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Rainwater management in urban areas in Poland: literature review

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Abstract. The work analyses and evaluates the results of research work carried out so far in the field of rainwater management in urban areas in Poland. Using the "biblioshiny" tool, a bibliometric analysis was carried out based on queries to the Scopus and Web of Science databases. As a result, information was obtained on selected bibliometric statistics of scientific publications in which the topic of rainwater in Poland was taken up. The probable direction of further research development in the field of the analysed issues was also determined. In addition, after a detailed review of all the articles obtained at the earlier stage of the bibliometric analysis, the main research contexts were indicated and discussed. Areas and issues requiring further analysis and supplementation were indicated in the work.

Key words:
rainwater,
urban,
stormwater management,
bibliometric analysis,
Poland

Introduction

The intensive development of urban areas in the world, especially in the second half of the 19th century, had socio-economic and environmental consequences. The most frequent and visible changes in the development of cities are transformations in land cover, land use and topography. These factors also combine to represent the greatest determinant of another extremely important element that is essential for the functioning of man and the entire natural ecosystem. This element is of course water: the intensive development of urban areas causes locally significant changes in its circulation. For this reason, the concept of Urban Water Cycles is becoming increasingly important (Mitchell et al. 2001; Amore et al. 2013). The concept relates to the hydrological cycle in urban areas that is transformed by multiple anthropogenic factors. As noted by Marsalek et al. (2008) Urban Water Cycles provide a good conceptual basis for studying the water balance of urban areas. The concept is also helpful in understanding the importance of water balance for the integrated management of urban water resources.

Water is essential to the functioning of every city. However, it is often also the source of many problems in urban areas. This applies especially to floods, which in urban areas may take on various forms and have various sources. In recent years, flash floods have become particularly important. Their occurrence is associated with short-term, intense precipitation in urban areas of highly sealed surfaces. The increase in frequency of flash floods seen in urban areas indicates the growing prevalence of this phenomenon. The other, converse phenomenon is droughts and water shortages in urban areas. Water scarcity is a growing problem in urban areas in many parts of the world.

Poland is one of the countries where the issue of precipitation waters has for many years been marginalised by national and local authorities. Poland has some of the lowest water resources in Europe. They amount to 61.6 km^3 (Gutry-Korycka et al. 2014). In addition, some forecasts indicate that, by 2030, the observed climate changes will have contributed to further unfavourable changes in water conditions in the country. This will happen despite almost no change in annual sums of precipitation. The reason will be the lengthening of drought periods, which are predicted to be followed by short-term heavy precipitation (Jarosińska 2016). This situation is particularly dangerous for urban areas, which are characterised by a large percentage of sealed surface area. In Poland, as in many other European Union (EU) countries, precipitation drains mainly through gravitational sewer systems (Dziopak 2018). This has the consequence of high peak flow rates in outflow channels and rapid rises in water levels in receiving bodies (Starzec et al. 2020). In many cases, after extremely intense short-term rainfall, the amounts of rainwater are too large for the drainage network to discharge. The result is local flooding and disturbances to transport systems.

Poland's approach to water resources management changed when the country began applying for EU membership. In order to join the EU, Poland had to meet a number of requirements and introduce many legislative changes. Of particular importance were issues related to implementing EU laws on environmental protection. One example is the *Water Law* Act adopted in 2001. This act treated rainwater and meltwater as sewage. It was only the adoption of the new *Water Law* Act in 2017 (Journal of Laws of 2017, item 1566), in which rainwater and meltwater ceased to be equated with sewage, that allowed for a change in the approach to this issue.

As a result of these legislative changes and global research trends, there has also been a significant increase in interest in research issues related to rainwater management in urban areas in Poland in recent years. So far, however, no synthetic consideration of the conducted research and results has been carried out. The present work tries to fill this gap. The aim of the work is to analyse and evaluate the results of research conducted to date in the field of rainwater management in urban areas in Poland. Addressing the following research questions was helpful in achieving this goal:

1. What are the bibliometric statistics of scientific publications on the topic of rainwater in Poland?
2. What are the predominant research contexts?
3. What is the likely direction for further research?

Materials and methods

The research questions were addressed and the objective achieved in several stages. In the first stage, the research tool was selected. The bibliometric method was chosen, which allowed for a quantitative and qualitative analysis.

The bibliometric analysis was performed based on queries to the Scopus and Web of Science databases. These inquiries took the following form:

1. for the Scopus database: (TITLE-ABS-KEY ("rainwater management*" OR "rain water management*" OR "rain-water management*" OR "stormwater management*" OR "storm water management*" OR "storm-water management*")) OR (TITLE-ABS-KEY ("rainwater harvest*" OR "rain water harvest*" OR "rain-water harvest*" OR "stormwater harvest*" OR "storm water harvest*" OR "storm-water harvest*")) AND (TITLE-ABS-KEY (poland OR polish)) AND (TITLE-ABS-KEY (urban* OR city OR cities OR town* OR resident* OR hous* OR buil* OR "real estate*")), for titles, key words and abstracts;
2. for the Web of Science database: (((TS=("rainwater management*" OR "rain water management*" OR "rain-water management*" OR "stormwater management*" OR "storm water management*" OR "storm-water management*")) OR TS=("rainwater harvest*" OR "rain water harvest*" OR "rain-water harvest*" OR "stormwater harvest*" OR "storm water harvest*" OR "storm-water harvest*")) AND TS=((poland OR polish))) AND TS=(urban* OR city OR cities OR town* OR resident* OR hous* OR buil* OR "real estate*"), for the category "topic".

The "topic" category in Web of Science includes searches for: title, abstract, author keywords, and Keywords Plus (Web of Science 2023).

The individual elements of the query to the databases included searching for all variants of the entry for the search items: "rainwater management" or "stormwater management", for the area of Poland: "polish" or "Poland" and for entries related to urban areas, i.e. "urban", "city", "town", "resident/residential", "hause/hausing", "bulid/built/building" or "real estate".

The inquiries were made in two stages. The first query was performed on February 12, 2023 and yielded 52 publications from the Scopus database and 42 from the Web of Science database. Then, the content of the found publications was reviewed in terms of compliance with the subject and objectives of the article. Ultimately, 47 publications from the Scopus database and 34 from the Web of Science database were accepted for further analysis. On February 20, 2023, the analysed databases were re-queried and no new publications were added. On February 20, 2023, files with the *.bib extension were downloaded with results for the selected 47 (Scopus) and 34 (Web of Science) publications.

The bibliometric analysis was performed using "biblioshiny" (Aria and Cuccurullo 2017), a web application for the "bibliometrix" package (Aria and Cuccurullo 2017) and RStudio software (Posit team 2022). RStudio is a development environment for the R language (R Core Team 2022). In addition, the article uses Inkscape v.1.0.1 and GIMP v.2.10.18.

The bibliometric analysis in the subject area covered basic statistics on: sources, authors, affiliations, citations of publications and author's keywords. Authors' affiliations were analysed in the traditional way (by reviewing each article) due to the questionable methodology implemented in the aforementioned bibliometric software. The methodology used in the programs counts all affiliations, regardless of whether they are in the same or different articles. So, for example, an article written by two people with the same affiliation is counted twice. For the author's keywords, an author keyword co-occurrence analysis (for number of nodes: 50) and a "thematic map" analysis were also performed. Analysis of "thematic map" indicates: "motor themes", "basic themes", "niche themes" and "emerging or declining themes". The choice of authors keywords instead of Keywords Plus was determined by the preliminary results obtained from "biblioshiny". For 34% of publications (16 articles) from the Scopus database there was no information about Keywords Plus. The analysis was performed taking into account all types of publications made available in the analysed databases and with no time limit (all available years were included). The bibliometric analysis allowed the first and third research questions to be answered.

The second research question was problematic to answer based on bibliometric analysis alone. This required that the research be extended to a subsequent stage. It consisted in detailed readings and qualitative analysis of all articles identified in the earlier bibliometric analysis stage. This allows the collected research papers to be grouped by

Table 1. Affiliations (for institutions accounting for more than 1 affiliated publication) within the analysed issue

Affiliation	Publications
Rzeszow University of Technology	14
Wroclaw University of Science and Technology	7
Lodz University of Technology	7
Kielce University of Technology	6
Warsaw University of Life Sciences—SGGW	5
Gdansk University of Technology	4
Opole University of Technology	2
Bialystok University of Technology	2
Wrocław University of Environmental and Life Sciences	2

Source: own evaluation

Table 2. Publications cited more than 10 times on the analysed issue

SCOPUS			Web of Science		
Publication	**DOI**	**Total Citations**	**Publication**	**DOI**	**Total Citations**
Burszta-Adamiak E, 2013, *Water Sci Technol*	10.2166/wst.2013.219	113	Burszta-Adamiak E, 2013, *Water Sci Technol*	10.2166/wst.2013.219	99
Wagner I, 2013, *Ecohydrol Hydrobiol*	10.1016/j.ecohyd.2013.06.002	64	Sakson G, 2018, *Environ Monit Assess*	10.1007/s10661-018-6648-9	30
Sakson G, 2018, *Environ Monit Assess*	10.1007/s10661-018-6648-9	35	Stec A, 2019, *Water*	10.3390/w11030458	29
Stec A, 2019, *Water*	10.3390/w11030458	33	Słyś D, 2020, *Resources-Basel*	10.3390/resources9010005	19
Słyś D, 2020, *Resources*	10.3390/resources9010005	24	Kordana S, 2020, *Sci Total Environ*	10.1016/j.scitotenv.2020.138711	14
Słyś D, 2014, *Ecol Chem Eng S*	10.1515/eces-2014-0045	19	Godyń I, 2020, *Water*	10.3390/w12010151	14
Burszta-Adamiak E, 2012, *J Water Land Dev*	10.2478/v10025-012-0018-8	18	Słyś D, 2014, *Ecol Chem Eng S-*	10.1515/eces-2014-0045	12
Musz-Pomorska A, 2020, *Sustainability*	10.3390/SU12124853	14			
Godyń I, 2020, *Water*	10.3390/w12010151	13			
Zawilski M, 2014, *Ecohydrol Hydrobiol*	10.1016/j.ecohyd.2014.07.003	12			

Source: own evaluation
Explanations: For co-authored publications, only the first author is listed

research context. Some articles were ascribed to more than one research context.

Results

The issue of rainwater management was addressed almost exclusively by scientists of technical

Fig. 1. Basic author keyword statistics (for author keywords used more than once)
Explanations: The percentages cited refer to the shares of author keywords for the "tree maps" range shown in the figure (i.e., for the set of author keywords used more than once).

universities. By far the most common affiliation by number of articles was Rzeszow University of Technology (Table 1). The following universities also boasted significant numbers of publications: Wroclaw University of Science and Technology, Lodz University of Technology and Kielce University of Technology. Non-technical universities accounted for very few publications each.

In both databases, the most frequently cited article is "Modelling of green roofs' hydrologic performance using EPA's SWMM" by E. Burszta-Adamiak and M. Mrowiec (Table 2). The works of Stec and Słyś also have numerous citations. These scientists are the authors of the largest number of publications on the analysed research topics.

The analysis of basic statistics on author keywords showed that authors usually use quite general phrases: “stormwater management”, “rainwater management”, “rainwater harvesting”. Next, attention should be paid to terms relating to the modelling of the stormwater runoff process (“SWMM”, “SWMM model”, “SBUH model”, “modelling”), as well as those emphasising that the area of analysis is the city (“urban catchment”, “urban drainage”, “urban hydrology”, “resilient cities”). The remaining author keywords are various types of variances related to, for example, solutions to stop or slow the runoff of rainwater (“green roof”, “green roofs”, “green infrastructure”, “retention”, “water saving”), financial issues, and the profitability of investments in rainwater collection (“payback period”, “financial analysis”, “life cycle cost”).

Analysis of author keywords co-occurrence for the Web of Science database distinguished two clusters (Fig. 2). The author keyword “rainwater harvesting” constitutes the largest node and has a relationship with the author keyword “life cycle cost”. The second cluster is the relationship between the author keywords “urban catchment” and “SWMM model”. For the Scopus database, four clusters were distinguished: as in the case of the Web of Science database, a cluster was distinguished with a node representing the author keyword “urban catchment” that has a relationship not only with author keyword “SWMM model” but also with “SBUH model”. It should be noted that the node representing the author keyword “green infrastructure” is clustered with “stormwater management” node

In the “thematic map” analysis, nine clusters of topics were identified for the Scopus database and seven for the Web of Science database (Fig. 3 and Appendix 1). In Figure 3, each cluster is labelled with the selected keyword it represents. Appendix 1 presents the complete composition of clusters. The differences in position between similar clusters (not with identical but similar composition of author keywords) should be pointed out – in particular, the clusters for “rainwater harvesting”, “ecosystem services” and “stormwater management” (Fig. 3). The “ecosystem services” and “rainwater” clusters were recognised to be “motor themes”. Within the Web of Science database, no cluster of topics has been identified to belong to “motor themes”. Only the “stormwater management” cluster lies on the border between “basic themes” and “motor themes” (Web of Science). Among the clusters identified in the Scopus database but not identified in the Web of Science database, the following clusters should be indicated: “nature-based solutions”, “modernization”

a) SCOPUS

b) Web of Science

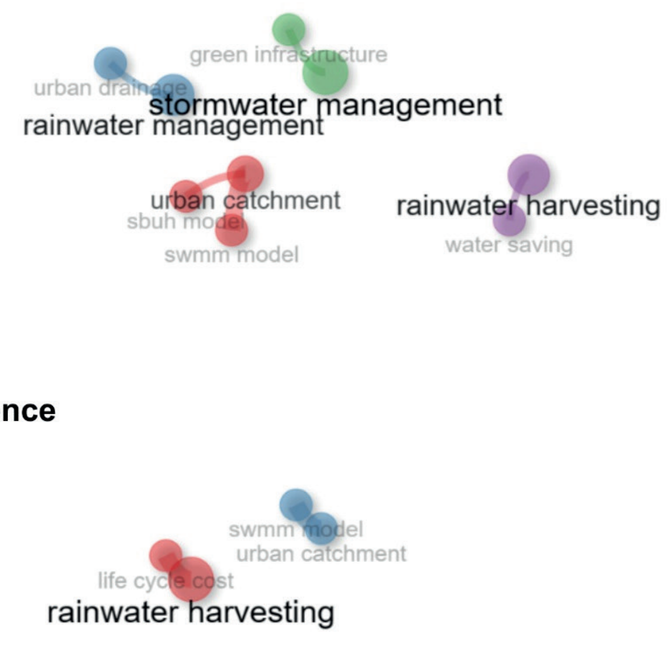

Fig. 2. Author keyword co-occurrence network (for number of nodes: 50)

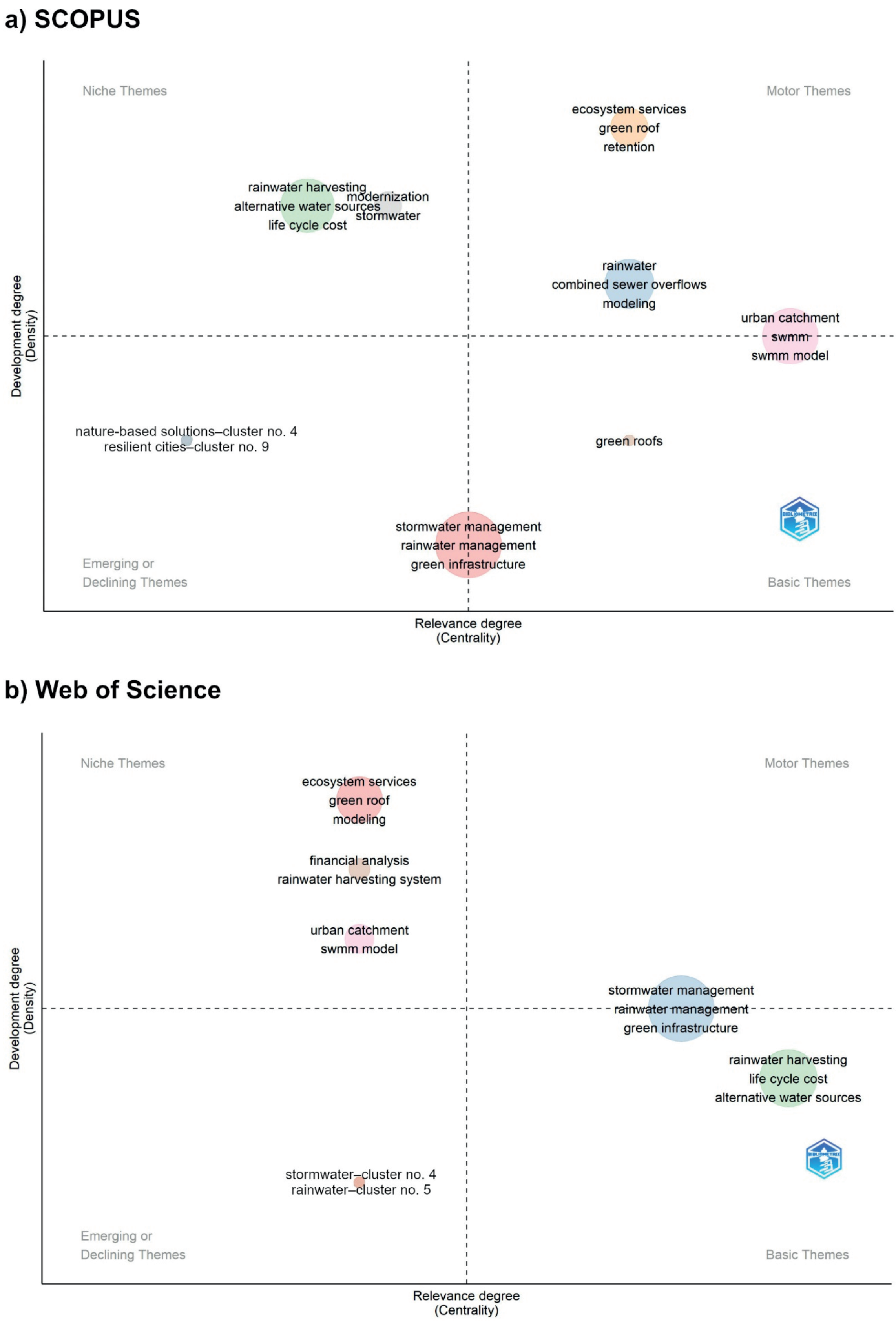

Fig. 3. Results of the “thematic map” graph analysis

and “resilient cities”. One of the clusters not identified in the Scopus database but identified in the Web of Science database is the “financial analysis” cluster (Appendix 1). These clusters were not classified as “motor themes”, nor as “basic themes” (Fig. 3).

The “thematic map” analysis allowed the third research question to be answered. According to the methodology, topics exhibiting high progress and the highest importance in the research field lie in the quadrant defined as “motor themes” (Cobo et al. 2012). “Motor theme” topics may indicate likely directions of future development in research. As already mentioned, only for the Scopus database were clusters (two: “rainwater”, “ecosystem services”) assigned to “motor themes”. Considering the author keywords within these two clusters, they can be interpreted as probable directions of future development in research. The “rainwater” cluster is interpreted as representing: modelling rainwater runoff from the urban catchment, with particular emphasis on the functioning of the combined sewerage system (i.e., stormwater overflow). The equivalent interpretation for the “ecosystem services” cluster is: analysis of the possibility of rainwater retention, with particular emphasis on green roofs. These two interpretations of clusters determine in detail the probable directions of future research development within the research issues.

A close familiarisation with all the publications included in the bibliometric analysis allowed them to be grouped according to the present research context. Eleven research contexts were distinguished. The research context most frequently adopted was analysis relating to technical solutions for rainwater management (14 articles). This context was very often combined with another research context relating to the analysis of economic aspects of rainwater management (10 articles). Similarly, the research context involving the hydrodynamic modelling of rainwater runoff in urban catchments was also frequently discussed (9 articles). Other research contexts in the analysed group of articles were approached much less frequently (2 to 5 articles).

Discussion

The analysis indicated interesting regularities and areas for discussion. Rainwater management in urban areas in Poland has proven to be a very hot topic in recent times. The articles addressing this research topic were published in the last few years. Most articles were created in 2020 and 2022. The significant proliferation of articles in the last three years may indicate the growing importance of this research problem. The articles were published mainly in international journals with high bibliometric indices, which further evidences the international importance of the issue. It should be noted that, of the 52 articles included in the study, as many as 19 have already been cited at least 10 times. This citation tally is quite high and confirms the dynamic development of research in the field of rainwater management in urban areas.

The assumption was that author keywords analysis would identify dominant research contexts. Unfortunately, the terms that authors used were too general to make this possible. Better results would probably be obtained using Keywords Plus. However, as already mentioned, for the analysed group of articles, this was not possible because Keywords Plus lacks information for 34% of the publications. Therefore, this work may be a good demonstration that bibliometric analysis based on publicly available databases is associated with certain difficulties. With a relatively small number of articles and incomplete bibliometric data, it seems that a traditional literature review and content analysis are needed. It should be emphasised that the quantitative (bibliometric analysis) and qualitative (content analysis) methods used complement each other. It is not always possible to use both methods fully. This possibility is mainly determined by the scope and size of the set of articles.

Extremely interesting results were obtained from the analysis of the author affiliations in the analysed articles. Almost all articles were written by scientists from technical universities. This is interesting, as the research subject has significant social and environmental dimensions. It also directly accounts for the research contexts that are addressed in the articles. As already indicated, most of the works concerned the analysis of technical solutions related to rainwater management. However, over the years, there have been changes in the solutions analysed and proposed. Initially, the dominant approach involved the use of green infrastructure (mainly green roofs) (Burszta-Adamiak 2012; Burszta-Adamiak and Mrowiec 2013). In subsequent studies, more attention was paid to the ecohydrology and restoration of watercourses (Wagner and Breil 2013; Zawilski et al. 2014) and the impact of land use and management of rainwater runoff drainage systems (Olechnowicz and Weinerowska-Bords 2014). An interesting aspect indicated by Żarnowiec et al. (2017) related to the drainage of rainwater from industrial areas through their evaporation from roof surfaces. The rapidly increasing number of spatially expansive facilities such as logistics centres, industrial plants and shopping centres in Poland in recent years indicates that this issue is very topical. The results of the cited authors clearly confirm the effectiveness of this solution. Żarnowiec et al. (2017) indicated that, in the seven-month research period, the amount of evaporation exceeded 1000 mm (with average annual precipitation for Poland amounting to about 610 mm). In recent years, research has focused on identifying the best criteria for selecting rainwater management solutions (Kordana and Słyś 2020b), and on analysing and comparing (Boguniewicz-Zabłocka and Capodaglio 2020; Godyń et al. 2020; Wojnowska-Heciak et al. 2020; Sobieraj 2022) and evaluating them (Kordana-Obuch and Starzec 2020). Of particular interest to urban decision-makers are the results of research by Kordana-Obuch and Starzec (2020). These authors have unequivocally indicated that the best way to manage rainwater is for it to infiltrate into the ground through ditches or infiltration tanks. Other solutions should be considered only when this method cannot be used. A slightly different approach was presented by Kasprzyk et al. (2022), who focused on the issue of rain gardens and their impact on ecosystem functions. They noted the effect of this solution in mitigating the effects of the "urban heat island" phenomenon.

The second most frequently discussed research context in the studied group of articles concerned economic aspects of rainwater collection. This aspect also exhibited a certain evolution of the research, in that the scope of analyses had expanded. In the first publications within this research context, the authors focused on analysing the financial efficiency of solutions that collected rainwater mainly for the sanitary purpose of toilet flushing (Słyś et al. 2015; Stec and Słyś 2017; Sakson 2018; Starowicz and Bryszewska-Mazurek 2019; Stec and Zeleňáková 2019). These works differ mainly in the type of facility studied, whether single-family house (Sakson 2018; Słyś et al. 2015), multi-family building (Starowicz and Bryszewska-Mazurek 2019), student dormitory (Stec and Słyś 2017; Stec & Zeleňáková 2019) or housing estate (Godyń et al. 2020), and in location (which is important due to spatial variability in sums of precipitation) and in the details of the methodology used to calculate financial efficiency. More recent publications have focused on comparing the financial (and hydraulic) efficiency of several solutions for collecting and using rainwater (Boguniewicz-Zabłocka and Capodaglio 2020; Musz-Pomorska et al. 2020; Słyś and Stec 2020). Particularly interesting results were obtained by Musz-Pomorska et al. (2020), after analysing 13 designs of rainwater harvesting systems (RWH). They pointed to the limited profitability of the examined designs (RWH), emphasising the insufficiency of governmental financial support. The authors stressed that this could significantly impact the social sustainability of local projects. The latest article dealing with the analysed economic context of rainwater collection is the work of Bus and Szelągowska (2021). This article analyses the economic efficiency of intensive and extensive varieties of green roofs. In the study, the authors included the 11 largest urban communes in Poland, with populations of over 250,000. The work succeeds in showing the spatial diversity of rainwater harvesting opportunities. Some of the adopted assumptions may raise doubts, such as one on the area of green roofs, which in the paper equals 1% of the area of each commune.

Within the research context related to the economic aspects of rainwater collection, one subcategory was distinguished. This was of works that, in addition to economic analysis, also conducted analyses of the life cycle costs (LCC) of various solutions for the collection and use of rainwater. The conducted LCC analyses focused mainly on the analysis of rainwater collection for flushing toilets, washing and watering gardens (Słyś and Stec 2014; Stec and Słyś 2018; Stec and Mazur 2019). Attention should be paid to the conclusions of the analysis carried out by Słyś and Stec (2020) for a rainwater collection system (decentralised or central) in a single-family housing state. Collecting rainwater (whether in a centralised or decentralised system) is not a financially viable solution for an estate. Financial efficiency is improved when the investment is 25% to 50% subsidised.

The third most frequently addressed research context was hydrodynamic modelling of rainwater runoff. Among the articles included, the hydrodynamic modelling program used most frequently was EPA's Storm Water Management Mode. Individual authors used this software to simulate: the operation of the sewerage network, including the rainwater drainage system (Wałęga et al. 2016; Nowakowska et al. 2017; Nowakowska et al. 2019; Szeląg et al. 2022), outflow from a small urban catchment (Boszcz 2017; Barszcz 2018, 2022), and the retention properties of green roofs (Burszta-Adamiak & Mrowiec 2013). An interesting analysis was conducted by Olechnowicz and Weinerowska-Bords (2014) on the impact of various forms of urbanisation on water runoff from an urban catchment. The authors considered seven land development variants and simulated three precipitation scenarios using the Hydrologic Modeling System designed by the Hydrologic Engineering Center of the US Army Corps of Engineers (HEC-HMS). The modelling results indicated that urban development raised but temporally shortened peak flow, while also increasing runoff volume. At the same time, the possibility to significantly reduce runoff was confirmed using various engineering solutions in the field of alternative rainwater management.

Another of the distinguished research contexts relates to the analysis of the physical and chemical properties of rainwater. In the studies included, heavy metal concentrations were most often analysed (Zawilski et al. 2014; Sakson et al. 2018; Jakubowicz et al. 2022). Every work emphasised increased concentrations. In addition, other indicators of pollution were also analysed, including suspended solids, COD, BOD5, N-NH4, P (Zawilski et al. 2014), polycyclic aromatic hydrocarbons, microplastics (Jakubowicz et al. 2022), ammonia, nitrites, nitrates, manganese, iron, and microbiological pollutants (Mazurkiewicz et al. 2022). Extremely important results were obtained by Mazurkiewicz et al. (2022) and Jakubowicz et al. (2022). The former showed that the physicochemical quality of rainwater collected in underground reservoirs as part of the research met the Polish and EU requirements for drinking-water standards. At the same time, the poor microbiological quality of water was emphasised, with the number of coliform bacteria reaching 19,300 CFU. The article by Jakubowicz et al. (2022) showed the possibility of significantly reducing some pollutants (heavy metals, microplastics, polycyclic hydrocarbons) using a pilot multi-stage wetland installation. Such installations may be important in reducing pollutants discharged through the rainwater drainage system to receivers (rivers, lakes).

Urban planning, including rainwater management, is another highlighted research context. The two oldest works assigned to this research context relate to the issue of sustainable development as part of urban planning (Ogielski et al. 2015; Surma 2015). Particularly comprehensive analyses related to stormwater management have been carried out by Surma (2015). The author showed current sustainable rainwater management scenarios for areas that differed in use, time of creation and socio-economic functions performed. A different approach to urban planning has been presented in two recent works within this research context. Fitobór et al. (2022) used a holistic and dynamic planning method called the "extreme weather layer". This method allows for determination of the impact of a single investment on the operation of a municipal sewage system and thus on the flood risk of an entire catchment. The many actions proposed by the authors to minimise flood risk in cities include the still-underestimated and underfunded Nature-Based Solutions (NBS). A very innovative idea has been presented by S.M. Rybicki et al. (2022). They present a model of an elementary autonomous housing complex called Bio-Morpheme. The essence of the proposed model is the idea of ensuring that urban developments of various types integrate the water circulation of the buildings into that of their immediate surroundings. A theoretical model was analysed to verify the possibility of comprehensive water management that included the collecting of precipitation from roofs, pavements, cycle paths and roads. Results obtained for the climatic and hydrological conditions of the city of Kraków (south Poland) indicated that 41% of the collected precipitation could be used for economic purposes. The rest of the water collected in a surface receiver would improve the microclimate and could be used over time for other purposes, such as irrigation.

Other research contexts related to rainwater management were decidedly less frequently addressed. In the context of research on legal regulations for rainwater management, authors emphasised the positive change in legal regulations relating to water management in Poland and their implementation of EU regulations. It should be noted that Sakson et al. (2017), Kordana and Słyś (2020a) and Godyń (2022) combined the legal regulations context with the economic instruments context in the rainwater management aspect. Saxon et al. (2017), analysing the impact of precipitation on the functioning of sewage treatment plants in a city (on the example of the city of Łódź), drew attention to the existence of regulations that do not ensure proper protection of water against pollution. They indicated that the regulations are too general and do not take into account local conditions, thereby preventing effective and economically viable water protection. Kordana and Słyś (2020a) and Godyń (2022) indicated gaps in the existing rainwater management policy in Poland, including the fees for the discharge of rainwater being too low, budgetary funds to offer grants for rainwater collection investments being too low, and fees for the discharge of rainwater into the municipal sewage system not being universal. Szpak et al. (2022) focused on the analysis of documents related to rainwater management in a selection of Poland's largest cities. The study draws attention to actions taken by individual cities to improve their resilience in terms of issues relating to rainwater.

The research context related to social aspects of rainwater management was addressed only twice by the analysed group of articles. Interesting results were presented by Stec (2018), who conducted a study of households in Poland on the use of alternative water sources. The results clearly indicate a lack of interest in the possibility of replacing household mains water with grey water and rainwater. In the opinion of respondents, if they collected rainwater, it would be used mainly for watering the garden. The work of Mantey (2021) is of a similar nature. The research objective was, among the inhabitants of three types of suburban area, to identify attitudes towards small retention in the context of changes in the water law. The paper draws attention to the diverse ways in which residents living in areas of different degrees of urbanisation perceive the problem of rainwater. It indicated, among other things, that a greater urbanisation is accompanied by a lower sense of responsibility for rational rainwater management. Residents are also not convinced about the effectiveness of investing in individual small retention equipment. The main factors that might encourage them to implement such investments are financial issues, such as reducing fees for discharging rainwater to the rainwater drainage system.

The last of the highlighted research contexts is related to quantitative analyses of the potential for collecting rainwater. In both works, the authors rely on 50-year data obtained for 19 synoptic meteorological stations throughout Poland. Canales et al. (2020) assessed long-term trends in 20-day cumulative precipitation periods throughout the year. They also indicated the impact of their results on issues relating to the design and operation of rainwater collection equipment. Gwoździej-Mazur et al. (2022) drew attention to the impact of long-term climate change on the possibility of using rainwater in households. The authors emphasised that the design of RWH systems should be based on archival data and take into account long-term changes in precipitation. The validity of this statement needs addressing. Climate change presents us with an intensification of extreme weather events that exceeds past levels. It is therefore reasonable to ask, "Shouldn't models extrapolating changes in climatic conditions be taken into account more fully when planning and designing RWH?"

Almost half of the works presented their research and analyses on the example of a city or part thereof. However, importantly, the research containing more detailed analyses related to just six Polish cities. Most works concerned Warsaw, Łódź and Wrocław. The other studies concerned Gdańsk, Kraków and Rzeszów. It should be noted that several articles include more cities. However, these articles were more general (e.g., Szpak et al. 2022) or focused only on comparing just one element related to rainwater (e.g., Canales et al. 2020; Gwoździej-Mazur et al. 2022).

One of the questions asked most often by scientists from various fields relates to the direction in which further research on their chosen research topic will go. In the analysed research issues, the answer was: analysis of "thematic maps". Two main research areas have been identified as probably the most intensively researched in the coming years. The first combines two important problems. It concerns modelling rainwater runoff from urban catchments and the functioning of the sewerage system in the event of extreme events that activate stormwater overflows. Modelling the outflow of rainwater from the urban catchment is very difficult, as it must take into account the specifics of local conditions. The activation of stormwater overflows results in untreated sewage being discharged directly to the receiver (usually a river or lake). The growing number of extreme events related to rapid, intense precipitation will increase the number of such situations in coming years. The proper development and subsequent implementation of stormwater runoff models will significantly reduce the frequency of storm overflows. The second of research area that will developed rapidly in coming years concerns the possibility of rainwater retention. This issue is extremely broad, as it includes a number of applicable methods and solutions. Therefore, in the coming years, further research should be expected to aim to find the most effective rainwater retention solutions. This research is likely to focus largely on the further development of a broad spectrum of green roof solutions.

This paper is limited to the analysis of articles indexed by the two most prestigious bibliometric databases. One should therefore be aware that not all scientific articles addressing the analysed research issues were included. Despite this, the conclusions that can be formulated on the basis of the conducted analysis seem to fully reflect the state of knowledge on the undertaken research issues.

Conclusions

Based on the analysis, the following conclusions can be drawn:

- The issue of rainwater in urban areas in Poland is a current and developing research area, as confirmed by the growing number of articles.
- The research issues analysed in the work in Poland are mainly undertaken by scientists from technical universities, which has a direct impact on the research contexts of the resulting scientific studies.
- Eleven research contexts have been distinguished within which the issue of rainwater in urban areas has been analysed to date. The research context most frequently adopted was analysis of technical solutions for rainwater management (14 articles). Another frequently discussed research context was that of hydrodynamic modelling of rainwater runoff in urban catchments (9 articles).
- Based on the “thematic map” analysis, two probable directions of further development of the problem of rainwater in urban areas in Poland were indicated: 1) Modelling rainwater runoff from an urban catchment, with particular emphasis on the functioning of the combined sewerage system (i.e., including stormwater overflow); and 2) Analysis of rainwater retention possibilities, with particular emphasis on green roofs.
- It has been shown that individual research contexts have increased the scope and methods of their analyses and the range of research tools used.
- Detailed analyses have been limited to selected larger cities in Poland and have omitted medium and small cities.
- There is a lack of broader integration of research results from different research contexts.

Furthermore, in terms of the bibliometric analysis, two conclusions can be drawn:

- The results of the bibliometric analysis may be influenced by the database on which the analysis is performed. This is particularly true when the researched group of publications is relatively small.
- The incompleteness of bibliometric information (which persists in the Scopus and Web of Science databases) may significantly limit the ability to draw conclusions based only on data obtained from bibliometric databases.

As it has been shown, rainwater is a current research problem that is analysed in many contexts. Despite the large amount of research, there are still areas in which gaps exist. The studies to date have provided a lot of valuable and important data and information. At present, there is a lack of studies using these results to synthesise and comprehensively analyse the issue from a regional (voivodship) or national perspective. Social studies into rainwater management are especially lacking. Research integrating environmental, economic, social and legal issues within the analysed issues should be considered essential. Ultimately, detailed analyses of these factors should be conducted for every city in Poland. In addition, efforts should be made to involve scientists from non-technical universities in these issues. It seems that geographers can play a special role in this respect (without dividing them into those dealing with socio-economic and environmental issues). They have appropriate environmental and socio-economic knowledge and tools for spatial analysis (GIS software).

In light of the dynamic development of Polish cities, the accompanying spatial transformations and progressing climate change, addressing the comments and postulates indicated in this work appears to be increasingly urgent. The failure to immediately undertake the indicated research and then to implement the results may contribute to significant socio-economic losses in the near future.

References

AMORES MJ, MENESES M, PASQUALINO J, ANTÓN A and CASTELLS F, 2013, Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach. *Journal of cleaner production* 43: 84-92. DOI: https://doi.org/10.1016/j.jclepro.2012.12.033.

ARIA M AND CUCCURULLO C, 2017, bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics* 11(4): 959–975. DOI: https://doi.org/10.1016/j.joi.2017.08.007.

BARSZCZ M, 2017, Porównanie przepływów o określonym prawdopodobieństwie wystąpienia obliczonych w zlewni miejskiej za pomocą modeli SWMM i SBUH. *Przeglad Geograficzny* 89(3): 429–449. DOI: https://doi.org/10.7163/PrzG.2017.3.5.

BARSZCZ MP, 2018, Radar data analyses for a single rainfall event and their application for flow simulation in an urban catchment using the SWMM model. *Water* 10(8): 1007. DOI: https://doi.org/10.3390/w10081007.

BARSZCZ MP, 2019, Quantitative rainfall analysis and flow simulation for an urban catchment using input from a weather radar. *Geomatics, Natural Hazards and Risk* 10(1): 2129–2144. DOI: https://doi.org/10.1080/19475705.2019.1682065.

BARSZCZ MP, 2021, Application of dynamic and conceptual models for simulating flow hydrographs in an urbanized catchment under conditions of controlled outflow from stormwater tanks. *Journal of Water and Climate Change* 12(8): 3899–3914. DOI: https://doi.org/10.2166/wcc.2021.211.

BOGUNIEWICZ-ZABŁOCKA J and CAPODAGLIO AG, 2020, Analysis of alternatives for sustainable stormwater management in small developments of Polish urban catchments. *Sustainability* 12(23): 1–20. DOI: https://doi.org/10.3390/su122310189.

BURSZTA-ADAMIAK E, 2012, Analysis of the retention capacity of green roofs. *Journal of Water and Land Development* 16(1): 3–9. DOI: https://doi.org/10.2478/v10025-012-0018-8.

BURSZTA-ADAMIAK E and MROWIEC M, 2013, Modelling of Green roofs' hydrologic performance using EPA's SWMM. *Water Science and Technology* 68(1): 36–42. DOI: https://doi.org/10.2166/wst.2013.219.

BUS A and SZELĄGOWSKA A, 2021, Green water from green roofs – The ecological and economic effects. *Sustainability* 13(4): 1–14. DOI: https://doi.org/10.3390/su13042403.

CANALES FA, GWOŹDZIEJ-MAZUR J, JADWISZCZAK P, STRUK-SOKOŁOWSKA J, WARTALSKA K, WDOWIKOWSKI M and KAŹMIERCZAK B, 2020, Long-term trends in 20-day cumulative precipitation for residential rainwater harvesting in Poland. *Water* 12(7): 1932. DOI: https://doi.org/10.3390/w12071932.

CHUDZICKI J, 2018, Problems of rainwater management: A case study of the city of Warsaw, Poland. *WIT Transactions on the Built Environment* 184: 69–79. DOI: https://doi.org/10.2495/FRIAR180071.

COBO MJ. LÓPEZ-HERRERA AG, HERRERA-VIEDMA E, HERRERA F, 2012, SciMAT: A new science mapping analysis software tool. *Journal of the Association for Information Science and Technology* 63: 1609–1630. DOI: https://doi.org/10.1002/asi.22688.

DZIOPAK J, 2018, A wastewater retention canal as a sewage network and accumulation reservoir. *E3S Web of Conferences* 45: 00016. DOI: https://doi.org/10.1051/e3sconf/20184500016.

FITOBÓR K, ULAŃCZYK R, KOŁECKA K, RAMM K, WŁODAREK I, ZIMA P, KALINOWSKA D, WIELGAT P, MIKULSKA M, ANTOŃCZYK D, KRZACZKOWSKI K, ŁYSZYK R, and GAJEWSKA M, 2022, Extreme weather layer method for implementation of nature-based solutions for climate adaptation: Case study Słupsk. *Science of the Total Environment* 842: 156751. DOI: https://doi.org/10.1016/j.scitotenv.2022.156751.

GODYŃ I, 2022, Economic Incentives in Stormwater Management: A Study of Practice Gaps in Poland.

Water 14(23): 3817. DOI: https://doi.org/10.3390/w14233817.

GODYŃ I, GRELA A, STAJNO D and TOKARSKA P, 2020, Sustainable rainwater management concept in a housing estate with a financial feasibility assessment and motivational rainwater fee system efficiency analysis. *Water* 12(1): 151. DOI: https://doi.org/10.3390/w12010151.

GODYŃ I, MUSZYŃSKI K and GRELA A, 2022, Assessment of the Impact of Loss-of-Retention Fees on Green Infrastructure Investments. *Water* 14(4): 560. DOI: https://doi.org/10.3390/w14040560.

GUTRY-KORYCKA M, SADURSKI A, KUNDZEWICZ ZW, POCIASK-KARTECZKA J and SKRZYPCZYK L, 2014, Water resources and their use. *Nauka* 1: 77-98.

GWOŹDZIEJ-MAZUR J, JADWISZCZAK P, KAŹMIERCZAK B, KÓZKA K, STRUK-SOKOŁOWSKA J, WARTALSKA K and WDOWIKOWSKI M, 2022, The impact of climate change on rainwater harvesting in households in Poland. *Applied Water Science* 12(2): 15. DOI: https://doi.org/10.1007/s13201-021-01491-5.

JAKUBOWICZ P, FITOBÓR K, GAJEWSKA M and DREWNOWSKA M, 2022, Detection and Removal of Priority Substances and Emerging Pollutants from Stormwater: Case Study of the Kołobrzeska Collector, Gdańsk, Poland. *Sustainability* 14(3): 1105. DOI: https://doi.org/10.3390/su14031105.

JAROSIŃSKA E, 2016, Local flooding in the USA, Europe, and Poland-an overview of strategies and actions in face of climate change and urbanisation. *Infrastructure and Ecology of Rural Areas* 3(1): 801-821. DOI: http://dx.medra.org/10.14597/infraeco.2016.3.1.059.

JOPEK D, 2018, Water in the city. The development of permeable surfaces in urban areas. *E3S Web of Conferences* 45(00109): 1-8. DOI: https://doi.org/10.1051/e3sconf/20184500109.

KASPRZYK M, SZPAKOWSKI W, POZNAŃSKA E, BOOGAARD FC, BOBKOWSKA K and GAJEWSKA M, 2022, Technical solutions and benefits of introducing rain gardens – Gdańsk case study. *Science of the Total Environment* 835: 155487. DOI: https://doi.org/10.1016/j.scitotenv.2022.155487.

KORDANA S and SŁYŚ D, 2020a, An analysis of important issues impacting the development of stormwater management systems in Poland. *Science of The Total Environment* 727: 138711. DOI: https://doi.org/10.1016/j.scitotenv.2020.138711.

KORDANA S and SŁYŚ D, 2020b, Decision criteria for the development of stormwater management systems in Poland. *Resources* 9(2): 20. DOI: https://doi.org/10.3390/resources9020020.

KORDANA-OBUCH S and STARZEC M, 2020, Statistical approach to the problem of selecting the most appropriate model for managing stormwater in newly designed multi-family housing estates. *Resources* 9(9): 110. DOI: https://doi.org/10.3390/RESOURCES9090110.

MANTEY D, 2022, Changes in the approach to rainwater and meltwater management in the suburban area from a resident perspective. *Prace i studia geograficzne* 67: 131-150.

MARSALEK J, CISNEROS BJ, KARAMOUZ M, MALMQUIST PA, GOLDENFUM JA and CHOCAT B, 2008, Urban water cycle processes and interactions: urban water series-UNESCO-IHP (Vol. 2). London: CRC Press. DOI: https://doi.org/10.1201/9781482288544.

MAZURKIEWICZ K, JEŻ-WALKOWIAK J and MICHAŁKIEWICZ M, 2022, Physicochemical and microbiological quality of rainwater harvested in underground retention tanks. *Science of the Total Environment* 814: 152701. DOI: https://doi.org/10.1016/j.scitotenv.2021.152701.

MITCHELL VG, MEIN RG and MCMAHON TA, 2001, Modelling the urban water cycle. *Environmental modelling & software* 16(7): 615-629. DOI: https://doi.org/10.1016/S1364-8152(01)00029-9.

MUSZ-POMORSKA A, WIDOMSKI MK and GOŁĘBIOWSKA J, 2020, Financial sustainability of selected rain water harvesting systems for single-family house under conditions of Eastern Poland. *Sustainability* 12(12): 4853. DOI: https://doi.org/10.3390/SU12124853.

NOWAKOWSKA M, KAŹMIERCZAK B, KOTOWSKI A and WARTALSKA K, 2017, Identyfikacja, kalibracja i walidacja hydrodynamicznego modelu systemu odwadniającego tereny miejskie na przykładzie Wrocławia. *Ochrona Środowiska* 39(2): 51–60.

NOWAKOWSKA M, WARTALSKA K, KAŹMIERCZAK B and KOTOWSKI A, 2019, Verification of the stormwater drainage system overloads in Wrocław for an assessment of climate change effects. *Periodica Polytechnica Civil Engineering* 63(2): 641–646. DOI: https://doi.org/10.3311/PPci.12668.

OGIELSKI P, DRAPELLA-HERMANSDORFER A, STOJAK M and TARCZEWSKI R, 2015, Geo flagship - new model of green campus. In 2nd International Multidisciplinary Scientific Conference on Social Sciences and Arts, SGEM 2015: conference proceedings, Albena, Bulgaria, 26 August - 1 September, 2015. Book 4, Arts, performing arts, architecture and design: history of arts, contemporary arts, performing and visual arts, architecture and design. Sofia: STEF92 Technology, 431–438.

OLECHNOWICZ B and WEINEROWSKA-BORDS K, 2014, Impact of urbanization on stormwater runoff from a small urban catchment: Gdańsk Małomiejska basin case study. *Archives of Hydroengineering and Environmental Mechanics* 61(3–4): 141–162. DOI: https://doi.org/10.1515/heem-2015-0009.

POSIT TEAM, 2022, RStudio: Integrated Development Environment for R. Posit Software, PBC, Boston, MA. Available at: http://www.posit.co/.

R CORE TEAM, 2022, R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/.

RYBICKI SM, SCHNEIDER-SKALSKA G and STOCHEL-CYUNEL J, 2022, Bio-Morpheme as innovative design concept for "Bio City" urban structure in the context of water-saving and human health. *Journal of Cleaner Production* 369: 133266. DOI: https://doi.org/10.1016/j.jclepro.2022.133266.

SAKSON G, 2018, Cost analysis of a rainwater harvesting system in Poland. *E3S Web of Conferences* 45(00078): 1-8. DOI: https://doi.org/10.1051/e3sconf/20184500078.

SAKSON G, BRZEZIŃSKA A and ZAWILSKI M, 2017, Możliwości ograniczenia wpływu ścieków deszczowych odprowadzanych z obszarów zurbanizowanych na jakość wód powierzchniowych w aspekcie uregulowań prawnych. *Ochrona Środowiska* 39(2): 27–38.

SAKSON G, BRZEZIŃSKA A and ZAWILSKI M, 2018, Emission of heavy metals from an urban catchment into receiving water and possibility of its limitation on the example of Lodz city. *Environmental Monitoring and Assessment* 190(5): 281. DOI: https://doi.org/10.1007/s10661-018-6648-9.

SŁYŚ D and STEC A, 2014, The analysis of variants of water supply systems in multi-family residential building. *Ecological Chemistry and Engineering S* 21(4): 623–635. DOI: https://doi.org/10.1515/eces-2014-0045.

SŁYŚ D and STEC A, 2020, Centralized or decentralized rainwater harvesting systems: A case study. *Resources* 9(1): 5. DOI: https://doi.org/10.3390/resources9010005.

SŁYŚ D, STEC A and DZIOPAK J, 2015, The Analysis of Possibilities of Using the Rainwater Harvesting Systems in Residential Buildings in Poland. In: Hlavínek P and Zeleňáková M (eds), Storm Water Management: Examples from Czech Republic, Slovakia and Poland. Cham Heidelberg New York Dordrecht London, 67–81. DOI: https://doi.org/10.1007/978-3-319-25835-5_6.

SOBIERAJ J, BRYX M and METELSKI D, 2022, Stormwater Management in the City of Warsaw: A Review and Evaluation of Technical Solutions and Strategies to Improve the Capacity of the Combined Sewer System. *Water* 14(13): 2109. DOI: https://doi.org/10.3390/w14132109.

STAROWICZ A and BRYSZEWSKA-MAZUREK A, 2019, Rainwater harvesting system in a multi-family building located in Poland. *Polish Journal of Natural Sciences* 34(3): 415–432.

STARZEC M, DZIOPAK J and SŁYŚ D, 2020, An analysis of stormwater management variants in urban catchments. *Resources* 9(2): 19. DOI: https://doi.org/10.3390/resources9020019.

STEC A, 2018, Rainwater harvesting and greywater recycling as alternative water resources: A survey of public opinion. *E3S Web of Conferences* 45: 00090. DOI: https://doi.org/10.1051/e3sconf/20184500090.

STEC A and MAZUR A, 2019, An analysis of eco-technology allowing water and energy saving in an environmentally friendly house-A case study from Poland. *Buildings* 9(8): 180. DOI: https://doi.org/10.3390/buildings9080180.

STEC A and SŁYŚ D, 2017, Rainwater Potential Use in Dormitory Building: Drinking Water Savings and Economic Costs. *Ecological Chemistry and Engineering A* 24(1): 43–64. DOI: https://doi.org/10.2428/ecea.2017.24(1)4.

STEC A and SŁYŚ D, 2018, The Impact of Rainwater Harvesting System Location on Their Financial Efficiency: A Case Study in Poland. In: Zeleňáková M (ed), Water Management And The Environment: Case Studies. Cham, 43–63. DOI: https://doi.org/10.1007/978-3-319-79014-5_3.

STEC A, and ZELEŇÁKOVÁ M. 2019, An analysis of the effectiveness of two rainwater harvesting systems located in central eastern Europe. *Water* 11(3). DOI: https://doi.org/10.3390/w11030458.

SURMA M, 2015, Sustainable urban development through an application of green infrastructure in district scale - A case study of Wrocław (Poland). *Journal of Water and Land Development* 25(1): 3–12. DOI: https://doi.org/10.1515/jwld-2015-0007.

SZELĄG B, MAJEREK D, KICZKO A, ŁAGÓD G, FATONE F and MCGARITY A, 2022, Analysis of Sewer Network Performance in the Context of Modernization: Modeling, Sensitivity, and Uncertainty Analysis. *Journal of Water Resources Planning and Management* 148(12). DOI: https://doi.org/10.1061/(ASCE)WR.1943-5452.0001610.

SZPAK A, MODRZYŃSKA J and PIECHOWIAK J, 2022, Resilience of Polish cities and their rainwater management policies. *Urban Climate* 44: 101228. DOI: https://doi.org/10.1016/j.uclim.2022.101228.

WAGNER I and BREIL P, 2013, The role of ecohydrology in creating more resilient cities. *Ecohydrology and Hydrobiology* 13(2): 113–134. DOI: https://doi.org/10.1016/j.ecohyd.2013.06.002.

WAŁĘGA A, KACZOR G and STĘPLEWSKI B, 2016, The role of local precipitation models in designing rainwater drainage systems in urban areas: A case study in Krakow, Poland. *Polish Journal of Environmental Studies* 25(5): 2139–2149. DOI: https://doi.org/10.15244/pjoes/62961.

Web of Science, 2023, Available at: https://www.webofscience.com/wos/woscc/basic-search (Accessed: 24 April 2023).

WOJNOWSKA-HECIAK M, HECIAK J and KŁAK A, 2020, Flood resilient streetscape. *Journal of Water and Land Development* 44: 158–164. DOI: https://doi.org/10.24425/jwld.2019.127057.

ZAWILSKI M and DZIEDZIELA B, 2018, Stormwater quality modeling in urbanized areas. *E3S Web of Conferences* 45(00104): 1-8. DOI: https://doi.org/10.1051/e3sconf/20184500104.

ZAWILSKI M and SAKSON G, 2002, Potential of alternative OSD/OSR technologies concerning reduction of urban stormwater flow. In: Strecker EW and Huber WC (eds), Global Solutions for Urban Drainage. Reston: ASCE, 1–15. DOI: https://doi.org/10.1061/40644(2002)70.

ZAWILSKI M, SAKSON G and BRZEZIŃSKA A, 2014, Opportunities for sustainable management of rainwater: Case study of Łódź, Poland. *Ecohydrology and Hydrobiology* 14(3): 220–228. DOI: https://doi.org/10.1016/j.ecohyd.2014.07.003.

ŻARNOWIEC W, BOGDAŁ A, KOWALIK T, KANOWNIK W, OSTROWSKI K and RAJDA W, 2017, Rainwater management in protected areas. *Journal of Ecological Engineering* 18(2): 69–77. DOI: https://doi.org/10.12911/22998993/67858.

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Appendix 1

Table. "Thematic map" analysis results: the composition of selected clusters

SCOPUS				Web of Science			
Authors keywords	Occurrences	Cluster No.	Cluster Label	Authors keywords	Occurrences	Cluster No.	Cluster Label
stormwater management	7	1	stormwater management	ecosystem services	2	1	ecosystem services
rainwater management	6	1	stormwater management	green roof	2	1	ecosystem services
green infrastructure	3	1	stormwater management	modeling	2	1	ecosystem services
payback period	2	1	stormwater management	swmm	2	1	ecosystem services
urban drainage	2	1	stormwater management	stormwater management	6	2	stormwater management
rainwater	4	2	rainwater	rainwater management	4	2	stormwater management
combined sewer overflows	2	2	rainwater	green infrastructure	2	2	stormwater management
modeling	2	2	rainwater	payback period	2	2	stormwater management
urban hydrology	2	2	rainwater	rainwater harvesting	6	3	rainwater harvesting
rainwater harvesting	6	3	rainwater harvesting	life cycle cost	3	3	rainwater harvesting
alternative water sources	2	3	rainwater harvesting	alternative water sources	2	3	rainwater harvesting
life cycle cost	2	3	rainwater harvesting	stormwater	3	4	stormwater
water saving	2	3	rainwater harvesting	rainwater	3	5	rainwater
nature-based solutions	2	4	nature-based solutions	financial analysis	2	6	financial analysis
ecosystem services	2	5	ecosystem services	rainwater harvesting system	2	6	financial analysis
green roof	2	5	ecosystem services	urban catchment	3	7	urban catchment
retention	2	5	ecosystem services	swmm model	2	7	urban catchment
green roofs	2	6	green roofs				
urban catchment	5	7	urban catchment				
swmm	3	7	urban catchment				
swmm model	3	7	urban catchment				
sbuh model	2	7	urban catchment				
modernization	2	8	modernization				
stormwater	2	8	modernization				
resilient cities	2	9	resilient cities				

Source: own evaluation