

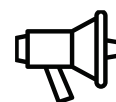
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THE INFLUENCE OF HYDRODYNAMIC ASPECTS OF GROUNDWATER LEVEL RISE ON URBAN WATERLOGGING

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Abstract. This article presents a systematic analysis of the hydrodynamic and hydrogeochemical aspects of groundwater level rise contributing to the waterlogging of urban areas. The study applies a differentiation approach based on the hierarchical organization of systems and characteristic zones, examining the influence of salt and water migration on the urban ecological environment. The degree of certainty of hydrogeological structures and their principal causal factors are investigated, while the transformation processes of groundwater under urban conditions are comprehensively described. Systemic factors determining the susceptibility of territories to waterlogging, as well as specific taxonomic units and criteria for geochemical classification, are also developed.

The article establishes a scientific basis for managing hydrodynamic processes aimed at mitigating waterlogging problems in residential areas. The research findings are of considerable importance for improving urban planning practices and environmental monitoring systems. During the study, the dynamics of salt and water migration were analyzed using the equation proposed by S.F. Averyanov, enabling the determination of groundwater mineralization levels and corrosive properties. Through the application of differentiation methods across characteristic zones and the identification of systemic susceptibility factors, the study develops a geochemical classification and taxonomic criteria for modified groundwater. These findings provide a scientific foundation for planning land reclamation measures aimed at improving the urban ecological environment and protecting building foundations from sulfate corrosion.

Keywords: groundwater, urban waterlogging, hydrodynamics, hydrogeochemistry, urban ecological environment, water migration, salt migration, geochemical classification, sulfate corrosion, environmental monitoring, land reclamation, hydrogeology.

Annotatsiya. Ushbu maqolada shahar hududlarining suv bosishiga olib keluvchi yer osti suvlari sathining ko'tarilishining gidrodinamik va gidrogeokimyoviy jihatlari tizimli ravishda tahlil qilingan. Tadqiqotda tizimlar ierarxiyasi va xarakterli hududlarga asoslangan differensial yondashuv qo'llanilib, tuz va suv migratsiyasining urban-ekologik muhitga ta'siri o'rganilgan. Gidrogeologik tuzilmalarning shakllanish darajasi va ularning asosiy sabab omillari tahlil qilinib, shahar sharoitida suvlarning transformatsiya jarayonlari tavsiflangan. Hududlarning suv bosishiga moyilligini belgilovchi tizimli omillar, shuningdek, geokimyoviy tasniflash uchun maxsus taksonlar va mezonlar ishlab chiqilgan.

Maqolada turar-joy hududlarida suv bosishi muammolarini kamaytirishga qaratilgan gidrodinamik jarayonlarni boshqarishning ilmiy asoslari yoritilgan. Tadqiqot natijalari shaharsozlik va ekologik monitoring tizimlarini takomillashtirishda muhim ahamiyatga ega. Tadqiqot davomida tuz va suv migratsiyasi dinamikasi S.F. Averyanov tenglamasi asosida tahlil qilinib, yer osti suvlarining minerallasuv darajasi va korrozion xususiyatlari aniqlangan. Xarakterli hududlar bo'yicha differensial usullarni qo'llash va moyillikning tizimli omillarini aniqlash orqali modifikatsiyalangan suvlarning geokimyoviy tasnifi hamda taksonomik mezonlari

ishlab chiqilgan. Ushbu natijalar urban-ekologik muhitni yaxshilash va bino poydevorlarini sulfat korroziyasidan himoya qilishga qaratilgan meliorativ tadbirlarni rejalashtirish uchun ilmiy asos bo'lib xizmat qiladi.

Kalit so'zlar: yer osti suvlari, suv bosishi, gidrodinamika, gidrogeokimyo, urban-ekologik muhit, suv migratsiyasi, tuz migratsiyasi, geokimyoviy tasnif, sulfat korroziyasi, ekologik monitoring, melioratsiya, gidrogeologiya.

Аннотация. В данной статье представлен системный анализ гидродинамических и гидрогеохимических аспектов повышения уровня подземных вод, способствующих подтоплению городских территорий. В исследовании применяется дифференцированный подход, основанный на иерархической структуре систем и характерных зонах, с целью изучения влияния миграции солей и воды на урбоэкологическую среду. Исследованы особенности гидрогеологических структур и основные факторы их формирования, а также подробно описаны процессы трансформации вод в условиях городской среды. Разработаны системные факторы, определяющие предрасположенность территорий к подтоплению, а также специальные таксоны и критерии геохимической классификации.

В статье обоснованы научные основы управления гидродинамическими процессами, направленными на снижение последствий подтопления жилых территорий. Результаты исследования имеют важное значение для совершенствования систем градостроительства и экологического мониторинга. В ходе исследования динамика миграции солей и воды была проанализирована на основе уравнения S.F. Aveyanov, что позволило определить уровень минерализации и коррозионные свойства подземных вод. Путём применения дифференцированных методов по характерным зонам и выявления системных факторов предрасположенности была разработана геохимическая классификация и таксономические критерии модифицированных вод. Полученные результаты служат научной основой для планирования мелиоративных мероприятий, направленных на улучшение урбоэкологической среды и защиту фундаментов зданий от сульфатной коррозии.

Ключевые слова: подземные воды, подтопление, гидродинамика, гидрогеохимия, урбоэкологическая среда, миграция воды, миграция солей, геохимическая классификация, сульфатная коррозия, экологический мониторинг, мелиорация, гидрогеология.

INTRODUCTION

One of the most pressing challenges in modern urban planning and urbo-ecology is the scientific assessment of waterlogging processes caused by rising groundwater levels in urban areas, together with their hydrodynamic and hydrogeochemical consequences [1–3]. Rapid urban expansion, increasing technogenic pressures, and the malfunction of engineering and utility networks disrupt the natural groundwater balance and worsen the land reclamation conditions of urban territories [4–6].

Within these processes, the migration of water and salts causes not only physical alterations but also complex chemical transformations. From a hydrogeochemical perspective, urban waterlogging represents the degradation of urban landscapes associated with increasing groundwater mineralization and the vertical and horizontal migration of salts. A systematic analysis of these processes requires the determination of system hierarchy levels and characteristic zones (km²), as well as the application of differentiation and zoning methods. Through the study of certainty factors and primary causative mechanisms, it becomes possible to identify the principal hydrogeological processes responsible for disturbances in the water–salt balance of urban environments [7–9].

The hydrogeological structure of systems and their response to external influences constitute the primary criteria determining the stability of urban ecosystems. The geochemical classification of modified groundwater plays an important role in identifying susceptibility to waterlogging, since anthropogenic activity significantly transforms the composition of natural waters and contributes to the formation of new hydrochemical facies [10–13]. The taxonomic units and criteria applied in this study enable the classification of territories not only according to groundwater level conditions, but also according to the degree of chemical aggressiveness and salinity.

Systemic factors contributing to susceptibility to waterlogging are closely related to topographic relief, soil filtration properties, and lithological structures, which accelerate the upward movement of groundwater under the influence of hydrodynamic forces. Therefore, considering the urban hydrogeological system as an integrated whole and investigating each of its components at both micro- and macro-levels is essential for forecasting future environmental risks.

At present, changes in groundwater levels and quality are increasingly assessed through the use of modern mathematical models and specialized software systems. Some of these tools are also applied to clarify the interrelationship between groundwater dynamics and agricultural activity [14–18].

LITERATURE REVIEW

To ensure the stability of engineering structures and protect public health, it is necessary to develop effective strategies for preventing and mitigating waterlogging processes. Such strategies should be based on hydrodynamic modeling and a systematic approach that considers groundwater flow direction, flow velocity, and solute dispersion patterns. By applying differentiated approaches, it becomes possible to design area-specific reclamation measures, including closed horizontal drainage systems and vertical drainage wells, for each characteristic zone.

Furthermore, the taxonomic analysis of hydrogeochemical indicators provides a scientific basis for implementing measures aimed at reducing groundwater aggressiveness and protecting building foundations from corrosion damage. Ultimately, the management of urban waterlogging involves not only reducing groundwater levels, but also restoring the balance of the entire urban hydrosphere and harmonizing natural and technogenic water cycles.

This study is devoted to addressing these complex scientific and practical challenges and proposes methodologically innovative systematic classifications for analyzing and managing urban groundwater-related waterlogging processes.

RESEARCH METHODOLOGY

The methodological framework of this study is based on a systematic-hierarchical analysis of urban territories and the mathematical modeling of hydrogeochemical processes. The territory of Gulistan was divided into several hierarchical system levels and characteristic zones (km²). Using the differentiation approach, the hydrogeological structure and groundwater flow formation conditions of each zone were evaluated individually.

To investigate the hydrogeochemical aspects of groundwater movement, the convective–diffusion model proposed by S.F. Averyanov [19] was applied. Through this method, the relationship between the actual groundwater flow velocity within soil pores (V), the diffusion coefficient (D), and the dissolution coefficient (β) was determined. In addition, the sources of waterlogging were statistically analyzed based on the principle of “certainty” or “primary causation.”

By applying the territorial differentiation (zoning) method, the urban area was classified into several systems according to the degree of hydrodynamic complexity [20]. The obtained results demonstrate that in local systems with characteristic areas of 5–10 km², groundwater level rise is mainly associated with water leakage from communal engineering and utility networks, which represents the primary causative factor.

In larger regional systems, covering areas of approximately 50–100 km², waterlogging processes are primarily influenced by the natural hydrogeological structure and the impact of river flow systems.

The analysis of salt and water migration dynamics revealed that, in waterlogged territories, groundwater mineralization levels increased by approximately 2.5–4 times compared with the natural hydrogeochemical background. Based on the geochemical classification of modified groundwater, specific taxonomic units and classification criteria were identified.

RESULTS AND ANALYSIS

The research findings indicate that the boundary state of phreatic groundwater in urban territories is directly associated with geological-structural conditions and the degree of natural drainage development. The waterlogging process within these areas is dynamic in nature and evolves progressively from an “unwaterlogged” condition toward a stable stage of persistent waterlogging.

The filtration properties of soil layers and the hydraulic gradient of the groundwater table were identified as the principal factors determining the intensity and rate of waterlogging development. The study established that deviations from drainage requirements specified in construction standards (SNiP 2.06.15-85) contribute to the gradual rise of groundwater levels over time and lead to disturbances in hydrogeological equilibrium.

The development of the waterlogging process was found to proceed through three principal stages:

Initial stage – characterized by a gradual rise in groundwater levels;

Intermediate stage – marked by seasonal fluctuations and increased amplitude of groundwater level variations;

Final stage – characterized by a stable shallow groundwater table.

Particularly in areas lacking artificial drainage systems, it was observed that the groundwater regime is regulated primarily through evapotranspiration and irrigation processes during the vegetation period. In the final stage, the reduction in the amplitude of groundwater-level fluctuations indicates that inflow and outflow

processes reach a critical hydrodynamic equilibrium. This finding scientifically substantiates the necessity of implementing artificial drainage systems to improve the reclamation condition of urban territories fundamentally.

Within the geological boundaries of the city, the groundwater massif is subdivided into separate filtration blocks that are either isolated by internal and external boundary conditions or interconnected through hydraulic interactions. Each filtration block, as well as the groundwater massif as a whole, is characterized by lateral boundaries, while both the groundwater table and the aquifer base also function as hydrogeological boundaries.

Along these lateral boundaries, groundwater inflow into the filtration block or massif contour and groundwater outflow are facilitated. Atmospheric precipitation and surface water infiltrate and percolate downward toward the groundwater table. From the groundwater surface, capillary rise processes occur toward the aeration zone, where water is subsequently consumed through evapotranspiration.

Water infiltrating from the groundwater table disperses throughout the aquifer volume and either flows laterally or percolates into deeper aquifers. Conversely, upward groundwater migration from underlying aquifers through the aquifer base may also occur. In this context, the “urban groundwater massif” can be interpreted as a structural component of the local water-exchange system, whose lower boundary interacts dynamically with subdivisions of the regional groundwater circulation system.

Within the observed groundwater regime, waterlogging occurs when groundwater inflow exceeds groundwater outflow. When the aeration zone becomes fully saturated, the waterlogging process transitions into flooding conditions. According to the definition provided in the annex of SNiP 2.06.15-85, flooding is defined as “the formation of a free water surface within a territory caused by the rise of surface waters, water bodies, or groundwater levels.”

The occurrence of flooding at the ground surface is associated not only with the complete saturation of the aeration zone but also with weak infiltration and low filtration capacity resulting from unfavorable hydro-physical properties of soils and rocks. In turn, prolonged waterlogging alters the hydro-physical characteristics of the aeration-zone materials themselves.

Water saturation initiates subsidence processes in loess and loess-like soils [6], while in fine-grained sandy and clayey deposits it may induce thixotropic behavior, resulting in soil liquefaction under mechanical loading. The saturation of geological materials changes their initial structural bonds and disrupts their natural texture [6]. Under such conditions, both the porosity and filtration coefficients of soils commonly decrease.

Therefore, the study concludes that during prolonged waterlogging processes, the hydro-physical properties of flooded geological layers continuously evolve over time and remain unstable under changing hydrodynamic conditions.

On a regional scale, the phenomenon of waterlogging associated with groundwater level rise, particularly within urban territories, is most commonly observed in large and medium-sized river valleys and deltas, intermountain and piedmont depressions, as well as marginal tectonic troughs. The oases of Uzbekistan and their irrigated agricultural massifs generally correspond to these geological and geomorphological structures.

The hydrogeological conditions of these oases have undergone significant transformation under the influence of irrigation infrastructure and agricultural water-management systems. The principal component of this system is river runoff, which is distributed through both natural and artificial hydrographic networks and extensively utilized for irrigation purposes. In major river basins, river flows are additionally regulated through hydraulic engineering structures. All these factors are directly reflected in the groundwater regime of the oases and in the hydrogeological-reclamation systems associated with them.

The nomenclature of hydrogeological systems is presented in Table 1. The hydrogeological-reclamation systems corresponding to the organizational levels shown in Table 1 are characteristic features of irrigated massifs and form their structural basis. Considering that waterlogged cities and settlements are predominantly located within oasis territories, it is scientifically justified to apply the same nomenclature of organizational levels to urban groundwater massifs.

The subdivision of the urban groundwater massif into smaller massifs of lower organizational levels, based on external and internal hydrodynamic boundaries, reflects the spatial heterogeneity and structural organization of the waterlogging process. The previously described filtration blocks of the urban groundwater massif correspond precisely to such lower-level systems.

The boundaries of these systems are formed by elements of intra-urban irrigation and drainage networks, as well as by contacts between permeable and impermeable geological layers. Malfunctioning water-supply and sewerage systems may also act as hydrodynamic boundaries contributing to groundwater accumulation.

The hydrodynamic manifestation of waterlogging within each city possesses distinct local characteristics due to differences in the spatial and temporal distribution of influencing factors. Nevertheless, in all cases, the continuity of groundwater flow forming the “urban groundwater massif” and its internal subdivisions is preserved.

It should be emphasized that the waterlogging of urban territories represents a specific hydrogeological

process involving the movement, recharge, discharge, and redistribution of groundwater within the general hydrological cycle, as well as quantitative and qualitative transformations arising from groundwater interaction with geological formations, the atmosphere, the hydrosphere, soil cover, the biosphere, and the technosphere.

The considered hydrodynamic interpretation of waterlogging processes is fully consistent with the established theory of groundwater movement [1,4].

As emphasized by S.F. Averyanov, the migration of salts and water in its simplest form can be described by the following equation:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - V \frac{\partial C}{\partial x} + \beta(C_m - C)$$

where:

- C — concentration (mineralization) of the solution (groundwater), g/dm³;
- t — time, days;
- x — distance, m;
- V — actual groundwater flow velocity within soil or rock pores, m/day

($V = V_0/n$);

- V_0 — filtration velocity, m/day;
- n — effective porosity;
- C_m — ultimate saturation concentration, g/dm³;
- β — dissolution coefficient, 1/day;
- D — coefficient of convective (filtration) diffusion, m²/day.

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - V \frac{\partial C}{\partial x} + \beta(C_m - C)$$

Equation (1) describes the variation in the concentration of salts and chemical elements at any point within the groundwater flow system occupying elementary pore spaces in soils and rocks. This equation reflects the combined effects of convective transport, diffusion processes, and dissolution dynamics, thereby forming the theoretical basis for analyzing hydrogeochemical transformations associated with urban groundwater waterlogging processes.

Calculations performed using the equation proposed by S.F. Averyanov revealed specific patterns in the migration of chemical elements within the elementary pore spaces of residential territories. The analysis demonstrated that in areas where the actual groundwater flow velocity decreases, diffusion processes become dominant, resulting in a significant increase in groundwater mineralization.

This process subsequently contributes to the corrosion of building foundations and the secondary salinization of soil layers. Therefore, the study scientifically substantiates that, when designing anti-waterlogging reclamation measures, it is necessary not only to reduce groundwater levels but also to optimize filtration velocity in order to regulate salt convection processes effectively.

In the conditions of the Syrdarya Region, it was determined that groundwater rise predominantly corresponds to the intermediate and final stages of the waterlogging process. During the irrigation season, groundwater level fluctuations were observed to reach amplitudes of approximately 1.2–1.8 meters.

Due to the extremely low degree of natural drainage characteristic of the region, the decline in groundwater levels during August and September occurs mainly through evapotranspiration processes. As a consequence, the accumulation of salts from groundwater on the ground surface intensifies considerably.

Calculations related to the dissolution coefficient (β) and groundwater mineralization level (C) in the

Syrdarya region showed that groundwater mineralization varies within the range of 5–10 g/dm³. Because of the low filtration velocity (V_0), estimated at approximately 0.1–0.3 m/day, the convective diffusion coefficient (D)

becomes the dominant factor controlling salt migration.

$$V = \frac{V_0}{n}$$

Under these conditions, salts are transported not only through groundwater movement but also through capillary rise mechanisms, resulting in the formation of so-called “salt prisms” within building foundation zones.

The susceptibility of the regional territory to waterlogging was classified as a second-order (meso-level) system. The principal “certainty factor” characteristic of the Syrdarya region was identified as seepage losses from irrigation canals combined with the hydraulic interconnectedness of the territory.

The analysis further demonstrated that in areas where the operational efficiency of collector-drainage

networks declined by approximately 30–40%, the waterlogging process became stable and groundwater salts acquired chemically aggressive properties capable of intensifying structural corrosion.

The findings indicate that, under the conditions of the Syrdarya region, eliminating waterlogging requires not only reducing groundwater accumulation volumes, but also accelerating groundwater circulation through vertical drainage systems and implementing soil-leaching measures while accounting for the saturation concentration parameter (C_m) (Table 1).

Table 1

Classification of hydrogeological-reclamation systems by organizational levels¹

System Order (Level) and Characteristic Area (km ²)	Differentiation (Zoning) Method	Factors of Certainty or Primary Cause	Hydrogeological Structure of the Systems
First (Supra-regional) n·105	Structural-geological	Geological-structural, climatic, and hydrological	Groundwater and unconfined-fissure waters of folded regions varying by altitudinal zones; also, platform regions varying by latitudinal zones.
Second (Macro-regional) n·104÷105	Structural-hydrodynamic	Same as above	Groundwater flow basin.
Third (Meso-regional) n·103÷104	Same as above	Same as above	Group of groundwater flows.
Fourth (Regional) n·102÷103	Same as above	Same as above	Groundwater flow.
Fifth (Sub-regional) 10÷n·102	Same as above	Same as above	Groundwater flow zones (recharge, transit, discharge/distribution).
Sixth (Macro-local) ... n·102	Same as above (boundaries within flow zones)	Same as above (determined by filtration non-uniformity within flow zones)	Local hydrodynamic structures — natural and artificial: catchments, flow channels, groups of irrigated areas, areas of groundwater pollution sources, etc.
Seventh (Meso-local) 1÷10	Same as above	Same as above	Local hydrodynamic associations: temporary flow catchments, irrigated plots, groups of groundwater intake structures, etc.
Eighth (Local) 0.1÷1	Same as above	Same as above	Local hydrodynamic structures: erosional rill catchments, irrigation maps or inter-drainage plots, individual groundwater extraction units, point-source pollution collection areas, etc.
Ninth (Sub-local) <0.1	Same as above	Same as above	Pore and fissure (water-bearing) associations.

When integrating the three-dimensional form of Equation (1) over the volume of soil solution and groundwater flow systems, as well as their combined interactions, the diffusion and salt-exchange components manifest as internal sources or internal fluxes. Salt exchange, or mass transfer across the flow volume, is determined by the difference between the convective component values at the system boundaries. This process occurs through lateral groundwater inflow and outflow, as well as through vertical seepage into the upper boundary and filtration exchange through the lower boundary.

Under these conditions, the water–salt balance, or ion-flux balance, can be interpreted as the generalized integral result of mass-transfer processes involving chemical substances. Mass transfer and phase-transition processes predetermine the variability of groundwater mineralization and chemical composition, as well as the composition of pore solutions within the aeration zone.

Among the phase-transition processes, in addition to dissolution and precipitation considered in Equation (1), particular importance should be attached to evapotranspiration and concentration processes caused by evaporation. Alongside the identified linear effects, numerous non-linear effects also occur, substantially complicating the formation of groundwater chemistry and pore-solution composition. The migration of chemical elements and chemical complexes is significantly constrained by the presence of geochemical barriers. Among these, oxygen, hydrogen-sulfide, gley, and evaporative barriers were identified as the principal hydrogeochemical obstacles. The oxygen barrier represents an oxidation zone for organic compounds, hydrogen-sulfide complexes, and other reduced chemical substances. Oxidation processes are promoted by dissolved free oxygen in groundwater, atmospheric oxygen within the aeration zone, and microbiological activity. The hydrogen-sulfide barrier constitutes a reduction zone for oxidized organic compounds and chemical complexes during the formation of hydrogen sulfide and its derivatives, including HS⁻ and S²⁻ ions[7].

¹ Author's development

This type of environment is characteristic of anaerobic conditions, where microorganisms oxidize organic matter by extracting oxygen from mineral compounds. Gley waters either lack oxygen entirely or contain very low oxygen concentrations, leading to the development of “gleying” processes that impart bluish-gray coloration to soils and rocks.

Under anaerobic conditions and elevated sulfate-ion concentrations, desulfurization processes intensify, resulting in the formation of hydrogen sulfide. Such conditions are typical for solonchaks (salt marshes), wetlands, and saline lakes in arid desert regions. These environments function as zones of salt accumulation and concentration in groundwater and pore solutions, as well as zones where dissolved substances transition into precipitated mineral phases.

In general, within the above-mentioned geochemical barriers, redox conditions, alkaline-acidic environments (pH), and groundwater salinity undergo significant changes. According to these characteristics, the geochemical classification of groundwater distinguishes taxonomic categories such as species, class, and family.

Furthermore, based on the classification terminology adopted in previous studies, the classification system proposed by O.A. Alekin was restructured in such a way that:

“generation” corresponds to the class;

“appearance” corresponds to the group;

“variety” corresponds to the type.

The geochemical classification of modified groundwater reflects the processes responsible for the formation of groundwater chemical composition. This classification framework accounts for environmental conditions, hydrochemical regimes, groundwater salinity, anion and cation composition, as well as the quantitative relationships among these components.

According to the industrial standard for groundwater classification by chemical composition and temperature:

the “family” category corresponds to the “group”;

the “variety” category corresponds to the “species.”

Groundwater classes are determined according to alkaline-acidic conditions (pH indicators). The classification of groundwater according to temperature occupies a distinct position within the overall hydrogeochemical classification system, which explains why separate independent taxonomic units are assigned to this criterion. At the same time, these units occupy a relatively high hierarchical level within the geochemical classification structure.

The three-dimensional expression of Equation (1), the migration of chemical elements within redox and alkaline-acidic environments, and the proposed modified version of the geochemical classification of natural waters collectively reflect the specific characteristics of hydrogeochemical processes and reveal important aspects of their evolution and progression within urban groundwater systems (Table 2).

Table 2
Geochemical Classification of Modified Waters²

No.	Taxon	Criteria
1	Groups	Temperature
2	Types	Oxidation-reduction potential (gases)
3	Classes (Groups)*	Alkaline-acidic conditions (pH)
4	Families (Groups)*	Total mineralization (salinity)
5	Generations (Classes)**	Principal anions
6	Appearances (Groups)**	Principal cations
7	Varieties (Types)**	Ratio of principal anions and cations

Observational data confirm that, in general, the determination of mass-transfer conditions and convection processes is primarily governed by the convective transport of substances across the boundaries of the investigated object. This is обусловлено the presence of ions and chemical complexes — including organic compounds, dissolved gases, and other substances — within filtering groundwater and soil solutions.

As a result, groundwater filtration and the transport of dissolved salts exhibit identical or closely related velocity characteristics. Under such conditions, the hydrodynamic aspects of the waterlogging phenomenon largely determine its hydrogeochemical behavior. Consequently, hydrogeochemical factors are closely interconnected with hydrodynamic processes and cannot be considered independently.

Under the hydrogeological conditions of Uzbekistan, almost all groundwater families classified according to salinity (mineralization) are encountered, including ultra-fresh, fresh, brackish, saline, and brine waters,

² Author's development

together with their respective subfamilies. Depending on local conditions, these groundwater families occur under various redox (oxidation–reduction) and alkaline-acidic environments.

Their composition in terms of “generation” and “appearance” varies according to different combinations of dominant anions and cations. At the same time, the “variety” classification presented in the table, or the “species” classification according to previous sources, is represented by four principal taxonomic categories across all generation–appearance combinations.

Depending on the geochemical history and the modern processes of halogenesis, the most widespread groundwater variety is the second (II) type, characterized by a sulfate–hydrocarbonate–magnesium composition.

According to the principles outlined in previous studies, the initial conditions for the migration of chemical elements are formed before the onset of the waterlogging process. These conditions are determined by:

the degree of natural drainage;

ion-flux velocity or salt mass-transfer intensity;

infiltration of atmospheric precipitation and the associated inflow of chemical substances;

seepage losses from watercourses and water bodies that regulate dissolved salt inflow and outflow processes.

In their natural state, territories susceptible to waterlogging — particularly under conditions of weak natural drainage, arid climate, and insufficient engineering protection systems — are predisposed to the salinization of landscapes, including soils, the aeration zone, and groundwater systems. Areas initially unaffected by waterlogging gradually undergo flooding processes over time.

During the initial stage, waterlogging manifests as a gradual rise in the groundwater table caused by saturation of the aeration zone. Depending on the intensity and duration of infiltration, waterlogging may develop either slowly over many years or relatively rapidly during the early stages of land development or modernization of water-supply systems.

Under these conditions, salts accumulated within the aeration zone during previous geological and historical periods dissolve and transition into groundwater and soil solutions. Infiltrating waters — whether originating from atmospheric precipitation or leakage from hydrographic networks — subsequently undergo concentration through evaporation processes.

Both salt dissolution and evaporative concentration contribute to the salinization of groundwater, particularly within its highly active upper layer, during the early stages of waterlogging development.

At the intermediate stage of the waterlogging process, especially under undrained conditions, the rate of salinization within aeration-zone materials and groundwater increases significantly as a result of intensified evapotranspiration.

In the final stage of waterlogging under undrained conditions, landscape salinization becomes stable, and “salt dew” begins to appear on the ground surface. Over time, these deposits transform into porous salt crusts.

Thus, under conditions lacking effective drainage systems, land development processes ultimately lead to a combined and interconnected phenomenon of waterlogging and salinization. All these processes arise due to insufficiently regulated water-supply regimes and inadequate wastewater management systems.

In general, the hydrogeochemical characteristics of waterlogging within each specific territory are determined not only by local hydrogeological conditions, but also by regional and basin-scale factors influencing the natural formation of groundwater chemistry, groundwater interaction with the geological environment, and various technogenic impacts. These combined factors significantly diversify the hydrogeochemical manifestations of the waterlogging phenomenon.

CONCLUSION AND RECOMMENDATIONS

The research conducted in Gulistan demonstrates that the waterlogging of urban territories is not solely a natural phenomenon, but rather a complex environmental problem formed through the interaction of hydrodynamic and technogenic factors. The low-lying topography of the city and the presence of impermeable geological layers significantly restrict the natural drainage of groundwater flow.

The analysis performed using the equation proposed by S.F. Averyanov confirmed that the actual groundwater flow velocity (V) in Gulistan is relatively low. Under these conditions, the influence of the convective

diffusion coefficient (D) becomes dominant, creating favorable conditions for the vertical accumulation of salts

within the upper geological layers. As a result, the territory has entered the most critical stage of waterlogging, characterized by a stabilized groundwater table at shallow depths of approximately 1.0–1.5 meters.

From a hydrogeochemical perspective, groundwater within Gulistan has undergone substantial modification,

with sulfate and chloride ion concentrations significantly exceeding permissible standard values. The chemically aggressive nature of these groundwater conditions poses a serious threat to engineering infrastructure and building foundations throughout the urban area.

In light of these findings, the study emphasizes the necessity of implementing comprehensive scientific and practical measures aimed at improving the reclamation status of Gulistan. First, considering the low filtration properties of regional soils, it is advisable to increase the operational effectiveness of vertical drainage wells and establish additional hydrodynamic monitoring networks.

Second, to mitigate sulfate-induced corrosion, specialized chemical protection methods for building foundations should be introduced alongside hydrochemical management measures designed to reduce groundwater mineralization levels.

The scientific conclusions obtained in this study provide a methodological basis for addressing similar high-risk waterlogging territories within the Syrdarya Region and are of considerable importance for future urban planning, environmental protection, and hydrogeological management practices.

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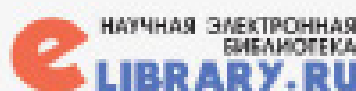
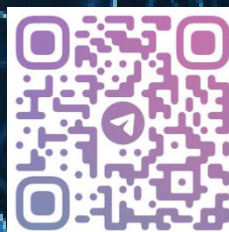
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