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USING REMOTE SENSING TECHNOLOGIES FOR MONITORING URBAN HEAT ISLANDS

(Представлено членом редакційної колегії д-ром геол. наук, ст. дослідником О. І. Меньшовим)

Background. The urbanization process is accelerating every day, which entails significant changes in the natural landscape. This leads to microclimatic changes, air pollution, thermal effect, etc. Due to air pollution by man-made emissions in urbanized areas, the thermal regime is changing; the concentration of carbon dioxide and water vapor has now reached 90 % of the total amount of pollutants. As a result, another problem arises that contributes to global warming – the "greenhouse effect". Elevated air temperatures affect human health leading to breathing problems, seizures, heat and sunstroke, heat stress, and increased mortality. Considering the potential danger of elevated air temperatures caused by urban heat islands affecting the lives of residents, an effective and relevant method for surface temperature analysis and heat island location determination should be developed.

Methods. During urban heat island monitoring, the main factor of analysis is surface temperature, which was determined in the study using indices such as: Normalized Difference Vegetation Index (NDVI), Urban Thermal Field Variance Index (UTFVI) and Normalized Difference Built-up Index (NDBI).

Results. This paper describes a study of the distribution of urban heat islands in three European capitals, including Kyiv, Oslo and Rome, from May 2013 to August 2023. Using the capabilities of the GoogleEarthEngine cloud platform and data from the Landsat 8 OLI/TIRS satellite, the condition of green spaces, the number of impervious surfaces and indices of surface temperatures (LST) were compared, resulting in maps of the distribution of urban heat islands (UHIs) in the areas of selected cities and towns demonstrating quantitative changes.

Conclusions. Thus, the study showed a decrease in the number of urban heat islands along with impervious surfaces in the city of Kyiv by 4 %. At the same time, Rome and Oslo experienced an increase in the number of urban heat islands along with impervious surfaces. The data obtained prove the feasibility of using the chosen research method and can be used to assess the environmental condition, identify risk zones, and develop effective measures to further prevent the spread of UHI in megacities.

Keywords: urban heat island, surface temperatures, impervious surfaces, green spaces, Landsat 8 OLI/TIRS, GoogleEarthEngine, Remote sensing, GIS.

Background

Over the past decades, human activities have led to unprecedented climate change and environmental degradation, making global warming and energy shortages extremely visible. As a consequence, there have been significant changes in people's attitudes and behavior prompting them to take strict measures to avoid further development of environmental disaster, one of which is reducing carbon emissions.

The urbanization process is accelerating every day, so this rapid development is turning the natural landscape into an artificial one (Ghosh, 2019). In turn, the growth of urbanization entails significant changes in the natural landscape. This leads to microclimatic changes, air pollution, thermal effect, etc. An urban heat island (UHI) is an area of a city whose air temperature exceeds the suburban temperature by 4 degrees or more (Solecki et al., 2011). Due to air pollution by man-made emissions in urbanized areas, the thermal regime is changing; the concentration of carbon dioxide and water vapor has now

reached 90 % of the total amount of pollutants. As a result, another problem arises that contributes to global warming – the "greenhouse effect". Elevated air temperatures affect human health leading to breathing problems, seizures, heat and sunstroke, heat stress and increased mortality (Sakhniuk et al., 2022).

Considering the potential danger of elevated air temperatures caused by urban heat islands affecting the lives of residents, an effective and relevant method for surface temperature analysis and heat island location determination should be developed.

The purpose of this work is to analyse the urban heat island problem using geographic information systems, technologies and publicly available remote sensing data to qualitatively and quantitatively analyse changes and conditions of impervious surfaces, and to investigate areas of interest as they are potentially susceptible to changes in surface temperatures over time. There should also be developed an effective algorithm of actions that will help solve the urban heat island issue. The research also aims to identify

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the relationship between the number and location of built-up areas in megacities and the spread of elevated temperatures as well as to propose an effective UHIs monitoring methodology to further prevent environmental disasters.

The objects of study in this work are surface temperatures, green spaces and built-up surfaces of such megacities as Kyiv, Oslo, and Rome.

The subject of the study is the monitoring of urban heat islands, their impact on residents, and the search for effective preventive solutions.

Methods

Despite concerns and attempts to limit global warming, temperatures in cities exceeded those in surrounding areas by an average of 4–5 °C, in some cases by 10 °C. This phenomenon is known as the urban heat island. In monitoring urban heat islands, the main factor to analyse is surface temperature, which is derived from satellites. Land surface temperature (LST), which is the radiant skin temperature of the Earth's surface and is determined by the energy exchange between the Earth's surface and atmosphere, regulates and impacts the biophysical and chemical processes of the Earth's system (Debele, & Beketie, 2024).

Hence, it is clear that the air temperature measured by weather stations and the temperature of the earth's surface obtained using satellite images (U.S. Geological Survey, 2018) are different concepts that must be clearly separated from each other in further work.

Therefore, having differentiated such concepts at first glance, it is necessary to highlight the order of actions necessary for a holistic and qualitative analysis of urban heat islands.

The first step involves collecting high-quality initial data that will make it possible to analyze changes over a certain period of time. Quality means the absence of clouds and distortions in the images, the complete location of the object of interest. In the case of UHIs analysis, the survey season is also important, since to correctly calculate LST it is necessary to choose a summer or winter period, for these seasons best reflect the temperature contrast.

The following steps, depending on the selected satellite, sensor and software in which the analysis will be carried out, can be the following:

- geometric and radiometric calibration of the image,
- restoration of pixels covered with clouds,
- visualization of a composite image from stripes.

In most cases, the vegetation map (NDVI) reflects heat islands quite accurately, since NDVI allows knowing the amount of photosynthetic active biomass in plants (OneSoil Blog, 2018). Therefore, the calculation of this index is the next step in the analysis of urban heat islands and their interaction with green spaces. This index is a measure of the difference in reflectivity between the red band (RED) and near-infrared (NIR) band of images. NDVI ranges from -1 to +1, with positive values indicating areas covered with vegetation and negative values indicating areas without vegetation.

This is calculated as follows:

$$NDVI = \frac{NIR-RED}{NIR+RED}, \tag{1}$$

where NIR is the reflectance in the near infrared band; RED – reflectance in the red band.

When working with spectroradiometer data, simply select the desired band that will display the desired data, in the case of urban heat islands, usually this is the surface temperature band, depending on the data set.

Another way to calculate surface temperature is to use RED, NIR and TIR (thermal infrared) satellite input signals.

In this case, it is necessary to find the ratio of vegetation in a pixel using a previously defined vegetation index, namely its minimum and maximum values (Quintano et al., 2015).

$$p(v) = \left(\frac{NDVI-NDVI_{min}}{NDVI_{max}+NDVI} \right)^2, \tag{2}$$

where NDVImin is the minimum NDVI value; NDVImax – maximum NDVI value.

Then, the emissivity of the earth's surface is required, which is found from the equation:

$$\varepsilon = mP(v) + n, \tag{3}$$

where m is the value of the soil emissivity and is equal to 0.004; n is the value of vegetation emissivity equal to 0.986.

The spectral irradiance value of the infrared thermal image is used to calculate the temperature. This temperature is also known as radiant or brightness temperature. For Landsat thermal infrared image data, the brightness temperature is given by (Sobrino, Jimenez-Munoz, & Paolini, 2004).

$$Tb = \frac{K2}{\ln\left(1+\frac{K1}{L\lambda}\right)}, \tag{4}$$

where Lλ is the value of spectral irradiation; K1 and K2 are constants obtained from the Landsat image metadata file.

After determining the surface emissivity, the brightness temperature will be adjusted to obtain the surface temperature value. Land surface temperature (LST) is defined as follows:

$$LST = \frac{Tb}{1+\left(\frac{\lambda Tb}{\rho}\right)*\ln\varepsilon}, \tag{5}$$

where Tb is the value of the image radiation temperature; λ – value of the central wavelength of the thermal infrared range; ε – surface emissivity; ρ – became Stefan-Boltzmann (1.38.10–23J/K).

The remaining step in the search for urban heat islands is to calculate the urban thermal field deviation index (UTFVI), which varies in the formula given below and is assigned a high value for the six categories of the environmental assessment index (Tab. 1).

$$UTFVI = \frac{Ts-Tm}{Ts}, \tag{6}$$

where Ts is the temperature of the earth's surface; Tm is the average temperature of the earth's surface.

Table 1
UTFVI and Environmental Assessment Index threshold values

UTFVI	Urban Heat Island	Environmental Assessment Index
< 0,000	None	Excelent
0,000–0,005	Weak	Good
0,005–0,010	Medium	Quite Good
0,010–0,015	Strong	Not Good
0,015–0,020	Stronger	Poor
> 0,020	The strongest	Very poor

Once urban heat islands are located, visualized and classified into environmental assessment groups, quantitative and qualitative analysis of changes that may have occurred over time is possible. Thus, the main criteria for analysis will be the values of plant indices, including the previously mentioned NDVI and the equally important Leaf Area Index (LAI).

The Leaf Area Index shows the ratio of total leaf area to ground area. In turn, the amount of light intercepted, the nitrogen accumulated by it, the surface temperature, etc., depending on the area of the leaves (Fang et al., 2019). This index is a dimensionless coefficient, but it is possible to reduce its dimension (m²/m², ha/ha).

A special feature of LAI is that it is usually calculated based on the ratio of NDVI values and other coefficients, which in turn depend on the location where the leaf area index is needed to be calculated. That is, the formula for taking into account LAI values will be one when analyzing forests in temperate latitudes and the other one when analyzing savannas, etc. Therefore, when calculating LAI, it is important to correctly select the formula, which is provided for the green spaces of the study area.

It is also useful to calculate the areas of urban heat islands and compare the values for different years, since in this way we can observe the trend of changes in the area of interest.

It may also be useful to visualize temperature changes in graphs, calculate changes in the amount of vegetation and built surfaces using open databases, classify using standards or calculate impervious surface indices.

So another factor directly affecting surface temperatures, and therefore the spread of UHI, is the amount of impervious surface, which can be easily calculated using the Normalized Difference Built-up Index (NDBI).

NDBI calculation is an effective method for mapping urban built-up areas, calculated based on the image difference between NIR and MIR (mid-infrared) (Zha, Gao, & Ni, 2003). This index is obtained from the equation:

$$NDBI = \frac{MIR - NIR}{MIR + NIR}, \quad (7)$$

where MIR corresponds to Landsat OLI band 6 (1.57–1.65 μm).

Index values range from -1 to $+1$, where negative values correspond to vegetation and water bodies, and positive values correspond to built-up areas (Zha, Gao, & Ni, 2003).

Using the Google Earth Engine (GEE) platform, which uses a combination of satellite imagery, Earth observation data and machine learning algorithms to allow users to identify and measure changes in land use, ecosystems and climate patterns on a global scale, it is possible to identify urban regions where to focus efforts should be made to reduce the impact of urban heat islands. Google Earth Engine relies on numerous technologies in the Google data center, such as the Flume Java framework, distributed databases Bigtable, Spanner (Chang et al., 2006), GEE is accessible through an API and web interface, allowing rapid prototyping and visualization of results.

Thus, high-quality and in-depth monitoring of urban heat islands can be carried out, which will allow analyzing trends that are spreading in the area of interest, selecting and timely applying preventive measures, etc.

Results

The study areas in this work were three European capitals – Kyiv, Oslo, and Rome. Each of the selected cities is a metropolis, respectively, most prone to the spread of UHIs.

The reason for choosing Rome as a territory for analysis was great historical status of the city, which, together with European standards, is the basis for serious restrictions on logging, and given the geographical location of this city, due to which residents suffer from heat in the summer, we would like to identify possible trends in temperature changes and factors that influenced this.

Oslo is known as the green European capital, so it is important to analyze the temperature regime in the city and compare the state of other capitals with the leader.

As for Kyiv, due to the irresponsibility of the authorities, the city is experiencing problems with massive illegal cutting of trees, accordingly serves as an example of a city that is experiencing changes in the amount of green spaces and impervious surfaces.

Kyiv and Rome are over a million people and have about three million inhabitants each, and also have many enterprises,

industrial production, and they are also large transport hubs through which supplies and transportation pass daily.

Oslo, in contrast, is much smaller in size, has only 702 thousand population, which since 2015 has prohibited private vehicles from traveling on public roads in the city center. Besides, since 2019 it has expanded this rule to a 60 km buffer zone.

All three capitals are located at different latitudes and form an imaginary triangle (Fig. 1). So, Kyiv is located at the latitude of $50^{\circ}27'16''$ N. and at the altitude of 187 meters above sea level. Oslo is located at the latitude of $59^{\circ}56'58''$ N. Rome, in turn, is located at the latitude of $41^{\circ}53'30''$ N. and at the altitude of 52 meters above sea level.

Accordingly, the meteorological conditions of these areas are different, which in turn gives us an excellent opportunity to analyze the distribution of urban heat islands in different climatic conditions, which also affect the state of vegetation, inhabitants, and surface temperature.

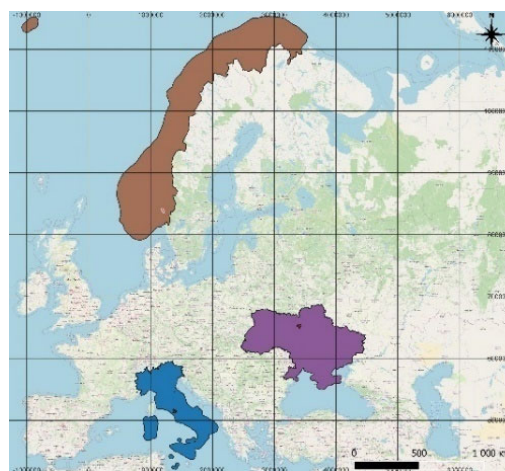


Fig. 1. Location of study areas according to OpenStreetMap

The climate of Kyiv is moderately continental, with mild winters and warm summers; the average temperature in July is about $+25^{\circ}\text{C}$. The climate of Rome is subtropical Mediterranean characterized by very long and hot summers, $+31^{\circ}\text{C}$ average temperatures in July, and mild, rainy winters. Oslo is located in a continental climate zone characterized by cool summers, the warmest month being July with an average temperature of $+17.8^{\circ}\text{C}$.

The issue of ecology is quite acute today, especially for megacities. The territories under consideration are no exceptions. But a serious advantage of these capitals is the large number of green spaces; more than 50 % of the area of Kyiv and Rome are forests, parks, squares, alleys, etc. As for Oslo, about 70 % of the territory is covered with green space, and recently the authorities have completely removed parking spaces in the city.

As European capitals of culture that attract visitors from all over the world have a correspondingly high level of tourism, and demonstrate different climatic conditions and decisions of city authorities, an analysis of the distribution of urban heat islands would be appropriate, and it would provide a basis for broader comparison.

According to the considered algorithm of actions, a code was written on the Google Earth Engine platform, so the first step was to load the geometry of the territory of interest, the analysis of which was carried out later. Optical and thermal channels were also scaled (Fig. 2).

```
var geometry = ee.FeatureCollection("users/sakhnyuk/Kyiv")
Map.addLayer(geometry, {}, 'geometry')
Map.centerObject(geometry, 9)

// Applies scaling factors.
function applyScaleFactors(image) {
  var opticalBands = image.select('SR_B.').multiply(0.0000275).add(-0.2);
  var thermalBands = image.select('ST_B.*').multiply(0.00341802).add(149.0);
  return image.addBands(opticalBands, null, true)
    .addBands(thermalBands, null, true);
}
```

Fig. 2. Code fragment with the definition of the area of interest

Subsequently, the obtained results of the processed code were exported in TIF format for each of the areas of interest. These files contain information about the Land surface temperature (LST) value and the Urban Thermal Field Variance Index (UTVFI) value for 2013 and 2023.

The obtained data was loaded into the ArcMap application for subsequent classification and mapping. Initially, the LST data was divided into six classes to better visualise temperature differences in different parts of metropolitan areas, and surface temperature maps were then created for each of the capitals (Fig. 3).

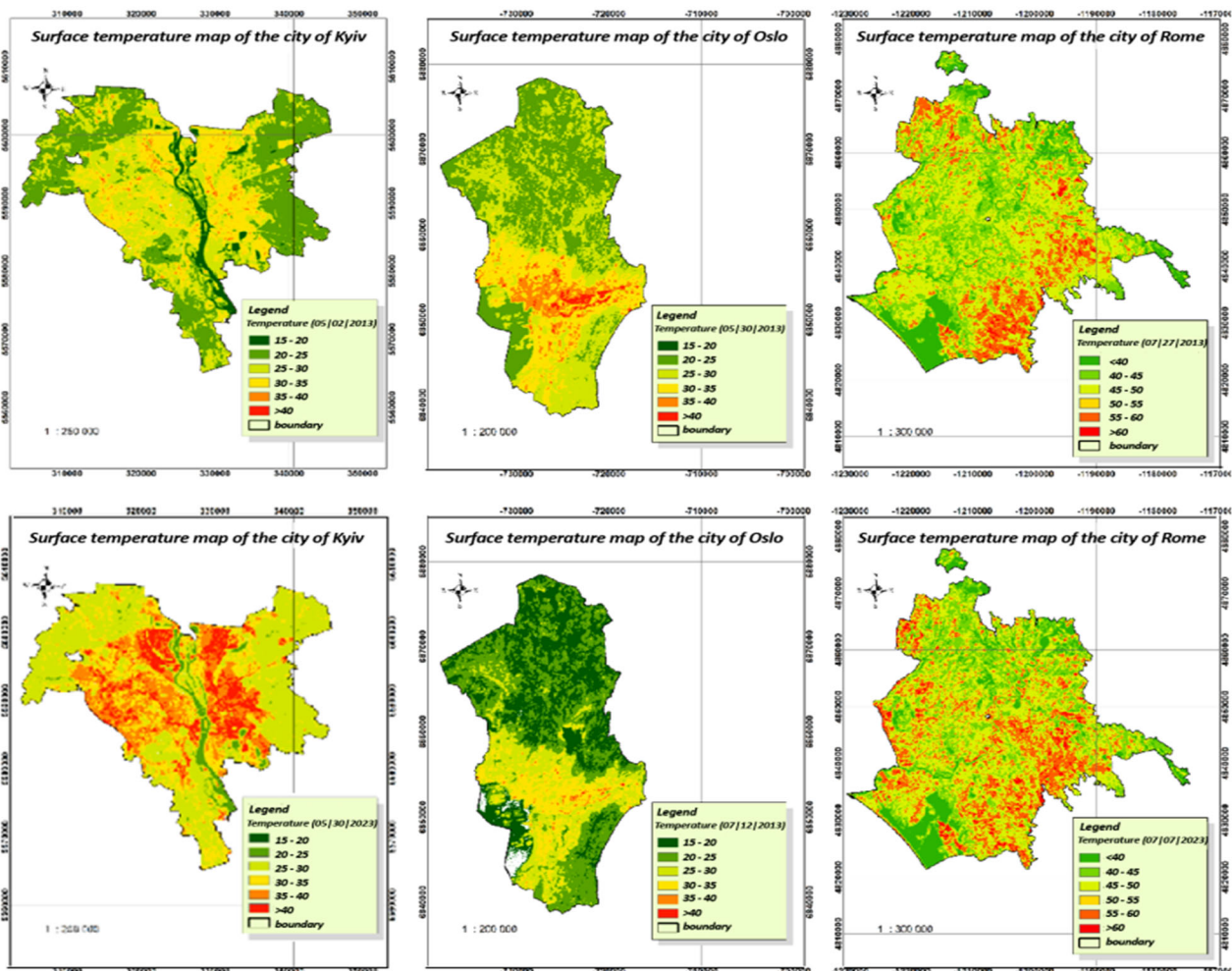


Fig. 3. Land surface temperature maps of selected cities made using Landsat 8 OLI/TIRS data. Date of access: 01/30/2024

Mapping land surface temperature of selected megacities, the approximate location of urban heat islands can be predicted, just as in the case of the vegetation index. It should also be noted that all cities except Oslo experienced a visual increase in surface temperatures, this is noticeable due to the increase in the number of hot color pixels.

The following step was to distribute the UTVFI data into six classes according to the level of Environmental

Assessment discussed earlier (Tab. 1), which in the future will also make it possible to calculate changes in the size of the UHIs. Based on the classification of the Urban Thermal Field Variance Index values, maps of the distribution of heat islands in each of the capitals for 2013 and 2023 were created (Fig. 4).

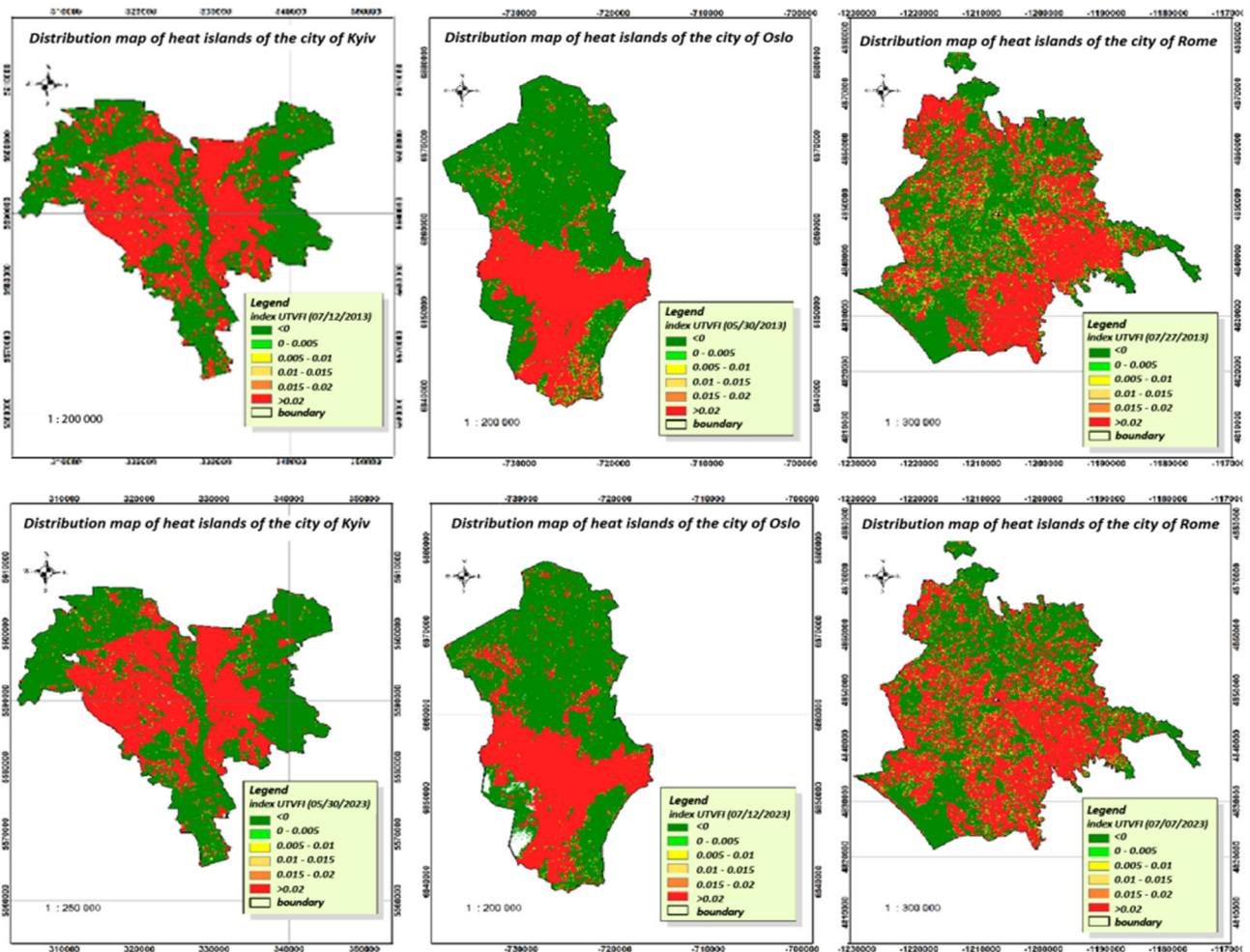


Fig. 4. Distribution maps of heat islands of selected cities made using Landsat 8 OLI/TIRS data. Date of access: 01/30/2024

As with Land surface temperature (LST) maps, visual changes in the UHI or an increase in the number of heat islands indicate a poor environmental assessment.

Since a detailed UHI analysis requires not only a qualitative assessment, but also a quantitative one, the next step was to calculate the areas occupied by the corresponding class of urban heat island in each year. This procedure was also performed in ArcMap using the Reclassify, Raster to Polygon, and Calculate Geometry tools.

Then, obtaining certain results regarding surface temperatures and urban heat islands and analysing them, it is possible to search for additional factors that could influence changes in the selected areas.

However, as previously noted, impervious surfaces have a significant impact on urban heat islands. Therefore, additional code was written and developed in GEE to calculate the development index for each city and the resulting values were subsequently exported to ArcMap.

The Normalized Difference Built-up Index (NDBI) values were similarly calculated from preliminary Landsat 8 OLI/TIRS data. Thus, maps were constructed to analyse and evaluate the distribution of urban development according to the interdependence of the distribution of elevated surface temperatures in selected capital cities.

In each case, the sums of land areas of each class (high, low vegetation, water bodies and urban development) were calculated. Thus, statistical data on changes in the area of built-up surface were obtained.

Exploring the territories of the cities of Oslo, Kyiv and Rome, there was carried out an analysis of changes in surface temperature and the distribution of urban heat islands in the period from 2013 to 2023 using data from Landsat 8 OLI/TIRS satellites. Although the changes in each city were different, certain trends were observed that influenced the spread and intensity of UHI (Fig. 5).

Analysing the results obtained, there could be observed an increase in the area of urban heat islands from 44 % in 2013 to 46 % in 2023 in Rome and from 35 % in 2013 to 37 % in 2023 in Oslo. Thus, the worst trend is in Rome, where the area of the strongest and worst heat islands according to environmental assessment has increased by 30 sq.km.

Despite the global increase in temperatures, some cities still manage to avoid increasing the area of UHI, among which is the capital of Ukraine (Fig. 6).

Analyzing these changes in the areas of impermeable surfaces over time (Fig. 7), there is a noticeable decrease in the values of the Normalized Difference Built-up Index in Kyiv, which could serve as a potential reason for the decrease in urban heat islands by 12.7 % of the total area of the city from 2013 to 2023. Note that this difference indicates an improvement in the ecological condition of the territory. Regarding the cities of Oslo and Rome, from 2013 to 2023 urban heat islands increased by 5.9 % (of the total area of the city of Oslo) and 12 % (of the total area of the city of Rome). In turn, the decrease in the number of impervious

surfaces could be caused by an increase in the overlying vegetation cover.

In contrast to Kyiv, two other European capitals experienced quite significant increases in impervious surfaces on their

territories of 100 sq.km. This exactly shows by how much the area of artificial surfaces increased in Rome, respectively by 28 sq.km more than in the capital of Norway.

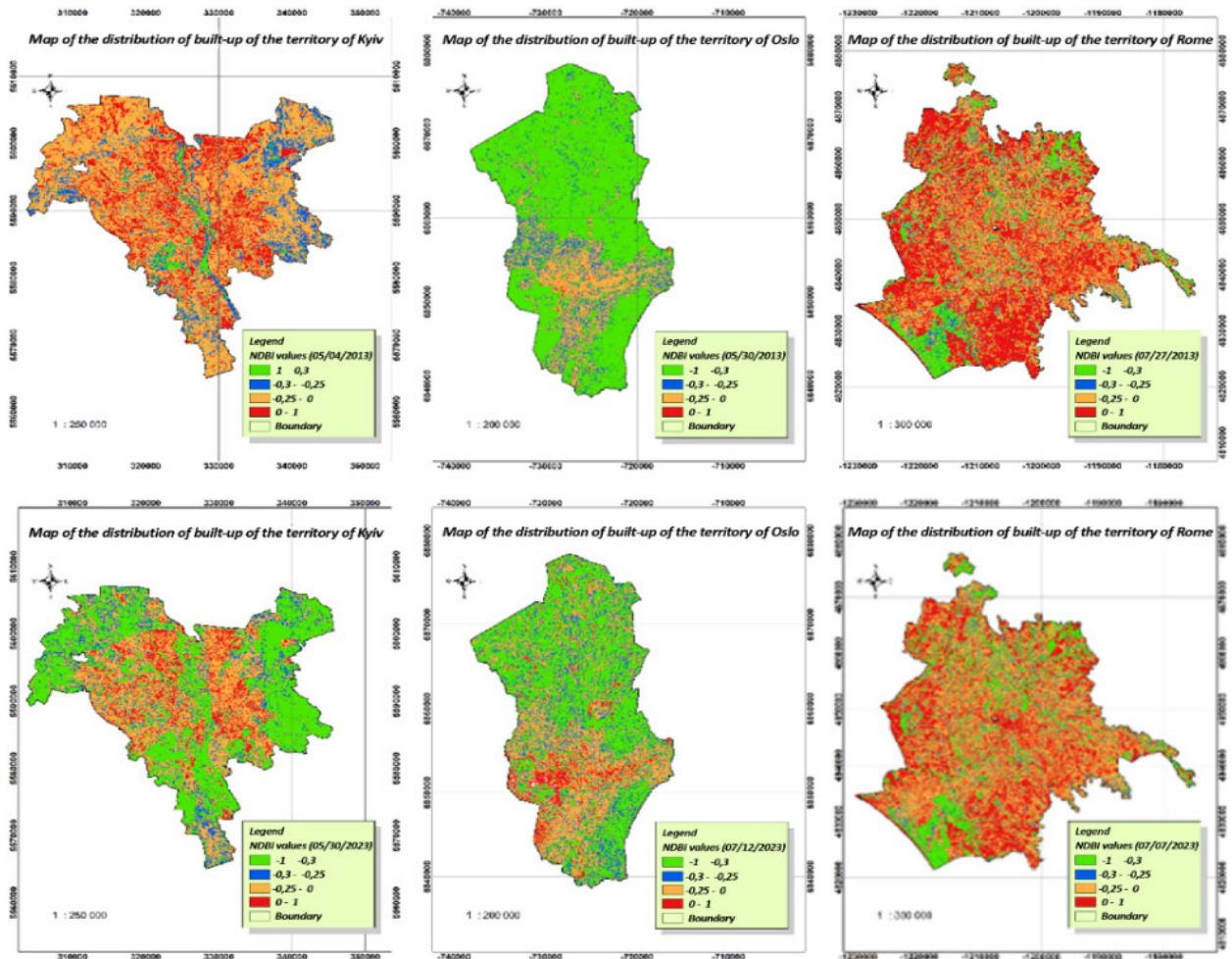


Fig. 5. Maps of the distribution of built-up of selected cities made using Landsat 8 OLI/TIRS data. Date of access: 01/30/2024

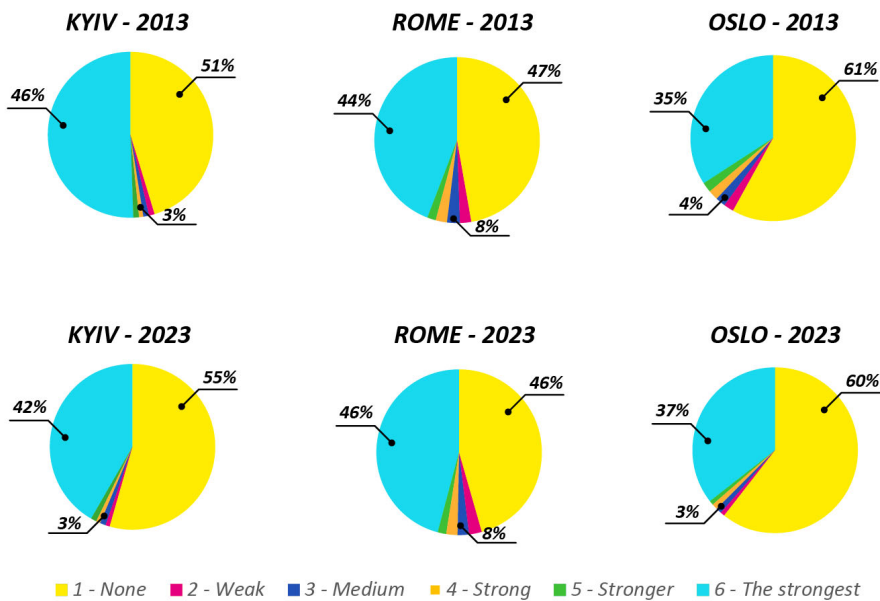


Fig. 6. Percentage charts of urban heat island area changes

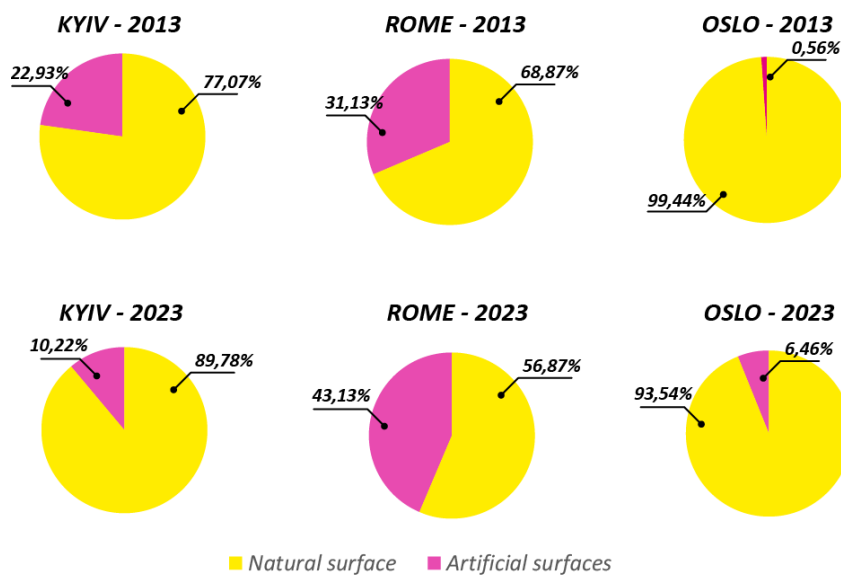


Fig. 7. Percentage charts of changes in the number of built-up surfaces

So, the territory of Kyiv, the city, shows a good trend in reducing the number of urban heat islands (by 30 sq.km in less than ten years), which is accompanied by a decrease in the number of impermeable surfaces.

As for Rome, the changes in the city are similar to those in Oslo, namely of a slight increase in the area of UHIs along with impervious surfaces.

Thus, comparing the trends in the distribution of urban heat islands and the amount of development, a possible relationship was assumed between these characteristics of the urban environment.

By investigating the distribution of urban heat islands in areas of interest, both negative and positive trends can be identified, which can serve as a good sign. In any case, it is necessary to remember about possible errors in the source data when performing calculations, etc.

Based on the remote sensing data reviewed, a relationship was assumed between the spread of UHIs and the increase in impervious surfaces. An effective algorithm of actions has been considered and applied allowing for high-quality and quick analysis and control of the temperature regime of the city. This, in turn, it makes it possible to create a unified geographic information system that can help local authorities ensure the comfort and safety of residents.

Discussion and conclusions

Thus, considering the potential danger involved that urban heat islands may pose for residents of modern megacities, it is important to calculate, develop, and implement a number of precautionary measures that will allow anticipating and avoiding negative consequences of these processes.

Using the example of European capitals such as Oslo, Kyiv, and Rome, the long-term influence of one of the factors (impermeable surfaces on urban heat islands) was analysed in detail, namely: using data from the Landsat 8 OLI / TIRS satellite, maps of surface temperatures were constructed allowing us to assume the dependence of LST on the number of impervious surfaces, particularly, a decrease in the number of UHIs simultaneously with a decrease in the number of impervious surfaces and vice versa.

The area of urban heat islands was found to increase from 44 % in 2013 to 46 % in 2023 in Rome and from 35 % in 2013 to 37 % in 2023 in Oslo. Thus, the worst trend is in Rome, where the area of the strongest and worst heat

islands according to environmental assessment has increased by 30 sq.km.

The data obtained indicate a noticeable decrease in the values of the Normalized Difference Built-up Index in Kyiv, which could serve as a potential reason for the decrease in urban heat islands by 12.7 % of the total area of the city from 2013 to 2023. Note that this difference indicates an improvement in the ecological condition of the territory. Regarding the cities of Oslo and Rome, from 2013 to 2023 urban heat islands increased by 5.9 % (of the total area of the city of Oslo) and 12 % (of the total area of the city of Rome). In turn, the decrease in the number of impervious surfaces could be caused by an increase in the overlying vegetation cover.

From the above mentioned opportunities and advantages provided to us by modern technologies and methods of research and monitoring of heat islands, it becomes clear that this process should be carried out precisely on the basis of Earth remote sensing data using geographic information systems.

The use of remote sensing and the products mentioned in this investigation should speed up and simplify the process of monitoring temperature regimes in cities and beyond.

The result of this investigation is a specific algorithm for monitoring urban heat islands, selected on the basis of the analysed scientific material, which proves the feasibility of further analysis of the relationship between two modern problems in megacities, that threaten the population more and more every day.

Using the collected materials, it becomes possible to search and evaluate the influence of constant and uncontrolled urbanization on the formation of the urban heat island effect, since, as mentioned earlier, it is the increase in population that is one of the main reasons for the formation of UHIs. Coverage of these issues provides a future basis for further research and review of its results.

Authors' contribution: Vitalii Zatserkovnyi – conceptualization, formal analysis, methodology, review and editing; Mauro De Donatis – conceptualization, methodology; Liudmyla Plichko – review of publications, selection of scientific novelty, conclusions, revision and editing; Stanislav Sakhniuk – formal analysis, data treating; Natalia Odarchuk – revision and editing; Tetiana Mironchuk – revision and editing.

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ВИКОРИСТАННЯ ТЕХНОЛОГІЙ ДИСТАНЦІЙНОГО ЗОНДУВАННЯ ДЛЯ МОНІТОРИНГУ МІСЬКИХ ОСТРОВІВ ТЕПЛА

Вступ. Процес урбанізації прискорюється з кожним днем, що спричиняє значні зміни у природному ландшафті. Це призводить до мікрокліматичних змін, забруднення повітря, теплового ефекту тощо. Через забруднення повітря техногенними викидами в урбанізованих районах змінюється тепловий режим – концентрація вуглекислого газу та водяної пари зараз досягла 90 % від загальної кількості забруднювальних речовин. Як наслідок, виникає ще одна проблема, що сприяє глобальному потеплінню – "парниковий ефект". Підвищені значення температури повітря впливають на здоров'я людини, призводять до проблем з диханням, судом, теплого та сонячного ударів, теплового стресу та підвищеної смертності. З огляду на потенційну небезпеку підвищених значень температур повітря, викиданих міськими островами тепла, що впливають на життя мешканців, необхідно розробити ефективний та актуальний метод аналізу температури поверхні та визначення розташування теплових островів.

Методи. Під час моніторингу міських островів тепла головним фактором для аналізу є поверхнева температура, яку визначали в дослідженні за допомогою таких індексів, як: нормалізований диференційний вегетаційний індекс (NDVI), індекс дисперсії міського теплового поля (UTVFI) та нормалізований диференційний індекс забудови (NDBI).

Результати. У пропонуваній роботі описано дослідження поширення міських островів тепла у трьох європейських столицях, серед яких Київ, Осло та Рим, у період із травня 2013 р. по серпень 2023 р. Користуючись можливостями хмарної платформи Google Earth Engine та даними супутника Landsat 8 OLI/TIRS було здійснено порівняння стану зелених насаджень, кількості непроникних поверхонь і показників поверхневих температур (LST), унаслідок чого побудовано карти поширень міських островів тепла (MOT) на територіях обраних міст і сформовано відсоткові діаграми, що демонструють кількісні зміни.

Висновки. Дослідження показало зменшення кількості MOT разом з непроникними поверхнями на території міста Київ на 4 %. Водночас Рим та Осло зазнали збільшення кількості MOT разом з непроникними поверхнями. Отримані дані доводять доцільність використання обраного методу дослідження та можуть бути застосовані для оцінювання екологічного стану, визначення зон ризику та розроблення ефективних заходів подальшого запобігання поширенням MOT у мегаполісах.

Ключові слова: міський острів тепла, поверхневі температури, непроникні поверхні, зелені насадження, Landsat 8 OLI/TIRS, Google Earth Engine, дистанційне зондування Землі, ГС.

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