88,78	38,87	67,9	50,06	41,8	56,34	0	100
5	104,21	20,08	81,05	44,45	52,1	53,69	0	100
6	114	1,24	90	37,79	60	52,04	0	100

Tables 1 and 2 in the first column indicate the numbers of the decades into which the modeling period is divided: N = 1 corresponds to 1968-1977, N = 2 corresponds to 1978-1987 yy. etc. Further, the soil salinity in the T-th year of drying up and the corresponding projective cover for each of the decades are given in pairs. The specificity of slope processes leads to relatively rapid desalinization of soils in 1-4 decades. A slowdown in desalinization processes with the appearance of sandy beaches adjacent to the Ustyurt cliff is observed in 5-6 decades.

Comparison with the data [6, 7, 8, 9] of field studies (N (t)) of the modeling results for both options showed greater adequacy of the second option and, consequently, the importance of the factor of the wind removal of salts (Tables 3, 4).As we can see, for all drying periods in both variants, the largest residual value was recorded in the first variant. As for the comparative analysis by periods of drying, the largest residuals were revealed for the T-10 period in both variants.

Note that the long-term data from field studies primarily depend on many exogenous and endogenous factors, in particular, on weather and climatic conditions, soil salinity, groundwater level, precipitation, the timing of phenological phases of plant development, moisture content, etc.This is probably why the projective cover (PC) indicators of each drying period may differ depending on the time interval of the distribution of these indicators in mathematical calculations.

Table 3
Comparative analysis of the dynamics of phytocenosis of the cliff part of the dry bottom depending on soil salinity based on field studies and simulation results

N	T=1			T=5			T=10		
	$N(t)$	$\delta_f(t)$	k	$N(t)$	$\delta_f(t)$	k	$N(t)$	$\delta_f(t)$	k
1	26	82,63	56,63	44	89,62	45,62	70	100	30
2	40	59,77	19,77	60	65,26	5,26	-	76,71	
3	-	52,66		-	56,06		67	64,51	-2,49
4	45	39,96	-5,04	48	51,15	3,15	50	57,42	7,42
5	42	21,17	-20,83	42	45,54	3,54	56	54,78	-1,22
6	56	2,33	-53,67	57	38,88	-18,12	50	53,134	3,134

Table 4
Comparative analysis of the dynamics of the phytocenosis of the cliff part of the drained bottom based on field studies and modeling results depending on the wind carry-over of salts

N	T=1			T=5			T=10		
	$N(t)$	$\delta_f(t)$	k	$N(t)$	$\delta_f(t)$	k	$N(t)$	$\delta_f(t)$	k
1	26	81,54	55,54	44	88,53	44,53	70	100	30
2	40	58,68	18,68	60	64,17	4,17	-	75,62	
3	-	51,57		-	54,96		67	63,42	-3,58
4	45	38,87	-6,13	48	50,06	2,06	50	56,34	6,34
5	42	20,08	-21,92	42	44,45	2,45	56	53,69	-2,31
6	56	1,24	-54,7	57	37,79	-19,2	50	52,04	2,04

Unfortunately, in the verification of the model, remote sensing data were not used, since remote sensing is distorted at large orographic slopes, which is a limitation of this method.

Conclusions. Thus, the environmental conditions on the Ustyurt Plateau in recent decades have changed negatively for the growth of vegetation due to the drying up of the Aral Sea and the development of the oil and gas industry. With distance from the roads, the PC indicators change in a positive direction. But with the reduction of traffic, due to the accumulation of sand with seeds of plants in the ruts, and due to atmospheric precipitation, the roads are overgrown, and in some places, the projective coverage of former roads increases to 80-90% (due to *Artemisia terrae-albae*). According to B. Sarybaev (1987), the flora of Ustyurt is estimated at 724 species belonging to 295 genera and 60 families.The leading position in the spectrum of families is occupied by *Chenopodiaceae*, *Asteraceae*, *Brassicaceae*, *Poaceae,* and *Fabaceae*. Perennial grasses occupy a specific weight in the vegetation cover, followed by annuals, semi-shrubs, shrubs, biennials, shrubs, and trees. The vital state of the dominants, the projective cover, and the species composition of the communities increase with distance from the center of wells and highways.

The performed calculations of mathematical simulation of the dynamics of the phytocenosis of the dry bottom of the Aral Sea made it possible to reveal the coefficient of reliability under the assumption that the only factor in the dynamics of the phytocenosis is soil salinity, which was $\rho = 4.06$. In the second variant of the calculation, which takes into account the effect of the wind carryover of salts on the degradation of vegetation cover and an increase in soil salinity during the infiltration of salt particles with precipitation, the coefficient of reliability was $\rho = 3.22$.

An important circumstance is that the transformation of the natural environment of the studied territory occurs due to various factors, in particular, the wind carryover of salts, an increase in the area of salt marshes, etc.

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