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ORIGINAL PAPER

Assessing climate change threats and urbanization impacts on surface runoff in Gdańsk (Poland): insights from remote sensing, machine learning and hydrological modeling

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Abstract

This study investigates the impacts of Land Use/Land Cover (LULC) changes and climate change on surface runoff in Gdańsk, Poland, which is crucial for local LULC planning and urban flood risk management. The analysis employs two primary methodologies: remote sensing and hydrological modeling. Remote sensing was conducted using Google Earth Engine and Land Change Modeler in IDRISI Terrset software to analyze historical (1985–2022) and future (2050–2100) LULC. Hydrological modeling was performed using the Natural Resources Conservation Service curve number method to assess the overall impact of LULC changes on Gdańsk's hydrology at the local scale. The Orunia basin, a critical area due to intensive LULC development, was selected for detailed hydrological analysis using the Hydrologic Modeling System (HEC-HMS). The analysis encompassed three scenarios: LULC changes, climate change, and combined LULC and climate change effects. The LULC analysis revealed a marked increase in urban area, a shift in forest and vegetation cover, and a reduction in agricultural land. HEC-HMS simulations showed an increase in the runoff coefficient across selected decades, which was attributed to the combined effect of LULC and climate change. The projected increases under the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios for 2050 and 2100 are projected to surpass those observed during the baseline period. The findings highlight that the synergistic effects of LULC and climate change have a more significant impact on Gdańsk's hydrology at both local and basin scales than their separate effects. These insights into LULC shifts and urban hydrological responses hold implications for sustainable urban planning and effective flood risk management in Gdańsk and similar urban settings.

Keywords Remote sensing · LULC · Random forest · Climate change · Surface runoff · Gdańsk

1 Introduction

Urbanization and deforestation impact catchment hydrology by reducing storage capacity through vegetation removal and expansion of impervious surfaces. This leads to altered hydrologic parameters and increasing surface runoff, a globally-observed phenomenon (Rogger et al. 2017; Szydłowski 2006). Contrary to global trends, European countries (Cegielska et al. 2017; Tretiak et al. 2021; Estonian Ministry of the Environment 2021; Wnęk et al. 2021; Prokešová et al. 2022), including Poland, have seen expansion of forest cover, which should theoretically mitigate runoff (Prokešová et al. 2022). Despite this, flash flood frequency has risen in recent decades, driven by extreme rainfall events across the European Union (EU) (Kahraman et al. 2021).

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Political shifts in 1989 and Poland's EU accession in 2004 led to significant transformations of agricultural land into forests and urban areas across Central and Eastern Europe. Supported by EU policies like the Common Agricultural Policy (CAP) and the Cohesion Policy, these changes profoundly impacted land use and hydrology (Cegielska et al. 2017; Tretiak et al. 2021; Estonian Ministry of the Environment 2021; Wnęk et al. 2021; Prokešová et al. 2022; Wojkowski et al. 2023), highlighting the need for mapping and quantification to enhance flood risk management.

Land use land cover (LULC) classification is a preliminary step essential for informed decision-making. Advances in remote sensing and modeling techniques (Huang et al. 2017), facilitated by cloud-based platforms like Google Earth Engine (GEE), have revolutionized LULC analysis by overcoming data accessibility challenges, enabling large-scale geospatial analysis, and a user-friendly interface (Noel et al. 2017; Saha et al. 2024).

Spatiotemporal modeling and simulation techniques have rapidly evolved to study LULC dynamics and forecast the changes (Verburg et al. 2004). Simulation models for LULC transition and prediction offer effective and replicable methods to assess past, present, and future scenarios under different conditions (Liu et al. 2017; Han et al. 2015) with cellular automata being commonly employed for their versatility in simulating LULC changes (Batty et al. 1997). Forecasted LULC changes often have complex and contradictory effects on the formation of runoff, hence requiring detailed computations.

Various methods, from simpler rational methods to more complex models like the Soil and Water Assessment Tool (SWAT) (Briak et al. 2016), have been used to analyze hydrological responses of LULC at the watershed scale (Mustafa and Szydłowski 2020). Despite data collection and modeling advances, challenges still need to be addressed, particularly in urban basins with limited measurements (Olechnowicz and Weinerowska-Bords 2014). The lack of data makes it difficult to employ complex models requiring calibration from extensive observations in ungauged basins. Given these challenges, the Natural Resources Conservation Service (NRCS) curve number (CN) method (USDA 1985) and Hydrologic Modeling System (HEC-HMS) (Peters 1998) presents a viable approach, having been successfully applied in several studies (Kabeja et al. 2020; Prokešová et al. 2022; Soulis 2021; Cieśliński et al. 2024) to demonstrate climate change and LULC impact on ungauged basins hydrology.

Previous studies in East Central Europe have projected LULC changes and analyzed their impacts on hydrology across various regions, including the Upper Vistula basin across Poland, Slovakia, and Ukraine (Wojkowski et al. 2023). Past and future LULC was also simulated in Romania (Kucsicsa et al. 2019; Mihai et al. 2006). LULC classifications have been mapped in multiple cities across Poland, Czechia, and Slovakia (Wnęk et al. 2021), and the effects of spatiotemporal LULC changes on surface runoff have been assessed in Slovakian catchments using the NRCS-curve number method (Prokešová et al. 2022). Although these regional studies provided valuable insights, this research explicitly addresses the Gdańsk area, offering localized insights that are highly relevant for urban planners and policymakers and connecting them to broader regional and European trends.

Locally and nationally, significant advancements have been made in LULC analysis, such as mapping LULC changes (Bielecka et al. 2020; Kwoczyńska 2021, 2022), LULC prediction (Dawid and Bielecka 2022; Dzieszko 2014) and LULC impact on surface runoff i.e., Gdańsk rainfall analysis (Szpakowski and Szydłowski 2018), and Orunia and Małomiejska basin runoff analysis (Kolerski and Kalinowska 2019; Olechnowicz and Weinerowska-Bords 2014). While previous studies have often focused on either historical or future LULC changes, this study uniquely integrates both perspectives. Furthermore, limited emphasis is given to future projections at sub-basin or basin-level studies. Analyzing historical LULC changes and projecting future scenarios leads to understanding the temporal dynamics of land use in Gdańsk.

Gdańsk faces three flood hazards: surface runoff from post-glacial Moraine hills, river outflow during intense precipitation, and rising sea levels in the Gulf of Gdańsk, necessitating comprehensive research (Cieśliński et al. 2024; Szpakowski and Szydłowski 2018; Walczykiewicz and Skonieczna 2020). Additionally, LULC in the Polish Baltic coastal region is sensitive to changing climatic conditions (Zaucha 2011). Despite this sensitivity, assessment of LULC changes related to climate change is lacking. This study addresses this critical gap by employing innovative methods to reconstruct historical land use scenarios and evaluate their hydrological impacts. By investigating historical and projected LULC changes, this study evaluates the individual and combined effects of these changes on surface runoff in Gdańsk. Moreover, integrating local, regional, and European trends contributes to understanding Gdańsk's hydrology and rainfall-runoff challenges and offers valuable insights for sustainable urban stormwater management practices.

Within this context, this study proposes a new approach aiming to achieve the following objectives:

- Classifying LULC in Gdańsk using the GEE platform.
- Analyzing and predicting LULC using LCM model.

- Employing the NRCS-curve number method to assess the impact of LULC changes on runoff in Gdańsk at the local scale.
- Qualitative evaluation of the contributions of climate change and LULC to runoff in the Orunia basin of Gdańsk, Poland, using the fixing-changing method for different scenarios.

2 Study area

Located on the southern coast of the Baltic Sea, Gdańsk is the largest city in northern Poland. It comprises the Vistula Delta Plain, Vistula Spit, and the eastern Kashubian Coast. Covering 262 km^2 (Fig. 1), Gdańsk is a part of the tri-city metropolitan area along with Sopot and Gdynia. The western side features post-glacial hills from the Kashubian Lakeland, reaching elevations up to 200 m above sea level (asl) and transitioning to mainly residential areas in the south. The northern and central regions constitute moraine hills with forests forming a tri-city landscape park (Szpakowski and Szydłowski 2018). The eastern part of Gdańsk includes lowland areas, often below sea level, called Żuławy Gdańskie. These low-lying areas of Gdańsk face coastal flood risks (Szpakowski and Szydłowski 2018).

Gdańsk's mean annual precipitation was recorded at 659 mm (Jakusik and Chodubska 2020). Gdańsk's location at the mouth of the Vistula River and proximity to the Gulf of Gdańsk make it historically and economically significant. However, this coastal positioning also renders Gdańsk highly vulnerable to the impacts of climate change, including sea-level rise and extreme weather events (Staudt et al. 2006; Szydłowski et al. 2023).

The city experiences land subsidence at an average rate of 1–2 mm per year, exacerbating its susceptibility to flooding (Staudt et al. 2006). Storm surges, driven by strong northern winds, can raise sea levels by over 1.5 ms, with projections indicating potential surges reaching up to 2.5 ms. The frequency of dangerous storms in the Gulf of Gdańsk has nearly quadrupled in recent decades (Jakusik and Chodubska 2020). These factors underscore the urgent need for Gdańsk to enhance its flood risk management and climate adaptation strategies.

The catchment area of Oruński/Orunia Stream (Fig. 1), known as Potok Oruński, has been chosen for local runoff analysis due to the significant LULC changes over the past 37 years. With an area of 16.55 km^2, the Orunia basin is located in the rapidly developing Południe district of Gdańsk, offering the potential for new construction projects. The Orunia Stream, the largest tributary of Radunia Canal and its tributaries, is crucial for draining water from

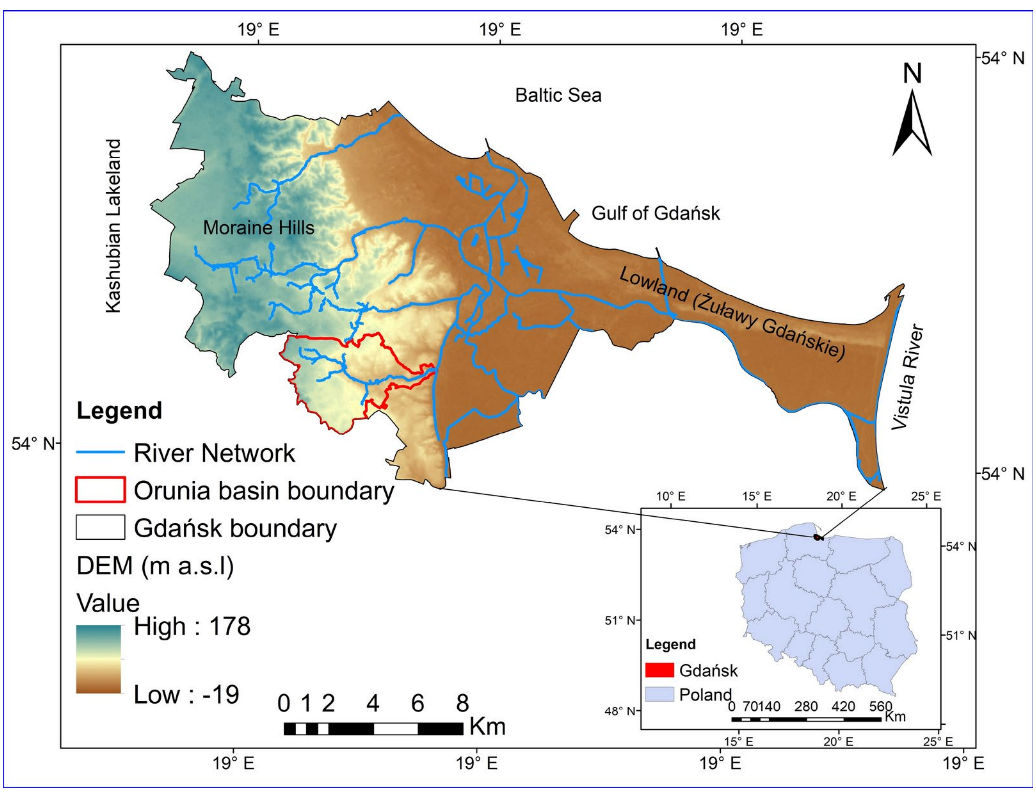

Fig. 1 The geographical location of the study area: Location map of Gdańsk in Poland (bottom right), Gdańsk (top left) with Orunia basin in the southwest

the plateau in the west to the east (Kolerski and Kalinowska 2019; Łukasz Pietruszyński and Cieśliński 2019).

3 Materials and methods

The methodological workflow implemented is depicted in Fig. 2. The process can be outlined as follows:

- Remote sensing data was collected using various sources.
- LULC maps for selected years were classified using the GEE platform (Noel et al. 2017).
- The LCM model (Eastman 2012) was utilized to predict future LULC changes for 2050 and 2100.
- In ArcMap 10.7, a CN grid was generated for each year using the HEC-GeoHMS tool, with soil and LULC maps as input data (Fig. 2).
- The NRCS-CN method (USDA 1985) was employed to evaluate the influence of LULC changes on the hydrology of the entire Gdańsk region.
- At the basin level, the HEC-HMS (Peters 1998) model was used to simulate the Orunia basin's historical and future hydrological response.

3.1 Data collection

The data source and details of the data used in LULC training, validation, and hydrological model are shown in Table 1. The data sources used in this study were selected based on their open access and the availability of the latest, high-quality datasets, ensuring comprehensive LULC analysis and hydrological modeling.

3.2 LULC classification

This study utilized a combination of imagery observation, auxiliary data, and existing LULC products (Table 1), namely Copernicus Global Land Cover Layers (100 m), Globeland30 (30 m), and ESA WorldCover (10 m), to collect training and validation samples. Since these LULC products represented different resolutions and LULC types, it was necessary to resample and reclassify them to a standardized LULC classification scheme using GEE. To ensure consistency in the training and validation samples, random points were generated for each LULC class (Pal and Saha 2018) and then overlaid with the reclassified LULC products to ensure points were representative across the multi-source LULC products. In this research, the Random Forest (RF) classification (Breiman 2001) was implemented within the GEE platform.

3.2.1 LULC validation

Hyper-parameter tuning was conducted to optimize the RF classifier by experimenting with different numbers of trees and minimum leaf sizes to identify the optimal settings based on overall classification accuracy. The tuning process revealed that 100 trees and a minimum leaf size of 10 provided the best results. To further ensure robustness and avoid over-fitting, a k-fold cross-validation approach was employed. This method involves partitioning the data into multiple subsets, training the model on each subset, and validating it on the remaining data, thereby offering

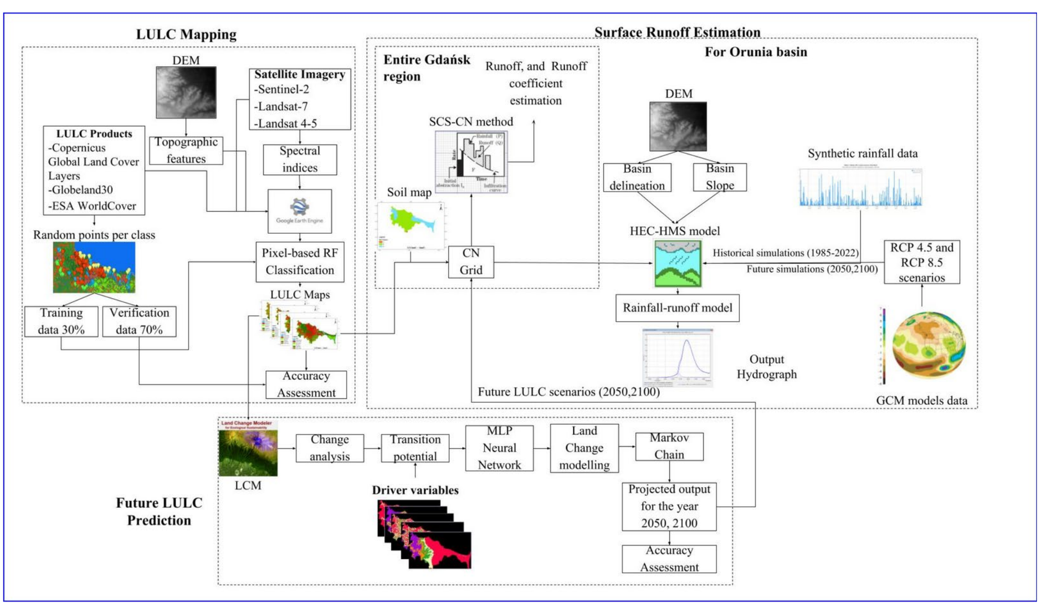

Fig. 2 Flow chart depicting the methodological framework

Table 1 Data sources and their applications

Data	Resolution	Source	Period	Reason for choosing data
Digital elevation model (DEM) and topographic data	1 m	Geoportal of Poland https://www.geoportal.gov.pl/	–	Open access and high resolution for accurate hydrological analysis
Meteorological data	–	Polish National Meteorological Service (IMGW-PIB) Rebichowo and Klukowo station (Gdańsk-Water 2022)	1974 to 2016 and 2018 to 2021	Comprehensive historical coverage and publicly available
Soil map	30 m	Food and Agriculture Organization (FAO) (FAO 2009)	–	Openly accessible with standardized global classification
Sentinel-2 multispectral imagery	20 m	https://search.earthdata.nasa.gov/search	2022, 2015	Open access for detailed LULC analysis
Landsat-7 enhanced thematic mapper Plus (ETM+)	30 m	https://search.earthdata.nasa.gov/search	2005	Open access with historical data continuity
Landsat 4–5 thematic mapper (TM)	30 m	https://search.earthdata.nasa.gov/search/	1995,1985	Open access with historical data continuity
Population density data	Per Census tract	Copernicus Land Monitoring Service, Urban Atlas LULC 2018 (Service 2018)	2018	High spatial resolution and free access for urban analysis
Road network and river network	–	OpenStreetMap (OpenStreetMap 2017)	–	Freely available with high accuracy and frequent updates
Copernicus global land cover layers	100 m	Copernicus Global Land Cover Layers (Marcel et al. 2020)	Annual, 2019: Globe, Version V3. 0.1	Open access and latest available
Globeland30	30 m	Globeland30 (Chen et al. 2014)	–	Open access and latest available
ESA WorldCover	10 m	ESA WorldCover (Daniele et al. 2022)	2021 v200	Open access and latest available

a comprehensive evaluation of the model's performance. Quantitative measures, such as overall accuracy (OA) and the kappa coefficient (Saha and Pal 2019), were employed to evaluate the accuracy of LULC classification using validation data.

3.3 Projections of future LULC Change by LCM

For future LULC prediction, the LCM within TerrSet software system (Eastman 2012) was utilized. LULC scenario modeling facilitates addressing uncertainty in LULC predictions by enabling the examination of various potential scenarios. Three scenarios were developed, considering historical rainfall data from the 20th century, rainfall data up to 2005, and data from 2000 to 2022, along with future rainfall projections. The three different scenarios are: (1) 1985–2005, (2) 2005–2022, and (3) 1985–2022.

- 1985–2005: This period captures the post-communist transition in Poland, marked by significant socio-economic changes that influenced land use.
- 2005–2022: This scenario focuses on the years following Poland's accession to the European Union in 2004, a time of accelerated urban development and EU-driven environmental policies.
- 1985–2022: Combining the entire period, this scenario provides a comprehensive overview of the long-term trends in LULC change, capturing the cumulative effects of socio-economic shifts and evolving climate conditions over nearly four decades.Each scenario's LULC maps were imported into LCM for analysis, allowing the evaluation of gains, losses, and net changes in land cover.

The selection of driving forces for LULC changes does not have a recommended approach (Mozumder and Tripathi 2014). In this study, the selected static variables included DEM, slope, aspect, and distance from water bodies, while the dynamic variable considered was a distance from the road network. Additionally, population density, a socio-economic factor, was included as a dynamic variable. To map the spatial trend of change, an 8th-order polynomial was employed.

A transition sub-model can represent single or multiple transitions driven by the same variables (Abuelaish and Olmedo 2016). Before prediction, the transition maps were derived using an MLP neural network. These maps and static and dynamic variables were used to predict LULC changes for 2050 and 2100 using the Cellular Automata (CA) Markov chain. In this study, a land cover prediction for the year 2022 (for which we had actual land cover information) was generated using the VALIDATE module of IDRISI Terrset, and its accuracy was evaluated by comparing it to a reference LULC map of the same year.

3.4 Local scale hydrological modeling in Gdańsk using NRCS-CN

The NRCS-CN (USDA 1985) method is an effective approach to calculating rainfall-runoff transformation. This study utilized synthetic heavy rainfall with p = 1% (return period 100 years) and T = 24 h daily maximum rainfall data from 1974 to 2000 (Table 1). In ArcMap, a CN grid was prepared using the LULC and Hydrologic Soil Group (HSG) map of the Gdańsk. CN values, which range between 100 (water bodies) to 30 (permeable soils), were applied to estimate direct runoff depth using the NRCS-CN formula (Eq. 1) in ArcMap (Hameed 2017).

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{1}$$

$$S = \frac{25400}{CN} - 254 \tag{2}$$

where P is the total rainfall (mm), S is the potential maximum retention (mm), CN is the curve number, while Q is the direct runoff (mm).

3.5 Hydrological modeling for Orunia basin using HEC-HMS

The HEC-HMS model is widely used for simulating rainfall-runoff processes at different temporal scales (Peters 1998). Using DEM, the HEC-GeoHMS (Feldman 2000) extension in ArcMap was used to define the basin's topographic and hydraulic characteristics. The basin was divided into 20 sub-basins for computational efficiency and accuracy. Key attributes such as basin slope, length, and slope of rivers of each sub-basin were identified using DEM. Figure 3 illustrates the topography and schematic of the hydrological model for the Orunia basin.

HEC-HMS computed the hydrological losses from total rainfall across the basin using the NRCS-CN (USDA 1985) loss method. The NRCS unit hydrograph transform model was applied to convert rainfall into runoff. The Muskingum method was utilized to route water through rivers and channels towards the basin outlet, enabling runoff calculations for each sub-basin.

3.5.1 Model validation

For the hydrological modeling of the Oruński Stream catchment, direct validation against actual stream-flow data was not possible due to the unavailability of observational data for this catchment. Therefore, to ensure the reliability of hydrological estimates, the Oruński Stream catchment model was aligned with the calculation parameters of the previously verified hydrological model of a neighboring Gdańsk catchment, the Strzyża Stream (Cieśliński et al. 2024; Mikos-Studnicka and Szydłowski 2022, based on their hydrological similarity. This approach allowed to qualitatively validate the model by ensuring that the hydrological behavior of the Oruński Stream was consistent with that of a similar, well-studied catchment. However, we acknowledge that the absence of direct observational data introduces a degree of uncertainty, which is why this study

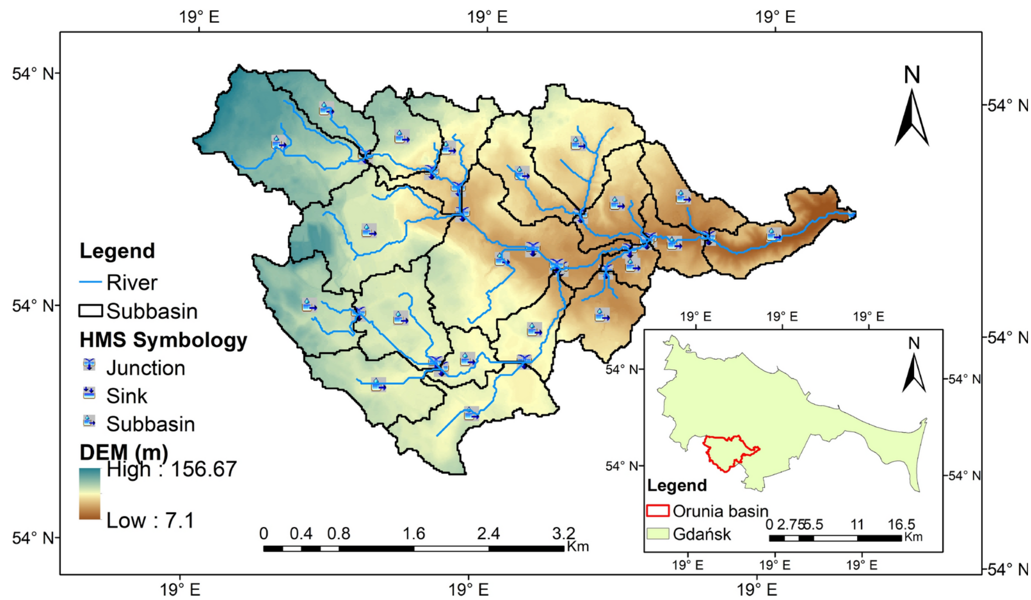

Fig. 3 Illustration of hydrologic elements in the HEC-HMS model, delineating the Orunia basin

Table 2 Data sets for the HEC-HMS simulation used to analyze the combined and separate effect of LULC and climate changes on surface runoff in the Orunia basin

Model run no.	Combined effect		LULC change effect		Climate change effect		Remark
	Climate data set	LULC map	Climate data set	LULC map	Climate data set	LULC map	
1	1974 to 2000	1985	1974 to 2000	1985	1974 to 2000	1985	Baseline period
2	1974 to 2000	1995	1974 to 2000	1995	1974 to 2000	1985	Baseline period
3	2000s	2005	1974 to 2000	2005	2000s	1985	Moderate development
4	2010s	2015	1974 to 2000	2015	2010s	1985	Human activities
5	2020s	2022	1974 to 2000	2022	2020s	1985	Human activities
6	2050s	2050	1974 to 2000	2050	2050s	1985	Climate change
7	2100s	2100	1974 to 2000	2100	2100s	1985	Climate change

primarily aims to identify hydrological trend changes rather than establish a fully operational model for flood prediction.

3.5.2 HEC-HMS simulation

- First method involved a division of the analysis period from 1974 to 2100 into four periods: 1974–2000 (baseline), 2000–2005 (moderate development), 2005–2022 (human activities), and 2022–2100 (climate change). LULC maps of 1985, 1995, 2005, 2015, 2022, 2050, and 2100 depict evolving LULC over these decades (Table 2). The HEC-HMS simulations were conducted using the corresponding land use map and weather data, with constant DEM and soil data.
- "Fix-changing" method (Mekonnen et al. 2018) was used to assess the impacts of LULC alone on the surface runoff. This employed precipitation data from the baseline (1974–2000) and LULC maps from 1985 to 2100, with constant DEM and soil data. The HEC-HMS was run seven times for the baseline period, with each run using a different LULC map from 1985 to 2100 while maintaining the constant weather dataset from 1974–2000.
- The Third approach is similar to the second one, but it assesses the impact of climate change. It consistently used the 1985 LULC map while altering the climate data for decades up to 2100.

This study used synthetic precipitation events (T = 24 h, p = 1%) as climate data for each approach adopted per the results of previously developed probability distributions (Szpakowski and Szydłowski 2018). The baseline period had a rainfall of 93.38 mm, while the period from 2000 to 2005 had a rainfall of 120 mm. For the subsequent periods, a rainfall of 116mm was used from 2005 to 2015, and 140 mm for 2015 to 2022, considering the corresponding land use conditions of 1985, 1995, 2005, 2015, and 2022.

Additionally, hydrological modeling was conducted for the worst-case scenario for the predicted LULC, i.e., pessimistic: future changes in LULC (2050, 2100) based on the intensification of development observed from 1985–2022.

Table 3 CORDEX Europe—Maximum 1-day precipitation (RX1day) Change %—Medium Term (2041–2060) and Long Term (2081–2100) RCP4.5, RCP8.5 (rel. to 1981–2010)—Annual (21 models), Annual (48 models) Regions: Western and Central Europe (Iturbide et al. 2021)

Period	Scenario	Median (%)
Medium Term (2041–2060)	RCP4.5	7.7
Medium Term (2041–2060)	RCP8.5	10.4
Long Term (2081–2100)	RCP4.5	11.8
Long Term (2081–2100)	RCP8.5	22.1

Table 4 Accuracy assessment of LULC classification

Accuracy measures	1985	1995	2005	2015	2022
Kappa	0.938	0.963	0.90	0.92	0.921
Overall Accuracy (%)	94.91	96.98	92.42	93.38	93.64

The HEC-HMS was used for future simulations, and the projected maximum daily rainfall data was obtained from bias-corrected Coordinated Downscaling Experiment-European Domain (EURO-CORDEX) (Iturbide et al. 2021) for the medium term (2041–2060) and long term (2081–2100), as presented in Table 3.

4 Results

4.1 LULC maps and accuracy assessment

Table 4 presents the results of an accuracy assessment conducted using a confusion matrix, which compares the pixel count across various LULC classes in the classified maps of 1985, 1995, 2005, 2015, and 2022. All five classified maps exhibit accuracy levels higher than 90%. The overall accuracy for these classified images o, as indicated by the Kappa coefficients, was 94.91% for 1985, 96.98% for 1995, 92.42% for 2005, 93.38% for 2015, and 93.64% for 2022.

Figure 4 illustrates the classified LULC maps for Gdańsk across 1985, 1995, 2005, 2015, and 2022 years with six major LULC categories. Table 4 presents a quantitative evaluation of the LULC classes, showing changes in an area measured in km^2 and the corresponding percentages (%) between 1985 and 2022.

From 1985 to 2022, significant declines were observed in the agricultural land and fallow land categories in Gdańsk. In 1985, the agricultural land covered an area of 51.93 km^2, accounting for 19.45% of the total area of Gdańsk. Similarly, the fallow land covered an area of 57.65 km^2. These two categories comprised the largest land cover extent of 109.58 km^2. The forest and vegetation category covers an area of 79.66 km^2, making it the second most prominent LULC category in Gdańsk. The built-up, bare land, and water bodies in the same year covered 58.64 km^2, 9.86 km^2, and 9.24 km^2, respectively.

By 2022, Gdańsk observed a noticeable reduction in agricultural and fallow land to 69.67 km^2, whereas forest and vegetation expanded to 97.37 km^2. The built-up area also increased, reaching 88.89 km^2. This comparison between 1985 and 2022 reveals that the built-up area, forest, and vegetation cover have surpassed the extent of agricultural and fallow land in Gdańsk. Additionally, the bare land and water bodies occupied a smaller area in 2022, with 5.11 km^2 and 7.81 km^2, respectively (Table 5).

4.2 LULC change analysis and prediction

A change analysis of LULC classes was conducted during different time intervals: (i) 1985–2005, (ii) 2005–2022, and (iii) 1985–2022 (Fig. 5). Each time interval exhibited a different quantity of change.

The lowest change quantity was observed during the first interval (1985–2005). The built-up area experienced a net gain of 3.61 km^2 (1.35% of the total area of Gdańsk), with an increase of 32.50 km^2 and losses of − 28.89 km^2. Conversely, the arable land (agriculture and fallow land) showed a net loss of – 15 km^2 (− 5.61% of total area), and forest and vegetation demonstrated a net gain of 13.10 km^2 (4.90%). At the same time, other classes exhibited a decrease (Fig. 5).

In the second interval (2005–2022), the built-up area increased by 25.66 km^2(9.6% of the total area), while arable land underwent a net loss of − 23.71 km^2 (− 8.8% of the total area). Forest and vegetation exhibited a net gain of 3.65 km^2 (1.36% of the total area), while other classes experienced overall reductions.

Over the 37 years from 1985 to 2022, the net change in built-up area was 29.28 km^2 (11.00% of the total Gdańsk area), while agricultural land, fallow land, forest and vegetation, water bodies, and bare land showed varying gains and losses. Notably, the growth rate of forest and vegetation was relatively high at 0.66 km^2 per year in the first interval (1985–2005), decreasing to 0.21 km^2 per year in the second interval (2005–2022). In contrast, the built-up area exhibited an increased rate of 1.51 km^2 per year during 2005–2022 compared to a lower rate of 0.18 km^2 per year in the first time interval, while arable land (agriculture and fallow land) lost 0.31 km^2 per year.

This analysis highlights that the most pronounced changes occurred during the second interval from 2005 to 2022, indicating accelerating urbanization.

4.2.1 Spatial trend of LULC change

In this research, the spatial trend of change in the built-up is significant due to its considerable influence on surface runoff, attributed to its impervious nature.

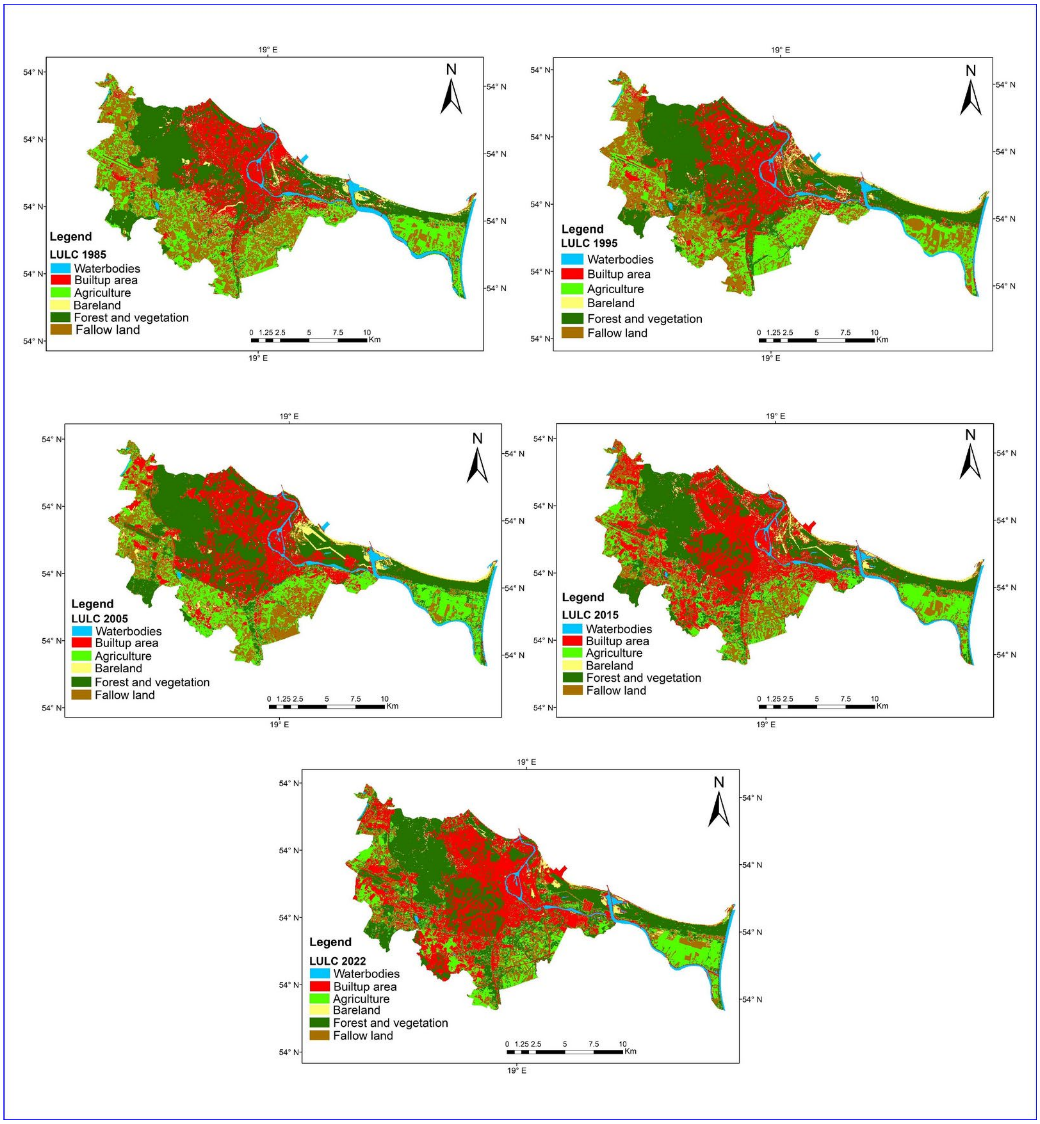

Fig. 4 LULC map for 1985, 1995, 2005, 2015, and 2022

Table 5 Area occupied by six LULC classes from 1985 to 2022

Classes	1985		1995		2005		2017		2022	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Waterbodies	9.24	3.46	7.89	2.95	8.35	3.13	7.43	2.78	7.81	2.90
Builtup area	58.64	21.96	58.58	21.94	62.43	23.38	85.48	32.02	88.89	33.06
Agriculture	51.93	19.45	46.28	17.33	45.61	17.08	41.97	15.72	40.34	15.00
Bareland	9.86	3.69	8.14	3.05	9.53	3.57	8.52	3.19	5.11	1.90
Forest and Vegetation	79.66	29.84	93.75	35.11	92.93	34.81	85.69	32.10	97.37	36.22
Fallow land	57.65	21.59	52.38	19.62	48.14	18.03	37.86	14.18	29.33	10.91

The analysis of transitions from other land use classes to the built-up area, depicted in Fig. 6, employs an eight-degree polynomial order. Initially, during 1985–2005, urban growth concentrated in the southern and southwestern Gdańsk, areas rich in arable land and deemed suitable for development. However, over time (2005–2022), the expansion of the built-up area has shifted further southward. Across the span of 37 years, south and southwest expansion has been a key factor in focusing this study on the Orunia basin.

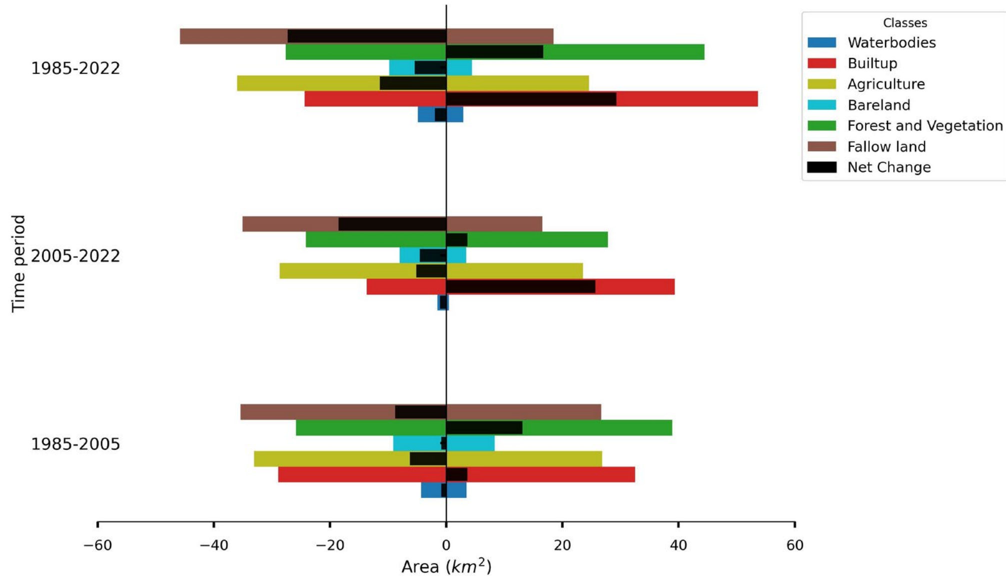

Fig. 5 LULC gains, losses, and net change for three scenarios: (i) 1985–2005, (ii) 2005–2022, and (iii) 1985–2022

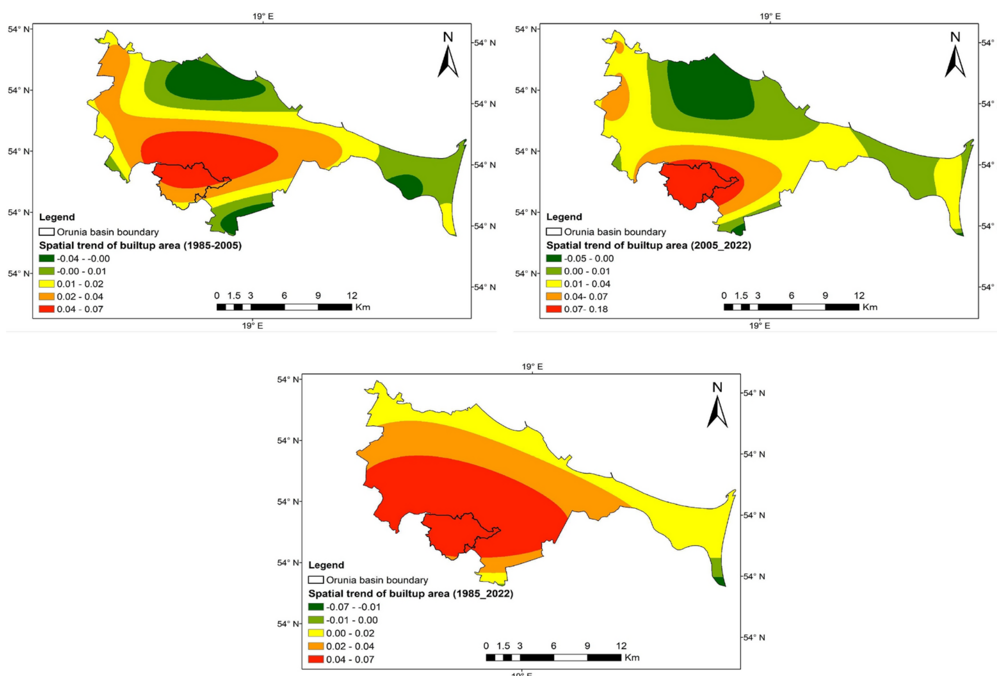

Fig. 6 Spatial trend of change from other LULC classes to the built-up area in Gdańsk across three periods: 1985–2005, 2005–2022, and 1985–2022

4.2.2 LULC future prediction

Future LULC changes were projected using the transition probability matrix obtained through the Markov chain analysis in LCM.

Figure 7 shows anticipated LULC for the years 2050 and 2100, generated using a hard prediction model. Figure 8 visually summarizes the distribution of six LULC classes across three scenarios (1985–2005, 2005–2022, and 1985–2022). The scenarios considered were as follows:

- Low demand scenario (1985–2005): This scenario projects the lowest demand for land and the lowest rate of land use change. It predicts a built-up area of 94.33 km^2 for 2050 and 97.19 km^2 for 2100.
- Intermediate demand scenario (2005–2022): This scenario projects a higher rate of land use change than the low demand scenario. It predicts a built-up area of 129.51 km^2 for 2050 and 154.47 km^2 for 2100.
- High demand scenario (1985–2022): This scenario considers cumulative land use change dynamics from the

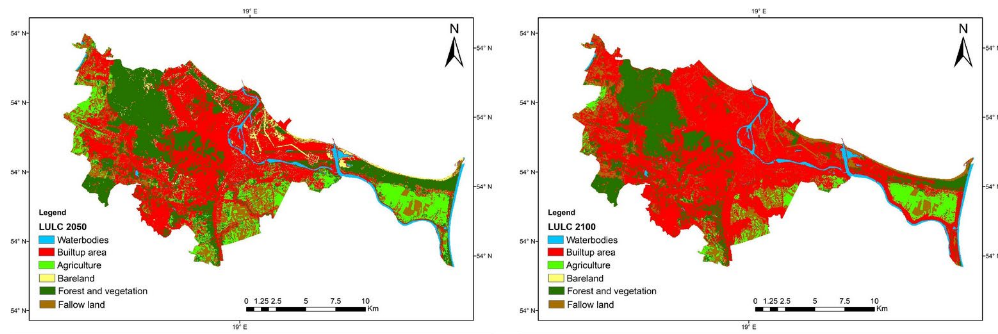

Fig. 7 Projected LULC map for the year 2050 and 2100 based on time interval 1985–2022

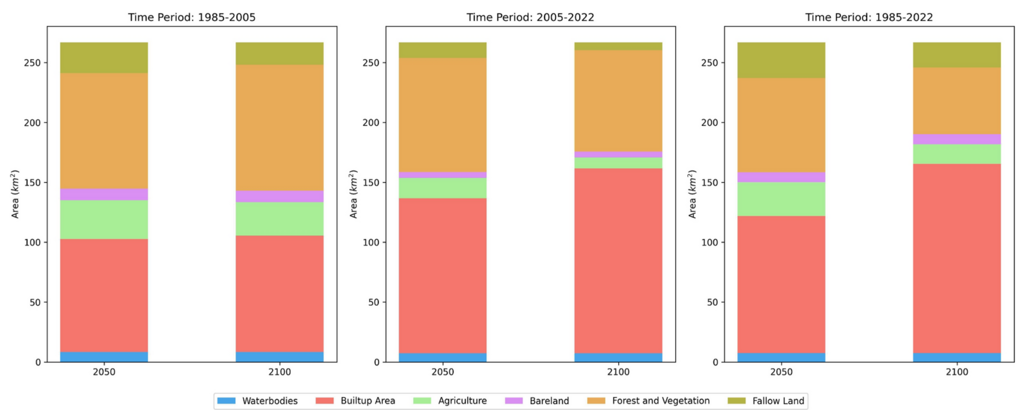

Fig. 8 Total change in each land cover class (km^2) for the projected LULC 2050 and 2100 based on periods 1985–2005, 2005–2022, and 1985–2022

Table 6 Summary validation statistics for the actual and projected LULC 2022

Agreement/disagreement	% Value
Agreement chance	14.29
Agreement quantity	25.68
Agreement gridcell	46.64
Disagreement gridcell	11.05
Disagreement quantity	2.35
Kno	84.38
Klocation	80.85
Kstandard	77.69

preceding periods. Therefore, it projects the highest rate of land use change and the overall demand for land during the entire period (1985–2022). It predicts a built-up area of 114.47 km^2 for 2050 and 157.96 km^2 for 2100.Table 6 provides insights about the level of similarity and dissimilarity between actual and predicted LULC 2022 using the VALIDATE module. It indicates an overall high match, reflecting a reliable prediction, while the total disagreement between the maps suggests some discrepancies in the classification due to allocation errors. The kappa statistics indicate substantial predictive accuracy, with Kno, Klocation, and Kstandard values showing the effectiveness of LULC prediction.

4.3 Influence of urbanization on surface runoff

This study evaluated LULC impacts on Gdańsk's hydrology using the NRCS-CN method, with a detailed focus on the Orunia basin's urban development impacts on surface runoff using the HEC-HMS model. Three scenarios were considered during the HEC-HMS simulation: (i) LULC change effect, (ii) climate change effect, and iii) combined LULC and climate change effect (Table 2).

4.3.1 LULC change influence on the surface runoff for the entire Gdańsk

Figure 9 illustrates the changes in the built-up area and its impact on the surface runoff. From 1985 to 2022, the runoff depth in Gdańsk increased from 41 to 47.03 mm, considering the total daily rainfall of P = 93.38 mm. Furthermore, the projected LULC for 2050 suggests that this runoff depth could rise to 51.10 mm.

Concurrently, the built-up area in Gdańsk expanded from 58.64 km^2 to 88.89 km^2, projected to be 114.47 km^2 by 2050. This expansion into impervious areas contributed to most of the runoff, while urbanization resulted in a decline in agriculture and fallow land. Nevertheless, an intriguing

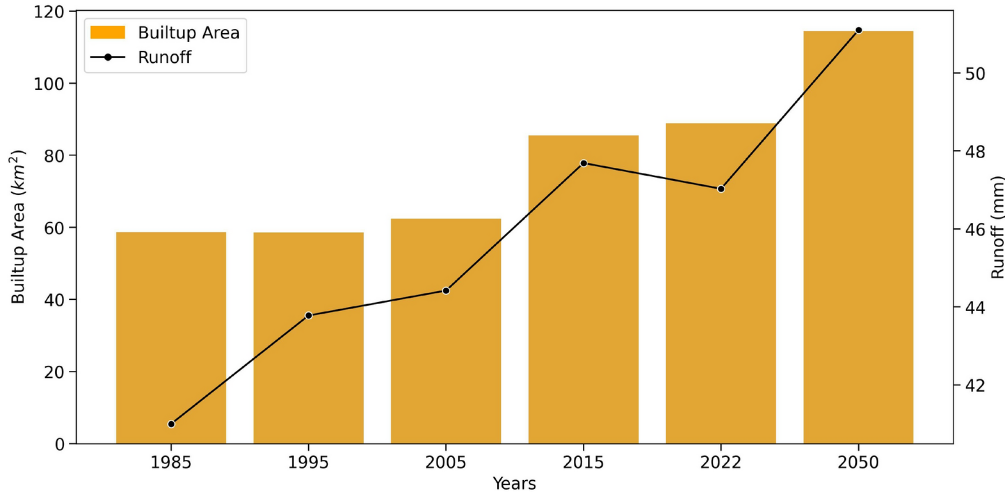

Fig. 9 Changes in built-up area and runoff depth in Gdańsk between 1985 and 2050

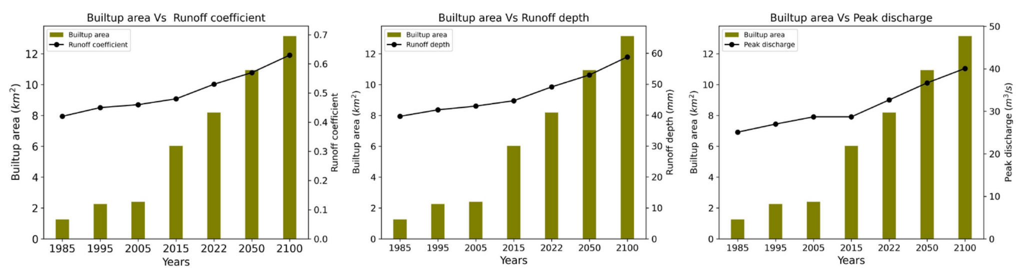

Fig. 10 Changes in runoff coefficient, runoff depth, peak discharge, and built-up area in Orunia basin under LULC change impact scenario

result was an increase in forest and vegetation cover, yet the runoff from these areas decreased from 23 mm in 1985 to 22.32 mm in 2022 and will further decrease to 21.96 mm in 2050. In contrast, the runoff depth generated from the built-up area is predicted to increase from 47.66 mm in 1985 to 72.96 mm in 2050.

4.3.2 LULC change effect on Orunia basin's runoff

Under this scenario, parameters from the baseline period (1974–2000), consistent DEM, soil, and rainfall data (93.38 mm) were used, while LULC maps were altered for different years. The comparison of the baseline period (1974–2000) and the human activities period (2005–2022) shows a notable increase of 24% in the runoff coefficient, particularly from 1985 to 2022. This is attributed to a net increase in built-up area of 6.75 km^2 in 2022, compared to its initial area of 1.25 km^2 in 1985 with no reservoir supporting surface runoff storage (Fig. 10). Notably, a considerable 10% of the overall runoff occurred in the last 7 years (2015–2022), driven by LULC transformations, surpassing historical LULC changes. This necessitates effective flood management strategies when the capacity of stormwater drainage system conduits is too low.

Future projections for 2050 and 2100 anticipate further increases to 0.57 and 0.63, respectively, representing 33.80% and 48.55% increases from the baseline period. These projections are driven by the projected expansion of the built-up area, reaching 10.94 km^2 (2050) and 13.15 km^2 (2100) under the worst-case scenario (Fig. 10). A similar trend for runoff depth (mm) and peak discharge (m^3/s) can be seen in Fig. 10 for the Orunia basin.

4.3.3 Climate change effect on Orunia basin's runoff

Climate change impacts on runoff were assessed using a consistent 1985 LULC map and varied weather data sets across several decades (Table 2). The analysis showed an overall increasing trend in the runoff coefficient from 0.42 in 1985 and 1995, with 93.38 mm rainfall, to 0.55 in 2022, with daily rainfall of 140 mm. From 1985 to 2022, the runoff coefficient increased by 28.70% from the baseline period value to the human activities period.

Projections for 2050 and 2100 under RCP 4.5 exhibited a substantial increase of 33.58% and 36%, resulting in a runoff coefficient value of 0.57 and 0.58. In the case of RCP 8.5, the runoff coefficient exhibited a notable increase of 38.57% in 2050, while 54.57% in 2100. The corresponding rise in estimated synthetic rainfall drives these significant

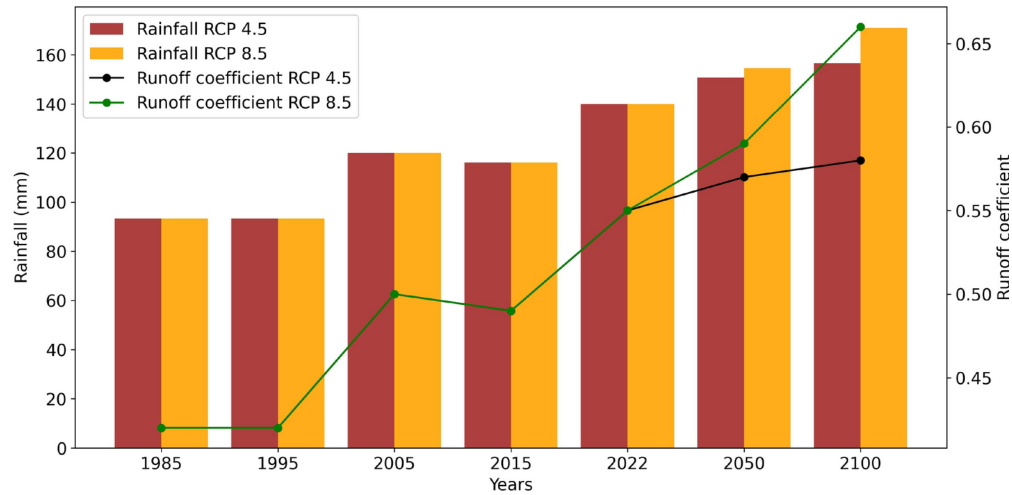

Fig. 11 Changes in runoff coefficient and rainfall in Orunia basin under climate change impact scenario for RCP 4.5 and RCP 8.5 (1985–2100)

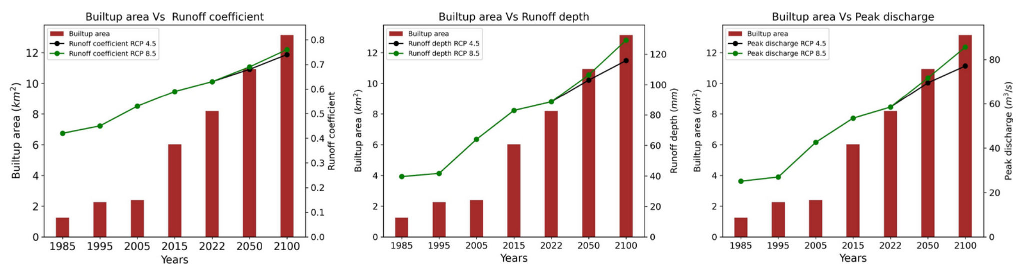

Fig. 12 Changes in runoff coefficient, runoff depth, peak discharge, and built-up area in Orunia basin under combined LULC and climate change impact scenario for RCP 4.5 and RCP 8.5 (1985–2100)

increments. The relationship between runoff coefficient and rainfall projections is visually illustrated in Fig. 11.

4.3.4 Combined effects of LULC change and climate change on Orunia basin's runoff

The combined impact of LULC changes alongside climate alternations reveals a significant 49.41% increase in the runoff coefficient from 1985 (0.42) to 2022 (0.63). Notably, the rate of change varied across different decades, which is represented in Fig. 12.

Between 2005 and 2015, the built-up area of the Orunia basin gained approximately 4.12 km^2. Despite a $-$ 3.3% (116 mm) reduction in rainfall for 2015, the runoff coefficient experienced a modest 11.09% increase. It showed a subsequent 6.88% increase from 2015 to 2022, coinciding with noticeable rainfall intensity and frequency compared to the 1990s, indicating the synergistic effects of LULC and climate change.

Figure 13 depicts the exacerbated combined effects under RCP 4.5 and 8.5. The results reveal a significant increase in the runoff coefficient of 61.08% and 74.58% under RCP 4.5 for 2050 (0.68) and 2100 (0.74), respectively, relative to the baseline period. Under the RCP 8.5 scenario, an even more pronounced increase to 62.33% and 78.26% by 2050 (0.69) and 2100 (0.76) is anticipated.

5 Discussion

This study analyzed the impacts of historical and projected LULC changes and climate change on surface runoff in Gdańsk, Poland. Using historical LULC data through GEE image classification with an accuracy exceeding 90%, the analysis showed Gdańsk experienced a significant decrease in agricultural land, expansion of built-up areas, and forestation from 1985 to 2022. This trend shows an increase in urbanization and forests at the expanse of agricultural land, reflecting local phenomena and broader regional land-use shifts.

The findings of this study are consistent with local trends observed in the Polish Baltic coastal zone, including Gdańsk, Sopot, and Gdynia, where there has been significant urban expansion and a 17% decline in agriculture over the past two decades (Kwoczyńska 2021), along with an increase in forest cover (Bielecka et al. 2020). These results also align with broader trends across Poland. For example, a study reported 24.78% increase in built-up areas, 24.12%

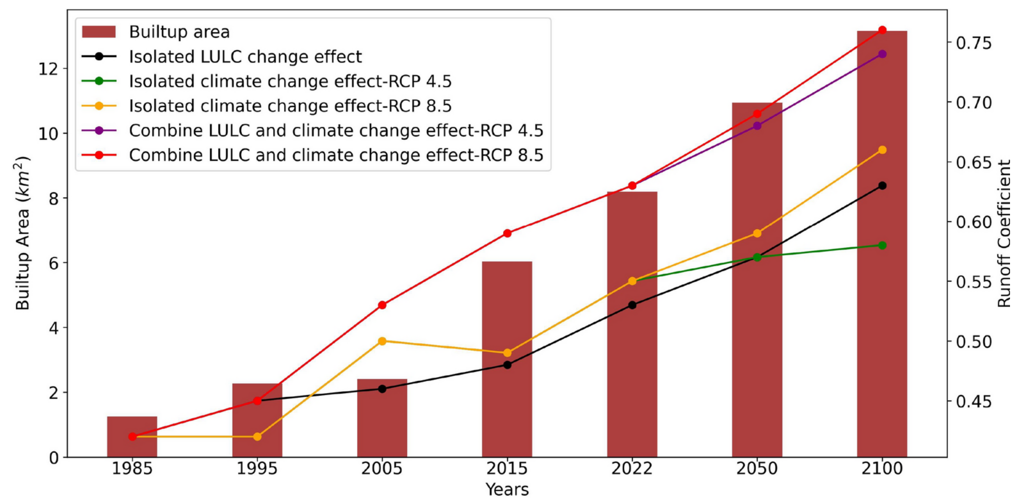

Fig. 13 Comparison between three simulations in HEC-HMS: (i) combined LULC and climate change effect, (ii) LULC change effect, and (iii) climate change effect

Table 7 Factors influencing LULC changes in Gdańsk

Factor	Influence on LULC	Details
Polish forest policy and EU membership (Wnęk et al. 2021)	Increase in forest and vegetation cover	Following World War II and membership to EU, Poland's forest policy aimed to increase sustainable forest management and biodiversity
National Program for Expending of Forest Cover (KPZL) (Borowska-Stefańska et al. 2018)	Increase in forest and vegetation cover	KPZL goal of increasing forest cover up to 30% by 2020 and further to 33% by 2050
EU CAP reform (Cegielska et al. 2017; Wnęk et al. 2021)	Decline in agriculture	CAP reform encouraged less economically viable land to transition to other land uses like forestation
Post-communist economic transition (Wnęk et al. 2021; Cegielska et al. 2017)	Decline in the agricultural area	Transition to a free market economy, privatized land especially East-Central Europe decreased agricultural interest,and land conversion to forested/developed areas
Geographical location, industries, tourism	Diversification of LULC	Presence of dominant shipbuilding industry and the significant influence of tourism

growth in forest cover, and 49.62% reduction in agricultural land from 1990 to 2012 (Borowska-Stefańska et al. 2018), which is consistent with our findings. Similarly, another study showed an increase in artificial surfaces and forestation in the Małopolskie Province, mainly around cities such as Tarnów, Nowy Sącz, Kraków, and Wieliczka (Cegielska et al. 2017). These trends, indicative of changing land use practices and reforestation efforts, are due to changes in national policies and economic conditions (Wnęk et al. 2021). The factors influencing the LULC changes in Gdańsk are detailed in Table 7.

The trend observed in Gdańsk and other regions of Poland resonates with similar patterns seen across Europe. Several countries, including Hungary (Cegielska et al. 2017), Carpathian of Romania (Mihai et al. 2006), Ukraine (Tretiak et al. 2021; Wojkowski et al. 2023), Estonia (Estonian Ministry of the Environment 2021), Czech Republic (Wnęk et al. 2021), and Slovakia (Wojkowski et al. 2023; Prokešová et al. 2022; Wnęk et al. 2021) have also experienced increase in forest cover and built-up area. Concurrently, there has been a decrease in agricultural land across southeastern Czech Republic, northern and central Bulgaria, north and southeastern Poland, southern Romania, and the Mediterranean (e.g., central and southern Italy, southern Spain, northern Portugal (Kuemmerle et al. 2016). These changes in European land use reflect broader environmental and socio-economic shifts that impact LULC. This context underscores the significance of Gdańsk's local dynamics as part of these broader European trends, highlighting the similarities and differences in how these shifts manifest regionally and locally.

The LCM model predicted future LULC in Gdańsk for 2050 and 2100. It projected an increase in built-up area to 114.47 km^2 and 157.96 km^2 under the high-demand scenario (1985–2022). This projection aligns with findings from comparative studies in the Tricity region, including Gdański and Kartuzy, which also indicate a trend toward expanding artificial surfaces and reducing agricultural areas, highlighting regional consistency in these patterns (Dawid and Bielecka 2022). Notably, in Gdańsk, most LULC transformations occur at low elevations (0–100 m), with a less pronounced trend at higher elevations. This suggests that future urbanization will likely move toward the Moraine hills to the west, influenced by decreasing elevation. The role of infrastructure, particularly the A1 Highway, is also critical in guiding urban growth and shaping neighborhoods in Gdańsk (Gdańsk-Municipality 2015).

Extending beyond the local context, the regional trend is further supported by the LCM model's predictions of increased built-up areas and reduced agricultural land across 33 catchments in Poland, Slovakia, and Ukraine by 2050 and 2100 (Wojkowski et al. 2023). However, it is important to acknowledge modeling limitations based on past transitions, particularly the 2005 to 2022 period in Gdańsk. Historical trends may not accurately predict the future, especially in dynamic contexts like Poland's post-EU accession after 2004, which led to significant infrastructural investments and land use changes (Kuemmerle et al. 2016). Although historical data offer insights, it might not be sufficient alone, as indicated by the differences in LULC patterns before and after 2004 (Table 5). In areas with complex land-cover patterns influenced by political changes, utilizing extended time-frames and diverse modeling approaches is crucial for accurate analysis. Nevertheless, despite these limitations, the model retains substantial predictive power and remains relevant for analyzing Gdańsk and similar areas.

Urbanization in Gdańsk significantly affected the city's hydrology, leading to a comprehensive analysis of how LULC changes impact the local hydrological system. From 1985 to 2022, runoff depth increased from 41 mm to 47.03 mm, with projections indicating a further rise to 51.10 mm by 2050. Similarly, the runoff coefficient is expected to increase from 0.44 to 0.50. These changes are driven mainly by urban expansion and loss of forest cover. Interestingly, Gdańsk has also experienced a consistent increase in forest cover (46% of total area), a trend observed in other European countries as well (Cegielska et al. 2017; Tretiak et al. 2021; Estonian Ministry of the Environment 2021; Wnęk et al. 2021; Prokešová et al. 2022). While this increase in forestation doesn't offset the impact of urbanization, it plays a significant role in moderating hydrological impacts at the local scale (Prokešová et al. 2022). The increase in Gdańsk's impervious area, from 58.64 km^2 in 1985 to 88.89 km^2 in 2022, has exacerbated runoff, emphasizing the need for runoff management strategies.

To manage increased runoff, Gdańsk has developed a surface retention system comprising 53 reservoirs with a total capacity of 0.74 million m^3. Despite a five-fold increase in capacity between 2001 and 2022 (Gdańsk-Water 2022), the NRCS-CN method reveals that the total runoff volumes for specific daily precipitation have escalated from 10.74 million m^3 to 12.32 million m^3 in 2022, with projections reaching 13.39 million m^3 by 2050. These results prove that the existing surface retention system cannot fully manage rainwater during intense rainfall, especially in changing climates.

Building upon the broader trends, the Orunia basin was analyzed in detail using HEC-HMS to assess the LULC and climate change impacts under three distinct scenarios;

- Isolated LULC change effect: The analysis of runoff coefficient, depth, peak discharge, and volume highlights the substantial influence of urbanization within the catchment. The Orunia basin's varied soil types, ranging from silt loam with better infiltration to sandy clay loam with poor drainage, complicate runoff dynamics (Kolerski and Kalinowska 2019). This variability and increased impervious surfaces due to urban area expansion affect CN value, leading to higher runoff. These local findings in the Orunia basin are consistent with broader local and national patterns observed in Gdańsk and other urban areas in the Polish Baltic coastal zone. Studies conducted in the Orunia basin (Łukasz Pietruszyński and Cieśliński 2019) and the Małomiejska basin of Gdańsk (Olechnowicz and Weinerowska-Bords 2014) similarly demonstrate that as urban areas expand, green and undeveloped spaces diminish, resulting in increased stormwater volume, which in turn affect peak discharge rates and accelerate transformation processes.
- Isolated climate change effect: The increase in runoff coefficient and depth necessitates enhanced stormwater retention to accommodate the changing precipitation patterns observed since the late 20th century. Historical data indicate a significant shift in Gdańsk's rainfall patterns; from 1974 to 2000, maximum daily rainfall did not surpass 80 mm. However, since 2000, there have been several instances where daily rainfall exceeded 100 mm, with a record of 170 mm in 2016—the highest recorded in Poland to date (Szpakowski and Szydłowski 2018). These changes reflect broader climatic shifts in the Baltic region (Meier et al. 2021), highlighting the need for updated drainage systems and community awareness for sustainable property development, including water retention solutions.
- Combined LULC and climate change effect: The combined impact of LULC changes and climate change (RCP 4.5 and 8.5) is significantly more severe, characterized by rising rainfall intensity and expanded urban areas. Despite the presence of six retention reservoirs in the Orunia basin (with a capacity of 0.213 million m^3), Gdańsk-Water (2022) there is a need not only to maintain or improve these systems but also explore additional strategies like rainwater harvesting techniques, low-impact development practices (LID) and efficient site selection for LID implementation (Gulshad et al. 2024).The relative impact from 1985 to 2022 shows that

under the high-demand scenario (1985–2022), LULC changes have a comparable effect on runoff as climate change under RCP 4.5. By 2100, however, LULC changes are expected to have a more significant impact than climate change alone under RCP 4.5, highlighting the powerful influence of urbanization on hydrological dynamics (Fig. 13). This finding aligns with previous research assessing LULC impacts on landscape hydric potential (LHP) relative to climate change (Wojkowski et al. 2023).

The most critical finding is that the synergistic effect of LULC and climate change will significantly impact Gdańsk. This synergy presents a significant challenge for urban and environmental planners, indicating that addressing only one factor may be insufficient to manage future flood risks.

5.1 Practical and policy implications

The study underscores the need for Gdańsk to enhance its flood protection measures. In light of the challenges, Gdańsk's new policy by Gdańsk City Hall has implemented a comprehensive climate adaptation policy, aiming for resilience by 2030. This involves integrating blue-green infrastructure and nature-based solutions at three levels: (i) managing runoff at source, (ii) within municipal reservoirs, and iii) prepare for rainfall events exceeding 100-year return period (Kasprzyk et al. 2022; Szydłowski et al. 2023).

Given Gdańsk's ongoing expansion, there is a need to invest in stormwater management infrastructure. The city's existing policies, such as retaining up to 30 mm of rainwater in new developments (Szydłowski et al. 2023), should be expanded to ensure infrastructure keeps pace with urban growth and changing climate conditions (Gdańsk-Municipality 2015).

Effective policy implementation requires public awareness and stakeholder collaboration. Encouraging participation through platforms like citizens' panels and the Gdańsk Climate Change Forum (Szydłowski et al. 2023) is crucial for gaining community support and successfully implementing flood mitigation strategies.

Understanding the local and regional interactions helps in designing more effective land use and environmental policies that address both local needs and regional objectives.

6 Conclusion

This study investigated the long-term (1985–2022) and predicted future (2050, 2100) LULC changes in Gdańsk, Poland, and their impacts on surface runoff. The key findings from this study are:

- LULC results showed significant urban expansion, a decline in agricultural land, and an increase in forest and vegetation cover. Projections indicate expansion in urbanization, further reducing agriculture by 2050 and 2100.
- The expansion of built-up areas has led to an increase in runoff depth and runoff coefficient from 1985 to 2022, with further increases expected by 2050. This highlighted that urbanization plays a major role in altering hydrological processes.
- The combined effects of LULC changes and climate change were found to significantly exacerbate runoff, with projections under RCP 4.5 and RCP 8.5 indicating even greater impacts by 2100.These findings underscore the critical need to integrate LULC changes and climate change effects in urban hydrological studies.

6.1 Limitations and future research

The study faced several limitations:

- Future research should incorporate high-resolution satellite imagery and soil datasets to improve the accuracy of LULC classifications and hydrological modeling.
- Extending LCM analysis by integrating climatic variables could lead to more precise and comprehensive predictions of hydrological impacts.
- To reduce uncertainties in model outputs, future studies should aim to validate predictions with extensive field data, which will provide ground-truthing for remote sensing and modeling efforts.
- Future research should explore the socio-economic implications of land use changes on urban development to provide a more holistic understanding of urban dynamics.
- Future research could explore varying additional model parameters or inputs to gain a deeper understanding of their effects on model predictions.

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Declarations

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References

Abuelaish B, Olmedo MTC (2016) Scenario of land use and land cover change in the Gaza strip using remote sensing and GIS models. Arab J Geosci 9:274. https://doi.org/10.1007/s12517-015-2292-7

Batty M, Couclelis H, Eichen M (1997) Urban systems as cellular automata

Bielecka E, Jenerowicz A, Pokonieczny K et al (2020) Land cover changes and flows in the polish Baltic coastal zone: a qualitative and quantitative approach. Remote Sens 12:2088. https://doi.org/10.3390/rs12132088

Borowska-Stefańska M, Leśniewska-Napierała K, Wiśniewski S (2018) Land cover changes in Poland between 1990 and 2012. Geografie 123:63–83. https://doi.org/10.37040/geografie2018123010063

Breiman L (2001) Random forests. Mach Learn 45:5–32. https://doi.org/10.1023/A:1010933404324

Briak H, Moussadek R, Aboumaria K et al (2016) Assessing sediment yield in Kalaya gauged watershed (northern morocco) using GIS and swat model. Int Soil Water Conserv Res 4:177–185. https://doi.org/10.1016/j.iswcr.2016.08.002

Cegielska K, Salata T, Gawroński K et al (2017) Level of spatial differentiation of anthropogenic impact in Małopolska. J Ecol Eng 18:200–209. https://doi.org/10.12911/22998993/67100

Chen J, Yifang B, Songnian L (2014) Open access to earth land-cover map. Nature 514:434

Cieśliński R, Szydłowski M, Chlost I et al (2024) Hazards of a flooding event in the city of gdansk and possible forms of preventing the phenomenon—case study. Urban Water J 21:1–17. https://doi.org/10.1080/1573062X.2023.2254745

Daniele Z, Ruben VDK, Dirk D, et al (2022) Esa worldcover 10 m 2021 v200

Dawid W, Bielecka E (2022) Gis-based land cover analysis and prediction based on open-source software and data. Quaest Geograph. https://doi.org/10.2478/quageo-2022-0026

Dzieszko P (2014) Land-cover modelling using Corine land cover data and multi-layer perceptron. Quaest Geograph 33(1):5–22

Eastman JR (2012) Idrisi Selva manual. Idrisi tutorial

Estonian Ministry of the Environment (2021) Forestry. https://kliimaministeerium.ee/en/water-forest-resources/forestry

FAO (2009) Harmonized world soil database (version 1.1)

Feldman AD (2000) Hydrologic modeling system HEC-HMS. Technical reference manual 158

Gdańsk-Municipality (2015) Urban water strategy for Gdańsk

Gdańsk-Water (2022) Gdańsk-water. http://www.gdmel.pl/

Gulshad K, Szydłowski M, Yaseen A et al (2024) A comparative analysis of methods and tools for low impact development (lid) site selection. J Environ Manag 354:120212

Hameed H (2017) Estimating the effect of urban growth on annual runoff volume using gis in Esub-basin of the Kurdistan region of Iraq. Hydrology 4:12. https://doi.org/10.3390/hydrology4010012

Han H, Yang C, Song J (2015) Scenario simulation and the prediction of land use and land cover change in Beijing, China. Sustainability 7:4260–4279. https://doi.org/10.3390/su7044260

Huang H, Chen Y, Clinton N et al (2017) Mapping major land cover dynamics in Beijing using all landsat images in google earth engine. Remote Sens Environ 202:166–176. https://doi.org/10.1016/j.rse.2017.02.021

Iturbide M, Fernández J, Gutiérrez JM, et al (2021) Repository supporting the implementation of fair principles in the IPCC-WG1 atlas. Accessed: insert date here

Jakusik E, Chodubska A (2020) Characteristics of precipitation conditions in Gdańsk in the years 1951–2018. In: Walczykiewicz T (ed) Contemporary problems of water management in the context of zoning. IMGW-PIB, pp 41–57

Kabeja C, Li R, Guo J et al (2020) The impact of reforestation induced land cover change (1990–2017) on flood peak discharge using hec-hms hydrological model and satellite observations: a study in two mountain basins, China. Water. https://doi.org/10.3390/w12051347

Kahraman A, Kendon EJ, Chan SC et al (2021) Quasi-stationary intense rainstorms spread across Europe under climate change. Geophys Res Lett 48(13):e2020GL092361

Kasprzyk M, Szpakowski W, Poznańska E et al (2022) Technical solutions and benefits of introducing rain gardens—Gdańsk case study. Sci Total Environ 835:155487. https://doi.org/10.1016/j.scitotenv.2022.155487

Kolerski T, Kalinowska D (2019) Mathematical modeling of flood management system in the city of Gdańsk, Oruński stream case study. Acta Sci Pol Formatio Circ 18:63–74. https://doi.org/10.15576/ASP.FC/2019.18.1.63

Kucsicsa G, Popovici EA, Bălteanu D et al (2019) Future land use/cover changes in Romania: regional simulations based on clue-s model and Corine land cover database. Landscape Ecol Eng 15:75–90

Kuemmerle T, Levers C, Erb K et al (2016) Hotspots of land use change in Europe. Environ Res Lett 11(6):064020

Kwoczyńska B (2021) Analysis of land use changes in the tri-city metropolitan area based on the multi-temporal classification of landsat and rapideye imagery. Geomat Land Manag Landsc 2:101–119. https://doi.org/10.15576/GLL/2021.2.101

Kwoczyńska B (2022) Analysis of land use change in selected metropolitan areas in Poland based on remote sensing data. Geomat Land Manag Landsc 1:73–101. https://doi.org/10.15576/GLL/2022.1.73

Liu X, Liang X, Li X et al (2017) A future land use simulation model (flus) for simulating multiple land use scenarios by coupling human and natural effects. Landsc Urban Plan 168:94–116. https://doi.org/10.1016/j.landurbplan.2017.09.019

Marcel B, Bruno S, Luc B et al (2020) Copernicus global land service: Land cover 100m: collection 3: epoch 2019: Globe. Version V3:01. https://doi.org/10.5281/zenodo.3518038

Meier HM, Kniebusch M, Dieterich C et al (2021) Climate change in the Baltic sea region: a summary. Earth Syst Dyn Discuss 2021:1–205

Mekonnen DF, Duan Z, Rientjes T et al (2018) Analysis of combined and isolated effects of land-use and land-cover changes and climate change on the upper blue Nile river basin's streamflow. Hydrol Earth Syst Sci 22:6187–6207. https://doi.org/10.5194/hess-22-6187-2018

Mihai B, Savulescu I, Sandric I et al (2006) Application of change detection to the study of vegetation dynamics in the Bucegi mountains (Southern Carpathians, Romania). Teledetection 6:215–231
Mikos-Studnicka P, Szydłowski M (2022) Impact of spatial distribution of precipitation in an urban catchment on the quality of rainfall-runoff hydrological modeling. In: 17th international symposium on water management and hydraulic engineering-WMHE
Mozumder C, Tripathi NK (2014) Geospatial scenario based modelling of urban and agricultural intrusions in Ramsar wetland Deepor Beel in northeast India using a multi-layer perceptron neural network. Int J Appl Earth Obs Geoinf 32:92–104. https://doi.org/10.1016/j.jag.2014.03.002
Mustafa A, Szydłowski M (2020) The impact of spatiotemporal changes in land development (1984–2019) on the increase in the runoff coefficient in Erbil, Kurdistan region of Iraq. Remote Sens 12:1302. https://doi.org/10.3390/rs12081302
Noel G, Matt H, Mike D et al (2017) Google earth engine: planetary-scale geospatial analysis for everyone. Remote Sens Environ 202:18–27. https://doi.org/10.1016/j.rse.2017.06.031
Olechnowicz B, Weinerowska-Bords K (2014) Impact of urbanization on stormwater runoff from a small urban catchment: Gdańsk małomiejska basin case study. Arch Hydro Eng Environ Mech 61:141–162. https://doi.org/10.1515/heem-2015-0009
OpenStreetMap (2017) Planet dump. https://planet.osm.org
Pal S, Saha TK (2018) Identifying dam-induced wetland changes using an inundation frequency approach: the case of the Atreyee river basin of Indo-Bangladesh. Ecohydrol Hydrobiol 18(1):66–81
Peters JC (1998) HEC-HMS hydrologic modeling system: user's manual. US Army Corps of Engineers, Hydrologic Engineering Center, Davis
Pietruszyński Łukasz, Cieśliński R (2019) The impact of hydrometeorological events on the state of the urban river quality. Ecol Chem Eng S 26:521–533. https://doi.org/10.1515/eces-2019-0005
Prokešová R, Horáčková Š, Snopková Z (2022) Surface runoff response to long-term land use changes: spatial rearrangement of runoff-generating areas reveals a shift in flash flood drivers. Sci Total Environ 815:151591
Rogger M, Agnoletti M, Alaoui A et al (2017) Land use change impacts on floods at the catchment scale: challenges and opportunities for future research. Water Resour Res 53(7):5209–5219
Saha TK, Pal S (2019) Exploring physical wetland vulnerability of Atreyee river basin in India and Bangladesh using logistic regression and fuzzy logic approaches. Ecol Ind 98:251–265
Saha TK, Sajjad H, Roshani et al (2024) Exploring the impact of land use/land cover changes on the dynamics of Deepor wetland (a Ramsar site) in Assam, India using geospatial techniques and machine learning models. Model Earth Syst Environ 10:4043–4065
Service CLM (2018) Urban atlas lclu 2018. European Environment Agency, Copenhagen
Soulis KX (2021) Soil conservation service curve number (SCS-CN) method: current applications, remaining challenges, and future perspectives
Staudt M, Kordalski Z, Zmuda J (2006) Assessment of modelled sea level rise impacts in the Gdańsk region, Poland. Sea level Changes Affect Spat Dev Baltic Sea Reg Geol Surv Finl Spec Paper 41:121–130
Szpakowski W, Szydłowski M (2018) Probable rainfall in Gdańsk in view of climate change. Acta Sci Pol Formatio Circ 3:175–183
Szpakowski W, Szydłowski M (2018) Evaluating the catastrophic rainfall of 14 July 2016 in the catchment basin of the urbanized strzyza stream in Gdańsk, Poland. Pol J Environ Stud 27:861–869. https://doi.org/10.15244/pjoes/75962
Szydłowski M (2006) Mathematical modelling of flash floods in natural and urban areas. Kluwer Academic Publishers, New York, pp 143–153. https://doi.org/10.1007/1-4020-4902-1_14
Szydłowski M, Gulshad K, Mustafa AM et al (2023) The impact of hydrological research, municipal authorities, and residents on rainwater management in Gdańsk (Poland) in the process of adapting the city to climate change. Acta Sci Pol Formatio Circ 22:59–71. https://doi.org/10.15576/ASP.FC/2023.22.3.11
Tretiak N, Hebryn-Baidy L, Sakal O et al (2021) Cultivation of niche crops and prospects of eco-innovative agricultural production in Ukraine. Acta Sci Pol Formatio Circ 20(3–4):29–46
USDA S (1985) Hydrology, national engineering handbook, section 4. US Department of Agriculture, Washington, DC
Verburg PH, Schot PP, Dijst MJ et al (2004) Land use change modelling: current practice and research priorities. GeoJournal 61:309–324. https://doi.org/10.1007/s10708-004-4946-y
Walczykiewicz T, Skonieczna M (2020) Rainfall flooding in urban areas in the context of geomorphological aspects. Geosciences 10(11):457
Wnęk A, Kudas D, Stych P (2021) National level land-use changes in functional urban areas in Poland, Slovakia, and Czechia. Land 10(1):39
Wojkowski J, Wałęga A, Młyński D et al (2023) Are we losing water storage capacity mostly due to climate change-analysis of the landscape hydric potential in selected catchments in east-central Europe. Ecol Ind 154:110913
Zaucha J (2011) Territorial cohesion-baltic sea region examples. Baltic contribution to the revised territorial agenda of the European Union EcoRegion Perspectives, Baltic 21