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SPATIAL ZONING OF THE SOIL HYDROPHYSICAL CONDITIONS OF WATERLOGGED AREAS

ПРОСТРАНСТВЕННОЕ ЗОНИРОВАНИЕ ГИДРОФИЗИЧЕСКОГО СОСТОЯНИЯ ГРУНТОВ ПОДТОПЛЯЕМЫХ ТЕРРИТОРИЙ

СУ БАСҚАН АУМАҚТАР ТОПЫРАҚТАРЫНЫҢ ГИДРОФИЗИКАЛЫҚ КҮЙІН КЕҢІСТІКТІК АЙМАҚТАНДЫРУ

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waterlogging, liquidity
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ABSTRACT

This study examines the effects of changes in moisture content on the hydrophysical state of soils, using the left-bank area of Astana (Kazakhstan) as an example. The research is based on an analysis of data from 141 engineering-geological boreholes, grouped across 12 development sites. The main parameters used are natural soil moisture, the liquidity limit, the plasticity limit, and the liquidity index. To assess spatial changes in soil conditions, spatial modeling methods and Spline interpolation were applied in the ArcGIS Pro environment. Two scenarios were modeled: a baseline scenario based on the available engineering-geological data and a synthetic moisture-increase scenario, in which moisture values were increased by 20–50% to assess potential waterlogging susceptibility caused by utility leaks and/or a rise in the groundwater level. Moisture distribution maps and zoning of the study area based on the liquidity index were created. The results showed that under baseline conditions, the area was characterized by predominantly solid soil consistency, whereas an increase in moisture led to the formation of extensive zones of plastic and liquid consistency. The most potentially unfavorable conditions were identified in the southeastern and northwestern parts of the study area. At the same time, the proportion of the area with normal soil conditions decreases from 97.0% to 21.5%, while the risk and waterlogged zones increase to 56.1% and 22.4%, respectively. The proposed approach enables a spatial assessment of changes in the hydrophysical state of soils across large urban areas and can be used in engineering-geological surveys and the monitoring of building and facility foundations, including those in operation.



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Түйінді сөздер:

су басу, аққыштық
индексі, топырақ
ылғалдылығы, кеңістіктік
модельдеу, инженерлік-
геологиялық жағдайлар.

ТҮЙІНДЕМЕ

Жұмыста Астана (Қазақстан) қаласының сол жағалау аумағы мысалында топырақтың гидрофизикалық күйіне ылғалдылықтың өзгеруінің әсері қарастырылды. Зерттеу 12 құрылыс нысаны бойынша біріктірілген 141 инженерлік-геологиялық ұңғыманың деректерін талдауда негізделген. Негізгі параметрлер ретінде топырақтың табиғи ылғалдылығы, аққыштық шегі, икемділік шегі және аққыштық индексі қолданылды. Топырақ күйінің кеңістіктік өзгеруін бағалау үшін кеңістіктік модельдеу әдістері және spline-интерполяциясы ArcGIS Pro ортасында қолданылады. Екі сценарий модельденді: қолда бар инженерлік-геологиялық деректерге негізделген негізгі сценарий және жоғары ылғалдылықтағы синтетикалық сценарий, онда инженерлік желілерден ағып кету және/немесе жер асты суларының деңгейінің жоғарылауы нәтижесінде су тасқынының ықтимал әсерін бағалау мақсатында ылғалдылық мәндері 20-50 %-ға ұлғайтылды. Ылғалдылық таралу және аумақтандыру карталары аққыштық индексі бойынша салынған. Нәтижелер көрсеткендей, бастапқы жағдайларда аумақ негізінен топырақтың қатты консистенциясымен сипатталды, ал ылғалдылық жоғарылаған кезде пластикалық және сұйық консистенцияның кең аймақтары пайда болды. Ең ықтимал қолайсыз жағдайлар зерттелетін аумақтың оңтүстік-шығыс және солтүстік-батыс бөліктерінде анықталды. Бұл ретте топырақтың қалыпты күйі бар аумақтың үлесі 97,0 %-дан 21,5 %-ға дейін төмендеді, ал тәуекел және су басу аймақтары тиісінше 56,1 %-ға және 22,4 %-ға дейін ұлғайды. Ұсынылған тәсіл кең қалалық аумақтардағы топырақтың гидрофизикалық күйінің өзгеруін кеңістіктік бағалауға мүмкіндік береді және инженерлік-геологиялық зерттеулер мен имараттар мен имараттардың негіздерін, соның ішінде пайдаланылатын кезеңде мониторингтеу кезінде пайдаланылуы мүмкін.

Ключевые слова:

подтопление, индекс
текучести, влажность
грунтов,
пространственное
моделирование,
инженерно-
геологические условия.

АННОТАЦИЯ

В работе рассмотрено влияние изменения влажности на гидрофизическое состояние грунтов на примере территории левобережной части города Астана (Казахстан). Исследование основано на анализе данных 141 инженерно-геологической скважины, объединенных по 12 объектам застройки. В качестве основных параметров использованы природная влажность грунтов, предел текучести, предел пластичности и индекс текучести. Для оценки пространственного изменения состояния грунтов применены методы пространственного моделирования и Spline-интерполяция в среде ArcGIS Pro. Было смоделировано два сценария: базовый сценарий, основанный на имеющихся инженерно-геологических данных, и синтетический сценарий с повышенной влажностью, в котором значения влажности были увеличены на 20–50 % с целью оценки потенциальной подверженности подтоплению в результате утечек из инженерных сетей и/или повышения уровня грунтовых вод. Построены карты распределения влажности и зонирования рассматриваемой территории по индексу текучести. Результаты показали, что при исходных условиях территория характеризовалась преимущественно твердой консистенцией грунтов, тогда как при увеличении влажности формируются обширные зоны пластичной и текучей консистенции. Наиболее потенциально неблагоприятные условия выявлены на юго-восточной и северо-западной

частях исследуемой территории. При этом доля территории с нормальным состоянием грунтов снижается с 97,0 % до 21,5 %, а зоны риска и подтопления увеличиваются до 56,1 % и 22,4 %, соответственно. Предложенный подход позволяет выполнять пространственную оценку изменения гидрофизического состояния грунтов на обширных городских территориях и может быть использован при инженерно-геологических изысканиях и мониторинге оснований зданий и сооружений, в том числе в эксплуатируемый период.

INTRODUCTION

The current urban development of Astana, Kazakhstan, is accompanied by an intensive transformation of the natural and man-made environment, leading to significant changes in the area's hydrogeological conditions (Atakhanova & Baigaliyeva, 2025). Increased building density, the expansion of impervious surfaces, disruption of natural drainage, and the active operation of utility infrastructure are creating water exchange conditions in the subsurface that are entirely different from those that existed before the area was developed (Błaszczak-Bak et al., 2025). Under these conditions, one of the most acute and systemic problems is anthropogenic waterlogging, a process of gradual rise in the groundwater level (GWL) and increase in the natural moisture content of soils caused by human factors (Zeydalinejad et al., 2024).

A distinctive feature of the phenomenon under consideration is its latent nature (J. Zhou et al., 2026). Unlike classic waterlogging, which involves groundwater clearly rising to the surface, so-called "hidden waterlogging" is more commonly observed in urban areas; in this case, soil moisture and saturation levels increase without a noticeable change in the water table (Li et al., 2024). The main causes of this process are filtration losses from water-carrying utilities, infiltration of atmospheric precipitation due to insufficient storm sewer efficiency, and changes in infiltration flows resulting from site engineering (Kravchenko et al., 2024).

The engineering-geological conditions of Astana are characterized by the widespread occurrence of cohesive clayey soils (in particular, loams and clays), whose physical and mechanical properties are largely defined by their moisture content (Mussabayev et al., 2023). Under natural conditions, these soils are typically in a solid or semi-solid consistency, possessing sufficient strength and resistance to deformation (Spoor & Godwin, 1979). However, as moisture content increases, their consistency changes predictably, a phenomenon described by the soil's plasticity limit (W_p) and liquid limit (W_L) (B. Zhou & Lu, 2021). The latter determines the soil's transition to an unstable state, upon reaching which the soil structure collapses and its shear resistance drops sharply (Nofrizal & Istijono, 2026). Quantitatively, this transition can be expressed using the liquidity index (I_L) (Mukhamejanova et al., 2026). Thus, when $I_L > 1$, the soil transitions to a liquid consistency, which is accompanied by a loss of bearing capacity in the foundation. Under waterlogged conditions, an increase in natural moisture content (W) leads to a rise in the liquidity index, making this parameter an indicator of geotechnical risk (Nofrizal & Istijono, 2026). Prolonged exposure to elevated moisture in clayey soils with a high plasticity index triggers a complex of negative processes, including reduced cohesion, increased compressibility, the development of uneven settlements, and the intensification of frost heave during the winter (Bragar et al., 2022). Collectively, this leads to a deterioration in the operational reliability of buildings and an increased risk of catastrophic deformations (Ayadat, 2021).

Recent studies (Qader et al., 2023; Samson et al., 2017) highlight the growing importance of integrating geographic information systems (GIS) with sensor technologies for continuous soil condition monitoring. The use of moisture sensors in combination with geoportal solutions enables the dynamic updating of geotechnical parameters (Kootanoor Sheshadrivasan et al., 2025; Tornese et al., 2024). A number of studies are devoted to the creation of digital maps of the distribution of geotechnical soil characteristics. For example, in (Haifani et al., 2023), which

addresses the mapping of geotechnical soil properties using GIS and interpolation via the inverse distance weighting (IDW) method, continuous surfaces of moisture content, plasticity limits, and other soil parameters, making it possible to identify potentially hazardous zones for construction. Similar approaches are used in the construction of geotechnical zoning maps and the assessment of subgrade bearing capacity based on Kriging and Empirical Bayesian Kriging (EBK) methods (Rahman et al., 2026). A separate area of research focuses on the spatial modeling of soil moisture and water saturation distribution, where GIS technologies, remote sensing, and geostatistical methods are used to create maps of areas' susceptibility to waterlogging and changes in hydrogeological conditions (Shirzadi et al., 2025). The work on creating a unified geotechnical database for Kazakhstan emphasizes the importance of spatial analysis of moisture content, plasticity, and liquidity limits in assessing the behavior of foundation soils (Zhussupbekov et al., 2020). Despite the widespread use of GIS technologies in the analysis of hydrogeological processes and engineering-geological conditions, most existing studies focus primarily on mapping individual parameters, such as soil moisture, groundwater level, or plasticity index at the moment of the survey, without considering scenarios of changes in the consistency of foundation soils caused by natural or anthropogenic water saturation during the operational period, as well as their spatial assessment. In this regard, this study proposes an approach aimed at the spatial assessment of the hydrophysical state of soils using a liquidity index and the zoning of waterlogged areas as their moisture regime changes.

The novelty of the present study is not limited to mapping individual hydrophysical parameters. The proposed workflow links engineering-geological survey data, scenario-based moisture modification, GIS interpolation, and soil consistency classification through the liquidity index within one spatial zoning procedure. This makes it possible to move from descriptive maps of soil moisture or plasticity limits to engineeringly interpretable maps showing the potential transition of foundation soils from a normal state to risk and waterlogging-prone states. The approach is transferable to other urban areas where borehole-based geotechnical data are available and can support preliminary geotechnical zoning, monitoring planning, and the identification of zones requiring more detailed field verification.

MATERIALS AND METHODS

The proposed approach was tested in the left-bank area of Astana, which was previously characterized by waterlogged and marshy conditions. Satellite imagery from 2006 and 2025 was used as the basis for analyzing the area's transformation (Figure 1). A comparison of the images shows that in 2006, the area consisted of a system of water bodies and waterlogged lands with a high water table. By 2025, the area had developed dense urban development, a road network, and engineering infrastructure, while natural water bodies had been largely dried up.



Figure 1. Condition of the left-bank area of Astana

Within the study area delineated using satellite imagery (Figure 2), 12 construction sites were identified for which engineering-geological survey (EGS) data were obtained (Guzyr, 2025). Based on the available data, a database was created containing information on 141 engineering-geological boreholes. For the present spatial assessment, the borehole data were first grouped by the 12 construction sites, and the mean values of W , W_L , W_p , and I_L were calculated for each site. These site-level averaged values were then linked to the geographic coordinates of the corresponding sites and used as interpolation points. This aggregation was used because the available archival materials were organized by development sites and because the objective of the study was to assess the spatial tendency of hydrophysical conditions at the urban-area scale rather than to reproduce local borehole-scale heterogeneity. At the same time, this averaging inevitably reduces the representation of small-scale spatial variability between individual boreholes; therefore, the resulting maps should be interpreted as generalized zoning maps suitable for preliminary assessment and monitoring planning.

According to the EGS data (Guzyr, 2025), the territory is characterized primarily by clayey soils in a solid and semi-solid consistency. This is confirmed by the average values of the hydrophysical properties summarized in Table 1.

Table 1. Hydrophysical properties of soils (Guzyr, 2025)

Site No.	Average W , %	Average W_L , %	Average W_p , %	Average I_L
1	11.85	25.29	18.14	-0.87
2	15.2	27.85	19.67	-0.54
3	14.7	28.63	19.27	-0.48
4	14.24	24.5	17.51	-0.46
5	15.59	31.43	20.17	-0.4
6	19.24	33.49	23.21	-0.38
7	17	25.97	19.47	-0.38
8	14.35	22.817	16.547	-0.35
9	19.16	31.77	21.91	-0.27
10	16.76	26.06	17.44	-0.07
11	14	26.17	14.83	-0.07
12	13	19.09	13.08	-0.01
<i>Note – The object locations are shown in Figure 1b</i>				

An analysis of natural moisture content shows that the highest values are observed at sites 5, 6, 9, and 10, indicating a higher degree of water saturation there compared to the other sites, apparently due to the presence of water bodies in those areas before urban development (Figure 1a). At the same time, even the maximum moisture values remain below the plasticity limit, which is consistent with negative I_L values. Nevertheless, given the historically established hydrophysical conditions of the territory, the spatial heterogeneity of the soil mass, as well as possible natural and anthropogenic changes in the soil profile, it can be assumed that even a slight increase in moisture content is capable of leading to a local deterioration of engineering-geological conditions and the development of hidden waterlogging processes. To assess such a scenario, synthetically modified W values were introduced (Figure 2). The moisture values were increased within a range of 20–50% relative to the baseline values, depending on the initial hydrophysical condition of each site and its location relative to historically waterlogged areas visible in the 2006 satellite image. The scenario should be regarded as a sensitivity-based waterlogging scenario rather than as a directly measured forecast. The lower increments were assigned to sites with lower initial moisture and less evident proximity to former water bodies,

whereas higher increments were assigned to sites with higher baseline moisture or location within historically waterlogged parts of the area. This approach was used to test how the liquidity-index zoning would respond to plausible anthropogenic moistening caused by utility leaks and/or GWL rise.



Figure 2. Synthetic and baseline values of W at the construction sites

According to (*GOST 25100-2020, Soils. Classification, 2020*), an increase in moisture content has a direct effect on the condition of clayey soils, which is quantitatively assessed using the I_L , defined by the following expression:

$$I_L = \frac{W - W_p}{W_L - W_p} \quad (1)$$

As moisture content increases, the I_L value rises, reflecting the transition of soils from a solid and semi-solid consistency to a plastic consistency, and, with further water saturation, to a liquid consistency. Depending on the I_L values, soil consistencies are classified as solid ($I_L < 0$), plastic ($0 \leq I_L \leq 1$), and liquid ($I_L > 1$) (*GOST 25100-2020, Soils. Classification, 2020*), which in [11] are proposed to be associated with the normal state, the risk state, and the state of waterlogging of the bases of buildings and facilities.

To assess the effect of changes in W on soil consistency when considering a scenario with synthetic data, the values of W_L and W_p were assumed to be constant, since these parameters were determined based on the results of engineering-geological surveys and are typical for soils found in the study area. The only variable parameter was W, an increase in which simulated possible soil moistening (e.g., a possible consequence of leaks in utility lines and/or a GWL rise).

The Spline interpolation method was used for spatial modeling of the distribution of soil hydrophysical properties (Mariani & Basu, 2015). This method was selected because the purpose of the study was to obtain continuous generalized surfaces of hydrophysical parameters over the study area, while the number of interpolation points was limited to 12 site-level averaged values. Compared with IDW, Spline produces smoother surfaces and avoids abrupt local changes around individual points; and compared with Kriging, it requires fewer assumptions about the variogram structure, which is difficult to estimate reliably when the number of points is limited (Igaz et al., 2021; Qaraghuli et al., 2025). Therefore, Spline was considered appropriate for preliminary urban-scale zoning. However, no independent borehole dataset was available for cross-validation; therefore, the interpolation results should be interpreted as generalized spatial tendencies rather than as validated point predictions. Future work should compare Spline, IDW, Kriging, and EBK using borehole-level data and independent validation points.

The interpolation was performed in ArcGIS Pro 3.5 software (ESRI, Environmental Systems Research Institute, Redlands, California, USA) using the Spatial Analysis tools (ESRI, 2026). The input layer consisted of 12 point features corresponding to the construction sites shown in Figure 1b. Each point contained the averaged values of W, W_L , W_p , and I_L . The same

interpolation extent was used for the baseline and synthetic scenarios, corresponding to the boundary of the study area shown in Figures 3 and 4. After interpolation of W and calculation of IL , the resulting raster was reclassified into three zones: normal state, $IL < 0$; risk state, $0 \leq IL \leq 1$; and waterlogging-prone state, $IL > 1$. The percentage of each zone was calculated as the ratio between the raster-cell area of the corresponding class and the total modeled area. Because the archival source data are associated with construction sites, the exact borehole coordinates are not reproduced in the paper; however, the point locations used for modeling are shown in Figure 1b and can be provided upon reasonable request.

RESULTS AND DISCUSSION

The results of spatial modeling under the baseline values of hydrophysical properties are presented below in the form of thematic maps of the W -distribution and IL -zoning (Figure 3).

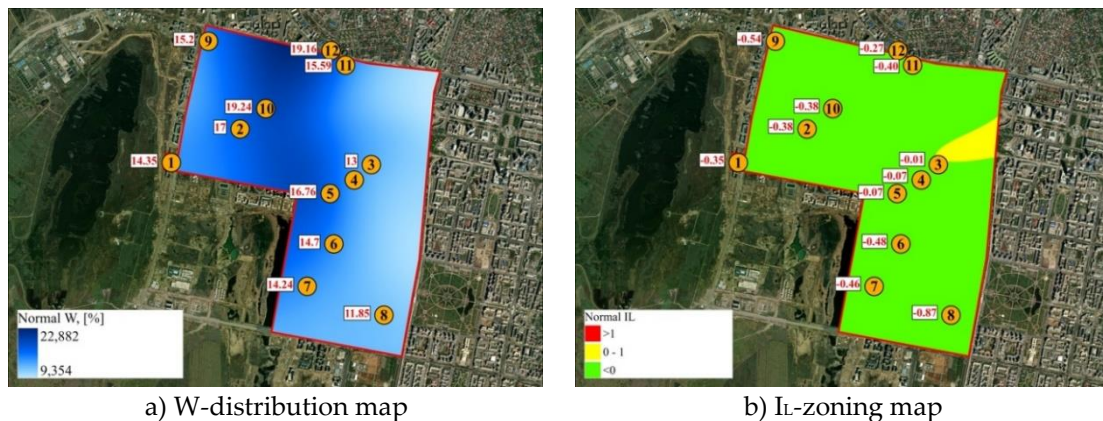


Figure 3. Modeled baseline hydrophysical conditions of the study area

The resulting maps reflect the current engineering-geological conditions of the study area without accounting for additional water saturation. Analysis of moisture distribution reveals the presence of localized zones with elevated moisture content, primarily in the central and northwestern parts of the study area. At the same time, the southern and southeastern sections are characterized by lower moisture values. IL zoning demonstrates the predominance of soils with a solid consistency (i.e., the normal zone with $IL < 0$) in the area. However, in certain zones, such as the southeastern part of the territory near site No. 3, values close to zero are recorded, indicating the potential sensitivity of the soils to additional moistening. The results of the simulation with synthetically increased soil moisture values are presented in Figure 4.

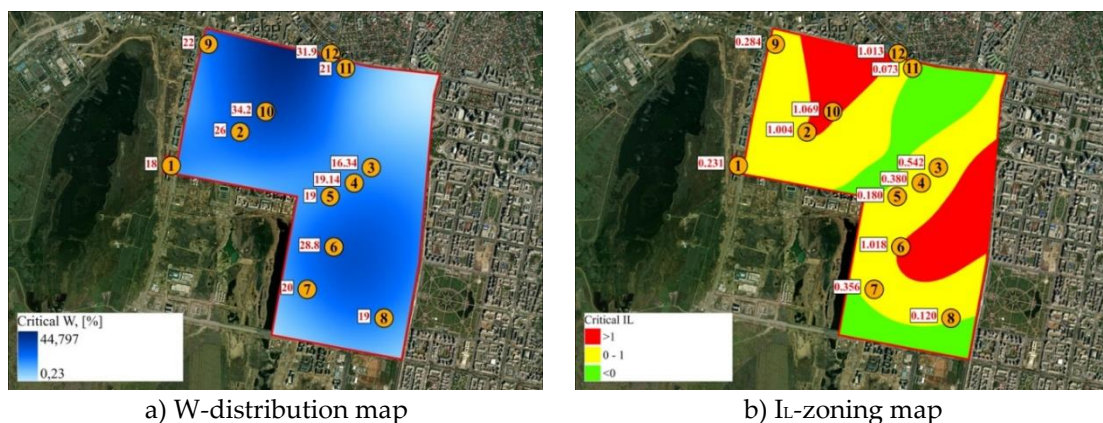


Figure 4. Modeled synthetic hydrophysical conditions of the study area

An analysis of the distribution map in Figure 4a reveals a significant increase in W values across the entire territory, with the highest values recorded in the southeastern and northwestern sections. The systematic change in soil consistency in these sections is demonstrated by the I_L zoning (Figure 4b). Thus, while under baseline conditions the territory was characterized primarily by a solid consistency ($I_L < 0$), increased moisture levels result in the formation of extensive zones of plastic ($0 \leq I_L \leq 1$) and liquid consistency ($I_L > 1$). The most unfavorable situation is observed near sites 2, 6, 10, and 12, where I_L values exceed one (highlighted in red in Figure 4b), corresponding to a waterlogged zone. The rest of the territory is predominantly classified as a risk zone, indicating high soil sensitivity to additional moistening.

The results obtained are consistent with the findings of (Haifani et al., 2023), where GIS modeling and spatial interpolation methods were used to identify local areas of geotechnical risk. However, unlike [18], where the main focus was on assessing potential soil liquefaction, the analysis in this study is based on changes in the liquidity index as moisture content increases, which allowed for the assessment of the transition of soils from a stable state to a plastic and liquid consistency when saturated with water. Unlike (Rahman et al., 2026), where spatial interpolation was used to assess soil bearing capacity, in this study, the spatial analysis was performed based on changes in the liquidity index, which allowed for the assessment of the potential transition of soils to a plastic and liquid consistency upon water saturation. The obtained patterns are also consistent with the conclusions of (Shirzadi et al., 2025); however, unlike that study, which focused on mapping susceptibility to waterlogging, this work assesses changes in the engineering state of soils using the liquidity index.

Figure 5 shows the ratios of the area coverage of various hydrophysical states for the baseline and synthetic scenarios.

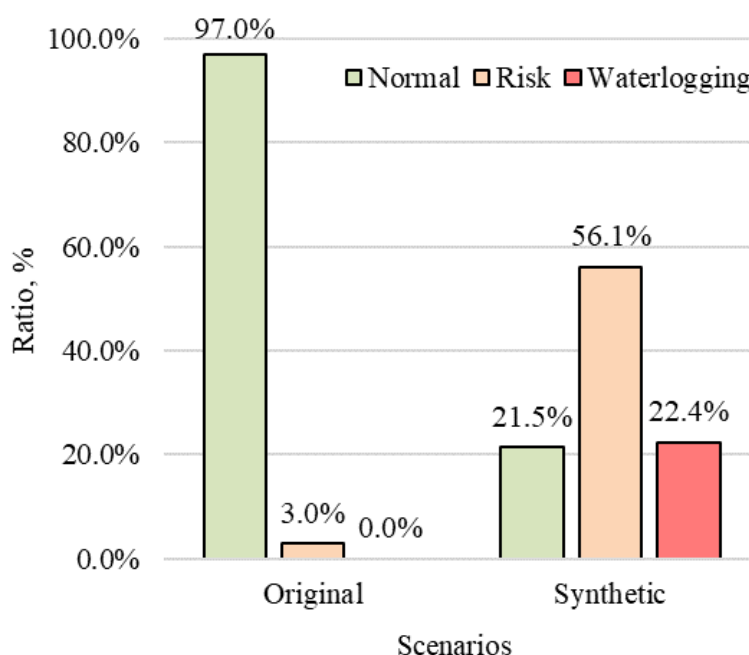


Figure 5. Area ratios of hydrophysical state zones under baseline and synthetic scenarios

Figure 5 shows a significant change in the hydrophysical state of the territory with an increase in moisture. Under baseline conditions, the normal zone predominates, covering 97.0% of the territory, while the risk zone accounts for only 3.0%, and there is no waterlogging. With

increased moisture, there is a sharp decrease in the ratio of the normal zone to 21.5%. At the same time, the ratio of the risk zone increases significantly to 56.1%, and a substantial waterlogged zone forms, covering 22.4% of the territory. Thus, the modeling showed that as moisture increases, even with constant W_L and W_p values, there is a sharp deterioration in the engineering-geological conditions.

The results obtained confirm the findings of (Nofrizal & Istijono, 2026), according to which an increase in moisture content leads to an increase in the liquidity index and a decrease in the stability of clayey soils. Unlike the laboratory modeling presented in (Nofrizal & Istijono, 2026), in this study, this relationship was spatially interpreted using GIS technologies, which made it possible to assess the distribution of risk and flooding zones within the urban area.

It should be emphasized that the synthetic scenario does not represent confirmed present-day waterlogging or a deterministic forecast of future waterlogging. The red and yellow zones in Figure 4b indicate the modeled susceptibility of the soils to transition into liquid or plastic consistency under the assumed moisture increase. Therefore, these zones should be interpreted as areas requiring increased attention, additional field verification, and possible monitoring, rather than as zones where waterlogging has already been empirically confirmed.

Figure 6 shows the results of the analysis of the distribution of I_L values by consistency and scenarios (baseline and synthetic) in the form of a Boxplot diagram.

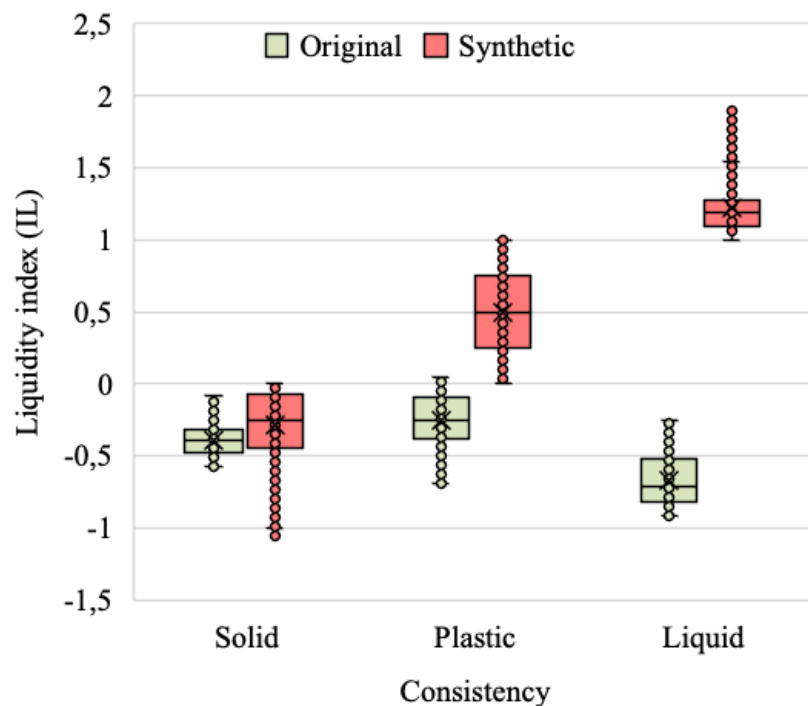


Figure 6. Distribution of I_L values by soil consistency and scenarios

Figure 6 was constructed using the I_L values extracted from the classified raster cells for each scenario. The groups labelled 'solid', 'plastic', and 'liquid' correspond to the soil-state classes defined by the I_L thresholds: solid consistency or normal state, $I_L < 0$; plastic consistency or risk state, $0 \leq I_L \leq 1$; and liquid consistency or waterlogging-prone state, $I_L > 1$. For comparison, the distribution of I_L values within the same spatial classes is shown for both the baseline and synthetic scenarios. Thus, the boxplots illustrate not only the change in median I_L values but also

the widening of variability caused by the assumed increase in moisture. As shown in Figure 6, in the baseline scenario, the I_L values for the solid consistency ranged from approximately -0.6 to -0.2, with a median of about -0.4, which corresponds to the normal hydrophysical state of the soils. As moisture content increases in the synthetic scenario, the range widens (from -1.0 to -0.1), and the median remains in the negative range (around -0.3); however, greater variability and isolated outliers appear, indicating the initial sensitivity of the soils to moistening. The most pronounced change is observed in the plastic consistency. In the baseline state, I_L varies between -0.7 and 0, with a median of about -0.3, meaning that most values still correspond to a normal hydrophysical state. In the synthetic scenario, the values shift to the range from 0 to 1.0, and the median is approximately 0.5, which clearly reflects the transition of soils into the risk zone. In the liquid consistency, the differences are greatest. Under baseline conditions, I_L values range from -0.9 to -0.3 (median is about -0.7), indicating a normal state. As moisture increases, the values rise sharply from 1.0 to 1.9, with a median of about 1.3, corresponding to the transition of soils into the waterlogging zone.

The observed patterns are consistent with (Bragar et al., 2022; Mukhamejanova et al., 2026; Nofrizal & Istijono, 2026; B. Zhou & Lu, 2021), which show that an increase in moisture content is accompanied by a deterioration in the strength and deformation properties of cohesive soils. However, (Bragar et al., 2022; Mukhamejanova et al., 2026; Nofrizal & Istijono, 2026; B. Zhou & Lu, 2021) focus primarily on laboratory evaluation of soil properties, whereas in this study, these changes were interpreted using spatial modeling and mapping of the liquidity index distribution. This made it possible to assess not only changes in individual soil parameters but also the spatial distribution of zones of potential waterlogging and geotechnical risk within the entire study area.

The proposed approach can be scaled through implementation in a geoinformation portal. However, to improve the accuracy and timeliness of the assessment, a system for dynamic monitoring of soil moisture using probes (at least one per site) must be established. Integrating incoming data into the model will enable automatic recalculation of the liquidity index and updating of soil state maps, facilitating the transition from static assessment to real-time monitoring and forecasting of waterlogged zones.

CONCLUSION

A study conducted based on the example of the left bank of Astana showed that an increase in soil moisture leads to a significant change in their hydrophysical state and the formation of areas prone to waterlogging within the territory. Spatial modeling established that, under baseline conditions, the area under consideration was characterized by predominantly solid soil consistency with negative values of the liquidity index (I_L) ranging from -0.87 to -0.01. With a synthetic increase in moisture content, extensive zones of plastic ($0 \leq I_L \leq 1$) and liquid ($I_L > 1$) consistency formed.

The modeled scenario indicates that the southeastern and northwestern parts of the study area are the most susceptible to unfavorable engineering-geological changes under additional moistening, with an I_L value exceeding 1.0, corresponding to areas prone to waterlogging. At the same time, the proportion of the territory with normal soil state decreases from 97.0% to 21.5%, while the area of the risk zone increases to 56.1%, and that of the waterlogging-prone zones— to 22.4%. Median I_L values in the liquid consistency increase to 1.3, which may lead to a sharp deterioration in the engineering condition of the soils with additional moistening.

The results obtained confirmed the high sensitivity of soils to changes in their hydrophysical condition and demonstrated the effectiveness of using I_L for the spatial assessment of the transformation of engineering-geological conditions. Unlike existing

studies, which focus primarily on mapping individual hydrophysical parameters, the proposed approach allows for the assessment of changes in soil condition and the potential transition of soils to a plastic and liquid consistency based on spatial modeling and mapping.

The practical significance of this work lies in the applicability of the proposed approach to preliminary engineering-geological zoning, monitoring planning, and the assessment of foundation-soil susceptibility to hydrophysical changes in urban environments. However, the results should be interpreted with several limitations. The synthetic scenario represents assumed moisture increases and does not confirm actual waterlogging at the modeled sites. The interpolation was based on site-level averaged data, which reduces the representation of borehole-scale heterogeneity. In addition, the generated maps were not validated against independent monitoring data or documented foundation performance. Therefore, future research should include borehole-level interpolation, comparison of several interpolation methods, installation of soil moisture monitoring probes, and validation using field observations.

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