Eco Cities 2025, 6(1), 3331.
https://doi.org/10.54517/ec3331

Article

Engineering and geological environment of urban areas: Experience from Kharkiv, Ukraine (1960–2020)

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CITATION

Iegupov V, Strizhelchik G. Engineering and geological environment of urban areas: Experience from Kharkiv, Ukraine (1960–2020). Eco Cities. 2025; 6(1): 3331.
https://doi.org/10.54517/ec3331

ARTICLE INFO

Received: 24 February 2025
Accepted: 15 April 2025
Available online: 23 April 2025

Abstract: The article presents the results of the generalization and analysis of the development of engineering-geological and hydrogeological environments in the territory of a large city, Kharkiv, Ukraine, from the 1960s to the present day. The study is based on the authors' many years of experience performing engineering surveys for construction in many cities of the former USSR, primarily Ukraine. Engineering-geological processes and phenomena with adverse consequences for buildings, structures, and populations that occur in urban areas as a result of insufficiently thought-out organizational, design, and construction solutions are listed. The process of flooding of urban areas by groundwater (FGW) is chosen as an example, which is a trigger for many negative and dangerous processes and phenomena, changes in the properties of soils and the geological environment. The main concepts associated with flooding, FGW indicators, causes and factors of its occurrence and development are given. The characteristics of FGW features for the conditions of the city of Kharkiv are given, and the most significant above-ground, near-surface and underground factors of flooding are highlighted. Some examples of construction and organizational solutions in the territory of Kharkiv are given. The article discusses approaches to combating flooding by installing protective structures, primarily drainage of various types, i.e., creating gray infrastructure. Much more promising is the installation of blue-green infrastructure (BGI), references are given to examples of its implementation, as well as other solutions based on nature. The creation of BGI is crucial for the harmonious coexistence of natural and anthropogenic landscapes, water management, and reducing the impact on the surface and underground hydrosphere.

Keywords: urbanization; adverse processes; groundwater flooding; blue-green infrastructure; Kharkiv

1. Introduction

This article is a preliminary attempt to summarize our extensive experience monitoring the development and change of geological and hydrogeological conditions within a large city. For more than half a century, we have accumulated this experience by conducting engineering-geological, hydrogeological, and geotechnical surveys for construction, processing and analyzing various materials, and conducting examinations in non-standard situations at construction sites and existing facilities, both aboveground and underground.

Obviously, it is impossible to fully summarize this topic within the framework of one article or even several. However, we believe it is important to highlight the key factors that have influenced the underground environment of the city, the emergence and development of unfavorable processes, as well as the ambiguous results of efforts to solve these problems. In addition, numerous natural and anthropogenic factors of influence are considered through the prism of the sustainability resource (SR) of the underground environment, meaning its ability to withstand various impacts while maintaining its integrity and functionality within acceptable limits.

2. Materials and methods

It should be noted that starting from the second half of the 20th century and up to the present day, scientists' interest in changes in natural conditions, including the geological environment of large cities and urban-industrial agglomerations, has increased significantly. Scientific works describe changes associated with climatic factors, the geological structure of individual areas, changes in the surface and underground hydrosphere regime, a decrease in some activity, and, conversely, an increase in the activity of other processes. In the 21st century, ideas are developing for creating a harmonious environment in cities that are resistant to climate change, floods, surface subsidence, and other negative processes [1–3] based on nature-based solutions, the creation of active green constructions, green and blue infrastructure, etc. [4–8].

The source materials for our analysis are scientific and technical survey reports, most of which are stored in the archives of the scientific and production and design institutes UkrvostokGIINTIZ, DIPROzavodtrans, and Kharkivmetroproekt in Kharkiv. There are many articles published by the authors in the public domain on the topic of the study; we will provide links only to our articles in English [9–14].

Our observations and special studies in the territory of Ukraine's largest cities—Kharkiv, Kyiv, Donetsk, Dnepr, and others—allowed us to establish several patterns in changes in the geological environment. The results obtained made it possible to make optimal decisions about the construction of protective structures, foundations, and building structures in complex engineering and geological conditions, and in some cases, to practically avoid accidents during urban construction.

As an example for this study, we chose the consideration and analysis of one of the main problems caused by changes in the geological environment during the development of the city of Kharkiv from 1960 to 2020.

3. Results and analysis

3.1. Brief description of the city

Kharkiv is the second largest and most important city in Ukraine with a population of over 1.4 million people and a correspondingly developed industrial, residential, and cultural infrastructure in an area of approximately 350 km^2. It is located in the northeast of the country within the loess plain, cut by numerous ravines, gullies, and valleys of the small rivers Udy, Lopan, Kharkiv, Nemyshlya, and Netech (**Figure 1**).

The age of the city of Kharkiv is more than 350 years. Urban civil and industrial construction was carried out at a gradually increasing pace, and suburban areas were developed. Kharkiv was chosen as the most industrially developed city in Ukraine.

Numerous large machine-building plants required many workers, and the intensive growth of the city's population was accompanied by mass housing construction.

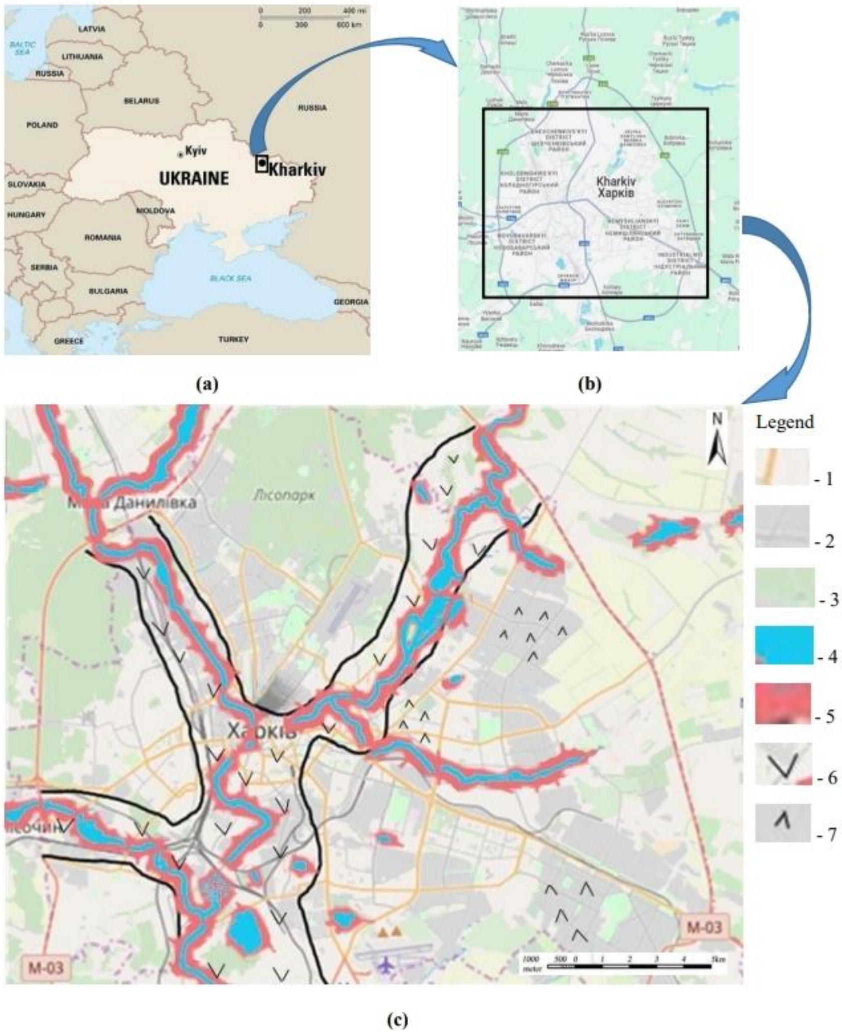

Figure 1. (a) Geographical location of Kharkiv in Ukraine; **(b)** City plan; **(c)** Development scheme, including surface and groundwater flooding: 1—older low-rise buildings mixed with high-rises; 2—mainly industrial and residential multi-story buildings (built since the 1960s); 3—green spaces; 4—rivers; 5—zones prone to flooding by surface water; 6—areas with elevated groundwater levels; 7—spots experiencing periodic flooding due to human activities.

Particularly intensive development of the lands adjacent to the city began in the early 1960s of the twentieth century. Mass housing construction began. At first, these were five-story buildings, and later nine-, twelve-, sixteen-story buildings. Both suburban areas were built up, and old single-story buildings were partially demolished and new multi-story buildings were built. To date, multi-story housing is being built mainly on empty city sites.

For transport communication, the Kharkiv metro system was built, including three operating lines with a total length of more than 40 km and 30 underground stations.

3.2. Changes in the engineering-geological environment

Scientific and technical reports and scientific literature provide a lot of information about changes in the geological environment in the process of residential and industrial development of territories. Many negative processes are caused by the following specific factors:

- Static and dynamic loads on soils during construction;
- Violation of existing natural conditions on the slopes of river valleys (changes in vegetation, road construction, construction);
- Violation of the surface water regime due to regulation of river flow by dams;
- Violation of the natural regime of groundwater due to intensive water intake in some areas with the creation of depression funnels and, conversely, an increase in the level and flooding of buildings and structures by groundwater in other areas;
- Increase in infiltration feeding during the construction of reclaimed areas for subsequent construction;
- Leaks from water communications and condensation of water vapor under asphalt and other surfaces.

These and other man-made impacts lead to the emergence of a whole series of negative and dangerous processes (landslides, karst, and suffusion failures, subsidence of the surface above underground workings, subsidence of loess soils, swelling and shrinkage of soils in the foundations of buildings and structures, changes in the strength properties of soils in the foundations of buildings, flooding of buried parts of houses, etc.). Often such changes are threatening and even dangerous and significantly complicate the engineering and geological conditions of the urban area.

Starting from about the 70s, negative engineering, and geological processes and phenomena, sometimes with dangerous consequences, began to manifest themselves increasingly in the city of Kharkiv. The authors of the article, who worked for many years in Kharkiv in research engineering and geological surveys for construction, often encountered negative manifestations and even emergencies associated with unforeseen changes in geological and hydrogeological conditions. The most memorable was the flooding of the main sewage pumping station, which could not cope with the huge volume of water that entered the sewage system after an exceptionally intense downpour, which led to the forced shutdown of the centralized water supply for a month [10]. There was a process of slow floating up of one of the shallow metro stations as a result of a sharp rise in the groundwater level, which required the reconstruction of the station with the weighting of the structures [9]. There were numerous cases of flooding of basements with groundwater, subsidence of loess soils, failures of the earth’s surface, activation of landslide processes in certain areas.

3.3. Flooding by groundwater

One of the most common unfavorable processes associated with the development of territories is flooding by groundwater (FGW). Briefly, it can be defined as a hydrogeological process in urban areas, due to the combined effect of causes and factors of both natural and man-made origin. During the billing period, soil moisture increases, or the groundwater level rises to limit values that violate the conditions for the construction and operation of buildings and structures.

The main concepts associated with flooding are given in **Table 1**. This table is based on the state building codes of Ukraine DBN, the text is shortened and edited.

Table 1. Terms and definitions [15].

Terms	Definition
Flooding, (inundation) by surface water	Formation of a free water surface on the territory due to an increase in the level of a watercourse, reservoir and accumulation of surface water in lowlands.
Flooding by groundwater	A hydrogeological process occurs under certain conditions, including in urban areas, due to the combined effect of causes and factors of both natural and man-made origin. During the billing period, soil moisture increases, or the groundwater level rises to limit values that violate the conditions for the construction and operation of buildings and structures. Green spaces are also oppressed and killed, and salinization and swamping of lands occur.
Areas prone to flooding by groundwater or surface water	All areas of cities and towns are prone to flooding and inundation, where increased soil moisture, rising groundwater levels, or flooding have already led or may lead in the future (according to forecasts) to a significant deterioration in living conditions of the population and economic activity.
Flooded areas	Areas where the groundwater level rises permanently or temporarily above a critical depth for a sufficiently long period (a month or more) or where flooding occurs that significantly affects buildings and structures.
Flooded areas requiring urgent protection	Flooded areas where an emergency has developed related to flooding, inundation, and their consequences, resulting in unsatisfactory sanitary and hygienic or environmental conditions.
Potentially flooded areas	Areas where the conditions for classifying them as flooded have not yet developed but this is possible according to the forecast or with the simultaneous action of several factors and causes. These are areas where a high occurrence of water-resistant soil layers, a lithological structure, and relief contribute to the accumulation of precipitation and infiltration of waters, including man-made leaks.
Limit depth of groundwater	Depth from the earth’s surface to the maximum groundwater level permitted by the project or forecast for the entire period of operation of territories, buildings, and structures.

It should be immediately emphasized that it should not be confused with a similar process, flooding (inundation) by surface water (FSW), which has a fundamentally different nature and course [16].

As noted above, flooding is unfavorable in itself but is often a trigger for other, even more dangerous processes (landslides, surface failures, increased seismicity).

Groundwater flooding is observed in many cities around the world, including Naples [17], Almaty [18], and Milan [19]. In Ukraine, besides Kharkiv, this issue also affects Kyiv, Dnipro, Zaporizhzhya, and Odesa, and to varying degrees, it is present in many other areas as well [10,15,20].

The causes and factors causing this process are very numerous. The time of their impact is either constant, periodic, or irregular. The influence of one or another factor on the development of flooding in any particular area can be determined by one or two main reasons, while in another area the reasons may be completely different. This depends on the location of the area relative to rivers, and ravines, the geological structure and permeability of soils, the intensity of infiltration, the screening effect of buildings, the presence of leaks from water networks and technological processes of enterprises, etc.

3.4. Features of flooding by groundwater in Kharkiv

In general, flooding of urban areas, compared to natural undeveloped lands, has a man-made or, one might say, anthropogenic nature and consists, first of all, in the violation of the water balance: incoming components, i.e., the amount of water entering the built-up area (water supply, increased precipitation infiltration, etc.), exceed outgoing components (water drainage, reduced evaporation and transpiration, etc.). This causes an increase in groundwater infiltration and, as a consequence, an increase in their level.

The same applies to the urban areas of Kharkiv. Based on our experience and analysis of the history of flooding, we have compiled a diagram of the main factors causing this process (**Figure 2**).

The main factors can be divided into three groups: above-ground, near-surface, and underground.

Above-ground factors (above the earth's surface):

- Poor drainage of precipitation from the territory. Due to deficiencies in the design, construction, or operation of storm sewers. This has become especially noticeable in recent years with the increase in precipitation and the intensification of downpours. Storm sewers built 30–50 years ago were not designed for such volumes of water;
- Reduction in forest area. Excessive felling of natural forests, protective forest belts during construction, and degradation of existing trees lead to a decrease in the transpiration of water from soils and grounds;
- Deficiencies in surface planning, when surface runoff slows down or obstacles to rapid runoff arise, puddles that do not dry out for a long time or areas with increased infiltration are formed, etc.;
- Excessive watering of plants is typical for vegetable gardens where moisture-loving crops (tomatoes, strawberries) are grown. Low-permeability soils (e.g., loams, and clays) increase moisture significantly, and even perched water may form. Highly permeable soils (coarse-grained sands) undergo intensive irrigation water infiltration.

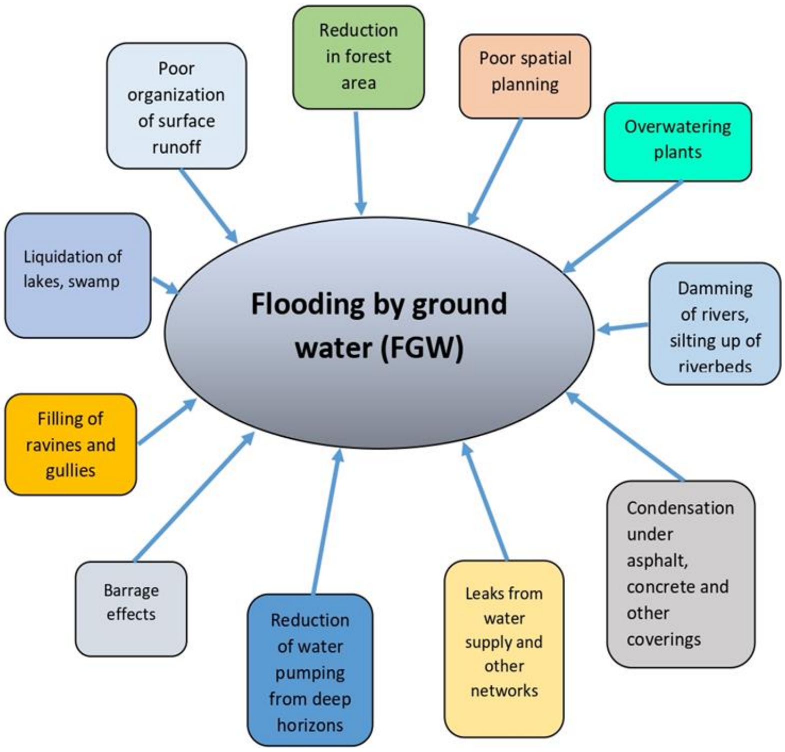

Figure 2. Main factors of flooding by ground water (FGW) in Kharkiv.

The main factors can be divided into three groups: above-ground, near-surface, and underground.

Above-ground factors (above the earth’s surface):

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Near surface factors:

- Deterioration of groundwater drainage conditions by rivers. The surface hydrosphere in the city is characterized by a sharp decrease in the speed of river flow and, accordingly, a sharp reduction in deep and lateral erosion due to the construction of dams in riverbeds, lining the banks with granite, swallowing, and silting of riverbeds. In Kharkiv, the water level in the rivers is regulated by eight small dams, which raise the level by 1–3 m compared to the natural one;
- Liquidation of small lakes and swamps. Throughout the history of the city, the number and area of these reservoirs have steadily decreased due to backfilling, which has reduced the physical evaporation of surface water and the natural drainage of groundwater;
- Elimination of gullies and ravines—natural drains that drain rain and groundwater. Historically, backfilling was spontaneous—residents of neighboring areas dumped household waste, construction waste, and some enterprises—industrial waste and displaced soils into the gullies. The backfill material is very heterogeneous, has high water permeability, and gullies from natural drains turned into sources of intensive infiltration. Only in recent decades have gullies begun to be improved and turned into recreational areas.

Illustrations of some features of the factors influencing the city’s groundwater are shown in **Figures 3** and **4**.

Underground factors:

- Condensation of water vapor under asphalt, concrete, and other low-permeability surfaces, under building foundations. All these surfaces in the city prevent the evaporation of groundwater (screening effect of development) and contribute to the condensation of water vapor;
- Leaks from underground water supply networks. Water leaks from external water supply networks, heating mains, storm and domestic sewage systems, and

industrial networks of enterprises inevitably get into the soil, and then into groundwater. Emergency leaks—more intense (with breakthroughs to the earth's surface) are eliminated relatively quickly, and systematic leaks with a small water consumption associated with wear of networks, and pipeline defects, manifest themselves weakly but can continue for many years;

- Reduction in the volume of water pumped out of deep aquifers. After the cessation of exploitation of the chalk-marl aquifer in the 1960s, a gradual multi-year increase in its level by several tens of meters began, and it almost reached the level of groundwater (the first from the surface of the horizon).
- Barrage effect. The construction of the subway had a significant impact on hydrogeological conditions, as it led to processes such as a barrier effect on the underground hydrosphere in construction zones during artificial freezing of waterlogged sandy and sandy loam soils, suffusion surface failures observed in zones of lowering groundwater levels, and dehydration surface subsidence in the zone of influence of intensive lowering of the water level.

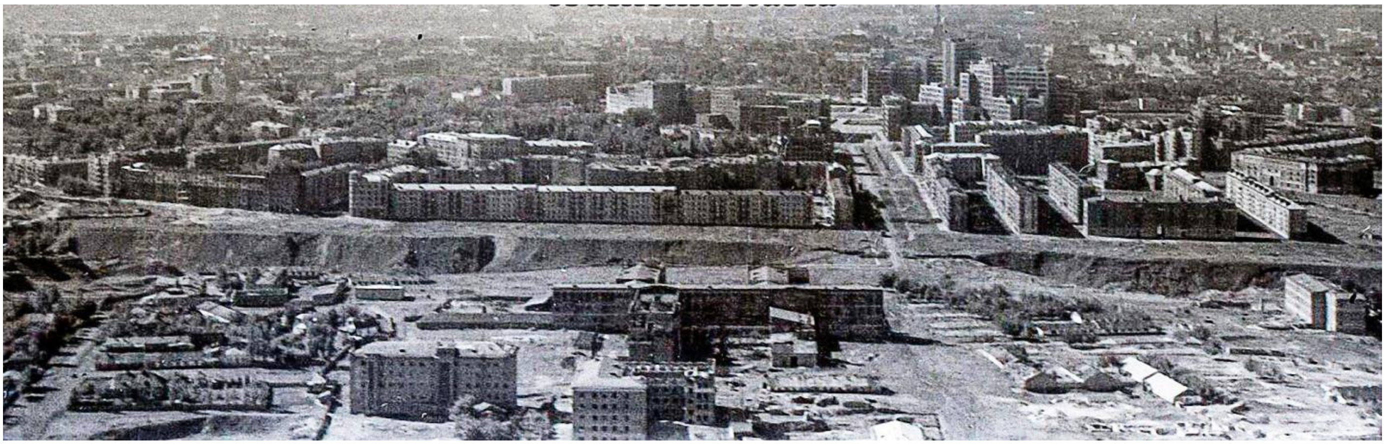
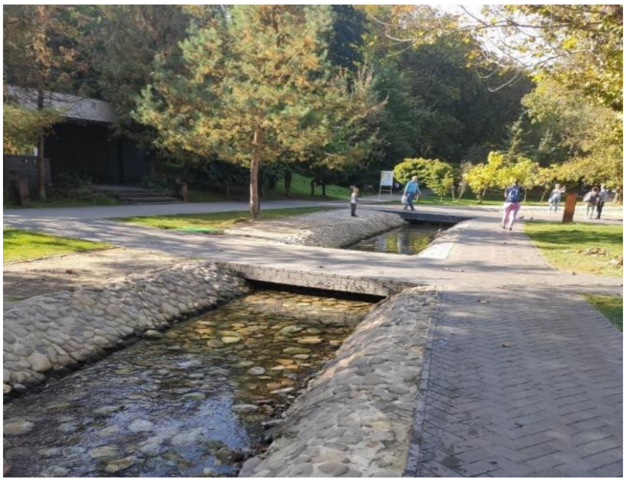


Figure 3. The Shatilovsky Yar ravine in the middle of the photo (early 1930s). The ravine was 10 m deep. It was subsequently filled with construction waste and displaced soil.

(a)



(b)

Figure 4. The Sarzhin Yar ravine transformed into a recreation area for Kharkiv residents: **(a)** Children's and sports grounds; **(b)** landscaped streambed at the bottom of the ravine and pedestrian paths.

3.5. Combating FGW

The aggravation of the FGW problem was gradually realized by the city and republican authorities around the end of the 70s—beginning of the 80s, mainly due to complaints from city residents living in flooded areas, mainly in single-story houses. Funds were allocated for survey and design work and some drainages of different types were built (horizontal, vertical, stratal, and even complex and expensive radial shaft drainages). Despite the more or less successful operation of the drainages, it became clear that the costs of capital construction and operating costs were too high compared to the efficiency, the relatively small area of the protected territory, and, therefore, such a method of protection from FGW would require exorbitant costs and time.

One of the co-authors of this article Prof. Strizhelchik back in 1987 proposed alternative ways to solve engineering-geological, hydrogeological problems of cities. An article on this topic was published in the USSR Academy of Sciences journal [16]. A fundamentally different approach to interaction in the "man—geological environment of the city" system was substantiated, which can be described in a very simplified way as the need to first assess the sustainability resource (SR) of the territory to external influences, assess the risks of the system going beyond the permissible state, and then consider measures to prevent negative impacts, and only if prevention is impossible, consider protection methods [10,12,13].

Subsequently, the scientific and technical community approved this approach. The authors of this article are the developers and co-authors of several current state building codes in Ukraine, including FGW and FSW protection [15].

Starting in the 2000s, Kharkiv began gradually reconstructing old water networks. Thoughtless backfilling of ravines ceased, new construction was carried out according to improved building codes, and increased attention was paid to green spaces. These measures gradually had a positive effect on the city's hydrogeological environment. FGW was controlled, and FSW was prevented.

3.6. Urban development prospects

At present, scientific research is intensively developing and nature-based solutions (NBS) are being implemented in practice in urban planning and construction [17–20]. Moreover, this direction has proven its effectiveness not only in highly developed countries of Europe and America, but also in developing countries of Africa, Asia, and South America. The main feature of NBS is the desire to create a harmonious synergetic coexistence of urban residents, and urban nature by preserving or recreating blue-green infrastructure [21–27]. NBS helps prevent floods and inundations, in contrast to the previously prevailing approach to protection through the installation of engineering structures, i.e., gray infrastructure. The ideas of sponge cities, which effectively resist the FGW and FSW, smart cities, eco-cities, landscape cities, etc., are gaining popularity.

Many breakthrough urban development technologies have been implemented in Singapore, which has become a leader in NBS and an example for many cities in creating an eco-city [28–30]. Many countries around the world are studying the eco-city concept and implementing its elements in practice. The main experience of a successful ecological garden city is due to the close connection between land use planning, development, and planning of the urban green space system.

It should be emphasized that to avoid formalism in the implementation of large-scale construction of environmentally friendly facilities, it is necessary to constantly monitor the effectiveness of the project after completion of construction, adhering to strictly scientific principles. In addition, it is necessary to check the effectiveness of strategies both in design and implementation through a comprehensive operational assessment of the effectiveness of completed projects and to form a feedback mechanism for the further development of targeted proposals to improve strategies and design methods. This is the only way to generalize effective and reliable experience in environmental practice to improve the quality of new ecological urban projects.

4. Discussion and conclusion

The experience of our research as well, as the works of other authors shows that the impact on the natural components of the geological environment in cities causes the emergence and development of more than fifty varieties of natural-technogenic and technogenic processes that were not observed before the development of the territories. Moreover, this applies not only to the lithosphere but also to the atmosphere and biosphere. In other words, cities are clots of the noosphere, significantly different from the environment, and at the same time, each city has a uniqueness associated with the natural basis, as well as with temporary and parametric impacts. Moreover, the main volume of negative changes can be caused by measures aimed not at preventing but at protecting objects from adverse and dangerous impacts.

As a result, we concluded that the management of sustainable development of the geological environment requires some changes in the methods and traditions of interaction between participants in urban development. In this regard, it is recommended to introduce into practice methods for assessing the resource of environmental sustainability to external influences, risk assessment methods, and two-level forecasting methods.

The essence of two-level forecasting can be characterized as follows. Research forecast (genetic, exploratory)—reasonably predicts what states the forecast object will reach after a given time under certain (currently existing) initial conditions. Exploratory forecasting determines the possible, expected state of a process or object in the future and answers the question, "What is most likely to happen if current trends continue?" Unlike exploratory forecasting, normative forecasting shows possible methods for achieving a given, desired target state of the forecast object. Normative forecasting also determines the ways and timeframes for achieving the desired state and answers the question, "What are the methods for achieving the desired state?" Thus, it is possible to assess the trends of processes in the geological environment, including hydrogeological conditions, and make decisions on preventing hazards or, if prevention is impossible protecting against them.

Our generalized experience with the allocation of FGV factors will help architects, administrators, and decision-makers, who (unfortunately!) are often poorly acquainted with engineering and geological issues and the long-term development of unfavorable processes that arise during construction when adopting urban development strategies.

A general strategy for flood protection measures in Ukraine, developed with the authors' participation, has now been developed and included in state building codes of Ukraine [15].

We believe the costs of implementing blue-green infrastructure are significantly less than the benefits received, ensuring sustainable development goals. Their implementation entails a shift from flood protection, where cities are protected from rising river, sea, or groundwater levels by engineering structures, to flood resilience, where water is quickly transported and removed through natural systems. In addition, blue-green infrastructure (BGI) can be used to retain, store and use water on-site.

Blue-green infrastructure (BGI) is critical to protecting natural and cultural landscapes, managing urban water resources, and reducing urban and industrial impacts on the hydrosphere. Mandatory implementation of BGI for new construction is recommended, where all large commercial or public projects, especially developments over large areas must include BGI.

Ultimately, preparing urban areas for the uncertainties associated with climate change requires a paradigm shift in the design of new and the management of old infrastructure that was not designed to cope with today's challenges. Integrated approaches using traditional and new principles of environmental engineering can help cities improve their resilience, protect their populations, and promote sustainable development. Future research could focus on the evaluation of different design and organizational solutions, long-term monitoring, and resilience assessment, adaptability to different urban and climatic conditions, and cost-effectiveness.

Author contributions: Conceptualization, VI; methodology, VI and GS; software, VI; validation, VI and GS; formal analysis, VI and GS; investigation, VI and GS; resources, VI and GS; data curation, VI and GS; writing—original draft preparation, VI and GS; writing—review and editing, VI and GS; visualization, VI and GS; supervision, VI and GS; project administration, VI and GS; funding acquisition, VI and GS. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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