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Stormwater runoff management in Sandomierz, as an example of medium-sized European city, using SCALGO Live

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Abstract: European cities face urban, demographic and climate challenges. According to forecasts, annual extreme phenomena will intensify – including torrential rains. Comprehensive solutions (also those based on nature), climate adaptation strategies, runoff management, incorporation of new design (e.g. sponge cities) are urgently required in order to strengthen urban resilience and to minimise the effects of extreme weather events (droughts, floods or heat islands).

The aim of the research was to develop a methodology for activating selected elements of blue-green infrastructure within areas of natural and cultural protection as an adaptive tool of urban planning. Modelling of infiltration possibilities, programmed with SCALGO Live Poland software, was performed as a case study based on a research city – Sandomierz (in Poland). Selected parameters (stormwater surface runoff, chosen runoff areas, land cover) are strongly correlated with urban indicators relating to the vegetation coverage (biologically active area – BAA).

Results pointed out urban units, which BAA is lower than 25% (e.g. Old Town Square, courtyards of tenement houses). Modelling was carried out for these units by concentrating on the undeveloped area for which the BAA was increased. The enhancement assumed values in the range of 41–45%. In analysed cases, an improvement (decrease) in runoff volume was obtained, even by 8.69%. Simultaneously, infiltration increased by 19.61%, calculated over entire runoff area. Implementation of solutions based on these results, in the form of appropriate planning provisions, can raise the quality of environment (e.g. improving water infiltration) and life (e.g. more effective air cooling on hot nights).

Keywords: adaptation strategy, blue-green infrastructure, climate change, protected areas, rainwater retention, surface runoff

INTRODUCTION

Apart from global, urban (Ren *et al.*, 2020; Li *et al.*, 2021) and demographic problems (depopulation and city sprawl), new challenges faced by cities include primarily climate issues. They pose both a direct and indirect threat to the environment, local economies and communities (44mpa, 2018; IPCC, 2022), and have for many years been the main focus of international organisations, such as the UN, UNESCO, the World Bank, the European Union, and others. Droughts, floods or even heat islands affect not only highly, but also less urbanised areas with increasing frequency (Cremen, Galasso and McClockey, 2022). Although the attention of researchers and officials has until now been given to metropolises and large entities, the municipalities of all sizes ought to be oblige to prepare their cities for actions mitigating negative effects, to develop strategies (or plans) for adaptation to new phenomena, and to support the processes of self-regulation of the urban tissue (44mpa, 2018; EC, 2021; Lin *et al.*, 2021; IPCC, 2022).

The effects of extreme weather events could be minimised by undertaking urgent comprehensive solutions based on nature, ecosystem and pro-environmental activities (Lin *et al.* 2021), including among others – improvement of water retention. The first stage of a properly constructed stormwater management strategy would be the recognition of the problem (questions like where, how, how much, etc.), which in consequence could help to reduce surface runoff, and so allowing subsequent use of precipitated waters, e.g. by vegetation. Such interventions are already known as urban planning remedies. One of those – a sponge city – is focused on water infiltration, purification, retention, use, and others. The disposal of such tools, the incorporating of technologies and elements of blue-green infrastructure (BGI) into urbanscape (Zeng *et al.*, 2023) could so be carried out coherently and consciously.

Improvement and/or a rational determination of the coefficient value of biologically active area BAA, which is based on BGI, is a subject of research done by the authors of this article. In order to do so, the thesis formulated in this manner requires the presence of software background that would help conduct numeric studies. The (basic) hydrological (hydrodynamical) modelling conducted with software such as SWMM or SCALGO Live (Wiberg, 2018), e.g. based on the methodology described below, can bring preliminary outcome. This can enable the recognition of the scale and potential of further investigations or advanced projections, even if the results obtained with this software in terms of the amount of water can only be approximated.

The aim of this research was to indicate the possibilities and limitations of modelling the size of surface runoff (using the SCALGO Live software) through changes in land cover in the central urban areas (concentrating on Sandomierz, as a medium-sized city), which may also be subject to legal protection (due to cultural and/or natural values). In order to specify this study three research questions were formulated.

1. To what extent, by changing the proportion of vegetation in land cover (biologically active area BAA), can the infiltration capacities of the areas in the city centre zone be increased?
2. Which environmental parameters (software input data like precipitation amount, terrain characteristics) should be included in modelling of rainwater surface runoff in such areas?
3. Assuming only a change in land cover, how much water (additional volume) can be infiltrated within the researched area, and what percentage would it take in the runoff (as an addition to the overall rainwater balance)?

The purpose of the methodology described below is to identify the accessible basic indicators necessary in modelling of the surface runoff, with regard to projected climate change, so that they could become a primary element for building the cities adaptation strategies. Due to the determination of the common urban planning (e.g. biologically active area) and hydrological parameters (rainfall, runoff, and others), the analysis of the level of rainwater retention and the possibility of its modelling for selected, particularly sensitive urban areas can be conducted. This preliminary study should enable more efficient management of urban space, based on a good understanding and recognition of the subject beforehand.

The suitability of SCALGO Live software for such modelling is being tested in this research. The confirmation of the results' usefulness appears to be extremely relevant for strategic planning, whose objective is to maintain the spatial order, mitigation and prevention of the negative effects of climate change – a solution to improve urban resiliency.

LITERATURE REVIEW

In recent years, scientific research focusing on the statistical approximation of the trajectory of climate forecasts dating forward to the end of the 21st century has been published (Rajczak and Schaer, 2017; Hosseinzadehtalaei, Tabari and Willems, 2020). Additionally, Cardell *et al.* (2020) focus mainly on the amount of the extreme precipitation days (24-hour duration). The other two publications concentrate more on the precipitation amount in the future perspective (predicted increase up to 25%). All authors agree that the general rise in the frequency of the heavy and extreme precipitation will intensify.

The integration of green engineering systems inspired by nature, also known as nature-based solutions (EC, 2015), can have a significant impact on local laws and practices in the development of city planning when based – in particular – on green infrastructure (GI) (Dorst *et al.*, 2019) as a network of natural and semi-natural areas and elements (EC, 2013). The task of GI is, among others, to support adaptation strategies to climate change, contribute to (storm)water management (Fu, Hopton and Wang, 2021; Li *et al.*, 2021), reduce the risk of flooding (Fu, Hopton and Wang, 2021; Li *et al.*, 2021; Junqueira *et al.*, 2022) and/or strengthen resiliency of the cities (Fu, Hopton and Wang, 2021; Dong *et al.*, 2023). Nevertheless, the effectiveness of different types of green infrastructure, in order to mitigate extreme rainfall events, still remains unclear (Junqueira *et al.*, 2022). Not only the growing use of GI within the urban tissue (Li *et al.*, 2021), but also support and maintenance of already existing, well-functioning green structures are strongly advocated in the literature. Moreover, incorporating new structures and further research into the effectiveness of nature-based solutions to counteract the climate change enriches this list.

Therefore, many authors urge for more integrative actions and legislative procedures to activate GI as a tool of urban planning. These measures need to distinguish themselves with a systematic approach as well as be easily and widely applicable in order to promote a resilient urban environment, mitigate negative impact of climate change or reduce urban heat island (Marando *et al.*, 2022).

Very few studies deal with the deployment of effective methods of GI implementation on a city scale – usually these would be large-extent coastal regions, threatened by the rising sea levels worldwide. Nevertheless, Zhou *et al.* (2021) indicate spatial analysis based on parcel-level to support urban planners on such a scale in the USA. It is closely related to land use and land cover, as well as the definition of hydrological conditions within specific watershed and stormwater runoff areas. In spatial planning in Poland, urban indicator supporting the implementation of GI requirements within the urban units – a building plot – is the index of biologically active area (BAA). Being normalised in the Construction Law Act (Ustawa, 1994) as well as the Regulation of the Council of Ministers (Rozporządzenie, 2022), it refers directly to municipal legislation at the level of local governments. This provision states that if the territory of a given municipality was covered by neither the masterplan nor the General Urban Ordinance Plan – GUOP, the area covered with greenery (as a BAA index) should take minimum 25% of the total plot (legal status as of May 2023).

Existing general spatial planning guidelines were mainly focused on the issues concerning sewage system solutions and the fastest possible water drainage from the city. Due to the issue of climate change, perception of surface runoff is being re-designed, or rather re-defined, and no longer treated as waste, a threat to life (floods) or health (sanitary challenge) (Wiberg, 2018). It would also be compared with, for example, the concept of a sponge-city.

MATERIALS AND METHODS

The methodology of the research was based on several basic research methods. The primary one used in this process was a case study, which was carried out for the city of Sandomierz. A literature review was also applied, covering – above all – legal conditions (local and general law), concerning the conservation requirements for the urban protected area (General Plan of Urban Ordinances for the city of Sandomierz).

Special attention was devoted to the selection of basic indicators, necessary in the process of modelling the volume of surface runoff and, partially, for determining their values/ dimensions (climatic factors and scenarios, amount and duration of precipitation, return period). This formed the basis for answering the second research question. The indicators listed above were selected and derive from literature research.

By applying a quantitative method based on analyses of cartographic materials, indicators of the degree of vegetation coverage of the analysed area (percentage value of the coverage in relation to the total plot area) were determined. The land slopes, as one of the important parameters for modelling the amount of surface runoff, were calculated. The interpretation of the provisions of the planning documents, combined with the analysis of the cartographic materials, allowed the identification of areas protected due to their high natural and/or cultural values. Simulation and modelling were performed on such sites.

Answers to research questions one required the use of a modelling (and simulation) research method, which was based on the SCALGO software, performing a simplified hydrological analysis of the study area. The conclusions were based on the interpretation of the results (mainly quantitative methods).

The research object is a city of Sandomierz, located in south-eastern Poland (coordinates: 50°40'56"N 21°44'56"E). With its 22,997 inhabitants (data for 2020) it is classified as a medium-sized city, i.e., 20,000–100,000 inhabitants (GUS, 2014). This pilot research covered areas within the town's administrative and urban conservation borders (Provincial Conservator of Monuments in Kielce, Pol.: Wojewódzki Urząd Ochrony Zabytków w Kielcach). The natural elements and topography, which form the identity of the city include the Pepper Mountains, the Vistula Valley and the loess ravines. Cultural elements include the urban, architectural and landscape complex of the old town, the return of vineyard cultivation, and the fruit-vegetable cultivation. Within the city centre, areas of high natural [European network of bird habitats, Polish Nature Conservation Law (Ustawa, 2004)] and cultural values (Register of immovable monuments can be found). They are of particularly high sensitivity to the effects of climate change and can be divided into three categories, as those being under natural protection: Natura 2000 corridor, Piszczele Park, Saski Park, cathedral's cemetery; cultural protection: Royal Castle, cathedral, old town square, Collegium Gostomianum – Jesuit college, synagogue; and natural-cultural protection: monastery-and-garden complexes both within and outside city walls, Queen Jadwiga Ravine; as shown on Figure 1. Above all, the last two classifications point to elements of the natural-cultural landscape that, within the centuries, eventually formed this royal settlement (Urząd Miejski w Sandomierzu, 2020).

The land cover within the city centre can be read up from SCALGO directly and identified by the semi-dense historical built-up structure, which is balanced with the greenery (parks, ravines, monastery gardens, floodplains, detached housing, and allotment gardens). The upland terrain is fairly flat and without water features, but also prone to surface erosion with annual rainfall up to 800 mm high (Urząd Miejski w Sandomierzu, 2020).

The city's territory is gradually being covered by the local development plans, however, no such plan has yet been adopted for the urban conservation zone. The only provisions at the local level regulating the development of the area are to be found in GUOP (Urząd Miejski w Sandomierzu, 2020). This also applies to the indication of the percentage coefficients of biologically active areas BAA.

SCALGO Live, as a main research tool, is a software used to conduct hydrological modelling and visualise landscape in hydrological terms. In this manner it can support adaptation

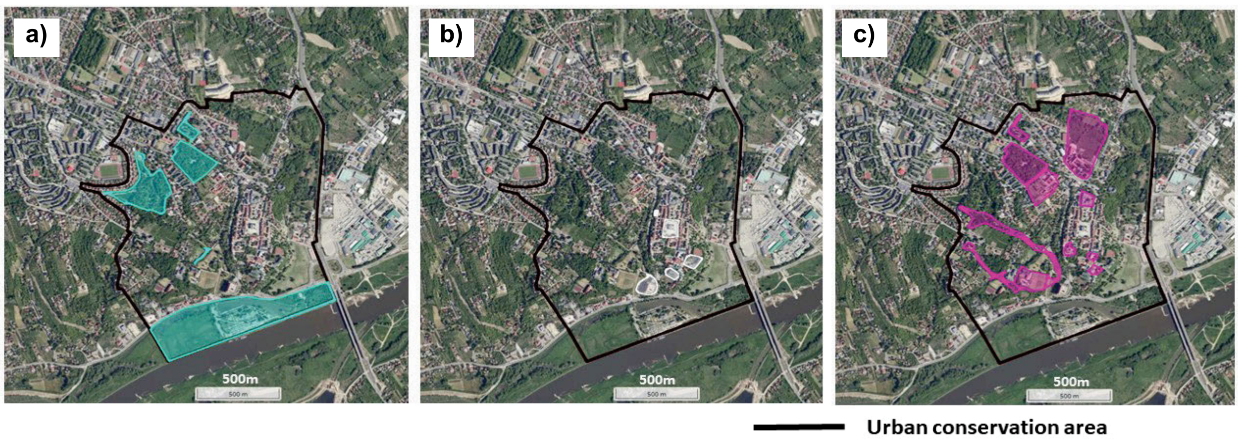

Fig. 1. A number of protection areas in Sandomierz centre: a) natural, b) cultural, c) natural-cultural. This shows the complexity of the natural-cultural landscape of the city (compare with Fig. 2; source: own elaboration based on SCALGO Live (no date)

processes to climate change in urban contexts or in crisis water management and watercourse administration (SCALGO Live, no date). It also enables determination of the general hydrological processes (Nedza, 2019; SCALGO Live, no date). Moreover, by using this GIS supported, vector- and map-based software, it is possible to calculate and depict the amount of surface runoff, determine the extent of runoff areas and directions of water flow in the natural topography. Furthermore, SCALGO allows edition of the land cover within selected sectors by changing the calculation parameters.

The necessary input data used in the research can be divided into two groups, as follows: numerical and geographical data, and parameters with indicators. Numerical data were obtained directly from SCALGO platform (orthophoto map, topographic map, land cover), as well as from the Geoportal (land use plans, from which information on the register of individual land parcels derives). Indication of the urban conservation zone and territories under protection helped to identify the size and location of the runoff areas of interest in the online software SCALGO Live. The main data sources for parameters and indicators have their origin in the literature. From Rajczak and Schaer (2017), Huq and Abdul-Aziz (2021), and Junqueira *et al.* (2022) – values of precipitation duration, climatic factors and scenarios were acquired; from PMAXTP model: AMP (Ozga-Zieliński (ed.), 2022) – precipitation amounts for Sandomierz; GUOP (Urząd Miejski w Sandomierzu, 2020), Li *et al.* (2021) and Dong *et al.* (2023) – return period; from Królikowski and Królikowska (2009) – the parameter of surface runoff.

In order to specify the analysis three groups of assumptions were selected.

1. Selection of the runoff area for simulation: a) site (as a runoff area) located within protected areas (natural and/or cultural values); b) location within the historically built-up (urbanised) zone. The selection was carried out in such a way that as many protected areas as possible are within the range of the runoffs and – at the same time – within the urban protection area.
2. Selection of the area for modelling the volume of runoff by changing the degree of vegetation cover of the area: a) units forming a functional whole (e.g. courtyards of townhouses, old town square); b) location within one surface runoff area.
3. Parameters characterising surface runoff considered in the modelling (selection and values): a) based on literature analysis: return period of 10 and 50 years; rainfall duration: 24 h; rainfall amount; climate factor for 2022, 2049 and 2099; climate scenarios: RCP4.5 and RCP8.5; b) based on the interpretation of topographic data – an indicator of the degree of vegetation cover of the studied area, the slope of the terrain (weighted average of 5%).

RESULTS

Designation of the main runoffs (A–C) in SCALGO was conducted in such a manner that the largest possible number of protected areas would lie within the urban conservation zone (Fig. 2a). This allows the comparison of similar data/results under different precipitation scenarios. Indication and modelling of biologically active area BAA was conducted for five chosen case studies: green and built-up areas (Fig. 2b), which have different land use and function/purpose.

According to the land register, the old town of Sandomierz is characterised by small fragmentation of building plots for most properties. Consequently, the authors decided to demarcate units forming a functional whole, e.g. courtyards of tenement houses (both, the Old Town Square and the grounds of St. Spirit Hospital appear in the records as one plot). For them, the current coverage

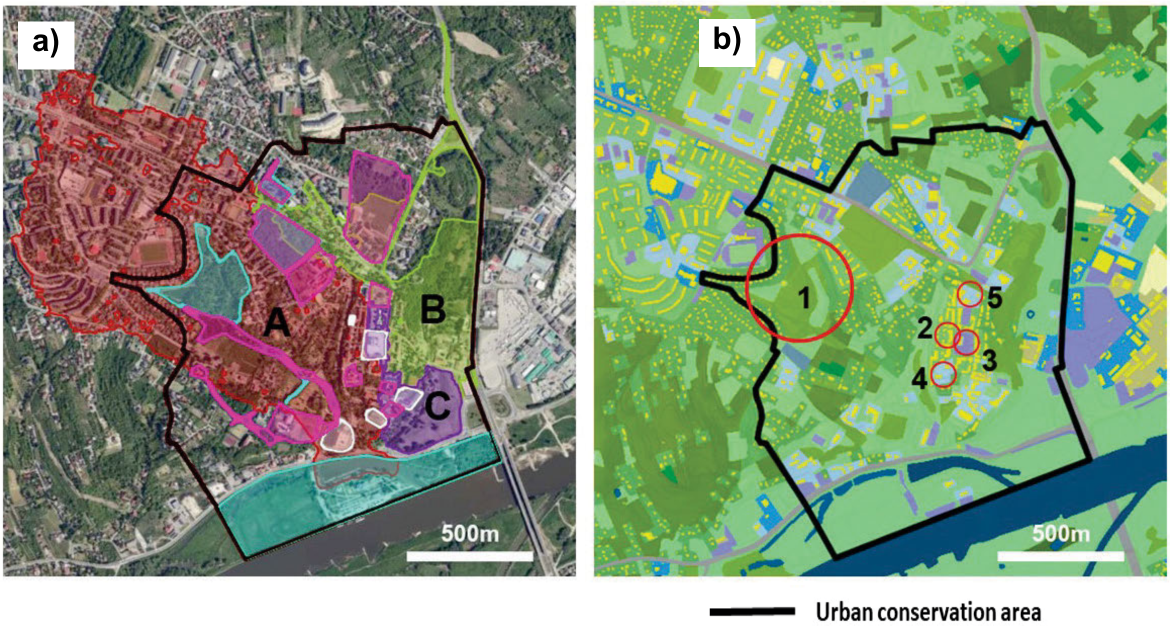

Fig. 2. Research scope within the city of Sandomierz: a) three main runoff areas A, B, C (chosen and named clockwise) overlapped with protected areas (compare with Fig. 1), b) selection of case studies for calculating and modelling of biologically active area on land cover layer: 1 = Piszczele Park, 2 = tenement houses courtyard in the old town, 3 = Old Town Square, 4 = town hall, 5 = St. Spirit hospital; source: own elaboration based on SCALGO Live Poland

of the plot units with BAA was marked out directly in Geoportal (http://geoportal.gov.pl). Three out of five researched areas – case study 2, 3, and 4 – have an existing BAA index lower than 25% (Rozporządzenie, 2022), and so were selected for the further land cover modification with the purpose to increase the retention capacity of this historical, climate-sensitive area (Tab. 1).

For the further simplification, three sub-runoff areas (accordingly AA to CC) of similar/comparable sizes (runoff area AA: 2.63 ha, runoff area CC: 2.59 ha – Fig. 3) were indicated. For them, modelling of absorptiveness by changes in land cover was conducted in three scenarios.

1. **Scenario I** assumes that for the research scope, the surface runoff is equal to the rainfall (no outflow to the sewage system).
2. **Scenario II** corresponds to the first scenario in which precipitation is subject to runoff with its indicators assigned to the type of land cover (current state, however, e.g. without water flowing to the sewerage system). In this case, only the absorptiveness of individual unbuilt areas is considered.
3. **Scenario III** (based on scenario II) means modelling – increasing the infiltration probability by changing the land cover. The value of the surface runoff index of BAA for given functional units was changed to capabilities of allotment gardens. Within the Old Town Square it was an attempt to restore the area of non-existent greenery, according to archival photos from the beginning of the 20th century; for courtyards – to give these spaces the character of home gardens.

Table 1. Calculation results of biologically active area (BAA) percentage before and after modelling

Selected areas	Runoff area	Land use	Plot area (m^2)	Green area (m^2)	Green area – added value[1] (m^2)	BAA current state (%)	BAA according to General Urban Ordinance Plan (GUOP) for Sandomierz	Current BAA and added value (%)	BAA, increas in (%)
Case study 1 Piszczele Park	A	park	68,808	68,808	0	**100.00**	min. 75%	**97.33**	
Case study 2 Tenement houses courtyard in the old town	A	multi-family housing with services	2,048	310	445	**15.14**	no data[1]	**36.87**	**41.06**
Case study 3 Old Town Square	C	roads/ square	10,309	481	615	**4.67**	no data[1]	**10.63**	**43.89**
Case study 4 Municipal hall	A	services	5,597	2,139	0	**38.22**	no data[1]	**38.22**	
Case study 5 St. Spirit hospital	B	services	6,184	763	916	**12.34**	no data[1]	**27.15**	**45.44**

[1] Required min. 25% of BAA. Data not meeting this criterion and being modelled are in bold.
Explanations: background filling within runoff areas indicates their colours for marking in SCALGO Live (no date), see Figure 2a.
Source: own study based on geoportal.gov.pl and the Rozporządzenie (2022).

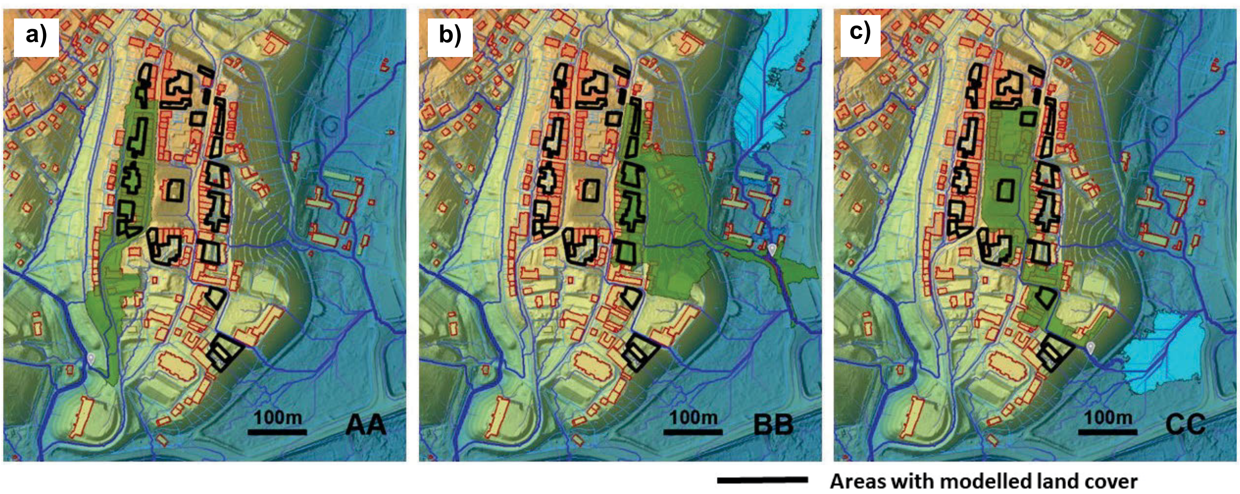

Fig. 3. Three (sub)runoff areas (as green markings) during modelling – scenario III, which determine the surface runoff amount and the range for the studied spaces: a) AA, b) BB, c) CC; source: own elaboration based on SCALGO Live Poland

The results of calculating the percentage of BAA after modelling the size of the green area showed an index improvement of 41 and 45% compared to the current state (Tab. 1). Its value after the change (except for the area of the Old Town Square) was more than twice as high. Studies have shown that for areas with significantly limited opportunities to increase BAA (e.g. old town complexes), even if measures are limited to merely restoring the historic land cover, the retention of these areas will significantly improve. In addition, areas covered by natural, cultural and natural-cultural protection (as being invaluable) can play an uneasy but key role as an element of the strategy for climate adaptation.

According to the methodology of the research described above, a summary presentation of the part of the results was made (Tab. S1). Main conclusions from the study are listed below.

1. The infiltration process reduces the range of some runoff areas, which can be seen with increasing rainfall – runoff area CC changed its range between scenario I (rainfall only), scenarios II and III (infiltration capabilities) with 0.31 ha of its relative size.
2. Along with the increasing rainfall, a slight decrease in the infiltration effect of the soil can also be noticed – for the runoff area BB with 59 mm of precipitation, in scenario III there was a 5.15% increase in infiltration, for 95 mm of precipitation this result was 5.06%. For the runoff area AA, the change is between 8.67 and 8.69% for the tested parameters (precipitation from 59 to 95 mm).
3. For the runoff area AA and precipitation >93 mm and >95 mm, the value of "infiltrated or drained" was 5.99%, for the remaining precipitation volumes (from 59 to 88 mm) – 9.99%.
4. With extreme rainfall (93 and 95 mm) the soil infiltration values (undeveloped/green areas) decrease.
5. For the runoff area BB, for 59 mm of precipitation, the scenario III corresponds to a 5.15% increase in infiltration, for 95 mm of precipitation this result was 5.06%. For the runoff area AA, the change is between 8.67% (precipitation for 59 mm) and 8.69% (95 mm) for the parameters studied.
6. The results were independent from the season's data – the same for winter, summer and annual average precipitation – it was extreme precipitation, which was more important.

DISCUSSION

The authors of this study have not yet come across research within small or medium-sized cities in the methodology and procedure described above. The increasing frequency of heavy and extreme precipitation events indicated in climate change scenarios justifies the search for solutions to this problem at the level of planning and surface runoff management. Studies carried out confirm that these phenomena are particularly relevant for inner-city areas (with low BAA values), especially when characterised by diversified terrain relief (high elevation/height differences). However, the research was not intended to confirm these obvious claims. The aim was to identify a quick (easy to carry out and cheap) modelling tool for surface runoff correlated with landform, land cover, and basic (publicly available) indicators related to water infiltration.

Another important objective was to develop a methodology for the implementation of this tool in spatial planning and climate change adaptation strategies, by identifying the scale of the problem of the inefficiency of inner-city areas to capture rainwater. The research carried out shows that the tool tested – SCALGO Live – meets these conditions (user-friendliness) and, at the same time, the results obtained can be used in urban spatial management and planning. The simulations carried out also show some shortcomings of the software, which are the estimated values and – under Polish conditions – the lack of widely available source materials with full coverage of the country's area, such as soil maps.

The authors of this paper note the need to extend the parameters of the methodology described, taking into account soil conditions in further procedures (Nedza, 2019). Therefore, the succeeding research process should complement the modified retention capacity of the soils but also the parameters attributed to the land cover within the greenery, by correlating infiltration rates with the type of vegetation (e.g. including layers of large trees, small trees, shrubs, undergrowth, grasses, etc.), and its multi-layering. Ren *et al.* (2020) came to similar conclusions after conducting studies on both imperviousness and rainfall intensity in an urban context. However, he caveats that an increase in the infiltration properties of soils in an urban environment may lead to problems with water stagnation, and the extent and manner of this impact requires consecutive research.

Future studies should also include the modelling of surface runoff of natural protected areas located within urban boundaries – due to their high natural and social values. The rationale for the need for such research is also their distinct characteristics (mainly land cover, often linked to terrain relief and difficult building conditions, which determined the present use of these areas and the high or very high BAA indicator). This peculiarity – directs further studies to other research problems no longer related to increasing the BAA rate, but to other measures that favour the retention or uptake of rainwater from neighbouring areas.

CONCLUSIONS

1. The methodology conducted and described in this article will enable the development of indications to formulate adaptation strategies to current climate challenges in terms of the possibility of using blue-green infrastructure (BGI).
2. The SCALGO software is a fast and inexpensive tool (but with limited estimated calculation accuracy). With this tool, basic data on the amount and direction of surface runoff can be estimated. The results of the simulations (modelling) should become the basis for strategic and planning work in the area of more efficient and effective urban and water management, maintenance of spatial order and climate change mitigation.
3. Increasing the biologically active area factor by changing the surface area/land cover within the old town zone is limited, especially for towns with medieval roots. In this view, in order to increase the effectiveness of rainfall retention, great attention should be paid to the quality of the proposed planting.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_Warzecha.pdf.

REFERENCES

44mpa (2018) *Climate change adaptation plans in 44 Polish cities Summary report*. Available at: http://44mpa.pl/wp-content/uploads/2018/12/MPA_NET-ENG-20-12.pdf (Accessed: April 19, 2022).

Cardell, M.F. *et al.* (2020) "Future extremes of temperature and precipitation in Europe derived from a combination of dynamical and statistical approaches," *International Journal of Climatology*, 40(11), pp. 4800–4827. Available at: https://doi.org/10.1002/joc.6490.

Cremen, G., Galasso, C. and McClockey, J. (2022) "Modelling and quantifying tomorrow's risks from natural hazards," *Science of The Total Environment*, 817, 152552. Available at: https://doi.org/10.1016/j.scitotenv.2021.152552.

Dong, X. *et al.* (2023) "Planning for green infrastructure based on integration of multi-driving factors: A case study in pilot site of sponge city," *Sustainable Cities and Society*, 93, 104549. Available at: https://doi.org/10.1016/j.scs.2023.104549.

Dorst, H. *et al.* (2019) "Urban greening through nature-based solutions – Key characteristics of an emerging concept," *Sustainable Cities and Society*, 49, 101620. Available at: https://doi.org/10.1016/j.scs.2019.101620.

EC (2013) *Building a green infrastructure for Europe*. Luxembourg: Publications Office of the European Union. Available at: https://doi.org/10.2779/54125.

EC (2015) *Towards an EU research and innovation policy agenda for nature-based solutions & Re-Naturing cities. Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities' (full version)*. Luxembourg: Publications Office of the European Union. Available at: https://doi.org/10.2777/765301.

EC (2021) *European Green Deal. Striving to be the first climate-neutral continent*. Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (Accessed: September 15, 2022).

Fu, X., Hopton, M. and Wang, X. (2021) "Assessment of green infrastructure performance through an urban resilience lens," *Journal of Cleaner Production*, 289, 125146. Available at: https://doi.org/10.1016/j.jclepro.2020.125146.

Geoportal. Available at: https://www.geoportal.gov.pl/ (Accessed: April 28, 2023).

GUS (2014) *Miasta w liczbach 2012 [Basic urban statistics*. Warszawa: Główny Urząd Statystyczny. Available at: https://stat.gov.pl/files/gfx/portalinformacyjny/pl/defaultaktualnosci/5499/3/7/1/miasta_w_liczbach_2012_07_31_internet.pdf (Accessed: May 17, 2022).

Hosseinzadehtalaei, P., Tabari, H. and Willems, P. (2020) "Climate change impact on short-duration extreme precipitation and intensity–duration–frequency curves over Europe," *Journal of Hydrology*, 590, 125249. Available at: https://doi.org/10.1016/j.jhydrol.2020.125249.

Huq, E. and Abdul-Aziz, O. (2021) "Climate and land cover change impacts on stormwater runoff in large-scale coastal-urban environments," *Science of The Total Environment*, 778, 146017. Available at: https://doi.org/10.1016/j.scitotenv.2021.146017.

IPCC (2022) *Climate change 2022: Impacts, adaptation and vulnerability*. The Intergovernmental Panel on Climate Change. Available at: https://www.ipcc.ch/report/ar6/wg2/ (Accessed: April 26, 2022).

Junqueira, J.R. *et al.* (2022) "Using green infrastructure as a social equity approach to reduce flood risks and address climate change impacts: A comparison of performance between cities and towns," *Cities*, 131, 104051. Available at: https://doi.org/10.1016/j.cities.2022.104051.

Królikowski, A. and Królikowska, J. (2009) "Ocena wpływu współczynników spływu i opóźnienia na przepływy obliczeniowe w sieci kanalizacji deszczowej [Estimation of impact of run-off and delay coefficients on computational flows in storm sewage system]," *Środkowo-Pomorskie Towarzystwo Naukowe Ochrony Środowiska. Rocznik Ochrona Środowiska*, 11, pp. 165–171. Available at: https://ros.edu.pl/images/roczniki/archive/pp_2009_010.pdf (Accessed: May 21, 2023).

Li, C. *et al.* (2021) "Evaluating the runoff storage supply-demand structure of green infrastructure for urban flood management," *Journal of Cleaner Production*, 280(2), 124420. Available at: https://doi.org/10.1016/j.jclepro.2020.124420.

Lin, B.B. *et.al.* (2021) "Integrating solutions to adapt cities for climate change," *The Lancet Planetary Health*, 5(5), pp. e479–e486. Available at: https://doi.org/10.1016/S2542-5196(21)00135-2.

Marando, F. *et al.* (2022) "Urban heat island mitigation by green infrastructure in European functional urban areas," *Sustainable Cities and Society*, 77, 103564. Available at: https://doi.org/10.1016/j.scs.2021.103564.

Nedza, N.M. (2019) *Dimensioning detention systems for small urban catchments. Suggestions for method improvements*. MSc Thesis. Trondheim: Norwegian University of Science and Technology. Available at: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2621012 (Accessed: May 08, 2022).

Ozga-Zieliński, B. (ed.) (2022) *Modele probabilistyczne opadów maksymalnych o określonym czasie trwania i prawdopodobieństwie przewyższenia – Projekt PMAXTP [Probabilistic models of maximum precipitation with specified duration and probability of exceedance – PMAXTP Project]*. Warszawa: Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy. Available at: https://www.imgw.pl/sites/default/files/2022-12/imgw-pib-monografia_modele-probabilistyczne-opadow-maksymalnych.pdf (Accessed: May 06, 2022).

Rajczak, J. and Schaer C. (2017) "Projections of future precipitation extremes over Europe: A multimodel assessment of climate simulations," *Journal of Geophysical Research: Atmospheres*, 122, pp. 10773–10800. Available at: https://doi.org/10.1002/2017JD027176.

Ren, X. *et al.* (2020) "Effect of infiltration rate changes in urban soils on stormwater runoff process," *Geoderma*, 363, 114158. Available at: https://doi.org/10.1016/j.geoderma.2019.114158.

Rozporządzenie (2022) "Rozporządzenie Ministra Infrastruktury w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie [Regulation of the Minister of Infrastructure on the technical conditions to be met by buildings and their location]," *Dz.U.* 2022 poz. 1225. Available at: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20220001225.

SCALGO Live (no date) *Main website*. [Online]. Available at: https://scalgo.com/en-US/ (Accessed: May 26, 2023).

Urząd Miejski w Sandomierzu (2020) *Studium uwarunkowań i kierunków zagospodarowania przestrzennego gminy Sandomierz zmiana nr 5. Uchwała Nr XXI/256/2020 Rady Miasta Sandomierz z dnia 27 maja 2020 r. [General Urban Ordinance Plan for the city of Sandomierz change no. 5. Resolution No. XXI/256/2020 of the Sandomierz City Council of May 27, 2020 – GUOP]*. Available at https://bip.um.sandomierz.pl/164/wykaz-studium-uwarunkowan-i-kierunkow-zagospodarowania-przestrzennego.html (Accessed: November 17, 2022).

Ustawa (1994) "Ustawa z dnia 7 lipca 1994 r. Prawo budowlane [Construction Law Act]," *Dz.U.* 1994 nr 89 poz. 414 with amendmends. Available at: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU19940890414/U/D19940414Lj.pdf (Accessed: March 22, 2022).

Ustawa (2004) "Ustawa z dnia 16 kwietnia 2004 r. o ochronie przyrody [Polish Nature Conservation Law]," *Dz.U.* 2004 nr 92, poz. 880 with amendmends. Available at: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20040920880/T/D20040880L.pdf (Accessed: March 22, 2022).

Wiberg K. (2018) *Waterscapes of value: Value creation through climate adaptation in everyday landscapes*. PhD Thesis. Aarhus, Aarhus School of Architecture.

Zeng, C. *et al*. (2023) "Comments and recommendations on Sponge City – China's solutions to prevent flooding risks," *Heliyon*, 9(1), e12745. Available at: https://doi.org/10.1016/j.heliyon.2022.e12745.

Zhou, L. *et al*. (2021) "Impacts of land covers on stormwater runoff and urban development: A land use and parcel based regression approach," *Land Use Policy*, 103, 105280. Available at: https://doi.org/10.1016/j.landusepol.2021.105280.