Amphibious Buildings as a Response to Increased Flood Risk
European Case Study

Piątek, Łukasz; Cin, Francesca Dal; Gireesh, Nanma

DOI
10.1007/978-981-97-0495-8_46

Publication date
2024

Document Version
Final published version

Published in
Proceedings of the Third World Conference on Floating Solutions

Amphibious Buildings as a Response to Increased Flood Risk—European Case Study

Łukasz Piątek, Francesca Dal Cin, and Nanma Gireesh

Abstract As reported in the most recent IPCC report (2022), the risk of flooding in Europe has increased over the last five decades, becoming the second largest cause of both economic and social losses caused by climate change-induced extreme events. Nowadays, the adaptation of vulnerable urban areas has become a priority objective in the political and legislative management of cities. Among the different architectural measures to adapt the city to the negative externalities caused by the rise in the mean sea level is the design of amphibious buildings (AB) to reduce the vulnerability of private space in the city. ABs are buildings composed of a structure that allows flotation while remaining anchored to the point of origin on land. During floods, the floating foundation of ABs allows it to rise from the ground and float on the surface of floodwater. Although several AB prototypes are nowadays built both in North America and Asia, only four projects have already been built in Europe. The aim of the article is to collect, catalog and describe the characteristics of ABs as a response to urban flood risk. Methodologically, the architectural qualities of ABs are researched by comparing, through a matrix, the four constructed European cases. Then, the architectural qualities are investigated in a SWOT matrix analysis. Indeed, through a review of the existing cases, with a focus on data related to the construction and implementation of ABs in the urban fabric, results are presented on the parameters of safety, purpose, aesthetics, technology, sustainability, utility, and cost-efficiency. We consider that through the orderly classification and cataloging

Ł. Piątek (✉)
Faculty of Architecture, Warsaw University of Technology, Ul. Koszykowa 55, 00-659 Warsaw, Poland
e-mail: lukasz.piatek@pw.edu.pl

F. D. Cin
Lisbon School of Architecture, CIAUD, Research Centre for Architecture, Urbanism and Design, Universidade de Lisboa, Rua Sá Nogueira, Polo Universitário do Alto da Ajuda, 1349-063 Lisboa, Portugal
e-mail: francescadalcin@fa.ulisboa.pt

N. Gireesh
Faculty of Architecture and the Built Environment, Delft University of Technology (TU Delft), Julianalaan 134, 2628 BL Delft, Netherlands
e-mail: n.gireesh@tudelft.nl

T. Ikoma et al. (eds.), *Proceedings of the Third World Conference on Floating Solutions*, Lecture Notes in Civil Engineering 465, https://doi.org/10.1007/978-981-97-0495-8_46

of the state of the art of built AB buildings, it is possible to define new paths for architectural and urban implementation in order to respond to the need for urban adaptation to extreme water events.

Keywords Amphibious building · Flood-resilient community · Flood-proof shelter · Flood adaptation · Flood impact mitigation

1 Introduction

Climate change and the resulting environmental and urban degradation are a contemporary challenge for cities [1]. Indeed, cities are of specific interest for their vulnerability to climate change because the largest share of the world population lives in urban areas, and many cities are located in areas that have a high exposure to climate hazards [2]. To achieve the UN 2030 Sustainable Development Goals, it is critical to improve the quality of human settlements [3]. Concerning the recurrent phenomenon of urban flooding, climate change research has been warning the fact that traditional flood management practices must be reassessed, namely if projected impacts are to be managed, such as the likely increased frequency and greater intensity of storms (precipitation and storm surges) together with a rise in sea level [4].

In urban spaces, impermeable surfaces cause changes in the water cycle, such as surface runoff accelerates, significantly increasing the peak and volume of flood waves [5]. For these reasons, adaptation to climate change must therefore be integrated into urban and regional planning through efficient infrastructures [1].

Based on this premise, how to resist these potential hazards is a hot topic in the field of urban planning. With the acceleration of urbanisation, resilience, as an important frontier theory in the field of public security, provides a systematic framework for solving urban security risks and enhancing urban disaster resistance. Therefore, enhancing urban resilience has become a key link to achieving sustainable development under increasing urban pressure, and resilience theory has been gradually applied in urban management [6].

Built-up city areas create unique microclimates because they have artificial surfaces instead of natural vegetation. This affects air temperature, wind direction, and precipitation patterns, among others. Climate change already affects all of these components to varying degrees. Heat, flooding, water scarcity, and droughts are the main climate threats relevant specifically to cities. Others can also be important for some cities, such as forest fires, damage from high wind speeds during intense storms, and the spread of pests and infectious diseases. They can have additional impacts on human health, well-being, and economies [7].

With the emergence and prominence of many urban problems, the main concern of urban resilience research is to improve the capacity of cities to cope with various natural disasters and socio-economic risks under the background of climate change, globalisation, and urbanisation [6]. Cities are also the centre of economic and political activity, and there is a growing resonance in considering city-level issues as a means to progress climate policy discussions [8]. NOAA and the IPCC estimate that floods will occur more frequently and flood depths are expected to increase.

Despite all climate change adaptation measures—including those planned—it will not be possible to prevent flooding and storm damage in cities, so innovative infrastructures and technical/structural solutions are needed to avoid or at least minimise casualties and damage during extreme events. There are a variety of potential solutions to urban flooding, including both structural and non-structural measures. Structural measures involve physical changes to the built environment, such as the construction of new drainage systems or the installation of green infrastructure [9]. Non-structural measures, on the other hand, focus on changing the way that cities are planned and managed, such as through improved zoning regulations or better public education campaigns [10].

Among the various strategies to reduce risk are land-use planning and preventive construction, which are considered an effective measure to reduce flood damage in existing settlements in floodplains. Nowadays, there are many solutions for flood-proof built environment that may be applied on different levels of planning and designing. On the level of individual buildings, which is relevant to the topic of this paper the following strategies are used: dry-proofing, wet-proofing, static elevation, floating, and amphibious construction [11].

In this paper, we focus on the least known and rarely implemented technique, namely, amphibious buildings (also called "can-float" or "semi-floating"). Even though the term "amphibious architecture" is being used in different meanings, often very widely to name all structures interfering with land and water, in this paper as "amphibious buildings" we define only structures that are permanently located on land and capable of floating (buoyant), although they are not floating unless there is a flood. During the flood, the watertight foundation of the building rises due to buoyancy force with the incoming water instead of being submerged and slides vertically upwards but does not drift with the current due to an anchoring system made of guiding posts (also called dolphin piles).

Although in technical solutions amphibious and floating buildings are similar or even identical, in this study, we exclude floating buildings as structures located on water lots and permanently floating. This implies also to floating buildings located in the water bodies that are usually aground due to low waters, like Mur Island [12].

Our paper aims at building a comprehensive descriptive multiple case study of all known amphibious buildings in Europe. Our hypothesis is that amphibious buildings may be a relevant and viable concept for Europe, although due to large differences in spatial and cultural context, European cases are likely to be different than American and Asian ones and so would be the conclusions on the possible implementation and upscaling of this concept. In the course of this research we aim at understanding what are the characteristics of amphibious buildings in Europe, what do they have in common, where and how are they used, and, most importantly, if they are successful. We assume that the findings can help in understanding why amphibious buildings are so uncommon in Europe and how to remedy that.

The shift from the paradigm of design, planning, and urban management to an approach that prioritises the human being and its relationship with the environment can be supported by the new emerging concepts of biophilic and green urbanism [13].

2 State of Knowledge

2.1 Urban Flooding in Europe

Around 70% of the European population resides in the territories along water bodies, be they rivers, lakes, or seas [14]. Flood risk in Europe, which has increased over the last five decades, is the second biggest cause of losses, both economic and social, caused by extreme events as reported by the IPCC (2022) [14].

Urban flooding is a phenomenon that occurs when an excessive amount of water overwhelms the drainage capacity of a city's infrastructure [10]. It can cause significant damage to both property and human life, and it has become an increasingly common problem in many parts of the world.

The urban system consists of many interdependent and interactive networks containing different physical and social elements. The vulnerability of cities exists everywhere, from infrastructure to transport, energy, and resource supply [6].

Urban flooding can be caused by a variety of factors, including heavy rainfall, inadequate drainage systems, and land-use changes. In particular, urbanisation and the associated expansion of impermeable surfaces such as roads and buildings have led to a significant increase in the severity and frequency of urban flooding [10]. As a result, many cities have been forced to invest in new infrastructure and urban planning strategies to reduce the risk of flooding.

The effects of urban flooding can be severe, ranging from property damage and loss of life to economic disruption and environmental degradation [15]. In addition to the direct costs of repairing flood damage, there are also indirect costs such as loss of productivity and increased insurance premiums. The most vulnerable populations are often the most affected by urban flooding, particularly those living in low-lying areas or in informal settlements [16].

2.2 Amphibious Building Concept

Amphibious building—built on the ground, rising due to floatation with increasing floodwaters and returning to its original position as the flood recedes—is a long-term smart solution that improves everyday well-being, saves lives and properties during the flood as well as facilitates quick post-disaster recovery [17]. According to studies, it has limitations like debris stuck under the building and large waves vulnerability [17] but they can be overcome by additional protection and suitable location. According to [18] amphibious buildings "may be used to create safe havens (…). It may also be used to protect a sensitive part of a larger building, such as the emergency dept. in a hospital, a communications centre, or a local electricity sub-station". The amphibious buildings are expected to be perfect flood shelters, emergency storages, and evacuation points and could play a crucial role in saving lives during the flood (especially flash flood) and directly after it and facilitate quick flood recovery.

The amphibious concept is not new. It has long been around in different vernacular forms around the world in places where communities have come up with local adaptation strategies to fluctuating water levels. Amphibious buildings have been built in the United States and Canada, and new projects are under development in France and Canada [19]. In vulnerable low-lying coastal areas of Asia (Vietnam, Thailand, Bangladesh, and Philippine) in recent years the amphibious concept has been getting more interest from governments, scientists, and communities. For example, in Vietnam, low-tech amphibious buildings built on empty oil tanks saved people living in rural areas during many floods since 2010 [20]. In Thailand, an amphibious building was completed and tested by Thailand's National Housing Authority in September 2013 [21]. Nevertheless, these structures are not common and not popular. Especially in Europe, according to available sources, there are only four locations where amphibious buildings were realised. Two of them are in the Netherlands: Marina Oolderhuuske in Roermond (1996), comprising 40 twin vacation amphibious houses [22], and Maasbommel neighbourhood with 32 houses [23]. Other places are Warsaw (Poland), where eight amphibious public pavilions were built along the Vistula River [11] and Marlow (UK) with one amphibious house [24].

3 Methods

In the article, we adopted the method of multiple case studies. We covered five cases in four locations, aiming at presenting the amphibious concept in different contexts and flood conditions, serving different functions, with different sizes and construction methods. We expected contrasting results of the performance of amphibious buildings in different conditions (theoretical replication case study design [25]. By the "case", we define the distinctive type of the building realised in many units in the location. The number of units constituting a single case varies from one (Marlow) to 32 (Maasbommel).

All cases were investigated and described on the basis of multiple sources: literature, personal communication with designers and users, field visits, and blueprint analysis.

4 Case Study

4.1 Gouden Kust Amphibious Houses, Maasbommel, Netherlands

In Europe, the Gouden Kust Quarter in Maasbommel, the Netherlands, is considered the oldest AB built, designed by Factor Architecten and Dura Vermeer, and located by the Maas River.

The neighbourhood is composed of two types of houses: 14 floating buildings located on the water and accessible from the floating jetty, and 32 amphibious houses placed on the slope of the shore, accessible from the road running between the dike and the river. This neighbourhood of vacation houses was built in 2005, thanks to an experimental Dutch project of adaptable construction.

All amphibious homes share the same basic construction method. A cuboid base made of 72 tonnes of waterproof reinforced concrete, which provides buoyancy during flood conditions, was produced on-site and placed by crane on the concrete foundation slab in a half-open pit dug in the sloping river bank. The bases are open from the top, accessible from the inside of the house and may be used as 1.5 m high storage. The 22-tonne timber frame built on it encompasses the 2- or 3-bedroom house. The bases are coupled in pairs with steel framing to improve stability and increase inertia and with terraces facing the water, which creates the confusing impression of twin houses. Steel dolphin piles hidden between each pair, necessary to secure them in place while floating, are not too visible. Despite minor differences in internal layouts, all houses have the same form with characteristic barrel roofs.

All houses have individual fenced lots with gardens and parking places, which makes them look similar to typical buildings when seen from the land. The slope of the shore was utilised to design a flush entry to the house from the rising terrain. Buoyant bases are visible only from the water.

In this location the risk of flooding is high and houses are anticipated to float once every five years. Water, gas, electrical, and sewage are connected using flexible pipes and do need special preparation despite the very high maximum rise of 5.5 m, but homes are not accessible during the flood [26, 27].

The first flood after construction happened in January 2011 [28] and the last was in July 2021 (according to a site visit and an interview with one of the owners also showed that his home was elevated by 0.8 m).

During the site visits in July 2016 and August 2022, most of the houses were closed confirming their recreational occasional use. According to research by Elizabeth Victoria Fenuta on Amphibious Architectures, they were offered for the equivalent of $420,000, which was a relatively high price [29, 30] (Figs. 1 and 2).

Fig. 1 Amphibious homes in Maasbommel in July 2016 seen from the jetty. Concrete buoyant base visible under the terrace (image taken by author)

Fig. 2 Amphibious homes in Maasbommel in July 2016 seen from the road. Steel dolphin pile visible between houses. Maas River in the back (image taken by author)

4.2 Amenity Building, Resort Marina Oolderhuuske, Roermond, Province Limburg, Netherlands

Marina Oolderhuuske is a holiday resort in Roermond, the Netherlands, located on a peninsula between the Maas River and the Maasplassen, a system of small and large lakes. The resort has 74 privately owned floating buildings that were built through 1993 using concrete buoyant foundation technology. These structures are always floating and will survive high-water levels as well.

The resort also contains three amenity buildings that serve as washrooms and toilets, and, interestingly, two among them are constructed as amphibious buildings using concrete buoyant foundation technology. The amenity structures, built between 2010 and 2015, are located approximately 35–40 m from the Maas riverbank (Fig. 3).

The concrete buoyant foundation of the amenity buildings, which is about 1.5 m high, is situated on the ground level. Two guidance posts are given per structure to ensure that these buildings remain in position.

Fig. 3 Amenity building with concrete buoyant foundation (*source* Resort Marina Oolderhuuske)

According to personal communication with resort personnel, it always floats during high waters, although it was mentioned that during the summer floods of 2021, the amenity buildings were trapped in the mud and failed to float.

4.3 Amphibious Chalet, Resort Marina Oolderhuuske, Roermond, Provincie Limburg, Netherlands

In Oolderhuuske, we also observed several wooden holiday cottages known as "chalets" or "vakantiehuisje" (vacation houses), which were once designed as mobile homes ("stacaravans") on wheels. According to an interview with a resort personnel, it was found that between the years of 2020 and 2022, a total of four chalets underwent retrofitting with aluminium buoyant foundations in order to make them capable of floating during periods of high-water levels. These chalets are one-story wooden structures designed to house a single family for recreational use. The original mobile buildings were placed on the aluminium pontoons of ca. 0.5 m height that rests on ground level and is attached to two guidance posts (steel pipes) per building. One of these chalets is around 10 m from the Maas riverbank, while the others are about 14 m (Figs. 4 and 5).

Overall, the Marina Oolderhuuske holiday resort has about 74 permanent floating buildings, and about 6 amphibious buildings including two amphibious amenity buildings, and four retrofitted chalets that use new buoyant foundations.

Fig. 4 Chalet originally built as a "stacaravan" in 2013 transformed into an amphibious building in 2022 using an aluminium buoyant foundation (images taken by author)

Fig. 5 Chalets with aluminium foundation during construction and afloat during floods (*source* Resort Marina Oolderhuuske)

4.4 Amphibious House by Baca, Marlow, England

A very characteristic amphibious building was built in Marlow, Buckinghamshire, England, on a small island on the Thames River. Despite the enchanted and peaceful surroundings—there is no vehicular access on the island and the south side of the plot faces the river—the site was challenging: the zoning restrictions of the conservation area and location in Flood Zone 3 were the main drivers for the idea of replacing the old single story house with new amphibious construction.

The client's request to design a three-bedroom, 225 m^2 house combined with the restriction of not exceeding the footprint and the height of the original 90 m^2 dwelling significantly, resulted in creating three-level-building with the lowest floor being a basement reaching 3 m below the terrain. This “basement” was designed as the buoyant waterproof concrete foundation for timber superstructure over it and was placed in the “wet dock” consisting of steel sheet piling walls, permeable concrete bottom slab, and reinforced concrete ring beam on the top. During the flood, the rising groundwater fills the dock and raises the floatable 220-tonne structure. The dock is large enough to allow walking around the base for inspection and repairs. The shape of the bottom allows for flushing the debris from underneath the base. When floating, the position of the house is kept by four 4 m-height dolphin piles made of steel I-beam profiles that were elegantly hidden in special niches on the longer sides of the house and a custom-made vertical sliding mechanism. Flexible insulated connections for water, electricity, sewage, and telephone can extend up to 3 m. Water is taken from the local borehole and wastewater is delivered from the house to the local treatment plant by the redundant system of two independent pumps. The house can raise up to 2.7 m which would happen in case of a 1/100 flood.

The buoyancy of the structure has been tested several times by pouring water into the dock. Two tests were done during the construction (for the first time to check the newly made floating base and for the second time to rebalance the whole house with upper frame and fit-out). During the building operation, the flotation is checked annually. Despite the relatively high construction cost induced by building a double foundation, the development turned out to be a great success. The architectural result, a modern minimalistic form of a simple pitched roof archetypal house combined with the innovative amphibious concept, was well received and the building gained a lot of attention [31] (Figs. 6 and 7).

4.5 Amphibious Pavilions, Warsaw, Poland

Boulevard Pavilions in Warsaw, Poland, are part of the joint winning entry by Architecture RSAK Architektura Krajobrazu in the competition for the revitalisation of the Vistula Boulevard organised by the municipality in 2009. Vistula River, semi-wild and partly channelised, is the largest Polish river. It is characterised by very high variability in water levels and poses a serious risk of both droughts and floods. This creates a challenge for all waterfront infrastructure.

The pavilions are located on the 2-km-long waterfront terrace, between Vistula River and a large 6-lines wide street. This terrace, reaching 4.5 m above the mean water level but still 3 m below the street level, lies in the area of flood risk 1–20, therefore using traditional fixed structures was not possible. At the beginning of the design process, the light modular buildings capable of being dismounted and raised by mobile cranes on the higher level in case of flood were planned. Since the necessary logistic and financial effort for such an operation carried out within 3 days of the flood warning was not feasible, the amphibious concept has been introduced and implemented instead.

Fig. 6 Amphibious home in Marlow (image by Baca Architects)

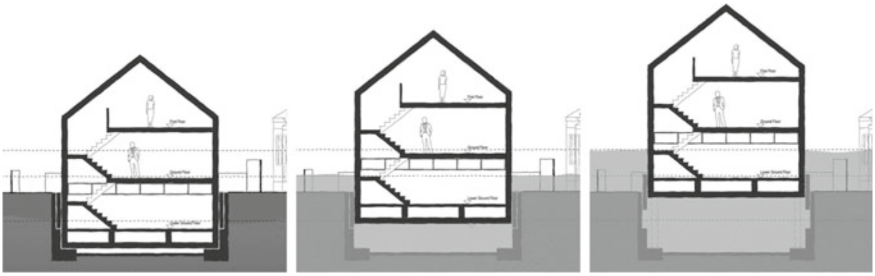

Fig. 7 Amphibious building in the wet dock in normal and flood conditions. House in Marlow (image by Baca Architects)

In 2017, eight prefabricated amphibious buildings were finished. According to the Polish building code they had to comply with, they are classified as temporary buildings due to no fixed connection to the ground.

All pavilions are made of modular units 2.5 × 7.0 m, consisting of a 0.7 m-high steel watertight pontoon and a 3 m-high steel container-like frame. The size of one building ranges from 7 to 15 modules joined together and placed on a concrete foundation slab. In floating conditions, the structure will be held by four corner clamps sliding along large dolphin piles (guiding posts) driven into the ground, capable of resisting the strong flood currents of Vistula.

Pavilions, with internal areas varying from 125 to 235 m^2, serve basic public functions like lavatories, tourist information, and restaurants. Designed as a part of a boulevard they blend into the surrounding with wooden shutters and dark-grey steel structure. Sandwich panels and glass are used for the walls and white fabric for the canopies.

Although the buildings are only one-story-height, the floating bases laid on the boulevard level make them relatively high and difficult to access—the floor is raised by 1.2 m over the surrounding terrain and for this reason, stairs and ramps had to be added, what made the bases even larger, especially on the quite narrow site ranging from 25 to 45 m between the river and the street.

Some preparations are necessary before flooding. The buildings must be closed and disconnected from utilities. According to construction documentation, when floating on the flood water, the movements of the pavilions must be monitored and special attention should be paid to removing debris from below the floats, to avoid skew settling or structural breakdown.

Since finishing the first pavilion in 2018, there has been no major flood in Warsaw. Therefore, the pavilions were never tested in floating mode—neither in the test in the construction phase nor in the real flood conditions (Figs. 8 and 9).

4.6 Case Comparison

The main features of investigated cases are compared in Table 1.

5 Results

5.1 Site Selection and Flood Risk Analysis

The amphibious buildings (AB) object of research are located on the banks of large rivers, in flood-prone areas. In the case of Maasbommel, where the development was part of an experimental programme, the idea of amphibious construction was prior

Fig. 8 Construction process on the amphibious pavilions in Warsaw in June 2017. Dolphin piles, concrete foundations, and steel pontoons are visible (image taken by author)

Fig. 9 The first pavilion finished in September 2016. Semi-wild Vistula River is visible in the back (image taken by author)

Table 1 Case comparison: the Houses, Maasbommel; the Amenity Building, Oolderhuuske; the Chalet, Oolderhuuske; the House, Marlow; the Public Pavilion, Warsaw

	Houses, Maasbommel	Amenity Building, Oolderhuuske	Chalet, Oolderhuuske	House, Marlow	Public Pavilion, Warsaw
	Bovendijk, 6627 KS Maasbommel, Netherlands	Oolderhuuske 1, 6041 TR Roermond, Netherlands	Oolderhuuske 1, 6041 TR Roermond, Netherlands	Marlow SL7 1QE, United Kingdom	G. S. Pattona, Warsaw, Poland
Year built	2006	2010–15	2020–22	2016	2016–17
Units built	32	2	4	1	8
Context	Rural	Rural	Rural	Rural	Urban
Max unit dimensions	12.0 × 7.0 m	13.0 × 9.0 m	10.0 × 4.0 m	12.0 × 8.0 m	61.0 × 7.4 m
Number of floors	2 + low basement	1	1	3	1
Function	Recreational	Service	Recreational	Residential	Public
Buoyancy system	Hull	Hull	Pontoons	Hull	Pontoons
Buoyant base construction material	Concrete	Concrete	Aluminium	Concrete	Steel
Static foundation	Concrete slab	–	None	Concrete slab on piles	Concrete slab
Visibility of the buoyant base	Half hidden in the slope	Visible	Visible	Hidden in the wet dock	Visible
Superstructure construction	Timber	–	–	Timber	Steel
Flood risk	1:5	–	–	1:33	1:20
Maximum rise	5.5 m	–	–	2.7 m	3.0 m
Large floods	2005 2021	2012	2012	–	Never

to selecting the site. In all other cases, the decision of using the amphibious concept was the result of a challenging location in a flood-prone area.

5.2 *Function, Standard, and Size*

Investigated buildings present high diversity in their functional features. Residential—permanent or recreational is the most common but not only use. Eight units from Warsaw provide a variety of functions themselves: from restaurants to the tourist information to restrooms they prove that amphibious buildings can fulfil many different needs. The cases also differ in standard significantly. From the European perspective, the example of Marlow is especially interesting, showing that the contemporary high-quality home can be built as an amphibious one without any concessions to living standards and modern aesthetics. No low-tech examples were found. All investigated buildings are also relatively small. Although the range of lengths goes from 10 m in Oolderhuuske to 61 m in Warsaw and the house from Marlow reaches 3 levels, amphibious buildings from the study in comparison to the average sample of building products in Europe are small structures.

5.3 Spatial Context and Architectural Form

All cases share the proximity of water, which strongly defines their spatial context. They were all designed to maximise views of the water. Nevertheless, buildings in Warsaw have typical urban surroundings while the others are set in rural areas and their diverse architectural forms and details reflect that. Investigated cases have flat or barrel or pitched roofs, are located along or perpendicular to the riverbanks, are finished in wood, steel, glass, or plaster, and are painted in various colours. In the study, no single architectural type can be exclusively assigned to amphibious construction. What differs in these cases is the architectural approach to the necessary elements of amphibious technology. In some of them, like in Maasbommel and Marlow special attention was given to hide the floating base, to provide a comfortable access from the site level to the ground floor, and to hide the guiding posts. This cannot be said about Warsaw and Oolderhuuske, where visible floating bases were laid on the terrain and the dolphin piles were exposed with negative effects on comfort and aesthetics.

5.4 Technology (Structural Design, Materials, and Utilities)

Two types of buoyant bases were found: systems similar to the ship hull, where the floating part is open at the top and can be used for living or storage, and modularised pontoons, closed compartments inaccessible from inside of the building. In all cases, the hulls were made of reinforced concrete while the pontoons were metal (aluminium or steel). The bases were resting the concrete foundations in all cases except for chalets in Oolderhuuske and three different methods of placing the base were presented: hiding in the wet dock (Marlow), half-hiding in the pit excavated in the sloping riverbank (Maasbommel) and setting on the flat terrain (Warsaw and Oolderhuuske). All buildings were kept in place by two or four steel guiding points. Superstructures were built in skeleton technique (timber or steel) to reduce weight. In all cases, the utilities were connected with flexible and insulated pipes, which sometimes (like in Marlow and Maasbommel) can also work in floating mode.

5.5 Maintenance and Flood Performance

All examined buildings have been in operation for at least six years, which is long enough to assess their long-time performance. Despite the simplicity of the amphibious concept, it adds some new problems in operation. As reported by designers, owners, or personnel, amphibious buildings require additional maintenance compared to traditional ones. The main problem is the conservation of mechanical elements like guiding posts with brackets and flexible connections. In the case of steel pontoons, additional corrosion prevention is needed. These costs are considered to be worth paying to survive the flood, although this very important issue cannot be resolved here easily. Some investigated cases, like Marlow or Maasbommel, prove to work well. The former was even tested for floating twice during the construction and it has to be repeated annually. Baca's house can be then treated as an example of a very successful implementation of the amphibious concept. On the other hand in Warsaw, which is a very interesting case of a large-scale use of the amphibious solution, a major flood has not occurred yet and these 8 pavilions have never been really tested. Oolderhuuske is the most complicated case. On one hand, the owner of the recreational settlement decided to refurbish four cottages into amphibious homes after years of having two amphibious amenity buildings, which suggests that the concept proved to be successful. On the other hand, in 2021 one amenity building failed to float during a large flood, probably due to suction force between the terrain surface and the bottom of the float, which could undermine the reliability of the amphibious idea. This issue should be investigated in detail to ensure the smooth working of the system in all conditions. In addition to maintenance issues and the process of river flood, in all cases, the problem of debris prevention and removal was mentioned.

5.6 SWOT Analysis

The comparison of investigated European cases of amphibious buildings allows for drawing some conclusions on the potential of the amphibious technology. This problem can be described using the structure of SWOT analysis, what was shown in Table 2.

6 Discussion

In the paper, we covered several cases in different locations, using the multiple case study research design. But at the same time, we included all European cases reported in the literature; therefore, this study could be also understood as the single case study

Table 2 SWOT analysis: the Houses, Maasbommel; the Amenity Building, Oolderhuuske; the Chalet, Oolderhuuske; the House, Marlow; the Public Pavilion, Warsaw

Strengths • Highly flood-proof (dry-proof—no flood water inside) • Originality • No limitations in location (compared to floating buildings) • Shore locations possible • Revitalising capacity	*Weaknesses* • Higher construction and maintenance costs compared to regular building induced by atypical elements (flotation, connections, anchoring, debris control) • Limitations regarding shape and size • Hampered access when flotation is not lowered into the wet dock • Elements of amphibious technology are difficult to hide • No tradition, limited confidence in amphibious
Opportunities • Increasing flood risk induced by climate change • Increasing risk awareness in the societies in EU • New water policies (designing with water) • Limited buildable area in developed countries • Growth in water sport and tourism business	*Threats* • Problematic legal conditions—lack of necessary regulations or the risk of legal changes increases insurance and mortgage costs • The limited number of professionals (designers, contractors) familiar with amphibious concept

of all amphibious buildings in Europe. Nevertheless, our main focus was defined as understanding the variety of amphibious solutions that are relevant to the European context.

These cases were investigated with care for acquiring vast and various data using different methods based on diverse sources. Even though it was not possible to use the same set of research tools for all buildings. Therefore, our study needs to be treated as an exploratory descriptive analysis of European amphibious buildings rather than as a representative qualitative study.

7 Conclusions

Successful flood risk management needs integrating adaptation and mitigation strategies. Amphibious construction is one of many innovative and affordable approaches applicable to individual buildings. In the study, we analysed and compared five examples of amphibious buildings in four locations in three European countries. We aimed at finding and investigating all amphibious structures in Europe and as of May 2023, no more amphibious buildings were reported in literature.

The following conclusions may be based on this study:

- Amphibious concept does not impact the architectural appearance of buildings to the extent larger than any other construction technology. If implemented with necessary concern about the architectural form of the building and its functionality and with an adequate budget, the most characteristic elements of amphibious construction—large buoyant base and high guiding posts can be successfully integrated within the whole.
- European amphibious buildings are similar to their land-based European counterparts. The large diversity of design concepts may prove that amphibious construction is very flexible and can be adopted in different spatial and cultural contexts. Functions, standards, and budgets are also very different between the simplest and the most sophisticated examples. Permanent resident use is still rare, although there is no doubt that amphibious buildings can be used for year-long occupation.
- European amphibious buildings are relatively small and this is no different from the cases outside Europe. The main reason for this is that they are almost everywhere perceived as pilot projects that test the amphibious concept and are associated with higher risk than ordinary buildings.
- Amphibious concept is technically feasible and well proven—everywhere where floods have already occurred, the structures floated as expected, except for one single incident in Oolderhuuske, which needs to be investigated further but does not question the idea of amphibious architecture.

The last issue to be addressed is the low popularity of amphibious buildings in Europe despite their ingenuity and robustness. Despite the extreme interest of the media, the amphibious concept has not been scaled up. In our view, there are several reasons for this problem. Firstly, what was already mentioned, they are usually considered as a curiosity, a single experiment rather than a future way of building with water. Secondly, the dissemination of knowledge on amphibious architecture is very poor. For instance, the municipality of Warsaw and the designers of its eight amphibious pavilions were not aware of other amphibious buildings in the world and "invented" the idea independently. Lastly, higher construction and maintenance costs are another obstacle. This limits the number of new builds and slows the dissemination process. We assume that this situation will be changing in favour of amphibious construction as more projects are being finished and popularised and as the awareness of flood risks is rising in societies and policymakers.

Acknowledgements We would like to thank Baca Architects, Architecture sp. z o.o. and Resort Marina Oolderhuuske for help with the preparation of this article.

References

1. Santos MM, Lanzinha JCG, Ferreira AV (2021) Review on urbanism and climate change. Cities 114:103176. ISSN: 0264-2751. https://doi.org/10.1016/j.cities.2021.103176
2. Voskamp IM, de Luca C, Polo-Ballinas MB, Hulsman H, Brolsma R (2021) Nature-based solutions tools for planning urban climate adaptation: state of the art. Sustainability 13:6381. https://doi.org/10.3390/su13116381
3. Hamdi R, Kusaka H, Doan QV et al (2020) The state-of-the-art of urban climate change modeling and observations. Earth Syst Environ 4:631–646. https://doi.org/10.1007/s41748-020-00193-3
4. Matos Silva M, Costa JP (2018) Urban floods and climate change adaptation: the potential of public space design when accommodating natural processes. Water 10:180. https://doi.org/10.3390/w10020180
5. Ciupa T, Suligowski R (2020) Impact of the city on the rapid increase in the runoff and transport of suspended and dissolved solids during rainfall—the example of the Silnica River (Kielce, Poland). Water 12:2693. https://doi.org/10.3390/w12102693
6. Kong L, Mu X, Hu G et al (2022) The application of resilience theory in urban development: a literature review. Environ Sci Pollut Res 29:49651–49671. https://doi.org/10.1007/s11356-022-20891-x
7. European Environment Agency EEA (2016) Reported flood phenomena per country. EEA, Copenhagen, Denmark. Available online: https://www.eea.europa.eu/data-and-maps/figures/reported-flood-phenomena-per-country. Accessed 15 July 2020
8. Hunt A, Watkiss P (2011) Climate change impacts and adaptation in cities: a review of the literature. Clim Change 104:13–49. https://doi.org/10.1007/s10584-010-9975-6
9. Guo J, Li Y, Yang Y, Liu J (2021) Green infrastructure planning for urban flood management: a review of current practices and future prospects. J Clean Prod 279:123732
10. Ashley R, Ashley WS, Ashley ST (2016) Urban flooding: sources and solutions. Cambridge University Press
11. Piątek Ł, Wojnowska-Heciak M (2020) Multicase study comparison of different types of flood-resilient buildings (elevated, amphibious, and floating) at the Vistula River in Warsaw, Poland. Sustainability 12(22):9725. https://doi.org/10.3390/su12229725
12. Acconci V (2003) Building an island. Vito Acconci, Acconci Studio Mur Island, Graz, Austria, Osfildern-Ruit, New York
13. Santos MM, Lanzinha JCG, Vaz Ferreira A (2021) A review on urbanism and climate change. Cities 114:103176. https://doi.org/10.1016/j.cities.2021.103176
14. IPCC (2022) In: Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Climate change 2022: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844
15. Rijnaarts HH, Zevenbergen, C (2017) Urban flood management. In: Handbook of climate change resilience. Springer, pp 1–17
16. UN-Habitat (2016) Water and sanitation in the world's cities: local action for global goals. Routledge
17. Barsley E, Royal Institute of British Architects (2020) Wydawca. Retrofitting for flood resilience: a guide to building & community design. RIBA, London (Print)
18. Barker R, Coutts R (2015) Aquatecture: buildings and cities designed to live and work with water. RIBA Publishing, London, UK
19. Nguyen TTT (2021) Promoting sustainability and resilience in Vietnam's floating community: the assessment of innovative housing units and materials for adaptation to climate change. Doctoral thesis. https://doi.org/10.26127/BTUOpen-5455

20. English E, Klink N, Turner S (2016) Thriving with water: developments in amphibious architecture in North America. E3S Web Conf 7:13009. https://doi.org/10.1051/e3sconf/20160713009
21. Tang A (2015) Thailand tests floating homes in region grappling with floods. Thomson Reuters Foundation. https://news.trust.org/item/20150305000156-r6las/?source=fiOtherNews2. Accessed 25 July 2021
22. https://www.buoyantfoundation.org/oolderhuuske. Accessed 30 Oct 2022
23. Nillesen AL, Flüggen G, Singelenberg J (2011) Waterwonen in Nederland: Architectuur En Stedenbouw Op Het Water (Amphibious housing in Netherlands: architecture and urbanism on the water). NAi Uitg, Rotterdam
24. https://www.baca.uk.com/amphibioushouse.html. Accessed 30 Oct 2022
25. Groat LN, Wang D (2013) Architectural research methods. Wiley, Wielka Brytania
26. Nillesen AL, Flüggen G, Singelenberg J (2011) Waterwonen in Nederland architectuur en Stedenbouw op het water (Amphibious housing in the Netherlands. Architecture and urbanism on the water). Rotterdam NAi
27. Hiltrud Pötz in collaboration with Tatjana Anholts, Martijn de Koning, Multi level safety. Water-resilient urban and building design, Amersfoort 2014 STOWA
28. https://www.stowa.nl/publicaties/meerlaagsveiligheid-waterrobuust-bouwen-stedelijk-gebied-nl-en-english-version
29. https://climate-adapt.eea.europa.eu/en/metadata/case-studies/amphibious-housing-in-maasbommel-the-netherlands/11310092.pdf
30. Fenuta EV (2010) Amphibious architectures: the Buoyant Foundation Project in post-Katrina New Orleans. University of Waterloo, Ontario, Canada
31. https://climate-adapt.eea.europa.eu/en/metadata/case-studies/amphibious-housing-in-maasbommel-the-netherlands