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Aitugan Meirbek, Abduova Aisulu*, Zhumagaliev Issatay, Makhatov Zhaksylyk
M.Auezov South Kazakhstan Research University, Shymkent, Kazakhstan
***Corresponding Author:** aisulu.abduova@mail.ru

E-mail: aisulu.abduova@mail.ru,

DEVELOPMENT OF A GEOECOLOGICAL MODEL FOR SANITARY PROTECTION MEASURES IN URBANIZED AREAS: THE CASE OF SHYMKENT CITY

Annotation. Currently, major megacities of Kazakhstan, including Shymkent, are undergoing intensive urbanization processes. One of the main consequences of urbanization is the increase in environmental burden caused by emissions of harmful substances into the atmosphere, soil, and groundwater from industrial enterprises, transportation, and municipal waste. In such conditions, scientifically grounded planning of sanitary protection measures becomes crucial to safeguard public health and create a favorable ecological environment. In this regard, conducting a comprehensive study of urbanized areas using Shymkent as a case study and developing a geoecological model represent a relevant scientific task aimed at ensuring environmental safety and sustainable regional development. The geoecological model considers the spatial organization of sanitary protection zones, the relationship between industrial facilities and residential areas, transport corridors, and green spaces. Such a model will enhance public environmental safety, ensure efficient urban land use, and promote the rational management of natural resources.

The proposed model provides a comprehensive assessment of the current environmental situation, evaluates the dynamics of pollutant dispersion in industrial areas, and explores methods of optimizing sanitary protection belts. Furthermore, it identifies the interrelation between the biogeochemical role of green plantings, the distribution of atmospheric pollutants, and population density. The developed geoecological model will serve as a basis for practical recommendations for administrative authorities, urban planning institutions, and environmental services.

Objective. To assess the ecological condition of urbanized areas in Shymkent and to develop a comprehensive geoecological model aimed at improving sanitary protection measures.

Tasks. To assess the ecological situation in the urbanized areas of Shymkent and to identify the features of pollutant distribution. To design a comprehensive geoecological model for the enhancement of sanitary protection measures.

Thus, the experience of Shymkent provides an opportunity to develop a new model for maintaining ecological balance and ensuring sanitary protection in urbanized territories. Such scientifically based solutions may be applied in other large cities and agglomerations of Kazakhstan.

Keywords: Shymkent city, urbanization, geoecology, sanitary protection measures, ecological model, industrial area, green spaces, pollutants, environmental safety, urban planning.

Introduction

The urbanization process of the 21st century affects the natural environment in multiple ways through city expansion, infrastructure development, and industrial concentration: problems such as air and soil pollution, deterioration of water quality, solid waste accumulation, and landscape degradation are intensifying. In large industrial-urban centers such as Shymkent, recent years have seen a decline in average air quality and technogenic pressures arising from landfills and solid waste disposal sites. This necessitates the detailed and large-scale modeling of sanitary protection zones [1].

A geoecological model is a system that evaluates the environmental conditions of urbanized areas (air, water, soil pollution, waste, etc.) by considering spatial, temporal, and factor-based relationships. Such a model can serve as the basis for planning sanitary protection measures (identifying SPZs, buffer zones, accounting for wind direction and hydrogeology, setting restrictions according to indicators). The integration of sanitary requirements and regulations into models aimed at protecting public health is a mandatory component [2].

This section outlines the main findings from research in Kazakhstan and international studies on geoecological models, methods of defining sanitary protection zones, and research specific to Shymkent. The ecological impact of urbanization in Shymkent and Kazakhstan (local research). Due to city concentration and industrial sources, studies in the Shymkent area have documented a decline in air quality and soil/snow cover quality. Research highlights increasing trends between 2019-2021, as well as the ecological risks of solid waste. These findings underscore the need for local monitoring and the development of regional models [3].

International development organizations and investment projects (e.g., ADB) have highlighted Kazakhstan's practices in defining water and sanitary protection zones, along with requirements considered at the project planning stage. These documents provide a basis for incorporating regulatory parameters and protective buffers into models [4].

In identifying sanitary protection zones, spatial (GIS) analysis is often used, integrating the spatial distribution of pollution sources, wind directions, relief, and hydrogeological conditions through multicriteria evaluation. Applied articles and case studies (e.g., at municipal landfills and water protection zones) demonstrate examples of combining model parameters such as NDVI, remote sensing data, and pollutant emission data [5].

The impact of air and water pollution on health the need for modeling. Studies collected from Kazakhstan's cities show that urbanization significantly impacts air quality, particularly levels of NO_2, CO, and PM (particulate matter). Based on these findings, it is recommended to include a health risk assessment component in the model [6].

Analyzing a city's material and energy flows (urban metabolism) helps identify ecological gaps caused by urbanization: increasing waste, demand for water and energy all intersect with sanitary protection requirements. Recent regional studies of urban metabolism propose indicators suitable for use in modeling [7].

Examples of spatial analyses conducted in other cities of Kazakhstan. Research based on GIS has been carried out in Pavlodar, Aktobe, and other cities to evaluate air and landscape conditions. These provide opportunities to adapt methodologies for Shymkent, taking into account local specifics (e.g., mapping industrial sectors, wind regimes, water flows, and landscape continuity).

Methods and Materials

The city of Shymkent, which is undergoing an intensive urbanization process, was selected as the object of research. The specific feature of this area is the high concentration of industrial enterprises, transport infrastructure, public utilities, and the rapid growth of the population. To assess and predict the effectiveness of sanitary protection measures, the method of constructing a geoecological model was applied.

The materials were based on ecological monitoring data on air, water, and soil quality within the city, official reports of the sanitary-epidemiological service, as well as Shymkent's master plan and urbanization indicators. In addition, remote sensing data (satellite images) and cartographic materials obtained through geographic information systems (ArcGIS, QGIS) were used.

Methodologically, to determine sanitary protection zones, multicriteria analysis, ecological risk assessment, buffer zone mapping, and comparison with ecological and sanitary standards were applied. To identify the level of environmental pressure in the urbanized environment, demographic, industrial, and transport flow data were comprehensively considered.

Overall, the materials used in the study made it possible to conduct a comprehensive assessment of the ecological situation in Shymkent, while the selected methods provided a scientific basis for substantiating sanitary protection measures.

Analysis and results

During the research, a comprehensive analysis of the ecological condition of Shymkent's urbanized areas was conducted. Monitoring data revealed that in sections with a high concentration of industrial facilities and traffic flows, air quality was found to be 1.5–2 times worse than the national average. Exceedances of the permissible concentration limits of carbon dioxide, nitrogen dioxide, and fine particulate matter were frequently recorded[8].

Soil sample analysis showed elevated levels of heavy metals (lead, zinc, copper) in the city's industrial zones. These indicators were close to or, in some locations, above sanitary standards. Research on water resources also confirmed the pressure of urbanization: in particular, the Badam and Koshkar-Ata rivers showed high levels of anthropogenic pollution.

The geoinformation model developed using the ArcGIS platform made it possible to delineate the precise boundaries of sanitary protection zones within the city. Mapping of buffer zones revealed that approximately 30% of residential areas are located within the impact zone of industrial enterprises. This factor directly threatens public health[9].

Based on the findings, a set of recommendations was developed, including expanding sanitary protection zones, strengthening green belts, and regulating traffic flows. Specifically, it was proposed to establish at least a 500-meter sanitary zone around industrial sites, increase the volume of green plantings by 15–20%, and redirect transit traffic in the city center to bypass roads.

Overall, the results confirm the need to reconsider sanitary protection measures for Shymkent based on the geoecological model[10].

1. General Model Structure (Components)
- Data input and preprocessing (Data layer).
- Atmospheric dispersion module (AERMOD / CALPUFF).
- Hydrogeological transport module (MODFLOW + MT3DMS).
- Risk assessment and health hazard module (HHRA).
- Multi-Criteria Decision Analysis (MCDA / AHP) - determination of sanitary protection zones.
- GIS visualization and outputs (shapefile, GeoJSON, maps).

2. Required Input Data (minimum)
- Emissions: coordinates of industrial and traffic sources, emission rates (g/s or kg/yr).
- Meteorological data: 1-year hourly T, U, wind direction, precipitation.
- DEM (SRTM), LULC (Sentinel/Landsat), land use map.
- Monitoring: PM2.5/PM10, NO_2, SO_2, CO — by station.
- Hydrogeology: layers, filtration, initial hydraulic head (aquifer levels).
- Demographics: population density (specified grid or administrative units).
- Sanitary standards (national/WHO).

3. Atmospheric Dispersion (brief configuration)
- Model: AERMOD (intra-urban).
- Input: emission sources (types: point/line/area), stakeholders, meteorological file (AERMET), terrain depth.
- Output: maps - average daily and annual concentrations (μg/m³).
- Exceedance detection: relative to specified limits (e.g., PM2.5 - 25 μg/m³ annual).

Example formula (inhalation dose): $ADDinh=BW \times ATC \times IR \times EF \times ED$

where:
- C - concentration in air (μg/m³),
- IR - inhalation rate (m³/day),
- EF - exposure frequency,
- ED - exposure duration,
- BW - body weight,
- AT - averaging time.

Sanitary Protection Zones of Shymkent (GeoJSON Sample). This document provides a sample GIS template (.geojson) of sanitary protection zones. It can be imported into QGIS or ArcGIS software for visualization as a map.

Structure of the Attribute Table

id	zone_type	recommended _buffer_m	pollutant	risk_ index	population_ affected	notes
1	High risk	1000	PM2.5, NO2	0.78	15420	Near industrial area, strengthening sanitary protection is required
2	Medium risk	500	SO2, Pb	0.55	8720	Along major road, expansion of green zones is recommended
3	Low risk	300	PM10	0.32	4130	Near residential area, continuous monitoring is needed

Full GeoJSON code is provided below:

{
"type": "FeatureCollection",
"name": "shymkent_sanitary_zones"
"crs": {
"type": "name",
"properties": {
"name": "EPSG:4326"
}

},
"features": [
{
"type": "Feature",
"properties": {
"id": 1,
"zone_type": "High risk",
"recommended_buffer_m": 1000,
"pollutant": "PM2.5, NO2",
"risk_index": 0.78,
"population_affected": 15420,
"notes": "Near industrial area, strengthening sanitary protection is required"
},
"geometry": {
"type": "Polygon",
"coordinates": [
[
[69.586, 42.325],
[69.595, 42.325],
[69.595, 42.335],
[69.586, 42.335],
[69.586, 42.325]
]
]
}
},
{
"type": "Feature",
"properties": {
"id": 2,
"zone_type": "Medium risk",
"recommended_buffer_m": 500,
"pollutant": "SO2, Pb",
"risk_index": 0.55,
"population_affected": 8720,
"notes": "Along major road, expansion of green zones is recommended"
},
"geometry": {
"type": "Polygon",
"coordinates": [
[
[69.605, 42.33],
[69.615, 42.33],
[69.615, 42.34],
[69.605, 42.34],
[69.605, 42.33]
]
]
}

}
{
"type": "Feature",
"properties": {
"id": 3,
"zone_type": "Low risk",
"recommended_buffer_m": 300,

"pollutant": "PM10",
"risk_index": 0.32,
"population_affected": 4130,
"notes": "Near residential area, continuous monitoring is needed"
},
"geometry": {
"type": "Polygon"
"coordinates": [
[
[69.62, 42.32],
[69.63, 42.32],
[69.63, 42.33],
[69.62, 42.33],
[69.62, 42.32]

Sanitary Buffers Recommended Approach (Methodological). Note: actual legal and sanitary protection distances depend on each country's regulations. The following recommendations are scientifically and logically grounded and should be compared with local standards.

AQ (Air-based, stationary industries):

High-risk (chemical, carcinogenic): buffer of 500–1500 m;

Medium-risk: 300–700 m;

Low-risk (noise/light, non-toxic signals): 100–300 m.

Fuel stations (AGZS): 50–200 m (considering potential fuel spills).

Municipal solid waste landfill: 500–2000 m (wind direction and geology are important factors). Transport routes/railways (dust/NOx): influence up to 100–500 m from the road.

Normalization: scale each pollutant concentration to a 0–1 range (e.g., divide by the 95th percentile threshold value).

Chemical hazard weighting Wc (example):

PM2.5 - 0.3

NO2 - 0.2

SO2 - 0.15

VOCs - 0.35

(This is an expert example - in practice, weights should be based on toxicological data.)

Vulnerability (V) = 0.4 × (children_share_normalized) + 0.3 × (elderly_share) + 0.3 × (socioeconomic_index)

Risk = Σ over pollutants (C_norm × Wc) × V

Then classify risk:

High: risk > 0.6

Medium: 0.3–0.6

Low: < 0.3

Short MCDA / AHP Guide (Example of Weight Selection)

Criteria:

Emission strength (W = 0.4)

Population exposure (W = 0.3)

Toxicity (W = 0.2)

Persistence in the environment (W = 0.1)

It is recommended to build a pairwise comparison matrix through AHP to verify the weights.

GIS: QGIS (method), ArcGIS (if available).

Dispersion modeling: AERMOD, CALPUFF, or simpler SCIPUFF/Gaussian plume implementation.

Hydrogeology: MODFLOW + MT3DMS.

Data processing: Python (pandas, geopandas, rasterio), R (sf, raster).

Tabular and reporting: Excel, LibreOffice.

Web mapping: Leaflet / Mapbox (if required).

Strategic control points: high-priority areas — zones with high risk and high population density.

Parameters: PM2.5, PM10, NO2, SO2, VOCs, heavy metals in soil (Pb, Cd) testing frequency weekly/monthly.

Validation: compare model predictions with monitoring data (R^2, RMSE), calibrate model parameters accordingly.

QGIS project (.qgz) + data (shapefiles or GeoJSON).
Sanitary protection map - PDF, PNG.
Tabular Excel/CSV risk index, priorities.
Methodological report - 25–40 pages with recommendations.

Comparison with local regulations: model results should be evaluated against Kazakhstan's and Shymkent's sanitary standards (buffers and threshold values). Public awareness: timely inform residents of high-risk areas; develop special protection plans for children and schools. Engineering measures: stationary pumping systems, air purification pipelines, biofiltration, noise barriers. Long-term: revise zoning of industry and residential areas in urban planning; establish green belts. For legal decisions, model results alone should not be used - they must be combined with monitoring data and sanitary regulations.

Conclusion

The development of a geoecological model for sanitary protection measures in urbanized areas, using the case of Shymkent city, highlights the pressing challenges and opportunities associated with rapid urban growth in Kazakhstan. Shymkent, as one of the country's largest industrial, demographic, and cultural centers, demonstrates how urbanization drives both economic development and environmental degradation simultaneously. Industrial emissions, transport-related air pollution, household waste accumulation, and the overuse of water and soil resources present serious ecological and public health concerns. In this context, the creation of a geoecological model is not merely an academic exercise but a practical tool for sustainable urban management.

The research emphasizes the necessity of integrating geographic information systems (GIS), remote sensing, and environmental modeling to map, analyze, and predict the impacts of urbanization. By combining data layers on air, water, soil, industrial zones, and demographic distribution, the model provides an evidence-based foundation for delineating sanitary protection zones. This approach ensures that spatial planning and decision-making are guided by scientific analysis rather than ad hoc or outdated regulatory norms. Furthermore, the case of Shymkent demonstrates that urban ecological modeling must account for not only physical geography but also socio-economic dynamics such as population growth, transportation expansion, and industrial diversification.

A key conclusion is that sanitary protection measures cannot be effective if they are limited to narrow legal regulations or administrative borders. Instead, they must be based on a holistic, systems-oriented understanding of urban metabolism, where air, water, energy, and waste cycles are interconnected. For example, the placement of new industrial facilities must consider prevailing wind directions and atmospheric dispersion patterns to minimize exposure to residential areas. Similarly, the management of water resources must integrate both surface and groundwater dynamics, as urban runoff and industrial effluents can travel far beyond municipal limits. The geoecological model offers predictive capacity, enabling policymakers to simulate various urban development scenarios and their ecological consequences, thus allowing proactive rather than reactive measures.

Another important insight is the value of multi-criteria decision analysis (MCDA) embedded within the model. Urban planners and environmental regulators often face conflicting priorities: economic growth versus environmental safety, housing development versus green space preservation, or industrial productivity versus public health. The model supports decision-making by weighting these criteria and identifying optimal strategies that balance human needs with ecological sustainability. In the case of Shymkent, such an approach is particularly urgent given the city's role as both a regional industrial hub and a rapidly growing urban settlement with increasing demands for residential, transport, and service infrastructure.

The study also demonstrates the necessity of aligning Kazakhstan's environmental policies with international best practices. As global cities confront similar challenges of urban pollution, climate change, and public health risks, the Shymkent model provides a platform for integrating international standards such as World Health Organization (WHO) air quality guidelines, European Union directives on industrial emissions, and sustainable urban planning frameworks. At the same time, it respects the local socio-economic realities of Kazakhstan, where rapid population growth, industrial restructuring, and limited public resources create unique pressures.

In practical terms, the geoecological model for Shymkent proposes concrete steps: establishing buffer zones around industrial and transport corridors, strengthening monitoring of air and water pollutants, creating green belts and ecological corridors within urban planning, and enhancing public participation in environmental governance. Equally important is the continuous updating of the model with new data, ensuring that it remains dynamic and adaptable to evolving urban conditions.

Ultimately, the conclusion of this study underscores that the creation of a geoecological model for sanitary protection is not the final goal but a starting point for a more resilient and sustainable urban future. For Shymkent, and for Kazakhstan more broadly, such models can serve as strategic tools in balancing urbanization with environmental protection, safeguarding public health, and fostering ecological responsibility. By adopting science-based sanitary protection measures, the city can transform urban growth from an ecological challenge into an opportunity for innovation in sustainable development. This approach ensures that urbanization does not undermine the natural systems on which human life depends, but rather evolves in harmony with them.

In sum, the case of Shymkent illustrates that geoecological modeling provides both a conceptual framework and a practical methodology for addressing the complex interactions between urbanization and environmental health. It empowers decision-makers, protects vulnerable populations, and creates a foundation for environmentally sound urban planning. As Kazakhstan continues to urbanize, such tools will be indispensable in achieving a future where economic progress and ecological integrity are mutually reinforcing rather than mutually exclusive.

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Айтуған М., Абдуова А., Жұмағалиев И., Махатов Ж.

ШЫМКЕНТ ҚАЛАСЫНЫҢ ҮЛГІСІНДЕ УРБАНИЗАЦИЯЛАНҒАН АЙМАҚТАРДЫ САНИТАРЛЫҚ ҚОРҒАУ ШАРАЛАРЫ ҮШІН ГЕОЭКОЛОГИЯЛЫҚ МОДЕЛЬ ҚҰРУ

Аңдатпа. Қазіргі таңда Қазақстанның ірі мегаполистері, соның ішінде Шымкент қаласы қарқынды урбанизация процестерін бастан өткеруде. Урбанизацияның негізгі нәтижелерінің бірі – экологиялық жүктеменің артуы, өнеркәсіптік кәсіпорындардан, көліктен және тұрмыстық қалдықтардан атмосфераға, топырақ пен жер асты суларына түсетін зиянды заттардың көбеюі. Мұндай жағдайда халықтың денсаулығын қорғау, қолайлы экологиялық ортаны қалыптастыру мақсатында санитарлық-қорғау шараларын ғылыми негізде жоспарлау аса маңызды.

Осы тұрғыдан алғанда, Шымкент қаласының үлгісінде урбанизацияланған аумақтарды кешенді түрде зерттеп, геоэкологиялық модель құру – өңірдің орнықты дамуына және экологиялық қауіпсіздігін қамтамасыз етуге бағытталған өзекті ғылыми міндет болып табылады. Геоэкологиялық модель санитарлық-қорғау аймақтарының кеңістіктік ұйымдастырылуын, өнеркәсіп пен тұрғын үй массивтерінің арақатынасын, көлік дәліздері мен жасыл аймақтардың үлесін ескере отырып жасалады. Бұл модель тұрғындардың экологиялық қауіпсіздігін арттыруға, қалалық аумақтарды тиімді пайдалануға және табиғи ресурстарды ұтымды басқаруға мүмкіндік береді.

Ұсынылып отырған модельде қазіргі экологиялық ахуалға кешенді талдау жүргізіліп, өнеркәсіптік аймақтардағы зиянды шығарындылардың таралу динамикасы бағаланады, санитарлық-қорғау белдеулерін оңтайландыру әдістері қарастырылады. Сонымен қатар қаладағы жасыл желектердің биогеохимиялық рөлі, атмосфераны ластаушы факторлардың таралу аймағы және халықтың қоныстану тығыздығы арасындағы өзара байланыс анықталады. Жасалған геоэкологиялық модель басқару органдарына, қала құрылысы құрылымдарына және экологиялық қызметтерге практикалық ұсыныстар беруге негіз болады.

Мақсаты. Шымкент қаласының үлгісінде урбанизацияланған аумақтардың экологиялық жағдайын бағалап, санитарлық-қорғау шараларын жетілдіруге бағытталған кешенді геоэкологиялық модель құру.

Міндеттері. Шымкент қаласының урбанизацияланған аумақтарындағы экологиялық жағдайды бағалап, ластаушы факторлардың таралу ерекшеліктерін анықтау. Санитарлық-қорғау шараларын жетілдіруге арналған кешенді геоэкологиялық модель әзірлеу.

Осылайша, Шымкент қаласының тәжірибесі урбанизацияланған аймақтарда экологиялық тепе-теңдікті сақтау мен санитарлық қорғауды қамтамасыз етудің жаңа үлгісін қалыптастыруға мүмкіндік береді. Мұндай ғылыми негізделген шешімдер болашақта Қазақстанның басқа да ірі қалалары мен агломерацияларына енгізілуі ықтимал.

Кілт сөздер: Шымкент қаласы, урбанизация, геоэкология, санитарлық-қорғау шаралары, экологиялық модель, өнеркәсіптік аймақ, жасыл желек, ластаушы факторлар, экологиялық қауіпсіздік, қала құрылысы.

Айтуған М., Абдуова А., Жұмағалиев И., Махатов Ж.

СОЗДАНИЕ ГЕОЭКОЛОГИЧЕСКОЙ МОДЕЛИ ДЛЯ САНИТАРНО-ЗАЩИТНЫХ МЕР В УРБАНИЗИРОВАННЫХ РАЙОНАХ НА ПРИМЕРЕ ГОРОДА ШЫМКЕНТА

Аннотация. В настоящее время крупные мегаполисы Казахстана, включая город Шымкент, переживают интенсивные процессы урбанизации. Одним из основных последствий урбанизации является увеличение экологической нагрузки, вызванное ростом выбросов вредных веществ в атмосферу, почву и подземные воды от промышленных предприятий, транспорта и бытовых отходов. В таких условиях особенно важно научно обоснованное планирование санитарно-защитных мер для охраны здоровья населения и формирования благоприятной экологической среды.

С этой точки зрения комплексное исследование урбанизированных территорий на примере города Шымкента и создание геоэкологической модели являются актуальной научной задачей, направленной на обеспечение экологической безопасности и устойчивого развития региона. Геоэкологическая модель разрабатывается с учетом пространственной организации санитарно-защитных зон, соотношения промышленных объектов и жилых массивов, транспортных коридоров и зеленых зон. Такая модель позволит повысить экологическую безопасность населения, эффективно использовать городские территории и рационально управлять природными ресурсами.

Предлагаемая модель включает комплексный анализ современного экологического состояния, оценку динамики распространения вредных выбросов в промышленных районах, а также рассмотрение методов оптимизации санитарно-защитных поясов. Кроме того, выявляется взаимосвязь между биогеохимической ролью зеленых насаждений, зонами распространения загрязняющих факторов атмосферы и плотностью заселения населения. Разработанная геоэкологическая модель станет основой для практических рекомендаций органам управления, градостроительным структурам и экологическим службам.

Цель. Оценить экологическое состояние урбанизированных территорий на примере города Шымкента и создать комплексную геоэкологическую модель, направленную на совершенствование санитарно-защитных мер.

Задачи. Оценить экологическую ситуацию в урбанизированных районах города Шымкента и определить особенности распространения загрязняющих факторов. Разработать комплексную геоэкологическую модель для совершенствования санитарно-защитных мероприятий.

Таким образом, опыт города Шымкента позволяет сформировать новую модель обеспечения санитарной защиты и сохранения экологического баланса в урбанизированных районах. Подобные научно обоснованные решения могут быть внедрены и в других крупных городах и агломерациях Казахстана.

Ключевые слова: город Шымкент, урбанизация, геоэкология, санитарно-защитные меры, экологическая модель, промышленная зона, зеленые насаждения, загрязняющие факторы, экологическая безопасность, градостроительство.