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Modeling of the Processes of Formation and Development of Phytocenoses of the Dried Bottom of the Aral Sea

Tleumuratova B.S.[1], Kublanov J.J.[1], Kochkarova S.A.[2], Mambetullaeva S.M.[1]

[1, 3]Karakalpak Scientific Research Institute of Natural Sciences, Karakalpak Branch of the Academy of Sciences of the Republic of Uzbekistan[1], Nukus

[2]Karakalpak State University named after Berdakh, Nukus

Abstract: ***The article discusses the issues of mathematical modeling of the processes of formation and development of phytocenoses of the dried bottom of the Aral Sea. Long-term dynamics and peculiarities of the overgrowing of various parts of the dried bottom of the Aral Sea are studied by methods of mathematical modeling with a high degree of spatial-temporal aggregation for the first time. A model of the dynamics of the western part of the dried bottom of the Aral Sea and analysis of the results are presented.***

Keywords: Dried bottom of the Aral Sea, phytocenoses, modeling, projective cover, salinization, wind carryover, dynamics

1. Relevance

Due to environmental cataclysms, at the turn of the 21st century, the international community has developed a new paradigm of human economic activity on earth - sustainable development. It requires the activation of national and international environmental institutions and movements towards sustainable, environmentally sound nature management. Mathematical modeling is one of the most important methods for developing scientific foundations for effective planning of environmental management, choosing a strategy, and supporting decision-making [1].

The drying of the Aral Sea is associated with many environmental, socio-economic, climatic and other problems, among which the problem of the removal of toxic salts from the dried 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. So, the salt 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 maximum permissible concentration of sulfates was exceeded tens of times. The death of young shoots of plants, pathology, and mortality of livestock that were grazing at that time were observed.

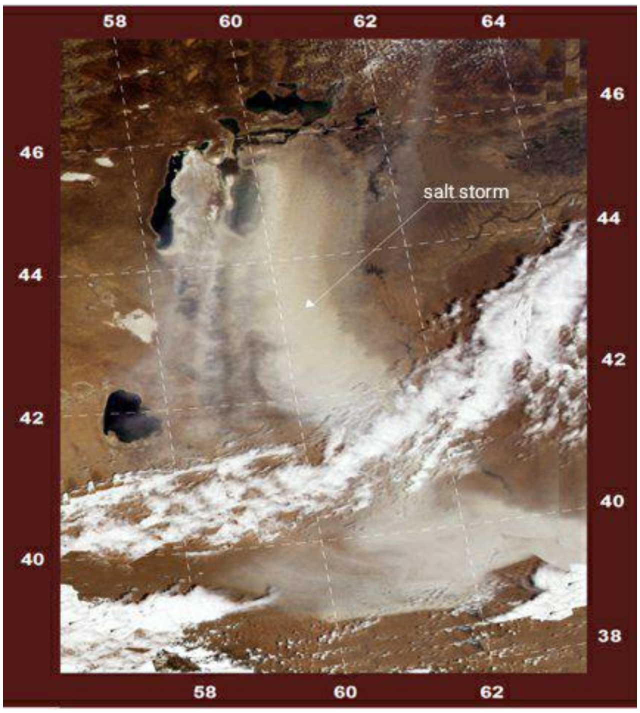

Figure 1: Synthesized snapshot dust and salt storm 05/27/2018 (satellite NOAA-18)

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

Along with 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, which 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. This work, carried out in this channel with the use of mathematical modeling, is aimed to identify the main regularities of the natural evolution of the phytocenosis of the dried bottom of the Aral Sea and its survival.

The scientific novelty of the research lies in the fact that the long-term dynamics and features of the overgrowing of various parts of the dried bottom of the Aral Sea are first studied by methods of mathematical modeling with a high degree of space-time aggregation.

2. Research Methods and Conditions

The main methodology of this research is mathematical modeling and ecosystem approach. Modeling 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 modeling period was 13% and 27%, respectively.

The main emphasis is placed on such a parameter of the phytocenosis as the projective cover since it is this characteristic that is most indicative in the aspect of the protective function of vegetation from the removal of salts.

The main simplification in modeling in this work is the assessment of the quantitative dynamics (total projective cover, TPC) of the phytocenosis without taking into account species differences, which is permissible in the ecosystem approach [7]. However, it should be noted that the proposed models can be implemented for individual species if there are representative data for these species.

The modeling period is 1968-2017 yy. divided into decades, since this is the minimum time for significant natural transformations. Accordingly, the dried bottom is divided into drainage strips in 1968-1977 yy., 1978-1987 yy., etc.(fig. 2).

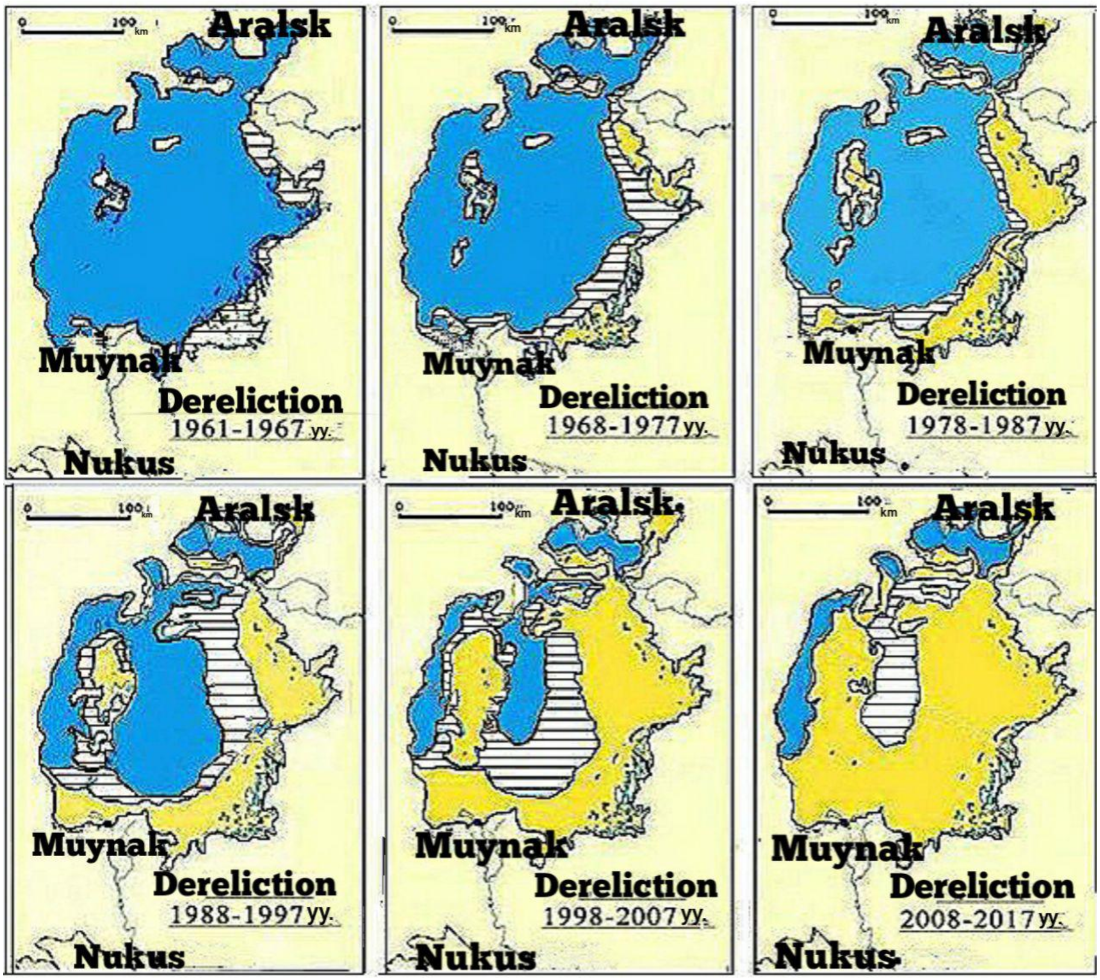

Figure 2: Long-term dynamics of the dried bottom process Aral Sea 1961-2017 yy. (shaded areas)

The territory of the dried bottom has significant lithological, orographic and climatic heterogeneity, which excludes the construction of a unified model of the dynamics of the phytocenosis of the dried bottom of the Aral Sea. Therefore, we conditionally divided it into 4 parts, which, for the accepted degree of model aggregation, can be considered homogeneous according to the above characteristics (Fig. 3).

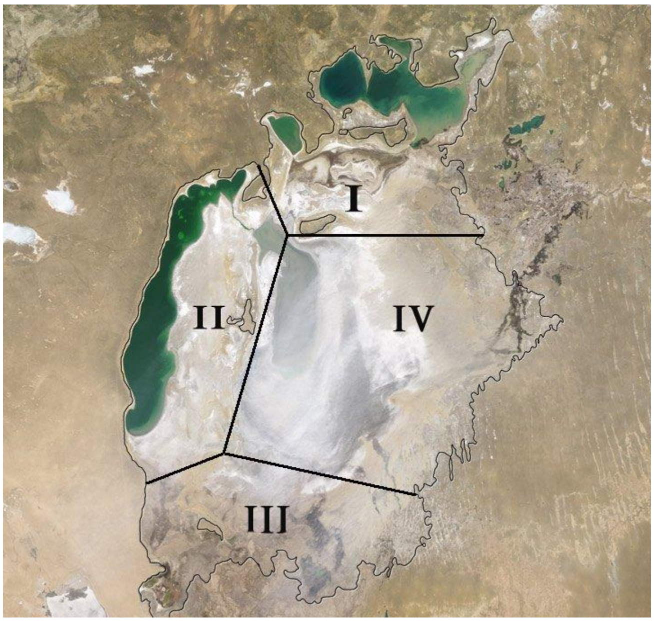

Figure 3: Model division of dried bottom of the Aral Sea into the northern (I), western (II), southern (III) and eastern parts (IV).

This work presents a mathematical model of the natural evolution of the phytocenosis in the western part of the dried bottom of the Aral Sea, more precisely, on the eastern cliff of the Ustyurt plateau.

Regression models developed on the basis of field data obtained during expeditions with the participation of the Institute of Oceanology of the Russian Academy of Sciences scientists and authors are used as a model (Fig. 4).

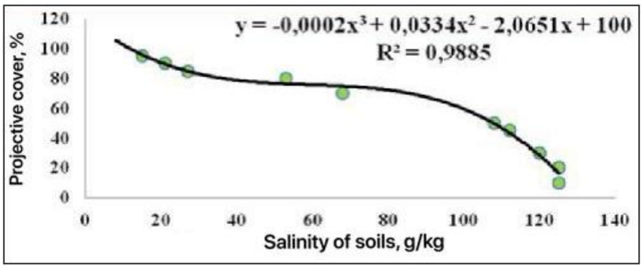

Figure 4: Dependence of vegetation cover density from soil salinity

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 TPC on soil salinity (f_1) and the function of the dependence of soil salinity on the drainage time (f_2):

$$\delta_f(T) = f_1(f_2(T)), \qquad (1)$$

$$f_1(S) = -0{,}0002S^3+0{,}0334S^2-2{,}0651S+100 \qquad (2)$$

$$f_2(T) = S(T) = \begin{cases} -1{,}5 * T + 38, & 1968-1977 \text{ г.} \\ -2{,}7 * T + 66, & 1978-1987 \text{ г.} \\ -3{,}48 * T + 94, & 1988-1997 \text{ г.} \\ -3{,}66 * T + 110, & 1998-2007 \text{ г.} \\ -3{,}8 * T + 120, & 2008-2017 \text{ г.} \end{cases} \qquad (3)$$

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 Sea.

3. Results and Discussion

Before presenting the modeling results, we will give a brief geographical and floristic description of the modeling area.

The eastern cliff of the Ustyurt plateau, which was formerly the western coast of the Aral Sea, extends from 44°37′ N. and 57°38′ E. up to 46°15′ N. and 58° 20′E. The dried bottom of the Aral Sea represents two sharply demarcated areas: a cliff (chink) with a steepness of 50-60° and an average height of 250 m and a beach with an average slope of 15°. This lithological heterogeneity determines the differences in vegetation cover and desalinization processes. The specificity of slope processes is manifested in relatively rapid desalinization of soils in 1-4 decades of the modeling period. A slowdown in desalinization processes with the appearance of sandy beaches adjacent to the Ustyurt cliff is observed in the 5th decade.

The spatial distribution of the projective cover degree of phytocenoses in the western part is extremely heterogeneous. Even in limited areas of several hectares, the TPC can vary from 0 to 100%.

According to 1987 data, the flora of the western part of the former Aral Sea, including the Vozrozhdeniye Island, was numbered by 724 species belonging to 295 genera and 60 families [8]. Currently, a preliminary floristic composition of vascular plants of the Vozrozhdeniye Island (an enclave of the Aral Sea) has been established within it in the Karakalpak part (Uzbekistan), numbering 123 species from 90 genera and 31 families [9].

The leading position in the spectrum of families is occupied by *Chenopodiaceae*, *Asteraceae*, *Brassicaceae*, *Poaceae* and *Fabaceae*. Perennial grasses have a specific weight in the vegetation cover, followed by annuals, semi-shrubs, dwarf shrubs, biennials, shrubs and trees [9, 10].

The development of vegetation cover in the pre-cliff line of the dried bottom of the Aral Sea is accompanied by a change in ecological regimes towards their stabilization and, at the same time, is characterized by the change of short-term phytocenoses to mono-dominant single-tier herbaceous phytocenoses, and then to two-three-tier tree-shrub phytocenoses by 4-6 years after drying. Salleros-tamarisk phytocenoses are characteristic of the initial period of aridization of the territory. They are confined to moist coastal crustal salt marshes or coastal highly saline soils with a close occurrence of groundwater. The stage lasts about 5-6 years. Further, one of the subsequent stages of colonization of phytocenoses can be communities of haloxerophilic plants - *Haloxylon aphyllum*, *Salsola orientalis*, *Anabasis salsa*.

In the course of numerical experiments, it was found that, in addition to the salinity of the soil, a significant factor in the deterioration of the state of the vegetation cover is the wind carry-over of salts from the dried bottom of the Aral Sea. The effect of this factor is manifested in the fact that salt particles precipitated during dust storms penetrate into the stomata of leaves and partially clog them, as well as excision and damage the entire supra-root part of plants. At present, during the growing season, an average of 250 kg/ha of salts fall out. At the same time, the decrease in the TPC degree reaches 20-30% [3, 5].

Therefore, according to the model (1)-(3), two variants of calculations 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 carry-over of salts on the degradation of the vegetation cover by impulse stimulation 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} is added to equation (2):

$$f_1(S) = -0{,}0002S^3+0{,}0334S^2-2{,}0651S+100-C(N)/C_{cr}, \quad (4)$$

where $C(N) = 3{,}3kV$ - is the average concentration of salts in the near-surface layer of the atmosphere (μg/m^3), *C*- is the critical concentration of salts at which the plant dies (1500 μg/m^3).

Table 1: Spatial-temporal dynamics of phytocenosis pre-cliff areas of the drying bottom (%) depending on soil salinity (g/kg)

N	T=1		T=5		T=10		T=20	
	S_{SL}	$\delta_f(t)$	$f_2(T)$	$\delta_f(t)$	$f_2(T)$	$\delta_f(t)$	$f_2(T)$	$\delta_f(t)$
1	36,50	59,40	30,50	62,41	23,00	67,74	8,00	85,51
2	63,30	52,38	52,50	54,70	39,00	58,40	12,00	79,68
3	90,52	42,93	76,60	48,66	59,20	53,31	24,40	66,59
4	106,34	22,91	91,70	41,85	73,40	49,28	36,80	59,27
5	116,20	3,03	101,00	26,08	82,00	44,97	44,00	56,76

Table 2: Dynamics of phytocenosis of pre-cliff part of the drying bottom (%) depending on soil salinity (g / kg) and wind carry-over of salts

N	T=1		T=5		T=10		T=20	
	S_{SL}	$\delta_f(t)$	$S_{\Pi C}$	$\delta_f(t)$	$S_{\Pi C}$	$\delta_f(t)$	$S_{\Pi C}$	$\delta_f(t)$
1	36,50	50,04	30,50	53,05	23,00	58,38	8,00	76,16
2	63,30	34,12	52,50	36,44	39,00	40,14	12,00	61,42
3	90,52	14,83	76,60	20,57	59,20	25,21	24,40	38,49
4	106,34	21,81	91,70	40,76	73,40	48,18	36,80	58,17
5	116,20	1,94	101,00	24,98	82,00	43,88	44,00	55,67

In tables 1 and 2, the first column indicates the numbers of the decades into which the modeling period is divided: N = 1 corresponds to 1968-1977 yy., N = 2 corresponds to 1978-1987 yy. etc. Further, the soil salinity (g / kg) in the T-th year of drainage and the corresponding projective cover (%) for each of the decades are given in pairs.

The modeling results indicate a nonlinear decrease in the TPC of the drying areas of the Aral Sea bottom. The highest rates of reduction in the overgrowing process are inherent in the first year of drainage. As T increases, the difference in rates for different decades gradually decreases.

Comparison of the modeling results with the data of field studies [6, 8, 9, 10] for both options showed greater adequacy of the second option and, therefore, the need to take into account the factor of the wind-driven salt carryover in the models of phytocenosis dynamics (Tables 3, 4).

Table 3: The dynamics of the phytocenosis of the cliff part of the dried bottom depending on soil salinity (g / kg) on field studies and modeling results

N	T=1			T=5			T=10		
	$H\delta_f(t)^*$	$P\delta_f(t)^{**}$	Disparity	$H\delta_f(t)$	$P\delta_f(t)$	Disparity	$H\delta_f(t)$	$P\delta_f(t)$	Disparity
1	55,2	59,40	4,2	62	62,41	0,41	59	67,74	8,74
2	30	52,38	22,38	35	54,70	19,7	60	58,40	-1,6
3	35	42,93	7,93	48	48,66	0,66	21	53,31	32,31
4	16	22,91	6,91	40,38	41,85	1,47	-	49,28	-
5	1	3,03	2,03	20	26,08	6,08	-	44,97	-

Table 4: The dynamics of phytocenosis of the cliff part of the dried bottom depending on soil salinity (g / kg) and wind carry-over of salts according to field studies and modeling results

N	T=1			T=5			T=10		
	$H\delta_f(t)$	$P\delta_f(t)$	Disparity	$H\delta_f(t)$	$P\delta_f(t)$	Disparity	$H\delta_f(t)$	$P\delta_f(t)$	Disparity
1	55,2	50,04	-5,19	62	53,05	-8,95	59	58,38	-0,62
2	30	34,12	4,12	35	36,44	6,44	60	40,14	-19,86
3	23	14,83	-8,17	30	20,57	-9,43	21	25,21	4,21
4	16	21,81	5,81	40,38	40,76	0,38	-	48,18	-
5	1	1,94	0,94	20	24,98	14,98	-	43,88	-

Note: *$H\delta_f(t)$- field data, **$P\delta_f(t)$- calculated data

In the first variant of the calculations, the average residual for the entire observation period was k = 8.55, while in the second variant of the calculations, this indicator turned out to be small and amounted to k = -1.18, which indicates the importance of the factor of the wind removal of salts, which audit increases the accuracy of the model by 0.14%.

Note that the data of field studies were obtained on a limited number of individual areas of the dried bottom of the Aral Sea, which have their own local characteristics of weather and climatic conditions, soil salinity, groundwater level, precipitation amount, soil moisture content, etc. Therefore, the model values of the TPC obtained in accordance with the purpose of the study with a high degree of aggregation may differ from the data of field studies.

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

In general, the inaccuracy of the model, representing the sum of the inaccuracy of the input data, the inaccuracy of the method and the computational inaccuracy, is 13%, which makes it possible to consider it a fairly accurate imitation of physical reality and justifies the adequacy of the identified patterns in the dynamics of phytocenosis in the western part of the dried bottom of the Aral Sea.

In addition to the regularities of the dynamics of soil salinity (Eq. (2)) fixed in analytical expression, the dynamics of the TPC of phytocenoses in terms of drainage time for dryings *T* in different decades was revealed:

$$\delta_f(t) = 129{,}18e^{-0{,}695x}$$

$$\delta_f(t) = 2{,}6943x^2 - 21{,}348x + 69{,}566$$

$$\delta_f(t) = 4{,}6986x^2 - 30{,}287x + 82{,}336$$

It should be noted that for 1 year of drying, an exponential trend was revealed towards a decrease in the dynamics of TPC, for the remaining 5 and 10 years of drying, a polynomial trend was revealed towards a decrease in the dynamics of TPC of phytocenoses in the area under consideration.

4. Conclusions

In conclusion of the article, we present the conclusions from the research performed.

1) The order parameters of the ecosystem of the western part of the dried bottom of the Aral Sea are geomorphology, soil salinity, and wind regime. The same parameters serve as the main factors of the spatio-temporal distribution of the vegetation cover with the correction that the wind regime determines the scale of the wind carry-over of salts, which directly affects the state of plants.
2) To identify the patterns of long-term dynamics, it is necessary to use mathematical modeling with a high degree of space-time aggregation in modeling. Quantization in time and space essentially depends on the object and subject of research.
3) Drainages of different decades differ significantly in salinization processes, which for this reason are approximated by different equations.
4) For each decade of the modeling period, the dynamics of phytocenoses is positive; with an increase of the drying time, the TPC increases.
5) The dynamics of overgrowing of the dried bottom of the Aral Sea by decades is negative. So, if in the first decade in the first year of drainage, the TPC was 88%, then in the last decade the TPC decreased to 1%.
6) The differences between field and model data on TPC can be explained by the fact that the model does not take into account adaptation processes, as a result of which, during successions, halophytes become dominant species, the projective cover of which on saline soils significantly differs from TPC. Thus, the implementation of this model for individual species must have a higher accuracy.
7) The regularity of the formation of vegetation in the study area is revealed in the fact that with an increase in soil salinity for the entire period under consideration (1968-2017), there is a decrease in the TPC of phytocenoses in this area at an increasing rate.

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