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Scientific And Theoretical Foundations Of Erosion Processes On Irrigated Lands

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Abstract: This article systematically analyzes the scientific and theoretical foundations of erosion processes in irrigated areas, in particular, the physicochemical mechanisms of erosion occurrence, the main causes of soil degradation, and the patterns of erosion development under the influence of irrigation water. The main goal of the research is to scientifically identify the processes of erosion and degradation arising as a result of irrigation, to clarify the factors that form them, and to illuminate the patterns of their interrelationship. According to the analysis results, erosion processes are not limited to surface erosion, but are accompanied by physical and chemical destruction of the soil structure, ion exchange, dispersion, and a decrease in salinity and infiltration. The quality, norms, methods of irrigation, and frequency of irrigation water application are defined as the main factors that intensify these processes. Soil porosity, pH equilibrium, sodium sorption coefficient (SAR), and organic matter content were identified as the main indicators characterizing the risk of erosion. The results of this scientific article serve as a scientific and practical basis for assessing degraded irrigated lands, forecasting risk zones, and developing agrotechnical and land reclamation measures for erosion prevention.

Keywords: Erosion, irrigated lands, soil degradation, physicochemical mechanisms, SAR, salinization, infiltration, sodium ions, vegetation density, agrotechnical load.

INTRODUCTION.

Land resources, in particular, irrigated agricultural lands, are one of the most important natural resources for the food security, economic stability, and ecological well-being of any country. Against the backdrop of a sharp increase in the population, an increase in the demand for crop yields in agriculture, and the development of intensive farming, the issue of rational and efficient use of irrigated land is coming to the forefront. However, unfortunately, as a result of improper management of irrigated lands, inefficient water use, and insufficient implementation of anti-erosion protection measures, such an environmental problem as soil erosion is emerging. This problem is becoming especially acute in areas with arid climates, such as Uzbekistan.

Erosion is a complex geobiochemical process associated with a decrease in soil fertility as a result of the erosion, migration, or loss of the soil layer under the influence of water, wind, or other natural and anthropogenic factors. In irrigated areas, erosion mainly manifests itself in the form of water erosion, and this process is directly related to a number of physical, chemical, and biological factors. In particular, such factors as the physical impact of water, the soil's aggregate state, ion exchange, the activity of soil cations, the layering of the soil cover, and vegetation cover influence the intensity of erosion processes.

Today, the results of numerous studies conducted by the scientific community show that erosion on irrigated lands leads not only to the mechanical loss of the soil layer, but also to a serious violation of its structural, physicochemical, and agrobiological properties. As a result, soil permeability in these areas decreases, fertility sharply decreases, carbonate and saline layers come to the surface, vegetation density weakens, productivity decreases, and ecological stability is disrupted [1,2].

It should be especially noted that the mechanism of erosion processes is directly related not only to physical or chemical factors, but also to human activity. The main sources of erosion are improper irrigation, in particular, excessive irrigation, low melioration status, steeply laid lands, insufficiently developed drainage systems, and the use of intensive water resources. Especially, the destruction of soil aggregates by the erosive force of water, a decrease in porosity, and an increase in surface runoff create an important initial ground for erosion.

Although erosion processes have been studied in the scientific literature through many approaches, the mechanisms of erosion in irrigated lands still need a deep scientific and theoretical explanation. In this regard, the relationship between the physical properties of the soil (density, porosity, moisture content, compaction), chemical composition (pH, cation exchange, ionic forces) and biological factors (microbiological activity, the structure of plant roots) with erosion has not yet been fully determined. In addition, the composition of irrigation water (degree of mineralization, ionic balance, pH) and the technological method (drip, flat-bedding, surface or underground irrigation) have a significant influence on the risk of erosion.

In Uzbekistan, there are such problems as a shortage of water resources, uneven distribution of water, obsolescence of irrigation systems, and soil degradation. In such conditions, it is necessary to study the scientific basis of erosion processes and develop methods aimed at preventing them to ensure the ecological safety of irrigated lands and maintain stable yields. In recent years, significant results have been achieved in the analysis of erosion processes using GIS technologies, remote sensing methods, model-based simulations, and laboratory experiments. However, research continues on adapting these methods to the conditions of irrigated areas, integrating them with agroecological features, and transforming them into practical solutions.

As part of this article, the scientific and theoretical foundations of erosion processes in irrigated lands are studied. In this case, on the one hand, a deep analysis of the physicochemical mechanisms of the erosion process is carried out, and on the other hand, the main factors leading to soil degradation are identified. The direct and indirect effects of irrigation water on the development of erosion are also discussed, i.e., how the patterns of erosion are related to irrigation technologies.

The relevance of this research lies in the fact that it not only contributes to a theoretical understanding of erosion processes, but also serves as a basis for their practical management, the introduction of efficient irrigation systems, the protection of agroecosystems from degradation, and ensuring sustainability in the agriculture of Uzbekistan. This, in turn, will have a positive impact on the country's water, land, and food security.

LITERATURE ANALYSIS

The study of soil erosion and its development processes in irrigated areas is one of the most pressing issues on a global scale today. Various approaches, models, geotechnologies, and statistical methods have been developed by the world scientific community to study this problem based on deep and systematic approaches. As a result of research conducted at the international level, the mechanisms of formation of erosion and degradation processes, factors associated with them, and indicators for predicting the intensification of erosion have been identified. In particular, the GloREDa database, developed by the scientific group of the European Union ESDAC (European Soil Data Centre) under the leadership of Panos Panagos, made it possible to conduct global modeling and mapping of soil erosion. On this scientific basis, it was established that 36 billion tons of soil are leached annually, and it was noted that the degradation of land resources is a serious threat to humanity. In them, based on the RUSLE (Revised Universal Soil Loss Equation) model, the practice of assessing the degree of erosion through indicators of relief, slope, vegetation, and precipitation has been established [3,4].

Chinese researchers Y. Huang and others found that irrigated lands affect the climate, as well as that as a result of irrigation, air humidity and rain intensity change, directly leading to increased erosion. They mathematically modeled this situation using the RegCM4 model. Observations conducted in the Southern YRB (Yellow River Basin) region showed that as a result of irrigation carried out over a wide area, the local microclimate changes, the probability of cloud formation increases, and precipitation is distributed unevenly. This increases the risk of erosion by up to 50%.

Also, in experimental studies conducted by Kazakhstani scientists - K. Saparov and his colleagues, methods have been developed to reduce the impact of erosion by increasing aggregate stability in loess soils using polymer compounds. These studies showed that with the help of biologically active substances and organic fertilizers, the abrasion force of aggregates is reduced by 30-40%, which leads to a significant reduction in washing.

In the works of American scientists Lawrence Schwankl and Anthony T. O'Geen (UC Davis, USA), the influence of modern irrigation technologies on the erosion process in irrigated areas was studied in depth. They scientifically substantiated the possibility of reducing surface runoff by 70% using drip irrigation technology and underground irrigation systems. In addition, as a result of applying the RUSLE model based on GIS in real agricultural conditions, erosion-risk zones were accurately mapped across large agro-territories.

These studies, conducted on the basis of international experience, serve as an important basis for scientific research in our country. In Uzbekistan, a number of scientific and practical developments have been carried out aimed at preventing the degradation of irrigated lands and monitoring erosion processes. In particular, scientists from the National Research University of TIIAME - S. Isaev, B. Matyakubov, G'. Bekmirzaev et al. developed methods aimed at improving the melioration state of lands, predicting salinization processes, modernizing drainage systems, and ensuring the physicochemical stability of soil structure. Their research is aimed at developing practical recommendations for reducing the risk of land degradation and erosion in the conditions of Uzbekistan.

Also, in articles published in the journals UZBAMIN, Agro.uz, and "Ecological Monitoring," soil salinity, pH imbalance, soil layer compaction, and the lack of land reclamation services are analyzed as the main internal factors of erosion. Based on available statistical data, they note that currently 45% of irrigated lands in Uzbekistan are prone to salinization, and more than 30% are directly at risk of erosion.

In addition, local field observations conducted in the Andijan, Namangan, and Fergana regions showed that in areas with a relief slope of 2-4%, as a result of each irrigation, the surface layer was washed down to 0.4 mm, and the soil density increased to 1.4-1.6 g/cm3. This leads to a decrease in infiltration and an increase in surface runoff. As a result, the structural and chemical stability of the soil is disrupted.

As can be seen from the analysis, while foreign researchers mainly used model-based assessment (USLE, RUSLE, AI, RS, GIS), modeling, and forecasting methods, Uzbek scientists mainly focused on the real physicochemical state of the soil, the effectiveness of melioration systems, and the optimization of agrotechnical approaches. The possibilities of managing erosion processes will be significantly expanded by adapting international approaches to national agroecological conditions, strengthening scientific integration, and introducing long-term monitoring systems.

Therefore, a complex of agrotechnical and environmental measures, developed in the synthesis of foreign experience and applied research conducted in our country, serves as an important scientific and practical basis for stabilizing the condition of irrigated lands, reducing the level of erosion, and efficient use of resources.

RESULT AND DISCUSSION

Physicochemical mechanisms of erosion formation

Soil erosion is a complex process that leads to the loss of its basic physical, chemical, and biological properties under the influence of natural or anthropogenic factors, developing especially rapidly and dangerously in irrigated areas. Although erosion is often assessed as merely mechanical erosion, in reality, this process has deep physicochemical roots and is accompanied by the destruction of soil structure, disruption of ion balance, dispersion, salinization, and changes in the hydrophysical properties of the soil. Especially in irrigated areas, these processes intensify each other and sharply expand the sphere of influence of erosion.

When irrigation water reaches the soil surface, it begins to destroy the soil surface aggregates with its impact kinetic energy. This phenomenon occurs especially rapidly in soils with lighter structures, such as loess, sandy loam, or those prone to salinization. Soil aggregates are complex structures formed on the basis of the physicochemical interaction of soil particles and organic matter in them, which ensure the structural stability of the soil. During irrigation, these aggregates break down as a result of water impact and cause the dispersion of soil colloids. As a result, soil porosity decreases, the degree of infiltration decreases, and surface runoff increases. This situation leads to mechanical soil displacement and accelerated erosion.

However, erosion is not solely related to physical processes. Among its root causes, disruption of chemical equilibrium, ion exchange, increased salt concentration, and changes in the hydrophilic environment of the soil occupy an important place. The physical properties of the soil are directly related to its chemical state, especially the balance of soil cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) is the key to structural stability. If the amount of sodium ions in the soil increases, displacing calcium and magnesium ions, this leads to dispersion. Sodium ions weaken the forces between soil particles, disrupt their interconnection, and as a result, the particles begin to move with water. This process is called resultant dispersion, and it destroys the most important structural elements of the soil [5,6].

The composition of irrigation water also plays a crucial role in the erosion process. If irrigation water contains sodium bicarbonate, sodium carbonate, chloride, sulfate, or other aggressive ions, they react chemically with Ca^{2+} and Mg^{2+} ions in the soil, leading to the leaching of these elements. Under these conditions, the pH of the soil increases, an alkaline environment arises, the microbiological activity of the soil decreases, and the process of decomposition of organic matter accelerates. This leads to further weakening of the aggregates and increases the risk of erosion.

An increase in the pH level in the soil (especially above 8.5), the degree of sorption of Na^+ ions (SAR), and an increase in electrical conductivity (EC) are important indicators characterizing the state of chemical erosion of the soil. Scientific research conducted on these indicators shows that in areas prone to salinization, especially on lands with long-term and improper irrigation, erosion processes are explained by changes in these physicochemical indicators. If the water mineralization is high, especially irrigation with sodium carbonate and chloride saline waters, then under these conditions the dispersion process intensifies sharply.

It is noteworthy that physical and chemical mechanisms are closely interconnected. For example, the decrease in porosity caused by physical destruction of soil structure (water impact, compaction), in turn, changes the balance of chemical ions. Conversely, the process of chemical dispersion disrupts physical stability. In this integrated system, even a small imbalance can activate the erosion process. This condition develops especially rapidly and dangerously in lands with a slope of 1-3%, loess soils, saline areas, and areas with insufficient vegetation cover.

The amount of organic matter in the soil is also an important factor in structural stability. Organic substances are the "cementing" component of aggregates, and their decomposition or reduction weakens the structure. In irrigated lands, especially due to constant tillage, increased agrotechnical load, monoculture, and improper application of mineral fertilizers, humus reserves in the soil decrease, which further intensifies the effects of chemical erosion.

As a result of numerous scientific studies, it has been established that if the physical and chemical balance of the soil is disrupted simultaneously, erosion intensifies, pre-water infiltration of the soil decreases by 2-4 times, and as a result of erosion, nutrients, especially phosphorus, nitrogen, and potassium, are lost. As a result, agroecosystems are degraded, yields decrease by 30-60%, and the soil layer becomes irreversible.

From these analyses, it follows that the physicochemical mechanisms of the erosion process are complex, multifactorial, and integrated, and only one approach is insufficient for its management. Conversely, through the integrated application of agrotechnical, meliorative, agroecological, and chemical measures, the preservation of soil structure, monitoring its pH and ionic balance, increasing organic matter, and the rational use of water resources, it is possible to manage erosion processes [7,8].

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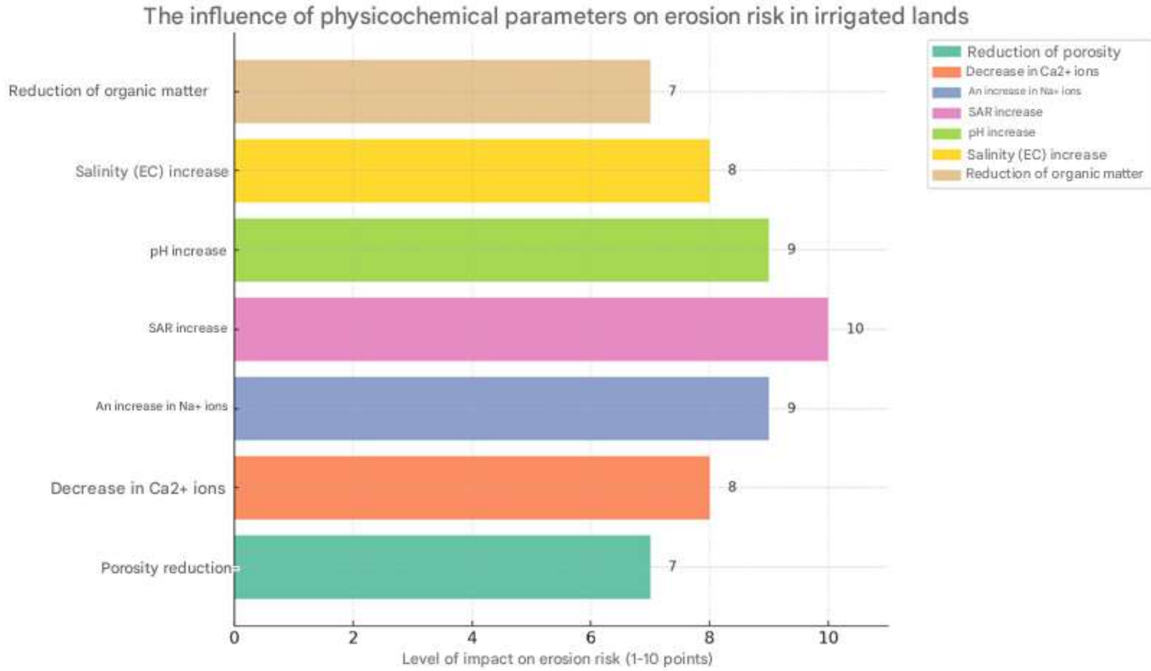

Figure 1. Influence of physicochemical parameters on the risk of erosion on irrigated lands

In addition, the use of physicochemical indicators in erosion monitoring is important. In laboratory conditions, such parameters as pH, EC, SAR, cation exchange capacity (CEC), aggregate stability, and dispersion index are determined, and based on their dynamics, the risk of erosion can be assessed in advance. Modeling these processes based on modern technologies, such as geoinformation systems (GIS), remote sensing (RS), and soil maps, allows for the precise determination of preventive measures.

In irrigated areas, the erosion process is associated not only with surface erosion, but also with a deep physicochemical imbalance, and a systematic scientific approach is necessary to manage this situation. In-depth analysis of the impact-destructive effect of physical mechanisms, the role of chemical components in ion exchange, serves as an important scientific basis for understanding erosion processes and developing a strategy for managing them.

Main causes and factors of soil degradation

Soil degradation is the decrease in soil fertility, disruption of its ecological functions, and disruption of the stability of agroecosystems as a result of the deterioration of its physical, chemical, biological, and agroecological properties. Especially on irrigated lands, the degradation process is complex, multifactorial, and proceeds at a rapid pace. This process is closely related to erosion, salinization, hardening, structural destruction, decrease in organic matter, weakening of microbiological activity, and other factors. One of the main causes of degradation is human activity, that is, improper irrigation, poor melioration services, excessive land load, low agrotechnical culture, and negligence towards the environment.

In Uzbekistan, irrigated lands constitute the main area of agriculture, and their condition is directly related to the country's food security. However, in many cases, these lands are subject to degradation as a result of continuous irrigation, intensive cultivation, monoculture, improper fertilization, technical pressure, and poor water quality. The most dangerous aspect is that degradation processes often occur latently, and fertility is already declining before clear signs appear on the soil surface. This necessitates preventive supervision.

The main cause of soil degradation can be improper irrigation technologies. Due to the fact that irrigation is based not on biological needs, but on available resources, that is, without measurement and systematic water supply, unevenness of the ground surface, non-compliance with irrigation norms, and the absence of laser leveling, surface runoff increases, infiltration is disrupted, and erosion intensifies. Excess ions entering the soil with irrigation water (especially Na^+, Cl^- , and HCO_3^-) weaken the soil structure, create a hydrophobic environment, and increase the tendency to erosion. These processes will eventually lead to degradation.

Another key factor is insufficient functioning or complete absence of land reclamation systems. If excess water entering the soil as a result of irrigation is not removed through drainage, it accumulates along the soil profile and leads to such negative consequences as salinization, compaction, disruption of air exchange, and oxygen deficiency. In many cases, salinization and degradation occur in parallel: initially, surface salinization occurs, followed by structural destruction and the loss of aggregates. This situation develops rapidly, especially in areas constantly irrigated with bicarbonate saline waters. This disrupts the soil's water-air regime.

Also, mechanical composition and morphological properties of the soil also determine the degree of susceptibility to degradation. For example, in light loamy or loess soils, in humid areas of lowlands prone to salinization, degradation occurs quickly. They have low binding strength of aggregates, weak cation exchange potential, and low water retention capacity. In these soil types, even under normal irrigation conditions, there is a high probability of disruption of the physicochemical balance [9].

Another powerful cause of soil degradation is increasing agricultural load. Continuous tillage, especially with heavy machinery, lack of tillage, organic matter introduction, improper fertilization, crop rotation, and compaction significantly limit the possibility of soil regeneration. The seasonal use of the same mineral fertilizers, especially excessive use of nitrogen and phosphorus fertilizers, disrupts soil biotics, disrupts the balance of microorganisms, and hinders the circulation of biogenic elements. As a result of these circumstances, the potential for natural soil regeneration (resource generation) is weakened.

Climate change is also considered one of the important factors in the intensification of degradation. Seasonal changes, uneven distribution of precipitation, intensive solar radiation, and strong winds slow down the mechanisms of soil self-restoration. In arid climates, the evaporation rate exceeding infiltration leads to soil saturation with saline solutions. Under these conditions, irrigated lands become dehydrated, saline, pH increases, and ultimately, degradation occurs.

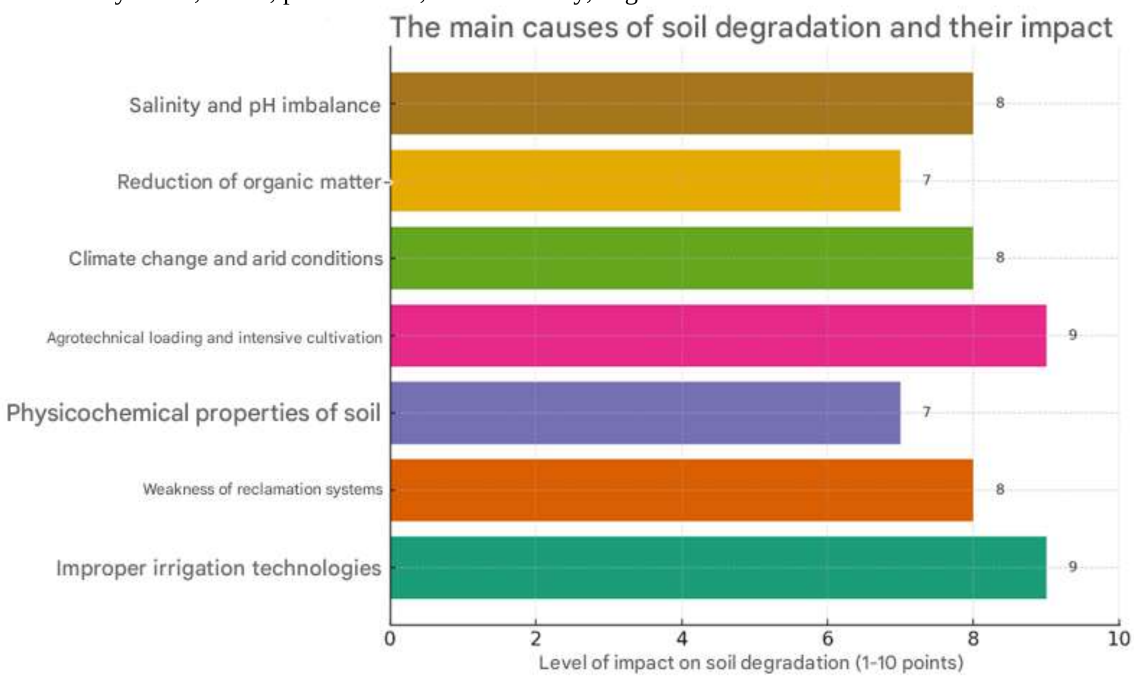

Figure 2. Main causes of soil degradation and the degree of their impact

Of course, in addition to human activity, such factors as the presence of mineralized layers, carbonate concentration, the natural pH level, mineral reserves, and the degree of structural stability can also contribute to degradation. However, practical observations show that these factors do not lead to degradation independently, but together with human activity.

As a direct consequence of degradation, the yield decreases by 40-60% as a result of physical compaction of the soil, a decrease in porosity, a decrease in water permeability, as well as a violation of the chemical balance, a decrease in the amount of organic matter and microorganisms, the washing away of essential nutrients, and the loss of aggregates. As a result, land resources cannot participate in production processes, and their recovery period extends for decades [10].

The main causes of soil degradation are a combination of improper anthropogenic impacts on land (improper irrigation, lack of land reclamation, heavy technical pressure, violation of agrotechnical discipline), natural characteristics (soil type, susceptibility to salinization), as well as global factors (climate change, water scarcity). In-depth analysis of these factors and the development of comprehensive approaches to soil protection from degradation is one of the most important agroecological tasks today.

Laws of erosion development under the influence of irrigation water

Soil erosion in irrigated areas is formed and develops primarily under the influence of hydrophysical and hydrochemical processes associated with irrigation water. Irrigation water is the main carrier, activator of the erosion process, and at the same time, under certain conditions, a factor that intensifies it. To fully understand the patterns of erosion development, it is first necessary to thoroughly analyze the interaction of water with soil and the physical and chemical processes occurring through it. These regularities are closely related not only to natural-geographical conditions, but also to such factors as irrigation technology, water quality, the degree of dip, the state of soil structure, and vegetation density, which form a complex system.

Irrigation water applied to the soil, if not distributed correctly and rationally, primarily impacts the surface part of the soil. It is this process - the impact energy of water - that destroys soil aggregates, breaks them down into small particles. These particles

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move along the surface with the flowing water. This occurs very quickly, especially in sandy and light loess soils. Also, in soils with saturated or dense layers, infiltration occurs slowly and excess water is removed through surface runoff, which leads to increased erosion. Experiments show that if the slope of the earth's surface is more than 2%, under improper irrigation conditions, erosion of the soil layer of 0.3-0.5 mm is observed after each irrigation.

Irrigation water quality also has a direct impact on erosion patterns. Ions in water, especially sodium ($Na+$), carbonate ($CO32-$), chloride ($Cl-$), and bicarbonate ($HCO3-$) salts, are involved in cation exchange in the soil. As a result of this exchange, stable aggregates in the soil weaken, sodium dispersion occurs, and the stability of the soil structure decreases. Sodium ions washed by water weaken the forces between soil particles, stimulating their separation. Therefore, in areas prone to salinization, processes carried out with irrigation water increase the risk of erosion. Water with a pH above 8.5 and a SAR coefficient above 10 is particularly dangerous in this regard.

Another regularity of irrigation water erosion is that this process is subject to the factor periodicity and frequency. With each repeated irrigation, the soil structure does not have time to recover, as a result of which surface runoff increases and erosion deepens with subsequent irrigation. If the irrigation interval is short and the water rate is high, the soil will always be in a hardened, compacted state. This sharply reduces infiltration and percolation, and surface runoff leads to regular displacement. Therefore, in modern agricultural techniques, it is precisely the frequency of irrigation systems and water norms that are strictly controlled.

The method of water supply during the irrigation process also has a great influence on the laws of erosion. For example, in flat-lying canals, during flood irrigation, or using artificial methods, water is unevenly distributed on the ground surface. As a result of this unevenness, water accumulates in some places, which leads to local erosion and the formation of depressions and cracks. In such zones, water accumulates during subsequent irrigations, completely washing away the soil. Conversely, in drip or underground irrigation methods, the degree of erosion is minimal due to the absence of impact effects at the contact level of water with the soil. For this reason, drip irrigation is currently considered an agronomically advantageous method, especially for lands prone to degradation [11].

Another important pattern between irrigation water and erosion is related to vegetation density. The denser the vegetation cover, the less water directly impacts the soil, and the more it diffuses into the soil through leaves and branches. This ensures the protection of the units from impacts. However, in bare land, especially when there are gaps between the vegetation stages of crops such as cotton and corn, water falls directly to the surface and the risk of erosion increases.

According to the regularities, there is a clear functional relationship between the thickness of the water level, the delivery time, the flow rate, and the physical properties of the soil (density, structural stability, mechanical composition). For example, an increase in water flow rate by 1 m3/sec leads to 10-12% more aggregate destruction at the soil surface. With an increase in soil density by 0.1 g/cm3, the degree of infiltration decreases by 8-10%. This, in turn, leads to an increase in surface runoff and an increase in the volume of erosion.

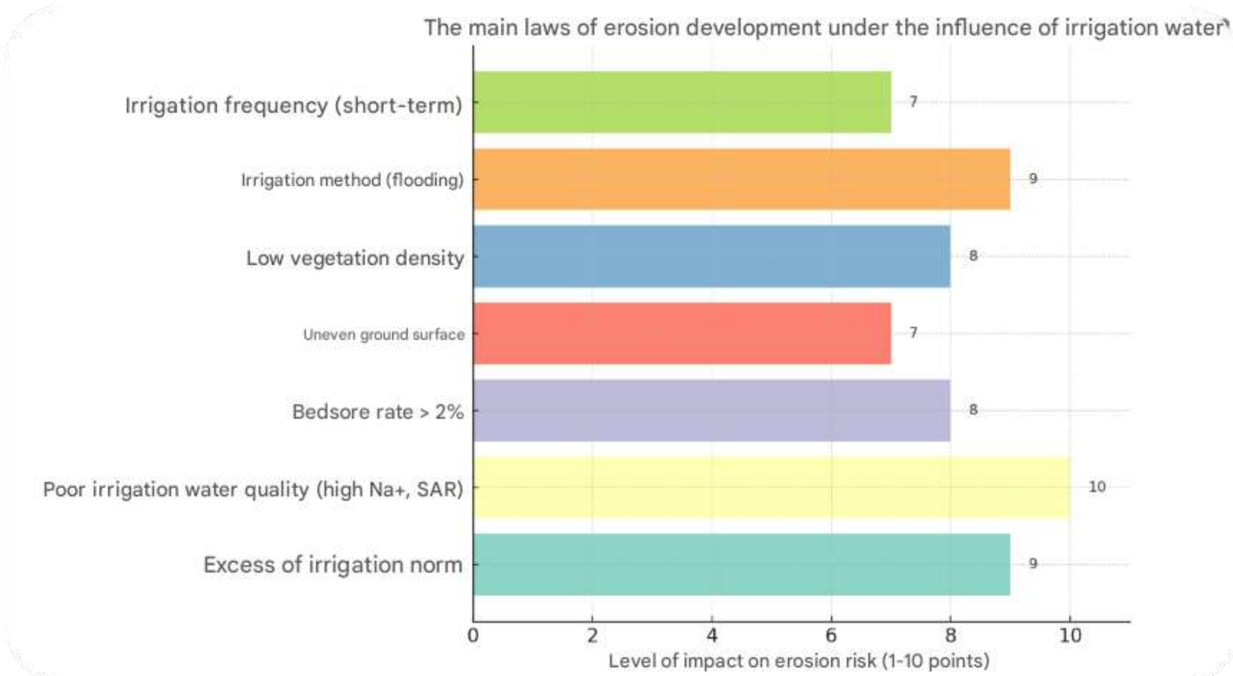

Figure 3. Main patterns of erosion development under the influence of irrigation water

When modeling and assessing the patterns of erosion development with irrigation water, modern methods are used - monitoring systems based on GIS, remote sensing, spectrometry, and mathematical modeling. With the help of these approaches, the direction of water flow, velocity, level change, salt distribution, and zones of soil structure disturbance are determined, and their relationship with erosion is assessed with high accuracy. In particular, the analysis of soil salinity and compaction indicators in conjunction with NDVI (vegetation index) and SAR maps makes it possible to predict erosion-prone zones [12,13].

In general, the development of erosion under the influence of irrigation water is based on complex, multifactorial patterns. These regularities arise directly from the interaction of physical (flow, infiltration, impact), chemical (ion exchange, salinity), technological (irrigation method, rate), and ecological (vegetation, climate, relief) factors. By deeply studying these regularities and applying them to agricultural technologies, it will be possible to prevent erosion, slow down degradation, and preserve the fertility of irrigated lands for a long time.

CONCLUSION

The conducted scientific analysis shows that the formation and development of erosion processes on irrigated lands is complex, multifactorial, and has an integrated character. Erosion manifests itself not only as mechanical erosion, but also as a complex process of degradation, arising as a result of the disruption of the physical and chemical balance of the soil. Physical factors, such as water shock, destruction of aggregates, a decrease in infiltration, an increase in sodium ions in the soil, the washing out of cations, such as calcium and magnesium, an increase in pH and the level of salinity, are especially strongly interacting with chemical factors. As a result of these changes, the structural stability of the soil is disrupted, and the susceptibility to erosion increases.

Soil degradation is a direct and long-term result of this process, which reduces soil fertility, disrupts ecological stability, and weakens agroecosystems. Improper irrigation technologies, weak melioration measures, increased agrotechnical load, a decrease in organic matter, natural soil characteristics, and climatic factors are the main reasons leading to this degradation. In particular, due to the destruction of soil structure, the loss of aggregates, and a decrease in infiltration, surface water flow increases, which sharply activates erosion processes.

Irrigation water plays a dual role in the erosion process: on the one hand, it is a necessary source of water for plants, and on the other hand, it becomes the main activator of erosion due to improper technologies, excessive quantity and poor quality of water. Such factors as aggressive ions in the water composition, flow velocity, water supply method, degree of dip, physicochemical state of the soil, and vegetation cover determine the patterns of erosion development. In conditions of periodic and excessive irrigation, bare ground without vegetation, as well as uneven relief, the risk of erosion increases sharply.

The above analysis shows that to ensure the stability of irrigated lands, it is necessary to conduct a deep scientific analysis of erosion processes, a full understanding of their physicochemical mechanisms, and the development of strategies aimed at managing them. Such an approach, on the one hand, ensures the long-term preservation of soil resources, and on the other hand, serves the economic, ecological, and social stability of agroecosystems.

Therefore, further research should be aimed at developing comprehensive approaches to early erosion detection, mapping of risk zones and their management using modern monitoring methods (remote sensing, GIS, modeling), criteria for agroecological assessment, diagnostic indicators of soil quality.

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