

Article

The Example of the “Green Class” Project in Krakow: A New, Mobile System of Educational Facilities That Takes Rainwater Retention into Account

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Abstract: Educational institutions in Poland often struggle with various problems, such as the lack of an adequate number of rooms or the poor technical condition of buildings. This is due to many factors, such as the age of the buildings, demographic trends, migration, political, social, historical, and cultural conditions and, above all, financial conditions. In order to address these problems, the Krakow University of Technology undertook the implementation of the “Green Classroom” scientific project as part of the “Science for Society” programme of the Ministry of Education and Science. The Green Classroom is a mobile, free-standing educational facility consisting of a geometric arrangement of four basic modules. Integrating this type of facility into existing infrastructure, especially in urban areas, requires the availability of suitable land, taking into account hydro-meteorological and wastewater conditions. This study presents a method using geographic information system (GIS) tools to select school areas where it is possible to locate “Green Classrooms”, taking into account sustainable land retention. Based on typical rainfall for the city of Krakow, stormwater runoff was calculated taking into account the adopted “Green Classroom” module. An additional sealed surface (a “Green Classroom” system) increases the rainwater runoff by approximately 1 m³. In order to balance the rainwater runoff, it is recommended to install a rainwater collection tank with a capacity of 1 m³ next to the “Green Classroom” module. In order to relieve the storm sewer system, especially in highly sealed urban areas, it is recommended to use aboveground or underground stormwater tanks. The size of the tanks should depend on the impervious surfaces and their number on the site conditions. Nomograms for the city of Krakow have been developed to estimate the size of tanks.

Keywords: “Green Classroom”; precipitation; urban stormwater retention; spatial analysis; QGIS



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1. Introduction

The situation of educational institutions around the world is varied and depends on many factors, including local realities, government policies, and socioeconomic conditions. Inequalities in access to education remain a problem in many regions of the world [1]. In some places, there is a lack of infrastructure, qualified teachers, or access to basic educational resources [2]. There are differences in the level of funding for education in different countries and regions [3]. Inadequate or poorly managed education budgets may be a problem in some places [4]. In addition, the COVID-19 pandemic [5] has had a significant impact on education around the world. The introduction of distance learning has become a necessity, creating new challenges for students, teachers, and educational institutions [6,7]. The use of e-learning platforms, educational applications, and innovative solutions has become

much more widespread than before the pandemic [8,9]. Many universities and schools have adopted online teaching, allowing students to receive their education from anywhere in the world [10]. In Poland, the COVID-19 pandemic also forced the introduction of distance learning. Few institutions were prepared for such a situation. This was an organisational challenge not only for the institutions themselves, but also for the staff and students. Educational institutions in Poland differ due to historical and economic conditions in different regions of the country [11,12]. Educational institutions are often located in city centres, in historical buildings, which causes problems related to the lack of an adequate number of rooms, gyms, small yards, and poor technical condition of the buildings. The diversity of the situation of educational units in Poland is the result of many factors, such as location, age of the buildings, demographics, migration and crisis trends, political, social, historical, and cultural conditions and, above all, funding [13–15]. State subsidies do not always fully cover the needs of educational institutions, and the level of subsidies varies from one municipality to another. The situation is particularly difficult for institutions in historic buildings, where the additional burden of costly renovations is often compounded by a lack of funding for many years [11].

The “Green Classroom” project, implemented by the Krakow University of Technology in 2022–2023 as part of the Minister of Education and Science’s “Science for Society” programme, aimed to develop and disseminate a good practice kit [16–18] in the field of new forms and educational spaces. The research was conducted in accordance with a cooperation agreement concluded between the Krakow University of Technology and the Education Department of the Krakow City Hall. It was of significant importance to utilise innovative technologies and identify novel applications for traditional building materials. Another significant objective of the project was to assess the capacity of educational institutions in Poland [19–21] to meet evolving demands [22]. A significant challenge for socioeconomic development has been identified, namely, the deterioration of the functioning of educational institutions in Poland. This state of affairs is frequently the consequence of the limited adaptability of the structural and functional–spatial systems of existing buildings to changing functions [23]. This includes challenges related to the threat of epidemics or the consequences of climate change. The project “School of the future: modular and mobile Green Classroom system” aimed to propose solutions that take into account the needs for changes diagnosed during the research. The project focused on two main areas: the quality of space and the increase in educational space. The “Green Classroom” is intended to be an additional autonomous educational space. The “Green Classroom” can be used as classrooms or auxiliary rooms (library, workshop, or a place to rest during breaks), implemented in a modular system that can be adapted to existing location conditions. An important issue was to ensure the energy independence of the modules implemented through renewable energy sources. In accordance with the project assumptions, it was assumed that the use of blue–green infrastructure solutions, including small retention and renewable energy installations, was necessary as an integral element of the “Green Classroom” concept. The development of solutions that facilitate the expedient implementation of low-cost and energy-efficient facilities may be a response to current [24] and future crisis situations, including the consequences of climate change. One of the stages of research conducted for the “Green Classroom” project was the verification of potential implementation possibilities. The objective of this article is to develop a preliminary method for locating modular “Green Classroom” facilities on plots owned by existing educational institutions within the city of Krakow, based on an analysis of hydrological conditions. The conventional approach to school construction does not consider the possibility of relocating facilities. Furthermore, in accordance with all legal regulations, buildings constructed within the original plot frequently have a detrimental impact on the potential for rainwater retention. One of the objectives of the Green Classroom was to develop a system that would enhance the efficacy of rainwater retention management. The utilisation of GIS enables the periodic evaluation of the efficacy of rainwater management strategies, facilitating the identification of optimal parameters for solutions and facilities. A geographic information system (GIS) consists of integrated computer hardware and software that store,

manage, analyse, edit, output, and visualise geographic data [25,26]. Geographic information systems are utilised in multiple technologies, processes, techniques, and methods, which relate to engineering, planning, management, transport/logistics, insurance, telecommunications, and business [27]. For this reason, GIS and location intelligence applications are at the foundation of location-enabled services, which rely on geographic analysis and visualisation. GIS provides the capability to relate previously unrelated information through the use of location as the “key index variable”.

As can be seen from the definition of GIS, tools, methods, and software are ideally suited to solving this type of design problem.

2. Materials and Methods

This study presents a straightforward and automated approach to the preliminary data preparation related to the location of “Green Classrooms”. This approach considers the potential for rainwater retention. “Green Classrooms” are situated in the vicinity of existing primary schools. The optimal solution is a site visit and field measurements, which are time-consuming and costly. However, these are not necessary at the initial stage of the project. In order to determine the location of “Green Classrooms”, it is necessary to take into account the area of the school site, the area and location of the buildings, and due to the retention of rainwater, dense surfaces, i.e., car parks, recreational areas, etc. As a consequence of the ongoing climatic changes, periods of precipitation and dry weather are becoming increasingly frequent, including in Krakow. In light of the aforementioned considerations, the design assumptions necessitated the incorporation of optimal arrangements for rainwater management. It is, therefore, necessary to use tools and methods that allow automatic or semi-automatic analysis of data, facilitating the quick and easy selection of primary school areas, taking into account the selection criteria (architectural and hydrological).

2.1. Study Area

The study area is the area of Krakow (Figure 1) within the administrative boundaries of the city. Krakow is located in southern Poland, in the central-western part of the Malopolska Voivodeship, on the Vistula River. The area of the city is 326.85 km². The average annual daily temperature is 8.7 °C and the total annual precipitation is 671.5 mm [28].



Figure 1. Study area—the city of Krakow.

The city of Krakow has a diverse development structure. For the purposes of this article, it has been divided into main groups: inner-city areas characterised by a significant proportion of historic buildings, housing estates built on the basis of the defunct urban planning standard (the period from the end of the Second World War to the mid-1990s), characterised by a significant proportion of green areas between blocks of so-called “large slabs” and ensuring adequate access to basic services for residents, and housing estates built in the last 30 years. In recent years, investment pressure in Krakow has steadily increased. Development sites are primarily intended for multi-family housing. This leads to an increase in the intensity of development without providing these areas with additional functions, including educational facilities. The most difficult situation is in peripheral

areas where there has been no need for such facilities. Despite intensive investment in high-density housing estates, in most cases investors do not take into account the need for educational facilities. In the absence of appropriate legislation, ensuring access to educational facilities remains the responsibility of the city, which usually does not have the financial resources to achieve such goals.

2.2. Data

Any GIS software (including QGIS) allows a project to be created using different types of data, which can be linked and integrated through common features, e.g., geometry or attributes (descriptive information). Compatibility and accuracy of the data are ensured by working with the correct coordinate system and appropriate data sources. The most reliable and accurate data sources have been used in our project.

The research used very detailed data, as follows:

- primary school addresses in Krakow, provided by the Krakow Education Office in the form of a .csv database [29],
- cadastral parcels in Krakow, provided by the Municipal Spatial Information System (MSIP) in the form of vector data in .shp format [30],
- the Topographic Objects Database (BDOT10k) for Krakow Poviast, provided by National Geoportal as vector data in .shp format [31],
- OpenStreetMap—a publicly available spatial database [32],
- precipitation distribution for the area of Krakow, prepared by the Krakow WATER—Precipitation model [33],
- soil and agricultural maps by the Institute of Cultivation, Fertilisation and Soil Science State Research Institute (IUNG) in Puławy [34].

2.3. Methods

2.3.1. “Green Classroom”

The assumptions established in the “Green Classroom” project were employed to create a geometric arrangement of at least four basic modules (Figure 2). Modules A and B feature projections of rectangular trapezoids with dimensions of 125 cm, 250 cm, and 750 cm. They are mirror images of each other. The combination of two A modules or two B modules results in the formation of a rectangle with dimensions of 750 cm by 375 cm, which provides a usable area of 23.88 m². The base module C is a rectangle with dimensions of 750 cm × 250 cm, providing an area of 16.36 m². An additional element is module D, with dimensions of 250 cm × 375 cm and a usable space of 7.86 m². It is intended mainly for the construction of technical and sanitary rooms. The modules come in various spatial configurations. A total of 14 different spatial variants are available for the basic modules.

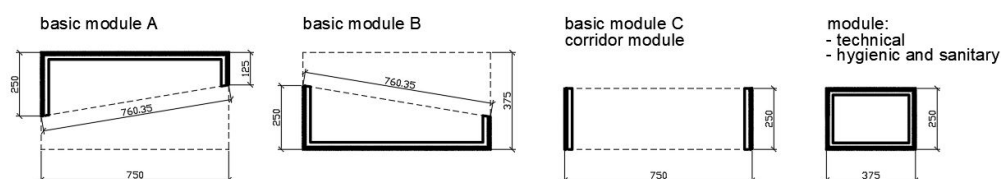


Figure 2. Top view of the basic modules (J. Dudek).

The combination of various modules allows for the creation of different configurations tailored to specific needs and user numbers (Figure 3). These modules consider the possibilities for spatial arrangements conducive to group work, discussions, presentations, and task solving on the board. It was assumed that the optimal area for each student is between 2 and 2.5 m² for classrooms. By combining four A or B modules, a space suitable for approximately 20–26 students was obtained. In accordance with the Regulation of the Minister of National Education of 17 March 2017, regarding the detailed organisation of public schools and kindergartens, the permissible number of students in grades 1–3 is

25, with the possible exception of allowing two additional students in special situations. Consequently, for classes 1–3, the resulting room met the minimum space requirements.

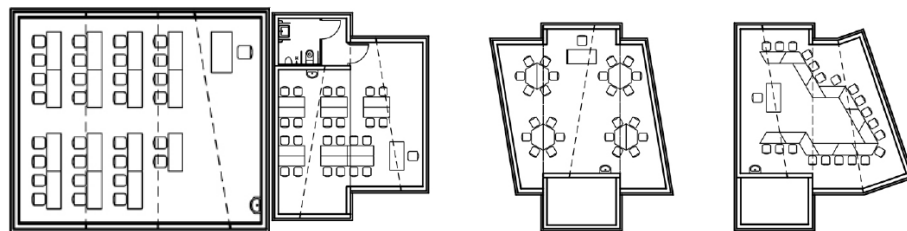


Figure 3. Examples of room arrangements for classrooms (J. Dudek).

2.3.2. The Analysis of Spatial Data

The data preparation, processing, and calculations were conducted utilising the publicly available QGIS3.30 software. QGIS is a user-friendly open-source geographic information system (GIS) licensed under the GNU General Public License. QGIS is an official project of the Open-Source Geospatial Foundation (OSGeo). It supports numerous vector, raster, text, and database formats and functions [35]. Such functionalities are plugins that automate the data processing. The main advantages of QGIS software are ease of use and free access to the software. QGIS is currently one of the most widely used GIS tools.

In order to prepare the data, the use of plugins was employed, as follows:

- **Geokodowanie Adresów UUG GUGiK**—The plugin Geocodes addresses for Poland in CSV file format. It uses UUG GUGiK web service (plugins.qgis.org/plugins/geokodowanie_adresow/, accessed on 18 January 2024). The locations of primary schools in Krakow were determined on the basis of primary school addresses obtained from the database of the Education Office in Krakow.
- **BDOT10k_GML_SHP**—This tool can be used to import BDOT10k shapefiles or GML files and adds them in the QGIS canvas. Also, layers can be symbolised to be similar to the topographic map in a 1:10,000 scale. (plugins.qgis.org/plugins/BDOT10k_GML_SHP_Loader, accessed on 18 January 2024).
- **Processing**—spatial data processing framework for QGIS.

The initial location of the “Green Classroom” has been divided into stages, with the first stage involving the analysis of spatial data. This entailed the selection of primary school areas in accordance with the established criteria, which involved six sequential steps, as follows:

1. To identify primary schools in the city of Krakow, address data provided by the Krakow Education Office [29] in the form of a .csv database (Figure 4) were used.

szkoly_kr2.csv

Pochodzenie pliku: 65001: Unicode (UTF-8) | Przekształć | Wykrywanie typu danych: Na podstawie pierwszych 200 wierszy...

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10	Column11	Column12
Typ	Nazwa	Województwo	Powiat	Gmina	Miejscowość	Rodzaj miejscowości	Ulica	Numer budynku	Numer lokalu	Pocztow.	Poczt.
Szkoła podstawowa	CHRYŚCIJAŃSKA SZKOŁA PODSTAWOWA Z ODDZIAŁ...	MAŁOPOLSKIE	Kraków	Kraków-Nowa Huta	Kraków-Nowa Huta	delegatura	os. Osiedle Unioce	14		31-954	Kraków
Szkoła podstawowa	DA VINCI PUBLICZNA SZKOŁA PODSTAWOWA W KRAKOWIE	MAŁOPOLSKIE	Kraków	Kraków-Nowa Huta	Kraków-Nowa Huta	delegatura	os. Osiedle Na Stoku	34		31-706	Kraków
Szkoła podstawowa	EDUKACJA SZKOŁA PODSTAWOWA DLA DOROSŁYCH...	MAŁOPOLSKIE	Kraków	Kraków-Śródmieście	Kraków-Śródmieście	delegatura	ul. Stawowska	1	5	31-014	Kraków
Szkoła podstawowa	FLAKA NR 1 SZKOŁY PODSTAWOWEJ SPECJALNEJ NR 6 W...	MAŁOPOLSKIE	Kraków	Kraków-Nowa Huta	Kraków-Nowa Huta	delegatura	os. Osiedle Delone	28		31-971	Kraków
Szkoła podstawowa	KATOLICKA SZKOŁA PODSTAWOWA IM. ŚWIĘTEJ JADW...	MAŁOPOLSKIE	Kraków	Kraków-Krowodrza	Kraków-Krowodrza	delegatura	ul. Władysława Łokietka	60		31-034	Kraków
Szkoła podstawowa	KATOLICKA SZKOŁA PODSTAWOWA IM. ŚWIĘTEJ RODZ...	MAŁOPOLSKIE	Kraków	Kraków-Śródmieście	Kraków-Śródmieście	delegatura	ul. Pętkowich	13		31-152	Kraków
Szkoła podstawowa	KATOLICKA SZKOŁA PODSTAWOWA MONTESSORI IM...	MAŁOPOLSKIE	Kraków	Kraków-Podgórze	Kraków-Podgórze	delegatura	ul. ks. Stefana Pawlickiego	1		30-320	Kraków
Szkoła podstawowa	KATOLICKA SZKOŁA PODSTAWOWA RUCHU ŚWIATŁO-Z...	MAŁOPOLSKIE	Kraków	Kraków-Nowa Huta	Kraków-Nowa Huta	delegatura	os. Osiedle Jagiellońskie	17		31-833	Kraków
Szkoła podstawowa	KOLEGIUM EUROPEJSKIE - EUROPEJSKA NIEPUBLICZNA...	MAŁOPOLSKIE	Kraków	Kraków-Podgórze	Kraków-Podgórze	delegatura	ul. Szuarska	9		30-710	Kraków
Szkoła podstawowa	MIEDZKULTUROWA SZKOŁA PODSTAWOWA "OTRĄB...	MAŁOPOLSKIE	Kraków	Kraków-Śródmieście	Kraków-Śródmieście	delegatura	ul. Karmelicka	45		31-128	Kraków
Szkoła podstawowa	NIEPUBLICZNA CHRYŚCIJAŃSKA SZKOŁA PODSTAWOW...	MAŁOPOLSKIE	Kraków	Kraków-Podgórze	Kraków-Podgórze	delegatura	ul. Zygmunta Miłkowskiego	9		30-349	Kraków
Szkoła podstawowa	NIEPUBLICZNA CHRYŚCIJAŃSKA SZKOŁA PODSTAWOW...	MAŁOPOLSKIE	Kraków	Kraków-Krowodrza	Kraków-Krowodrza	delegatura	ul. Armii Krajowej	4		30-150	Kraków
Szkoła podstawowa	NIEPUBLICZNA DWUJĘZYCZNA SZKOŁA PODSTAWOWA...	MAŁOPOLSKIE	Kraków	Kraków-Nowa Huta	Kraków-Nowa Huta	delegatura	ul. Longinusa Podbiegły	66		31-589	Kraków
Szkoła podstawowa	NIEPUBLICZNA INTEGRACYJNA SZKOŁA PODSTAWOWA...	MAŁOPOLSKIE	Kraków	Kraków-Krowodrza	Kraków-Krowodrza	delegatura	ul. Mydlnicka	5		30-120	Kraków
Szkoła podstawowa	NIEPUBLICZNA SPECJALNA SZKOŁA PODSTAWOWA "UL...	MAŁOPOLSKIE	Kraków	Kraków-Podgórze	Kraków-Podgórze	delegatura	ul. Wielicka	228		30-663	Kraków
Szkoła podstawowa	NIEPUBLICZNA SZKOŁA PODSTAWOWA "KAMIONOWA S...	MAŁOPOLSKIE	Kraków	Kraków-Krowodrza	Kraków-Krowodrza	delegatura	ul. Na Błonie	45		30-147	Kraków
Szkoła podstawowa	NIEPUBLICZNA SZKOŁA PODSTAWOWA "WOLNA SZKOŁ...	MAŁOPOLSKIE	Kraków	Kraków-Podgórze	Kraków-Podgórze	delegatura	ul. Zawila	4		30-423	Kraków
Szkoła podstawowa	NIEPUBLICZNA SZKOŁA PODSTAWOWA "WYOBRAZNIENIA"	MAŁOPOLSKIE	Kraków	Kraków-Nowa Huta	Kraków-Nowa Huta	delegatura	ul. bp. Piotra Tomickiego	22		31-982	Kraków
Szkoła podstawowa	NIEPUBLICZNA SZKOŁA PODSTAWOWA DLA DOROSŁYCH...	MAŁOPOLSKIE	Kraków	Kraków-Śródmieście	Kraków-Śródmieście	delegatura	ul. Andrzeja Sokółkowskiego	19		31-436	Kraków
Szkoła podstawowa	NIEPUBLICZNA SZKOŁA PODSTAWOWA DLA DOROSŁYCH...	MAŁOPOLSKIE	Kraków	Kraków-Podgórze	Kraków-Podgórze	delegatura	ul. Poczta	13		30-385	Kraków
Szkoła podstawowa	NIEPUBLICZNA SZKOŁA PODSTAWOWA EDUKACJI MAT...	MAŁOPOLSKIE	Kraków	Kraków-Nowa Huta	Kraków-Nowa Huta	delegatura	os. Osiedle Kolonowe	29		31-941	Kraków
Szkoła podstawowa	NIEPUBLICZNA SZKOŁA PODSTAWOWA WOSKOWE IM. MA...	MAŁOPOLSKIE	Kraków	Kraków-Podgórze	Kraków-Podgórze	delegatura	ul. Wileńska	57	LU 2	30-532	Kraków
Szkoła podstawowa	NIEPUBLICZNA SZKOŁA PODSTAWOWA KRAKOWSKIM WOLN...	MAŁOPOLSKIE	Kraków	Kraków-Podgórze	Kraków-Podgórze	delegatura	ul. Skońska	47		30-383	Kraków

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Figure 4. The database comprises a list of educational institutions and establishments in the Malopolska voivodeship of Poland. The data presented here are based on the Krakow Education Office report dated 30 September 2018 [29].

- Based on the acquired database, spatial data were generated in QGIS in the form of a point vector layer (Figure 5).

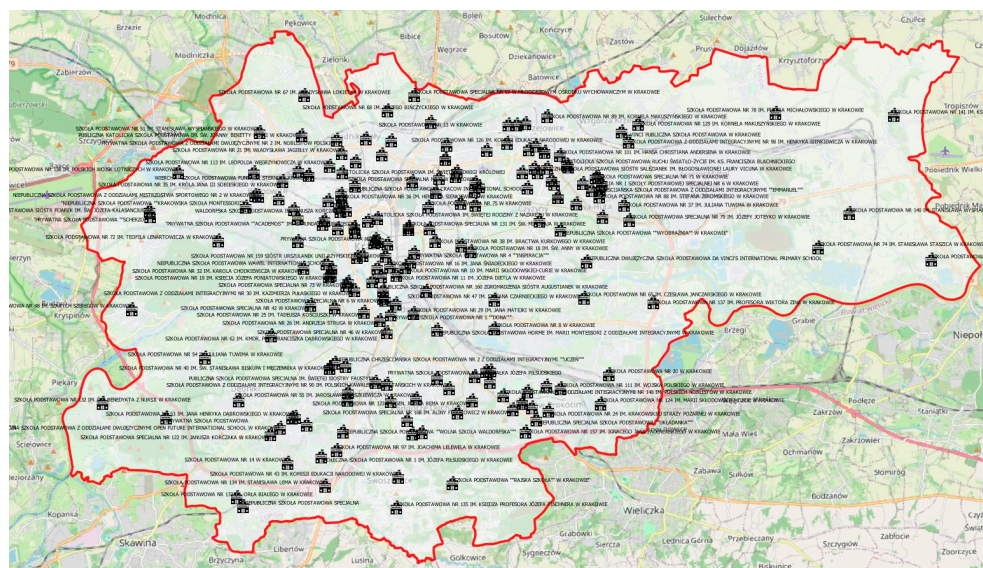


Figure 5. A map of the locations of primary schools in Krakow.

- The locations of the primary schools were assigned to record plots downloaded from MSIP—Municipal Spatial Information System (Figure 6).

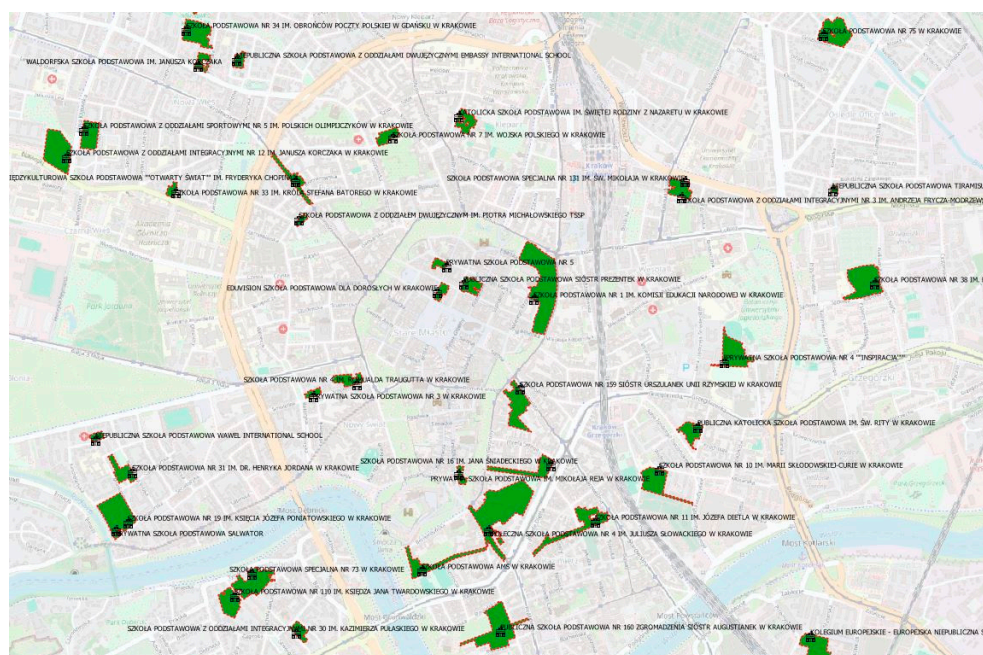


Figure 6. Record plots for school areas (areas in green).

- Layers were created with land cover and land use data that have the greatest impact on retention in school areas. The layers were created using data from the BDOTk10 and OpenStreetMap spatial databases. As a result of taking topology into account, layers were created containing the following areas: car park, sport/recreation areas, buildings, and school areas (Figure 7).

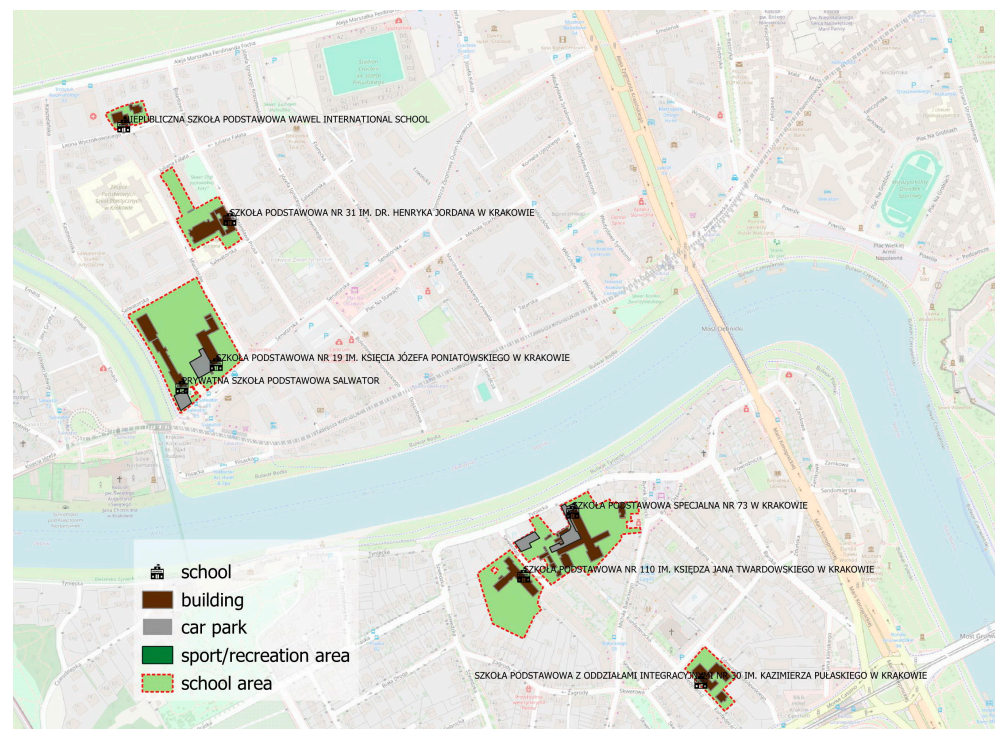


Figure 7. School area land cover and land use.

- Using the Processing plugin of the QGIS software, the potential areas for the location of “Green Classrooms” were determined (Figure 8), taking into account the optimal dimensions of the designed modular objects and the minimum distance from the plot boundary (4 m). The majority of regulations pertaining to the development of land properties in Poland originate from the provisions of the Construction Law and from local development plans, if any are in force in a given area.

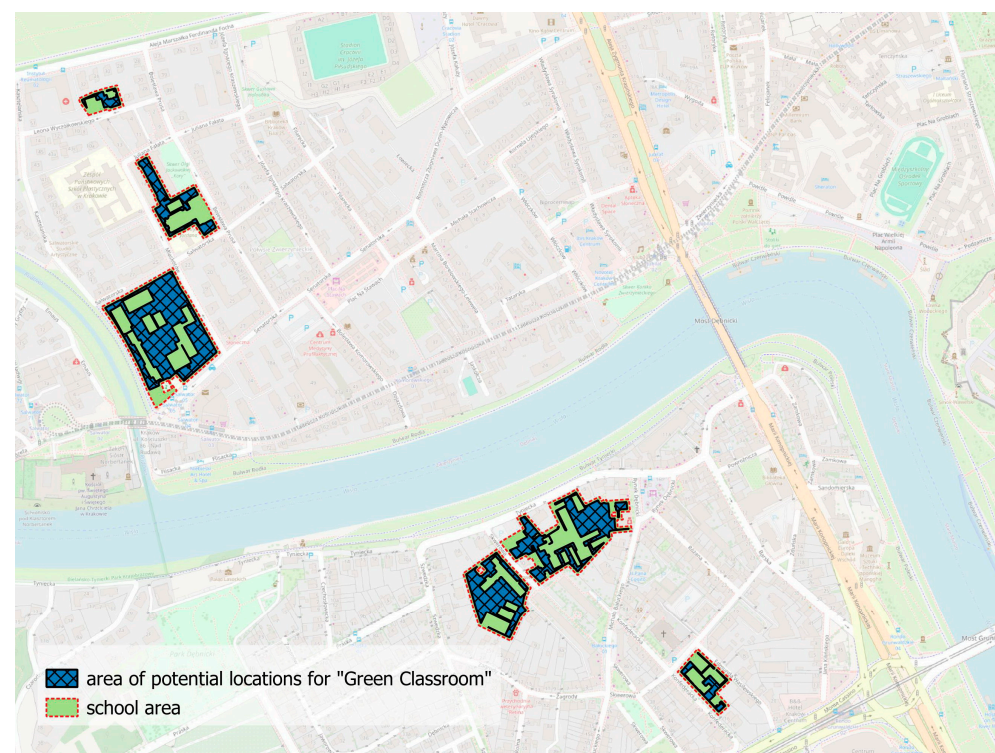


Figure 8. Potential “Green Classroom” location areas.

6. Based on the geometry of the assumed areas, the coordinates of the outer points of the area and the surfaces were determined in the attribute table of the QGIS software. The most optimal solution was a “Green Classroom” for approximately 31–39 students, with an area of 78.84 m² and dimensions of 750 cm × 1125 cm. In many cases, the potential site area is larger than the area of the “Green Classroom”, but the dimensions of the plot (length or width) are smaller than the dimensions of the class. In order to identify areas that meet both the area and dimension criteria, a test condition has been introduced. If the area is greater than the area of the “Green Classroom” (78.84 m²) and the CL index is greater than or equal to 7.5 m, the area is suitable for the location of the “Green Classroom” (Figure 9—area in blue). If the area is less than 78.84 m² or the CL index is less than 7.5 m, the area is excluded (Figure 9—area in red):

$$CL = \frac{area}{\max(dist_x, dist_y)} \quad (1)$$

where:

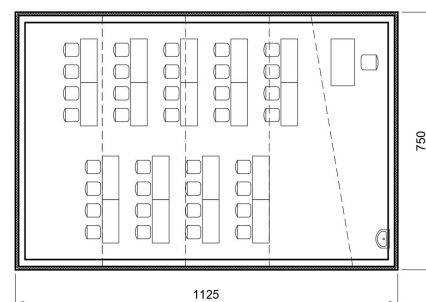
area—the area of a potential “Green Classroom” location:

$$dist_x = x_{max} - x_{min} \quad (2)$$

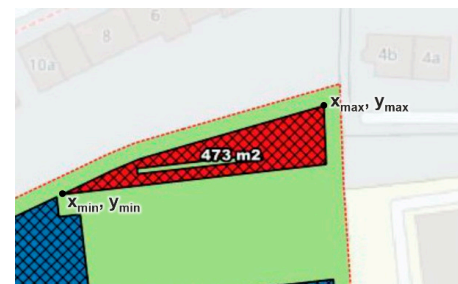
$$dist_y = y_{max} - y_{min} \quad (3)$$

x_{max} , x_{min} , y_{max} , and y_{min} —extreme coordinates of the area geometry (Figure 9b).

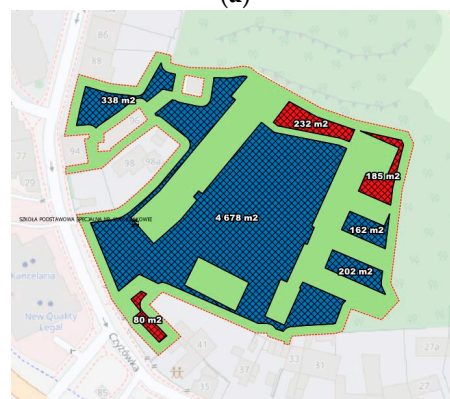
Class area: 78.84m²
(31–39 students)



(a)



(b)



(c)



(d)

Figure 9. Criteria for the location of “Green Classroom”: (a) dimensions of the adopted “Green Classroom” solution, (b) geometric coordinates of the area, and (c,d) example of the criteria used.

The second stage was to determine the stormwater volume outflowing from areas at the specified locations.

2.3.3. Hydrology

The determination of runoff volume from school areas consisted of determining the difference between the total surface runoff, calculated on the basis of the assumed design precipitation, and the retention resulting from the permeability of the soil and the type of land cover and land use. The volume of surface runoff (V) was determined according to the formula:

$$V = \sum_{i=1}^n P_{ef} \cdot A_i \quad (4)$$

where:

V —surface runoff volume (m^3),

P_{ef} —effective precipitation (mm),

A_i —area of specific land cover and land use (m^2).

The following precipitation distribution was assumed for the calculation: duration 15 min, probability of occurrence 20% (once in 5 years), typical for the study area (the city of Krakow) according to Krakow WATER (Figure 10).

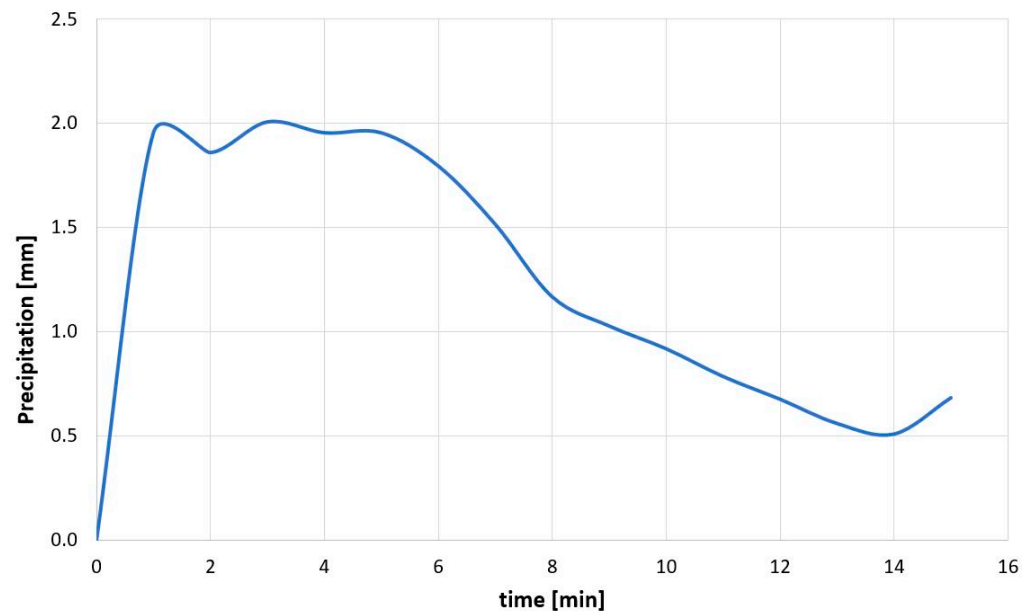


Figure 10. Typical 15 min precipitation distribution for the area of Krakow according to Krakow WATER.

The NRCS-CN method provides an example of the determination of effective precipitation due to the easy access to the necessary data for the city of Krakow and the simple and fast calculation method. The NRCS-CN [36] method of determining effective precipitation was used to determine the retention of areas of potential “Green Classroom” sites. The effective precipitation is calculated based on the relationship:

$$P_{ef} = \begin{cases} 0 & \text{if } P - 0.2 \cdot S \leq 0 \\ \frac{(P - 0.2 \cdot S)^2}{P + 0.8 \cdot S} & \text{if } P - 0.2 \cdot S \geq 0 \end{cases} \quad (5)$$

where:

P_{ef} —effective precipitation (mm),

P —accumulated precipitation depth (mm),

S —potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation (mm), calculated from the following relationship:

$$S = 25.4 \left(\frac{1000}{CN} - 10 \right) \quad (6)$$

The CN parameter was determined based on the soil group identified from the soil-agricultural map according to IUNG [34] (Figure 11) and the type of land cover and land use. Soils are classified into four HSG's (A, B, C, and D) according to their minimum infiltration rate, which is obtained for bare soil after prolonged wetting (Table 1) [37].

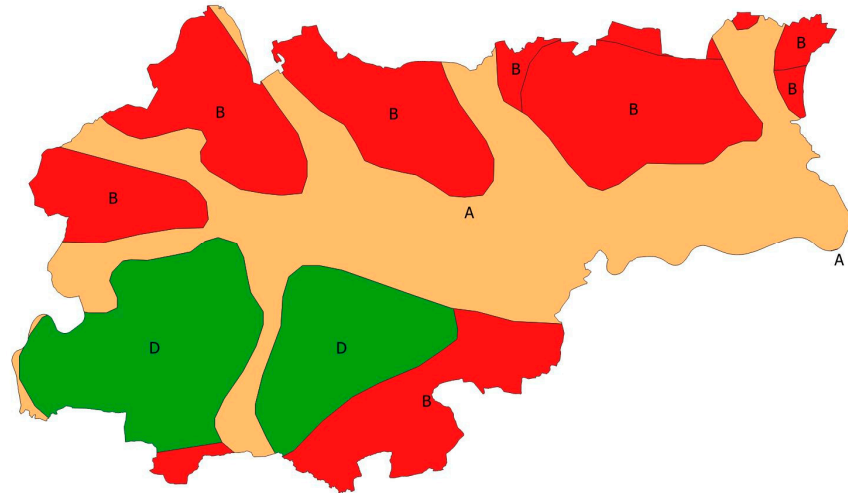


Figure 11. Soil groups of the Krakow area according to soil classes defined in the NRCS-CN method [36].

Table 1. Runoff curve numbers for urban areas [37].

Cover Description	Curve Numbers for Hydrologic Soil Groups			
	A	B	C	D
Cover type and hydrologic condition				
Good condition (grass cover > 75%)	39	61	74	80
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)	98	98	98	98

The stormwater volume from the school area was obtained as the final result.

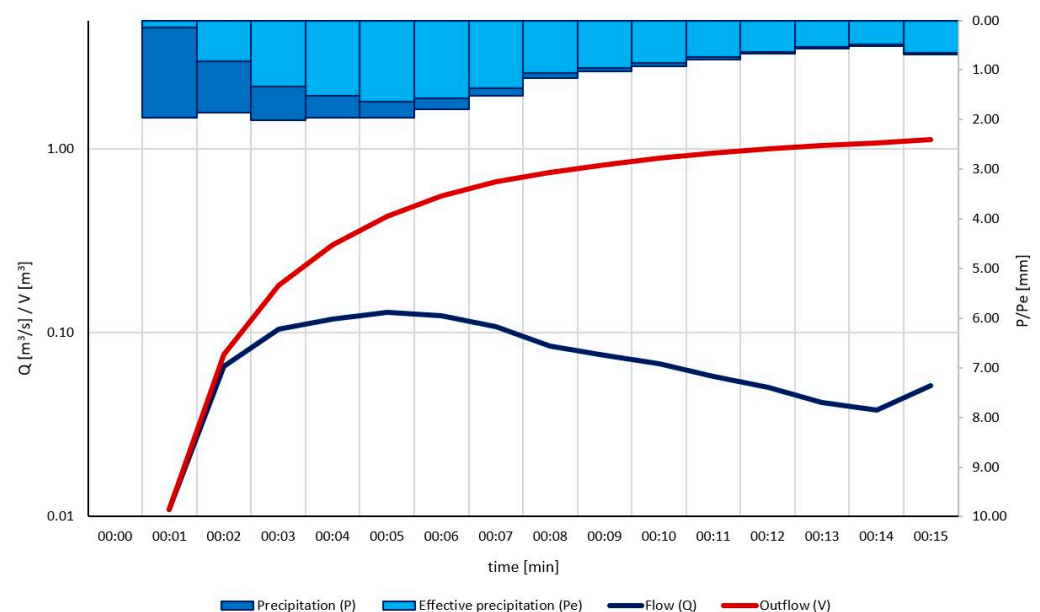
3. Results

A spatial analysis of 206 primary schools in the city of Krakow identified 190 areas of potential locations for “Green Classrooms” (Table 2). This was achieved by identifying plots on which land cover and land use areas were located (Figure 7). Subsequently, areas occupied by other objects on the plots were excluded, resulting in 279 potential locations for “Green Classroom” objects (Examples of locations in Figure 8). A total of 46 areas were rejected due to the minimum area and optimal module dimensions criteria, which consequently excluded five primary schools. It should be noted that the impact of the provisions of local spatial development plans, which could further limit the potential locations, was not included in the presented research. It is important to note that the parameters established in the Local Development Plans (MPZP) may be included at any stage of the analysis, which will narrow the implementation possibilities in individual locations and thus limit the size of the research sample.

Table 2. Summary of the results of spatial data analysis for primary schools in the city of Krakow.

Data Type	Number of Objects	Average Area (m ²)
Primary schools by address	206	-
Registered parcels allocated to addresses	190	14,596.9
Land cover and development:		
buildings	778	530.3
car parks	77	489.1
recreation and sports areas	268	610.0
Potential location of the “Green Classroom”:	279	
qualified areas	233	7743.5
excluded areas	46	
Primary schools:	190	
Qualified for the “Green Classroom” project	185	
Excluded from the “Green Classroom” project	5	

Stormwater runoff was calculated for all potential “Green Classroom” locations, taking into account land cover and land use. Figure 12 shows an example of a runoff hydrograph from the roof of a modular Green Classroom building with an area of 78.84 m². Precipitation is the typical distribution of 15 min precipitation for the area of the city of Krakow according to data made available by Krakow WATER, for which effective precipitation has been defined. Effective precipitation was used to determine flow from the roof of the “Green Classroom” building. Outflow is the sum of flow over time.

**Figure 12.** Example of stormwater runoff from the roof of a “Green Classroom” building.

The introduction of an additional impervious surface in a “Green Classroom” building resulted in an increase in runoff volume. Table 3 presents a summary of the average of stormwater runoff volume from school areas, including “Green Classroom” buildings, in relation to the school area.

Table 3. Summary of the average of stormwater runoff volume from the school area.

School Area (ha)	Number of Areas	Runoff Volume from the School Area (m ³)	Runoff Volume from the School Area with a “Green Classroom” Building (m ³)	Increasing the Runoff Volume from the School Area with a “Green Classroom” Building (m ³)
below 1	86	21.67	22.76	1.09
from 1 to 2	69	38.98	40.09	1.11
from 2 to 4	20	67.17	68.29	1.12
from 4 to 6	4	86.71	87.78	1.07
from 6 to 8	4	101.06	102.15	1.09

For a typical precipitation distribution, the implementation of the facilities in question resulted in an increase in stormwater runoff of approximately 1. It was suggested that the difference should be bridged by equipping the “Green Classroom” facilities with reservoirs of a minimum capacity of 1 m³ to collect stormwater from their roofs.

The Optimal Stormwater Storage Tank Selection

The main factor in determining the size and type of rainwater tanks in the Green Classroom project was the amount of water draining from the roof of the Green Classroom for the rainfall scenario adopted. The designed tanks are intended to retain water during rainfall and thus not increase the inflow of rainwater into the sewer system. A variety of impermeable surfaces are present on school grounds, including buildings and car parks. These surfaces impede the natural retention of stormwater, increasing the rate of runoff [38]. In the case of “Green Classroom” roofs, stormwater tanks have been proposed that collect precipitation and allow the collected water to be reused. On the one hand, they relieve the burden on the stormwater sewer system, and on the other hand, they have an impact on the ecological and economic aspect by allowing water to be used, among other things, during periods without precipitation. As the stormwater runoff volume from sealed areas (roofs of all buildings and car parks) constitutes practically the entire runoff (Table 4) from the school area, in addition to the retention of water from the roofs of “Green Classroom” buildings, an analysis was also conducted of the possibility of retaining stormwater from sealed areas. The efficiency and cost-effectiveness of different solutions depends primarily on the following:

- the design volume of the tank, which is related to the availability of a suitable site (area),
- the project budget,
- the type of tank: material and methods of operation (aboveground, underground, gravity or pumped discharge, rainwater treatment, and tank cleaning).

Table 4. Summary of the average stormwater runoff volume from sealed school areas.

School Area (ha)	Runoff Volume from the School Area (m ³)	The Stormwater Runoff Volume from the Roofs of Buildings and Car Parks in the Vicinity of the Educational Establishment (m ³)
below 0.1	4.21	4.02
from 0.1 do 0.5	17.23	16.31
from 0.5 do 1	27.81	25.40
from 1 do 1.5	32.45	29.88
from 1.5 do 2	53.91	49.51

The runoff volume is primarily dependent on the area and sealed surfaces. The assumed degree of runoff reduction determines the size of the stormwater reservoir. Consequently, a number of solution scenarios were developed, comprising reservoirs with

capacities ranging from 4 to 50 m³. For each reservoir, the degree of volume reduction was calculated. On this basis, the runoff volume was calculated for each of the adopted solutions. Figure 13 illustrates the relationship between the runoff volume and the school area when utilising distinct retention tank capacities. The selection of the reservoir size must consider the maximum runoff volume from sealed areas, the potential location (dependent on the type), and most importantly, economic considerations.

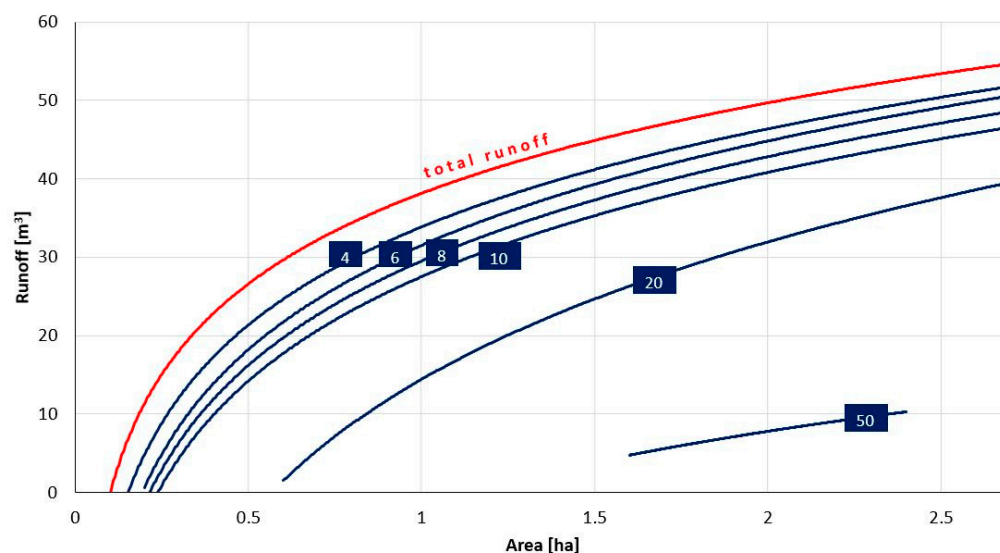


Figure 13. Dependence of the stormwater runoff volume on the surface of the school area with the use of retention reservoirs with capacities of 4, 6, 8, 10, 20, and 50 m³ (for the city of Krakow).

Nomograms have been drawn up for the city of Krakow based on local data (typical rainfall and hydrometeorological conditions, soil type, and land use and available areas for the potential location of “Green Classrooms”). This is not a universal solution—it can only serve as a pattern to develop similar solutions for other areas. The development of a nomogram (for the city of Krakow) for the degree of runoff volume reduction depending on the area (Figure 14) enabled the factors determining the size of the stormwater retention reservoir for primary school areas in the city of Krakow to be taken into account. This nomogram takes into account a typical 15 min precipitation distribution for the city of Krakow. Nomograms of a similar nature can be developed for different precipitation scenarios.

For smaller stormwater retention reservoir capacities, the use of aboveground, free-standing tanks located adjacent to the building was recommended. The typical capacity of such a tank is 1000 litres (1 cubic metre), which, for the adopted design assumptions, fully guarantees the retention of stormwater from the roof of a “Green Classroom”. This type of reservoir can also be used for the retention of stormwater from the roof surfaces of buildings in the primary school area by assuming the appropriate number of tanks (Figure 15). The extensive range of reservoir types and capacities enables the optimal solution to be tailored to specific requirements.

In order to retain a greater volume of stormwater, it is recommended that underground tanks be employed. These can be either standard solutions, such as plastic tanks, or can be designed according to individual requirements, such as concrete reservoirs (Figure 16).

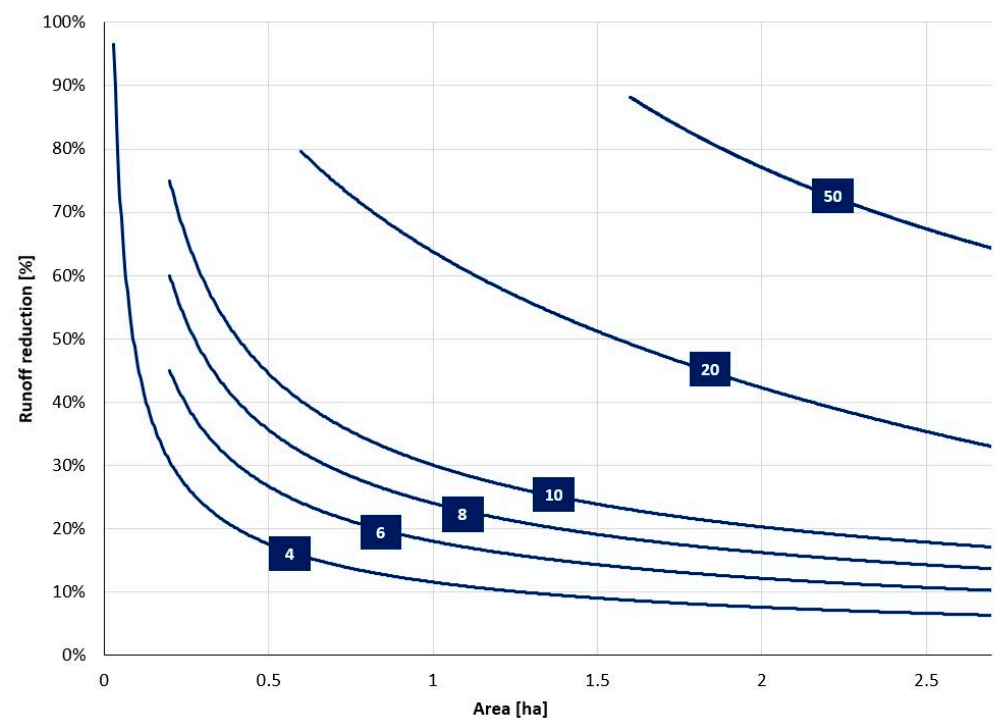


Figure 14. Nomogram for the city of Krakow for selection of the stormwater retention reservoir capacity.

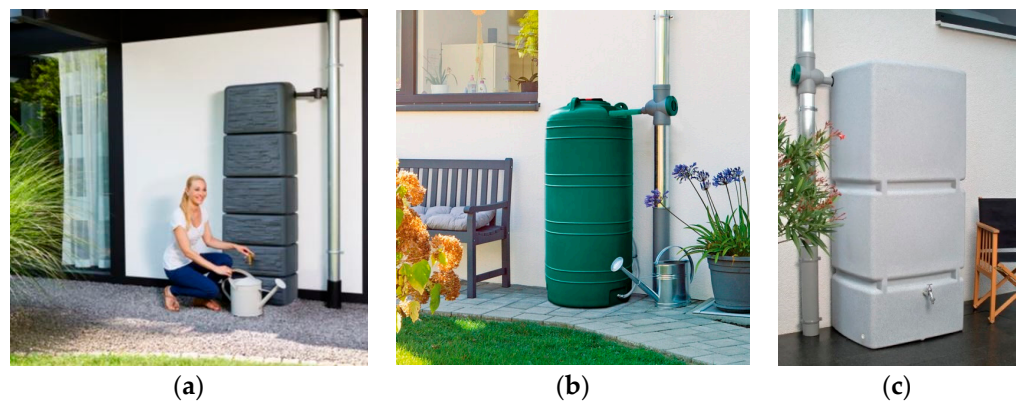


Figure 15. Examples of aboveground stormwater tanks: (a) Slim Stone tank manufactured by Ecodren, (b) VERDE tank manufactured by Impet, and (c) JUMBO tank manufactured by Hydromil.



Figure 16. Examples of underground stormwater tanks: (a) plastic tank, manufactured by WOBET HYDRET, and (b) concrete reservoir, manufactured by BE-TON TANKS.

4. Conclusions

The “Green Classrooms” project responds to the growing demand to improve the quality of educational space and increase school space by providing additional mobile classrooms. These can be used as classrooms or as multi-functional spaces, such as a library or a study or break area. The design is based on a modular system that can be easily adapted to the existing site conditions. A key element of the facilities is innovative ecological solutions, such as stormwater retention systems and renewable energy installations. The development of rapid, cost-effective, and energy-efficient solutions can provide an effective response to current and future emergencies, including the consequences of climate change. The financial report [39] prepared for the implementation of the “Green Classroom” project indicated that the modularity of solutions is an important element of the financial efficiency of the project. In order to achieve this, management methods, such as Agile Scrum, Lean Construction, and Activity-Based Costing, were proposed. These are particularly important in the implementation of modular construction projects due to their ability to streamline processes, increase cost and time efficiency, and enable flexibility in the event of changing requirements. The implementation of these methods enables construction companies to manage modular construction projects in a more effective manner.

Modular structures are designed to be more sustainable than traditional building methods [40]. The proposed modular system is more environmentally friendly and energy-efficient, which translates into long-term financial benefits. The use of advanced technologies and materials in such structures reduces energy consumption and carbon emissions. During the end-of-life phase, modular buildings can be dismantled and reused, while materials can be recycled, resulting in reduced environmental impact and promoting a more environmentally friendly approach to building design and management [41].

Furthermore, modular buildings frequently offer greater flexibility in terms of adaptation to changing educational needs. The ease with which existing modules can be extended or modified allows the school space to adapt to new curriculum requirements or increased student numbers [42]. The modular system design allows flexible adaptation to different urban conditions. Such a solution can also contribute to the revitalisation and renewal of urban areas through the use of unused land and spaces between buildings.

A method for the analysis of spatial data in the freely available QGIS software and basic hydrological calculations was developed. This method allows the adoption of potential locations and preliminary assumptions for the design of “Green Classroom” facilities. The use of a typical precipitation distribution enables the performance of rainfall–runoff transformation calculations that correspond to the actual hydrological conditions in a specific area.

The utilisation of stormwater tanks, which are readily accessible, straightforward to install (mobile), and which can be integrated into the existing infrastructure, enables the reduction of the stormwater runoff into the stormwater sewer system from school areas and the reduction of the associated costs. The retention of stormwater in the tanks allows it to be reused in periods without precipitation, which, in addition to ecological considerations, also has tangible financial benefits.

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