



DOCTORAL SCHOOL
DISCIPLINE OF ARCHITECTURE AND URBAN PLANNING

DOCTORAL DISSERTATION

**Hydro-Adaptive Architecture for Flood-Prone Waterfronts:
Typological Performance, Spatial Co-Benefits, and Planning
Integration**

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I would like to express my sincere gratitude
to all those whose guidance, support, encouragement
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The Author

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- Paper 1 - *Walkability and flood resilience: Public space design in climate-sensitive urban environments.*
<https://doi.org/10.17645/up.9561>
- Paper 2 - *Floating and amphibious architecture in waterfront built environments: A systematic review of climate adaptation and regenerative potential.*
<https://doi.org/10.3390/su18125966>
- Paper 3 - *Hydro-adaptive housing for flood-resilient planning: Elevated, amphibious and floating solutions.*
<https://doi.org/10.3390/buildings16101880>
- Paper 4 - *A laboratory for adaptation of urban areas to climate change: Flooding resilience and climate-sensitive waterfronts.*
<https://doi.org/10.5281/zenodo.14711488>
- Paper 5 - *Zero-Emissions, Off-grid, Autonomous Houseboat: A Case Study of Selected Locations in Europe.*
<https://doi.org/10.2478/pomr-2024-0035>
- Paper 6 - *Revolutionizing flood resilience: Human-centred AI for adaptive and regenerative urban design.*
<https://doi.org/10.1016/j.landusepol.2026.108218>

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Co-authors contribution statements

I. Abstract

Flood risk has become an important condition of contemporary waterfront development, particularly in lowland riverine and coastal environments where urban growth, climate change, hydrological variability, and redevelopment pressures increasingly intersect. In such contexts, conventional land-based approaches to urban development face growing challenges associated with recurrent and prolonged water exposure. Hydro-adaptive architecture, comprising elevated foundations, amphibious architecture, and floating architecture, has emerged as a promising means of accommodating changing water conditions. However, existing knowledge remains fragmented across architectural, engineering, environmental, infrastructural, and governance-related fields, limiting the development of integrated planning-oriented approaches for the comparative assessment and locally appropriate application of hydro-adaptive typologies across different waterfront contexts.

The aim of this dissertation is to investigate how waterfront cities can reconcile flood adaptation with sustainable urban development through the application of hydro-adaptive architecture across multiple scales of intervention. The research adopts a sequential, cross-scale, and multi-method framework integrating systematic knowledge synthesis, spatial analysis, hydraulic modelling, research-by-design, technical assessment, and governance analysis.

The dissertation is based on six peer-reviewed publications that provide complementary evidence concerning different dimensions of the research problem. **Publication P1** examines the relationship between flood adaptation, walkability, and public-space structure across nine Baltic Sea Region waterfront cities. The study demonstrates that flood-adaptive waterfront interventions, including hydro-adaptive structures and blue-green infrastructure, can generate measurable spatial co-benefits related to pedestrian connectivity, public-space continuity, route choice, and land-water accessibility. **Publication P2** synthesises the international state of knowledge through a PRISMA-guided systematic review of floating and amphibious architecture. It establishes the evidence base for the dissertation and identifies the principal research needs concerning comparative typological assessment, infrastructural and operational requirements, transferability, and governance-supported implementation. **Publication P3** develops and tests a comparative planning-oriented framework for assessing elevated, amphibious, and floating housing typologies under differentiated flood scenarios in three contrasting Lower Vistula case studies. The results demonstrate that the suitability of hydro-adaptive solutions depends on the interaction between flood conditions, site characteristics, adaptive mechanisms, infrastructural requirements, and planning constraints. **Publication P4** applies research-by-design and cross-contextual case-study analysis to examine the transferability of hydro-adaptive principles across contrasting European waterfront environments. The study provides design-based evidence concerning their cross-contextual interpretation and transferability while highlighting the importance of local spatial, cultural, and environmental conditions. **Publication P5** investigates the feasibility of an autonomous and zero-emission floating dwelling through integrated architectural, structural, technical, and infrastructural analyses. It demonstrates how hull configuration, spatial organisation, energy generation and storage, water management, wastewater treatment, and climatic conditions influence the operational autonomy of floating habitation. **Publication P6** examines Human-Centred Artificial Intelligence (HCAI) as a form of human-centred digital decision support embedded within broader flood-resilient governance and planning systems. The study shows that the planning relevance of digital and AI-enabled tools depends on institutional coordination, stakeholder participation, regulatory integration, transparency, accountability, and their connection with land-use and spatial-planning processes.

The findings confirm that hydro-adaptive architecture constitutes a coherent yet differentiated category of adaptive solutions. Elevated foundations, amphibious architecture, and floating architecture share the objective of maintaining habitation and functional continuity under changing water conditions, while differing in their adaptive mechanisms, infrastructural requirements, spatial implications, and conditions of applicability. The research further demonstrates that the planning relevance of hydro-adaptive

architecture depends on the integration of building-level flood adaptation with public-space continuity, walkability, land–water accessibility, blue-green infrastructure integration, operational autonomy, and governance-supported decision-making.

The principal scientific contribution of the dissertation is the development of an integrated architectural and planning framework for the early-stage comparative assessment and selection of hydro-adaptive typologies in flood-prone waterfront environments. The framework connects flood hazard, architectural typology, spatial quality, infrastructural operability, environmental conditions, and governance requirements while recognising that typological applicability remains conditional on local hydrological, spatial, and institutional conditions. More broadly, the dissertation contributes to a relational and multi-scalar understanding of hydro-adaptive architecture and to the transition from resistance-based flood management towards designing and planning with water. It demonstrates how architecture can mediate relationships between changing water conditions, built form, public space, and long-term habitation in water-sensitive territories.

Keywords: hydro-adaptive architecture; flood adaptation; waterfront development; floating architecture; amphibious architecture; elevated foundations; climate resilience; spatial co-benefits; walkability; blue-green infrastructure; Human-Centred Artificial Intelligence (HCAI); governance.

II. Streszczenie

Ryzyko powodziowe stało się istotnym uwarunkowaniem współczesnego rozwoju obszarów nadwodnych, szczególnie na nizinnych terenach rzecznych i przybrzeżnych, gdzie coraz silniej nakładają się na siebie procesy urbanizacji, zmiany klimatu, zmienność warunków hydrologicznych oraz presja związana z przekształceniami i ponownym zagospodarowaniem terenów. W takich uwarunkowaniach konwencjonalne, oparte na trwałym związku zabudowy z gruntem modele rozwoju miejskiego napotykają rosnące ograniczenia wynikające z okresowego, powtarzalnego lub długotrwałego oddziaływania wody. Architektura hydroadaptacyjna, obejmująca zabudowę wyniesioną, architekturę amfibijną i architekturę pływającą, stanowi obiecujący sposób dostosowania środowiska zbudowanego do zmieniających się warunków wodnych. Dotychczasowa wiedza pozostaje jednak rozproszona pomiędzy badaniami architektonicznymi, inżynierskimi, środowiskowymi, infrastrukturalnymi i dotyczącymi zarządzania, co ogranicza rozwój zintegrowanych podejść planistycznych umożliwiających porównawczą ocenę oraz dobór typologii hydroadaptacyjnych odpowiednich do lokalnych uwarunkowań różnych obszarów nadwodnych.

Celem rozprawy jest zbadanie, w jaki sposób miasta nadwodne mogą łączyć adaptację do zagrożenia powodziowego ze zrównoważonym rozwojem miejskim poprzez zastosowanie architektury hydroadaptacyjnej na różnych skalach interwencji. Badania wykorzystują sekwencyjne, wieloskalowe i wielometodowe podejście, integrujące systematyczną syntezę wiedzy, analizy przestrzenne, modelowanie hydrauliczne, metodę research-by-design, ocenę techniczną oraz analizę uwarunkowań zarządzania i wdrażania.

Podstawę rozprawy stanowi sześć recenzowanych publikacji naukowych, dostarczających komplementarnych dowodów dotyczących różnych wymiarów badanego problemu. **Publikacja P1** analizuje zależności pomiędzy adaptacją do zagrożenia powodziowego, *walkability* (przestrzenną zdolnością środowiska miejskiego do wspierania ruchu pieszego, dostępności i ciągłości tras) oraz strukturą przestrzeni publicznych w dziewięciu miastach nadwodnych Regionu Morza Bałtyckiego. Badanie wykazuje, że adaptacyjne przekształcenia terenów nadwodnych, obejmujące również struktury hydroadaptacyjne i błękitno-zieloną infrastrukturę, mogą generować mierzalne współkorzyści przestrzenne związane z poprawą spójności sieci pieszej, ciągłości przestrzeni publicznych, zwiększeniem możliwości wyboru tras oraz dostępnością na styku lądu i wody. **Publikacja P2** syntetyzuje międzynarodowy stan wiedzy poprzez systematyczny przegląd literatury dotyczącej architektury pływającej i amfibijnej, przeprowadzony zgodnie z wytycznymi PRISMA. Publikacja tworzy podstawę dowodową dla rozprawy oraz identyfikuje główne potrzeby badawcze dotyczące porównawczej oceny typologii, wymagań infrastrukturalnych, transferowalności rozwiązań oraz uwarunkowań ich wdrażania wspieranych przez systemy zarządzania. **Publikacja P3** rozwija i testuje porównawcze, ukierunkowane planistycznie ramy oceny zabudowy wyniesionej, architektury amfibijnej i architektury pływającej w zróżnicowanych scenariuszach powodziowych, wykorzystując trzy kontrastowe studia przypadku zlokalizowane w dolnym biegu Wisły. Wyniki wskazują, że przydatność poszczególnych rozwiązań hydroadaptacyjnych zależy od wzajemnego oddziaływania warunków powodziowych, charakterystyki lokalizacji, mechanizmów adaptacyjnych, wymagań infrastrukturalnych oraz ograniczeń planistycznych. **Publikacja P4** wykorzystuje metodę research-by-design oraz porównawczą analizę studiów przypadku w celu zbadania transferowalności zasad architektury hydroadaptacyjnej pomiędzy zróżnicowanymi europejskimi obszarami nadwodnymi. Badanie dostarcza eksploracyjnych, projektowych dowodów dotyczących możliwości interpretowania i adaptowania tych zasad w odmiennych kontekstach przestrzennych, a jednocześnie wskazuje znaczenie lokalnych uwarunkowań przestrzennych, kulturowych i środowiskowych. **Publikacja P5** bada wykonalność autonomicznego, zeroemisyjnego budynku mieszkalnego na wodzie poprzez zintegrowane analizy architektoniczne, konstrukcyjne, techniczne i infrastrukturalne. Wyniki pokazują, w jaki sposób konfiguracja kadłuba, organizacja przestrzenna, produkcja i magazynowanie energii, gospodarka wodna, oczyszczanie ścieków oraz warunki klimatyczne wpływają na autonomię

operacyjną architektury pływającej. **Publikacja P6** analizuje *Human-Centred Artificial Intelligence* (HCAI) jako formę cyfrowego wspomaganie decyzji zorientowanego na człowieka, osadzoną w szerszych systemach zarządzania i planowania odpornego na zagrożenie powodziowe. Badanie wykazuje, że znaczenie planistyczne narzędzi cyfrowych i wykorzystujących sztuczną inteligencję zależy od koordynacji instytucjonalnej, udziału interesariuszy, integracji regulacyjnej, przejrzystości, odpowiedzialności oraz ich powiązania z procesami planowania przestrzennego i polityką użytkowania terenu.

Wyniki badań potwierdzają, że architektura hydroadaptacyjna stanowi spójną, lecz wewnętrznie zróżnicowaną kategorię rozwiązań adaptacyjnych. Zabudowa wyniesiona, architektura amfibijna i architektura pływająca mają wspólny cel, którym jest utrzymanie możliwości zamieszkania oraz ciągłości funkcjonalnej w warunkach zmieniającego się poziomu wody, różnią się jednak mechanizmami adaptacji, wymaganiami infrastrukturalnymi, konsekwencjami przestrzennymi oraz warunkami zastosowania. Badania wykazują również, że znaczenie planistyczne architektury hydroadaptacyjnej zależy od integracji adaptacji budynków do zagrożenia powodziowego z ciągłością przestrzeni publicznych, dostępnością na styku lądu i wody, błękitno-zieloną infrastrukturą, zdolnością systemów infrastrukturalnych do zapewnienia ciągłości funkcjonowania oraz procesami decyzyjnymi wspieranymi przez odpowiednie mechanizmy zarządzania.

Głównym wkładem naukowym rozprawy jest opracowanie zintegrowanych architektonicznych i planistycznych ram wspomaganie decyzji, przeznaczonych do wstępnej, porównawczej oceny oraz doboru typologii hydroadaptacyjnych w obszarach nadwodnych zagrożonych powodzią. Ramy te łączą zagrożenie powodziowe, typologię architektoniczną, jakość przestrzenną, uwarunkowania infrastrukturalne, warunki środowiskowe oraz wymagania związane z zarządzaniem i wdrażaniem, przy jednoczesnym uwzględnieniu, że przydatność poszczególnych typologii pozostaje zależna od lokalnych uwarunkowań hydrologicznych, przestrzennych, technicznych i instytucjonalnych. W szerszym ujęciu rozprawa wnosi wkład w relacyjne i wieloskalowe rozumienie architektury hydroadaptacyjnej oraz wspiera przejście od podejścia opartego przede wszystkim na przeciwstawianiu się wodzie i ochronie przed nią w kierunku projektowania i planowania z wodą. Badania wskazują, że architektura może pełnić rolę mediatora pomiędzy zmieniającymi się warunkami wodnymi, formą zabudowy, przestrzenią publiczną, infrastrukturą oraz długoterminową możliwością zamieszkania i użytkowania obszarów wrażliwych na zmiany warunków wodnych.

Słowa kluczowe: architektura hydroadaptacyjna; adaptacja do zagrożenia powodziowego; rozwój obszarów nadwodnych; architektura pływająca; architektura amfibijna; zabudowa wyniesiona; odporność na zagrożenie powodziowe; współkorzyści przestrzenne; *walkability*; błękitno-zielona infrastruktura; *Human-Centred Artificial Intelligence* (HCAI); zarządzanie.

III. List of publications comprising the dissertation (dissertation-level analytical order)

The following six publications constitute the core scientific achievement of this publication-based dissertation and are referred to throughout the text as P1–P6.

ID	Short title	Authors, article title, and DOI	Journal details	Year	Ministerial points
P1	Walkability and flood resilience	Gorzka, J., Burda, I. M., & Nyka, L. Walkability and flood resilience: Public space design in climate-sensitive urban environments. https://doi.org/10.17645/up.9561	<i>Urban Planning</i> , 10, Article 9561	2025	70
P2	Systematic review	Gorzka, J., Burda, I. M., & Nyka, L. Floating and amphibious architecture in waterfront built environments: A systematic review of climate adaptation and regenerative potential. https://doi.org/10.3390/su18125966	<i>Sustainability</i> , 18(12), 5966	2026	100
P3	Hydro-adaptive typologies	Gorzka, J., Burda, I. M., & Nyka, L. Hydro-adaptive housing for flood-resilient planning: Elevated, amphibious and floating solutions. https://doi.org/10.3390/buildings16101880	<i>Buildings</i> , 16(10), 1880	2026	70
P4	Hydro-adaptive research-by-design laboratory	Gorzka, J., & Nyka, L. A laboratory for adaptation of urban areas to climate change: Flooding resilience and climate-sensitive waterfronts. https://doi.org/10.5281/zenodo.14711488	<i>World Transactions on Engineering and Technology Education</i> , 22(4), 261–266	2024	70
P5	Off-grid autonomous houseboat	Gorzka, J., Karczewski, A., Litwin, W., Matej-Lukowicz, K., Nawrot, N., Nyka, L., & Piątek, Ł. Zero-Emissions, Off-grid, Autonomous Houseboat: A Case Study of Selected Locations in Europe. https://doi.org/10.2478/pomr-2024-0035	<i>Polish Maritime Research</i> , 31(3), 42–60	2024	100
P6	Governance-supported hydro-adaptive implementation	Gorzka, J., Burda, I. M., Józekowski, J., & Nyka, L. Revolutionizing flood resilience: Human-centred AI for adaptive and regenerative urban design. https://doi.org/10.1016/j.landusepol.2026.108218	<i>Land Use Policy</i> , Article 108218	2026	140
Total number of ministerial points:					550

IV. Points value and Impact Factor

Publication venues, Polish ministerial point values, and journal bibliometric indicators for Publications P1–P6.

Publication	Journal	Ministerial points	JIF 2024	5-Year JIF 2024	JCR quartile 2024	CiteScore 2024 / Scopus quartile	Main subject category
P1	Urban Planning	70	1.7	2.2	Q3	3.8 / Q1	Urban Studies
P2	Sustainability	100	3.3	3.6	Q2	7.7 / Q1	Environmental Studies; Geography, Planning and Development
P3	Buildings	70	3.1	3.2	Q2	4.4 / Q1	Construction & Building Technology; Architecture
P4	World Transactions on Engineering and Technology Education	70	—	—	—	2.1 / Q3	Engineering; Engineering Education
P5	Polish Maritime Research	100	2.0	1.6	Q2	4.0 / Q2	Engineering, Marine; Ocean Engineering
P6	Land Use Policy	140	5.9	6.9	Q1	14.5 / Q1	Environmental Studies; Geography, Planning and Development
Total ministerial points:		550					

Note: Journal Impact Factor (JIF), 5-Year Journal Impact Factor, JCR quartiles, and CiteScore values refer to the 2024 metric year. Where journals are assigned to multiple subject categories, the category most relevant to the architectural, urban-planning, or methodological scope of the corresponding publication is reported. World Transactions on Engineering and Technology Education does not have a Journal Citation Reports Impact Factor; its Scopus CiteScore and quartile are therefore reported as the principal bibliometric indicators.

Source: Author's elaboration based on the Polish ministerial journal point values, Journal Citation Reports (Clarivate), Scopus CiteScore metrics, and journal/publisher data.

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Publication-specific information

No.	Publication	Publisher	Copyright, open-access status and licence
P1	Gorzka, J., Burda, I., and Nyka, L. (2025). Walkability and Flood Resilience: Public Space Design in Climate-Sensitive Urban Environments. <i>Urban Planning</i> , 10, Article 9561. https://doi.org/10.17645/up.9561	Cogitatio Press	© 2025 Jakub Gorzka, Izabela Burda and Lucyna Nyka. Published by Cogitatio Press. This open-access article is distributed under the Creative Commons Attribution 4.0 International licence (CC BY 4.0).
P2	Gorzka, J., Burda, I. M., and Nyka, L. (2026). Floating and Amphibious Architecture in Waterfront Built Environments: A Systematic Review of Climate Adaptation and Regenerative Potential. <i>Sustainability</i> , 18(12), 5966. https://doi.org/10.3390/su18125966	MDPI, Basel, Switzerland	© 2026 by the authors. Licensee MDPI, Basel, Switzerland. This open-access article is distributed under the Creative Commons Attribution 4.0 International licence (CC BY 4.0).
P3	Gorzka, J., Burda, I., and Nyka, L. (2026). Hydro-Adaptive Housing for Flood-Resilient Planning: Elevated, Amphibious and Floating Solutions. <i>Buildings</i> , 16(10), 1880. https://doi.org/10.3390/buildings16101880	MDPI, Basel, Switzerland	© 2026 by the authors. Licensee MDPI, Basel, Switzerland. This open-access article is distributed under the Creative Commons Attribution 4.0 International licence (CC BY 4.0).
P4	Gorzka, J., and Nyka, L. (2024). A Laboratory for Adaptation of Urban Areas to Climate Change: Flooding Resilience and Climate-Sensitive Waterfronts. <i>World Transactions on Engineering and Technology Education</i> , 22(4), 261–266. https://doi.org/10.5281/zenodo.14711488	World Institute for Engineering and Technology Education (WIETE)	© 2024 Jakub Gorzka and Lucyna Nyka. Published in World Transactions on Engineering and Technology Education by the World Institute for Engineering and Technology Education. The open-access version deposited in Zenodo is distributed under the Creative Commons Attribution 4.0 International licence (CC BY 4.0).
P5	Gorzka, J., Karczewski, A., Litwin, W., Matej-Lukowicz, K., Nawrot, N., Nyka, L., and Piątek, Ł. (2024). Zero-Emissions, Off-grid, Autonomous Houseboat – a Case Study of Selected Locations in Europe. <i>Polish Maritime Research</i> , 31(3). https://doi.org/10.2478/pomr-2024-0035	Sciendo, a De Gruyter Brill company; <i>Polish Maritime Research</i>	© 2024 The Authors. Published in Polish Maritime Research by Sciendo, a De Gruyter Brill company. This is an open-access article distributed under the Creative Commons Attribution 4.0 International licence (CC BY 4.0).
P6	Gorzka, J., Burda, I., Józekowski, J., and Nyka, L. (2026). Revolutionizing Flood Resilience: Human-Centred AI for Adaptive and Regenerative Urban Design. <i>Land Use Policy</i> , 170, Article 108218. https://doi.org/10.1016/j.landusepol.2026.108218	Elsevier Ltd	© 2026 The Authors. Published by Elsevier Ltd. This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International licence (CC BY 4.0).

VI. Glossary of key terms and abbreviations

The following glossary defines the principal terms, abbreviations, and other designations used throughout the dissertation. The definitions reflect their specific analytical and operational meaning within the present research and are intended to ensure terminological consistency across its architectural, spatial, hydraulic, technical, infrastructural, and governance-related components.

<i>Amphibious architecture (AM)</i>	Hydro-adaptive buildings (structures) that normally rest on or close to the ground and become buoyant during a flood, moving vertically with changing water levels along a guidance system. Amphibious architecture therefore operate in two states: grounded under normal conditions and buoyant during inundation.
<i>Blue-green infrastructure (BGI)</i>	An integrated set of water- and vegetation-based spatial measures supporting flood adaptation, water retention, environmental performance, and public-space quality. In this dissertation, BGI includes measures such as bioretention, blue-green corridors, and other retention-oriented interventions that may complement hydro-adaptive architecture.
<i>Building Damage Index (BDI)</i>	A relative indicator analysed in P3 to compare potential component damage to different hydro-adaptive typologies under modelled flood conditions. Within the dissertation, BDI supports comparative assessment and early-stage screening and is not interpreted as a detailed economic-loss model.
<i>Context-sensitive applicability</i>	The principle that the suitability of a hydro-adaptive typology cannot be determined from its technical characteristics alone but depends on the interaction between flood regime, adaptive mechanism, site morphology, spatial organisation, accessibility, infrastructure, environmental conditions, regulatory requirements, institutional capacity, and the intended form of occupation.
<i>Elevated foundations (EF)</i>	A hydro-adaptive strategy based on maintaining a fixed vertical separation between the occupied parts of a building and the design flood level through piles, stilts, raised ground, or comparable elevation systems. Unlike amphibious and floating solutions, the building does not become buoyant during flooding.
<i>Floating architecture (FA)</i>	Hydro-adaptive structures that remain continuously buoyant and accommodate changing water levels through appropriate mooring or guidance arrangements. Their applicability depends not only on buoyancy and stability but also on water conditions, access, servicing, infrastructure, regulation, and maintenance.
<i>Flood resilience</i>	The capacity of the built environment and associated spatial, infrastructural, and institutional systems to accommodate flood conditions while maintaining or recovering essential functions. In this dissertation, resilience is understood more broadly than flood protection alone and includes adaptation, accommodation, functional continuity, and spatial transformation.
<i>Governance-supported implementation</i>	The process through which adaptive spatial and architectural solutions are translated into planning practice through institutional coordination, regulatory pathways, stakeholder participation, infrastructure responsibilities, land-use integration, and transparent decision-support processes.

<i>Human-Centred Artificial Intelligence (HCAI)</i>	An approach to AI-enabled decision support in which computational capabilities are combined with meaningful human control, safety, reliability, trust, responsibility, transparency, interpretability, participation, and institutional accountability. In this dissertation, HCAI is examined as a governance-oriented component of flood-resilient planning rather than as an autonomous technological solution.
<i>Hydro-adaptive architecture</i>	A category of architectural responses that accommodate changing water conditions by modifying the relationship between built form, ground, and water. In this dissertation, the category comprises elevated foundations, amphibious, and floating architecture, which share an adaptive objective but differ in their operating mechanisms, spatial implications, infrastructural requirements, and conditions of applicability.
<i>Hydro-adaptive typology</i>	One of the differentiated architectural strategies included within hydro-adaptive architecture and characterised by a distinct mechanism of responding to changing water conditions. The dissertation comparatively examines three principal typologies: elevated foundations, amphibious, and floating architecture.
<i>Infrastructural autonomy</i>	The capacity of a building (structure) to operate with reduced dependence on conventional fixed utility networks through decentralised, flexible, or self-contained systems for energy, freshwater, wastewater, waste management, and other essential services. Its feasibility depends on local infrastructure, occupancy, service requirements, maintenance, environmental conditions, and regulatory constraints.
<i>Integrated planning framework (planning-support framework)</i>	The dissertation-level framework developed to support the early-stage, context-sensitive assessment and comparison of hydro-adaptive typologies. It links flood hazard, architectural typology, spatial quality, infrastructural operability, environmental conditions, and governance requirements. Its purpose is to organise evidence, compare alternatives, exclude contextually unsuitable options, identify potentially appropriate typologies, and indicate the further analyses required before implementation. It does not replace detailed hydraulic, geotechnical, structural, environmental, infrastructural, or statutory assessment.
<i>Land–water accessibility</i>	The degree to which the spatial and pedestrian structure of a waterfront provides direct and continuous connections between land-based public space and the water edge or water-based spaces. In the dissertation, it constitutes one of the spatial dimensions used to assess the wider co-benefits of flood-adaptive waterfront interventions.
<i>Operability</i>	The capacity of a building or hydro-adaptive solution to remain functionally usable under the analysed flood conditions. Operability extends beyond limiting physical damage and includes the maintenance of appropriate stability, safe access, essential services, and intended use.
<i>Operational autonomy</i>	The capacity of a building, particularly a floating dwelling, to maintain its intended operation over a defined period with limited reliance on external utility provision. In this dissertation, operational autonomy depends on the interaction between energy generation and storage, water and wastewater systems, climatic conditions, occupancy, user demand, and system capacity.
<i>Research-by-design</i>	An exploratory research approach in which design is used to generate, examine, compare, and interpret possible architectural and spatial responses to defined environmental and planning conditions. In P4, research-by-design supports the examination of cross-contextual

	transferability and knowledge transfer but does not constitute independent hydraulic, structural, or long-term performance validation.
<i>Spatial co-benefits</i>	Positive spatial effects generated in addition to the primary flood-adaptation function of an intervention. In this dissertation, these include improved pedestrian connectivity, public-space continuity, and land–water accessibility.
<i>Transferability</i>	The capacity of hydro-adaptive principles, assessment approaches, or design strategies to be meaningfully interpreted and adapted across different hydrological, spatial, climatic, cultural, regulatory, or institutional contexts. In relation to P4, transferability refers primarily to design-based and cross-contextual interpretation and should not be understood as independent hydraulic, structural, or long-term performance validation.
<i>Walkability</i>	The spatial capacity of an urban environment to support pedestrian movement through connectivity, accessibility, route continuity, and the structure of the pedestrian network. In this dissertation, walkability is assessed primarily through spatial and morphological indicators, including pedestrian-route length, the number and location of nodes near or on the water, and the link–node ratio. It should therefore be interpreted as a spatial-performance characteristic rather than as a direct measure of observed pedestrian behaviour.

Abbreviations and other designations:

AM	Amphibious architecture
BDI	Building Damage Index
BGI	Blue-green infrastructure
BSR	Baltic Sea Region
EF	Elevated foundations
FA	Floating architecture
GIS	Geographic Information System
HCAI	Human-Centred Artificial Intelligence
HEC-RAS	Hydrologic Engineering Center’s River Analysis System
LiDAR	Light Detection and Ranging
P1–P6	Publications comprising the dissertation, numbered according to the dissertation-level analytical order
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
Q50 / Q100 / Q500	50-, 100-, and 500-year design flood-event scenarios used in P3
RQ1–RQ4	Research Questions 1–4
T1–T3	Dissertation Theses 1–3
TAIA	Target-Applied Interventions Assessment

1 Chapter 1. Introduction

1.1 Research context

Flood risk has become a significant condition of contemporary urban development, particularly in lowland riverine and coastal areas where urban growth, hydrological variability, and climatic change increasingly intersect (Cea and Costabile, 2022; Koks et al., 2023; Rentschler et al., 2023). Across such environments, flooding is no longer a marginal hazard addressed only through emergency protection, but a long-term spatial condition that increasingly shapes planning priorities, infrastructure choices, and the future viability of settlement patterns (Cea and Costabile, 2022).

This condition is especially visible in waterfront environments, where the concentration of development pressures, environmental exposure, and redevelopment ambitions makes the relationship between land, water, and urban form particularly unstable (Nyka and Burda, 2020). For instance, in Baltic coastal contexts such as Gdańsk, long-term sea-level change and the intensification of extreme water conditions increase the vulnerability of urbanised waterfronts (Zielinski et al., 2023). In lowland river systems such as the Lower Vistula, flood hazard is additionally influenced by climatic and hydrological variability affecting river-flow conditions and catchment water balance (Bartczak et al., 2022; Badora et al., 2023; Cyberski et al., 2006).

These conditions require a renewed understanding of built structures located in areas exposed to periodic, recurrent, or long-term inundation. The resulting challenges are not merely technical, but also typological and spatial. Much of the inherited built environment in flood-prone territories remains grounded in land-based construction logics developed for conditions of relative hydrological stability, producing a growing mismatch between conventional settlement forms and increasingly dynamic water conditions. Conventional slab-on-grade development assumes that the ground remains a stable and permanently available basis for occupation. In flood-prone waterfronts, however, this assumption becomes progressively less reliable as water levels, inundation ranges, and periods of exposure become more variable.

Within this context, it is important to reconsider the role of architecture and built structures in relation to unstable water levels. The dissertation examines hydro-adaptive architecture not as a technological curiosity, but as an architectural and planning response capable of accommodating water dynamics more flexibly than conventional land-based development. Hydro-adaptive architecture encompasses built forms whose structural and operational logic reduces dependence on uninterrupted ground-level occupation under flood exposure (Ameh et al., 2024). In the dissertation, this category includes elevated buildings, amphibious foundations, and floating structures, understood as distinct but comparable responses to different hydrological and spatial conditions (Figure 1.1).

The development of such solutions reflects a broader transformation in approaches to flood risk. Earlier strategies were largely based on resistance and the physical exclusion of water through embankments, barriers, drainage systems, and other defensive infrastructure (Oneto and Canepa, 2023). Although these measures remain necessary in many contexts, increasing hydrological uncertainty has encouraged a parallel shift towards adaptation, accommodation, and spatial resilience (Cea and Costabile, 2022; Oneto and Canepa, 2023; Nardini, 2022). This shift does not imply abandoning conventional flood-protection measures. Rather, it expands the available repertoire by recognising that, in some locations, the built environment may need to coexist with periodic, seasonal, or persistent water exposure.

Despite the growing body of research on floating and amphibious architecture, important questions remain unresolved (Hadi et al., 2026; Ruzzo et al., 2026). The effectiveness of individual hydro-adaptive solutions requires further investigation in relation to specific environmental, hydrological, spatial, and institutional contexts. Their possible role in the regeneration and activation of waterfront areas also remains insufficiently examined, particularly with regard to public-space continuity, walkability, land–

water accessibility, infrastructural autonomy, and integration with wider planning strategies (Storbjörk and Hjerpe, 2022; Hadi et al., 2026; Ruzzo et al., 2026).

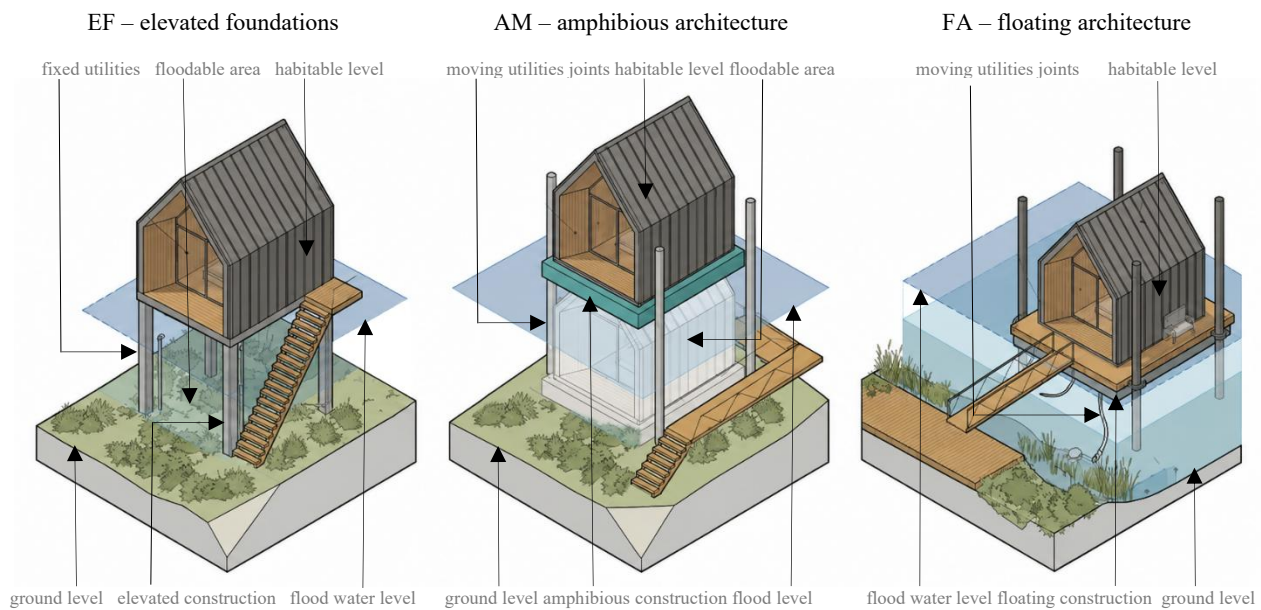
Although the principal typologies of hydro-adaptive architecture are increasingly discussed in international research (Adeola & Peters, 2025; Piątek et al., 2024), the evidence concerning their applicability has not yet been synthesised into a coherent decision framework linking hydrological exposure, typological performance, spatial co-benefits, infrastructural autonomy, and governance feasibility. Elevated, amphibious, and floating solutions are frequently examined through individual case studies, prototypes, technical experiments, or conceptual projects. However, substantially less attention has been paid to their comparative evaluation and to the conditions under which one typology may be more appropriate than another (Piątek and Wojnowska-Heciak, 2020; Piątek et al., 2024; Ghosh & Sanya, 2025).

This issue concerns a broader architectural and planning challenge: how different hydro-adaptive typologies can be comparatively evaluated and applied within diverse flood-prone waterfront contexts in a way that is scientifically grounded, spatially legible, and useful for planning judgement (Calcagni, et al., 2025). Existing knowledge remains fragmented across case-based architectural experimentation, engineering feasibility studies, flood-risk management, blue-green infrastructure research, public-space studies, and governance-oriented adaptation literature. As a result, designers, planners, and public authorities continue to lack a structured, research-oriented basis for assessing when, where, and under what conditions specific hydro-adaptive typologies may become justified components of climate-responsive waterfront development (Storbjörk and Hjerpe, 2022).

In effect, the relevance of hydro-adaptive architecture cannot be determined solely by whether a building is technically capable of floating, rising, or remaining above a projected flood level. Its planning value also depends on whether the selected solution corresponds to the local flood regime, can maintain liveability and access, can be supported by appropriate energy, water, wastewater, and transport infrastructure, contributes positively to the surrounding public realm, and can be accommodated within institutional and regulatory arrangements (Nilubon et al., 2016; Flikkema et al., 2021; Lin et al., 2022; Calcagni and Battisti, 2025; Maldar et al., 2026). Hydro-adaptive architecture should thus be understood as a multi-scalar architectural and planning issue rather than as an isolated building technology.

The dissertation is situated within this broader shift in flood-related thinking from resistance alone towards adaptation, accommodation, and spatial resilience (Oneto and Canepa, 2023). It treats hydro-adaptive architecture as a legitimate component of contemporary waterfront urbanism: not as a universal substitute for flood defence, land-use restriction, or managed retreat, but as a differentiated design and planning repertoire for territories where periodic, seasonal, or persistent water exposure must be addressed through spatial transformation rather than through the exclusion of water alone (Nyka and Burda, 2020; Nardini, 2022).

Accordingly, the dissertation focuses not only on hydro-adaptive architecture itself, but on the development of a structured basis for its assessment. It investigates how elevated buildings, amphibious foundations, and floating structures may be understood as related but non-interchangeable typologies, and how their applicability can be evaluated in relation to hydrological exposure, architectural performance, spatial implications, infrastructural conditions, and planning feasibility. This approach positions hydro-adaptive architecture as a context-dependent and planning-oriented response to the transformation of flood-prone waterfronts under changing climatic conditions.



Source: Author's elaboration.

Figure 1.1. Hydro-adaptive architecture as three differentiated relationships between building, ground, and water.

1.2 Research goal

The overarching aim of the dissertation is to investigate how waterfront cities can reconcile flood adaptation with sustainable urban development through the application of hydro-adaptive architecture across multiple scales of intervention. The study examines this challenge from the perspectives of architectural typology, public-space transformation, technical feasibility, and institutional decision-making in order to establish a scientifically grounded basis for climate-responsive waterfront planning.

1.3 Research objectives and sub-objectives

To achieve the overall research goal, the dissertation develops a sequential publication-based research programme that progressively examines hydro-adaptive architecture across scales ranging from public-space transformation and architectural typology to engineering verification, research-by-design validation, and governance integration. The six publications perform complementary analytical roles within a coherent publication-based research programme, in which different studies address successive dimensions of the research problem in which the findings of each study provide the basis for the next stage of investigation.

Accordingly, the research is organised around the following six interrelated objectives:

1. To investigate the relationship between flood resilience, public-space quality, and walkability in contemporary waterfront environments, identifying how adaptive spatial interventions can simultaneously enhance urban liveability and climate resilience (P1).
2. To synthesise the international state of knowledge on hydro-adaptive architectural typologies through a systematic literature review, identifying the principal conceptual, methodological, technical, and governance-related research gaps requiring further investigation (P2).
3. To develop and test a comparative planning-oriented framework for evaluating elevated, amphibious, and floating housing typologies under different flood scenarios, using hydrological modelling and case studies drawn from the Lower Vistula River corridor (P3).
4. To assess the transferability of hydro-adaptive architectural typologies through an international research-by-design study conducted across diverse European waterfront contexts, assessing their applicability under different environmental and cultural conditions (P4).
5. To verify the engineering feasibility and operational performance of floating residential buildings through the analysis of buoyancy, stability, energy systems, and operational safety under representative loading conditions (P5).

6. To investigate how governance mechanisms and human-centred artificial intelligence can support the implementation, institutional integration, and long-term scalability of hydro-adaptive architecture within adaptive waterfront planning systems (P6).

Together, these objectives establish a progressive research pathway linking spatial analysis, systematic evidence synthesis, comparative typological assessment, engineering verification, international design validation, and governance-oriented implementation. Their integration provides the methodological foundation of the dissertation and demonstrates how the six publications collectively contribute to achieving the overall research goal.

1.4 Key research questions

The dissertation is guided by four interrelated research questions addressing the architectural, technical, and planning dimensions of hydro-adaptive waterfront development.

RQ1. *How can hydro-adaptive architecture contribute to enhancing the resilience, liveability, and long-term spatial quality of flood-prone waterfronts while supporting climate-responsive urban development? (P1, P4)*

This question examines the architectural and urban role of hydro-adaptive interventions beyond flood protection alone, considering their contribution to public space, waterfront regeneration, and urban liveability.

RQ2. *Under what hydrological, spatial, and planning conditions are the principal hydro-adaptive architectural typologies (elevated foundations, amphibious architecture, and floating architecture) most appropriate for flood-prone waterfront environments? (P2, P3, P4)*

This question addresses the comparative applicability of the three principal hydro-adaptive typologies and investigates how their suitability varies according to flood regime, site characteristics, and planning context.

RQ3. *How can the technical performance, structural feasibility, and operational performance of hydro-adaptive architectural solutions be evaluated in order to support evidence-based planning and design decisions? (P3, P5)*

This question concerns the relationship between engineering feasibility, hydraulic conditions, structural behaviour, and architectural performance, recognising that technical verification constitutes an essential prerequisite for planning implementation.

RQ4. *How can hydro-adaptive architecture be integrated into contemporary planning systems through governance mechanisms that combine institutional coordination, stakeholder participation, and human-centred artificial intelligence? (P5, P6)*

This question explores how technically feasible hydro-adaptive solutions may be translated into planning practice through adaptive governance, participatory decision-making, and AI-supported planning processes.

Together, these research questions establish the structure of the dissertation and provide the basis for the formulation and subsequent verification of the dissertation theses.

1.5 Research thesis

The dissertation is founded on the overarching proposition that flood-prone waterfronts require an integrated architectural and planning approach in which hydro-adaptive architecture is evaluated not as an isolated technological solution, but as part of a broader system linking typological adaptation, spatial

quality, engineering performance, and governance capacity. Consequently, the scientific contribution of the dissertation lies in developing an evidence-based framework that supports the comparative assessment and locally appropriate application of hydro-adaptive architectural typologies within climate-responsive waterfront planning.

This overarching proposition is developed through three complementary dissertation theses.

T1. Conceptual Thesis

Hydro-adaptive architecture constitutes a coherent architectural and planning category comprising elevated foundations, amphibious, and floating architecture; however, these typologies represent differentiated adaptive strategies whose suitability depends on the interaction between flood regime, site characteristics, adaptive mechanism, infrastructural conditions, and planning constraints.

This thesis establishes the conceptual foundation of the dissertation by positioning hydro-adaptive architecture as an integrated analytical category while recognising the functional and spatial differences between its principal typologies.

T2. Methodological Thesis

The comparative assessment of hydro-adaptive architecture requires an integrated, multi-method research framework that combines systematic evidence synthesis, typological analysis, research-by-design, hydraulic modelling, engineering verification, spatial-performance assessment, and governance analysis.

This thesis argues that no single disciplinary method is sufficient to evaluate the role of hydro-adaptive architecture in building climate-resilient waterfront environments and only complementary methodological approaches generate convergent evidence across morphological, architectural, engineering, and planning scales.

T3. Planning Thesis

Hydro-adaptive architecture gains planning relevance when building-level flood adaptation is integrated with public-space continuity, land–water accessibility, blue-green infrastructure, infrastructural operability, and governance-supported decision-making, thereby contributing to resilient and liveable waterfront development.

This thesis positions hydro-adaptive architecture within broader climate-responsive planning systems. Its planning relevance depends not on technical feasibility alone, but also on its relationship with spatial quality, public-space systems, infrastructure, institutional capacity, stakeholder participation, and long-term governance arrangements.

1.6 Research structure

The dissertation is composed of six chapters. Its structure follows the analytical sequence of the publication-based research programme, moving from the definition of the research problem and state of knowledge, through methodology and publication-level results, to thesis verification, conclusions, and future research directions.

Chapter 1, *Introduction*, establishes the conceptual framework of the dissertation. It presents the research context, defines the overall research goal and objectives, formulates the research questions, and introduces the three dissertation theses. It also explains the position of hydro-adaptive architecture as a three related but functionally distinct hydro-adaptive typologies comprising elevated foundations, amphibious architecture, and floating architecture. In addition, the chapter outlines the publication-based character of the dissertation and presents the author's contribution to each appended publication,

as well as the author's original contribution to the dissertation as an integrated scientific work. The chapter provides the starting point for the integrated argument developed in the following parts of the dissertation.

Chapter 2, *State of Knowledge, Research Directions, and Identification of Research Gaps*, establishes the theoretical and evidential basis of the research. It discusses the transition from resistance-based flood protection towards adaptation, accommodation, and spatial resilience. It then presents the development of hydro-adaptive architectural typologies and examines the main research trends concerning advancements in this field of knowledge. The chapter concludes by identifying the overarching research gaps that guided the formulation of the research problem.

Chapter 3, *Methodology*, presents the dissertation as a sequential, cross-scale, and multi-method research programme. It explains the overall methodological and narrative framework, the logic of case-study selection, the four complementary case-study scopes, the principal data sources, and the methods used across publications P1–P6. It also defines the analytical scales and the evidential roles of the individual studies. The chapter demonstrates how spatial analysis, systematic review, hydraulic modelling, research-by-design, technical assessment, and governance analysis are integrated within one coherent methodological structure.

Chapter 4, *Results – Summary of the Appended Articles*, presents the six component publications in their analytical order: P1 – Walkability and Flood Resilience, P2 – Systematic Review, P3 – Hydro-Adaptive Typologies, P4 – Hydro-Adaptive Research-by-Design Laboratory, P5 – Off-grid Autonomous Houseboat, and P6 – Governance-Supported Hydro-Adaptive Implementation. Each publication is discussed in terms of its background, objectives, methodology, principal findings, limitations, identified research gaps, and future research directions. The chapter concludes with a comprehensive dissertation-level synthesis of the six publications and the development of an integrated planning framework that links flood hazard, hydro-adaptive typologies, spatial quality, infrastructural operability, and governance conditions within a coherent planning-support structure.

Chapter 5, *Verification of the Dissertation Theses*, evaluates the extent to which the conceptual, methodological, and planning theses are confirmed within the defined research scope. Drawing on the integrated evidence and planning framework developed in Chapter 4, the chapter examines the contribution of Publications P1–P6 to the verification of the three dissertation theses and demonstrates how the combined findings address the identified research gaps.

Chapter 6, *Conclusions and Future Research Directions*, presents the overall implications of the research. It explains how the research problem undertaken in the doctoral study has been resolved, the contribution of the dissertation to the discipline of architecture and urban planning, its planning relevance, and the conditions under which the proposed framework may be applied to Polish and comparable Central European waterfront contexts. The chapter also identifies limitations of the study and key areas for future research.

Together, the six chapters present hydro-adaptive architecture as a conditional, multi-scalar, and planning-oriented response to flood-prone waterfront development.

1.7 Author's Contribution to the Appended Publications and the Dissertation

1.7.1 Author's Contribution to the Appended Publications

The dissertation is based on six co-authored scientific publications. Detailed author-contribution statements, signed by all co-authors, are included in Appendix A. The present section summarises the individual contribution of the author to each publication and outlines the author's original contribution to the dissertation as an integrated scientific work.

Contribution to Publication P1

Walkability and Flood Resilience: Public Space Design in Climate-Sensitive Urban Environments

The author was responsible for the conceptualisation of the study, methodological development, preparation of the comparative framework and analytical indicators, case-study analysis, formal analysis, visualisation, manuscript preparation, and revision. The author's contribution amounted to approximately 60%.

Contribution to Publication P2

Floating and Amphibious Architecture in Waterfront Built Environments: A Systematic Review of Climate Adaptation and Regenerative Potential

The author was responsible for the conceptualisation of the review, methodological design, development of the analytical and coding framework, formal analysis, visualisation, manuscript preparation, and revision. The author's contribution amounted to approximately 60%.

Contribution to Publication P3

Hydro-Adaptive Housing for Flood-Resilient Planning: Elevated, Amphibious and Floating Solutions

The author developed the research concept, methodological framework, comparative assessment approach, case-study analyses, formal analyses, visualisations, manuscript preparation, and manuscript revision. The author's contribution amounted to approximately 60%.

Contribution to Publication P4

A Laboratory for Adaptation of Urban Areas to Climate Change: Flooding Resilience and Climate-Sensitive Waterfronts

The author was the principal contributor to Publication P4 and was responsible for the conceptualisation of the research, methodological development, investigation and case-study preparation, formal analysis, preparation of visual materials and figures, drafting of the manuscript, and manuscript revision. The author's contribution amounted to approximately 80% of the work undertaken for the publication.

Contribution to Publication P5

Zero-Emissions, Off-grid, Autonomous Houseboat: A Case Study of Selected Locations in Europe

The author contributed to the conceptualisation of the study, development of the methodology, architectural design of the proposed houseboat concept, architectural and design-related analyses, preparation of visualisations and scalability schemes, drafting of the architectural sections of the manuscript, and final manuscript editing. The publication was developed through interdisciplinary collaboration involving specialists in naval architecture, environmental engineering, energy systems, and architecture. The author's contribution amounted to approximately 20%.

Contribution to Publication P6

Revolutionizing Flood Resilience: Human-Centred AI for Adaptive and Regenerative Urban Design

The author developed the research concept, methodological framework, comparative governance framework, documentary and case-study analysis, formal analysis, visualisations, manuscript preparation, and revision. The author's contribution amounted to approximately 50%.

1.7.2 Original Contribution of the Author to the Dissertation

Beyond the contributions made to the individual publications, the author developed the overarching research problem, research objectives, research questions, dissertation theses, and the overall conceptual and methodological structure of the dissertation.

The original contribution of the dissertation does not lie solely in the inclusion of six individual publications, but in their integration within a coherent architectural and planning framework addressing the role of hydro-adaptive architecture in flood-prone waterfront development. The author developed:

- the overall research programme linking Publications P1–P6 into a sequential and complementary analytical structure;
- the synthesis of the state of knowledge and the identification of research gaps;
- the conceptualisation of the three dissertation theses;
- the integrative dissertation-level methodological and narrative framework;
- the integration of evidence generated by the six publications;
- the comparative interpretation of hydro-adaptive architectural typologies;
- the dissertation-level synthesis presented in Chapters 4–6;
- the integrated planning framework for the assessment and selection of hydro-adaptive typologies;
- the verification of the dissertation theses;
- the final conclusions, limitations, and future research agenda.

2 Chapter 2. State of Knowledge, Research Directions, and Identification of Research Gaps

This chapter reviews the state of knowledge and establishes the conceptual and empirical context for the research programme presented in the subsequent chapters. The review is organised around the central proposition that flood adaptation in waterfront environments has evolved from a predominantly engineering-based concern into a multi-scalar architectural, spatial, technical, and governance challenge. Consequently, understanding the role of hydro-adaptive architecture requires the integration of perspectives that have traditionally developed within separate research domains.

The chapter examines how changing interpretations of flood risk, resilience, and adaptation have influenced contemporary approaches to waterfront planning. Particular attention is given to the emergence of hydro-adaptive architecture as a distinct field of research and to the growing recognition that adaptive buildings should be understood not as isolated technical objects, but as components of wider urban-water systems. The review therefore considers contributions originating from architectural design, urban planning, landscape studies, hydraulic engineering, infrastructure research, environmental assessment, governance studies, and digital decision-support research.

Therefore, this chapter is structured in four stages. Section 2.1 examines the transition from flood control towards adaptive waterfront planning and the broader shift from resisting water to accommodating and integrating it within urban environments. Section 2.2 reviews the emergence of hydro-adaptive architecture and the development of elevated, amphibious, and floating typologies as distinct adaptive mechanisms. Section 2.3 analyses the expansion of research beyond individual architectural objects towards spatial, technical, environmental, infrastructural, and institutional systems. Section 2.4 synthesises the reviewed state of knowledge. It demonstrates both the progress achieved within individual research streams and the fragmentation that persists between them. It also provides the foundation for identifying the research gaps addressed by the dissertation and for justifying the integrated methodological framework presented in the following chapters.

2.1 From flood control to adaptive waterfront planning

Flood research was initially dominated by the protection of settlements through embankments, barriers, drainage networks, pumping systems, and river regulation. This approach treated water mainly as an

external hazard that should be separated from urbanised land. Jha et al. (2012) broadened this perspective by presenting urban flood risk as the combined result of hazard, exposure, vulnerability, urbanisation, infrastructure, and institutional capacity. More recent international assessments also position flood adaptation within wider processes of climate-resilient development, spatial planning, social vulnerability reduction, and environmental transformation (Dodman et al., 2022).

The transition from flood control towards flood-risk management introduced a more complex relationship between protection and adaptation (Aerts et al., 2024). Tempels and Hartmann (2014) describe the boundary between land and water as a co-evolving frontier. Their work shows that fixed protective systems may provide solid protection under defined conditions, while long-term uncertainty also requires flexibility in land use, spatial form, and infrastructure. Liao (2012) develops this argument through the concept of urban flood resilience, understood as the capacity to tolerate flooding and reorganise whilst maintaining essential functions. From this perspective, the continued exclusion of water is only one possible response. Accommodation, temporary inundation, adaptive occupation, and spatial transformation become equally relevant strategies.

This change also affected the meaning of resilience. Meerow et al. (2016) show that urban resilience may involve persistence, transition, or transformation and that its meaning depends on the system, spatial scale, temporal horizon, and social priorities being considered. Returning a waterfront to its previous condition may reproduce existing exposure and vulnerability. A more adaptive interpretation considers how buildings, public spaces, infrastructure, and institutions can change in response to new environmental conditions. Batica and Gourbesville (2016) and Prashar et al. (2023) further demonstrate that flood resilience includes physical, social, economic, environmental, and institutional capacities and therefore cannot be measured through protective infrastructure alone.

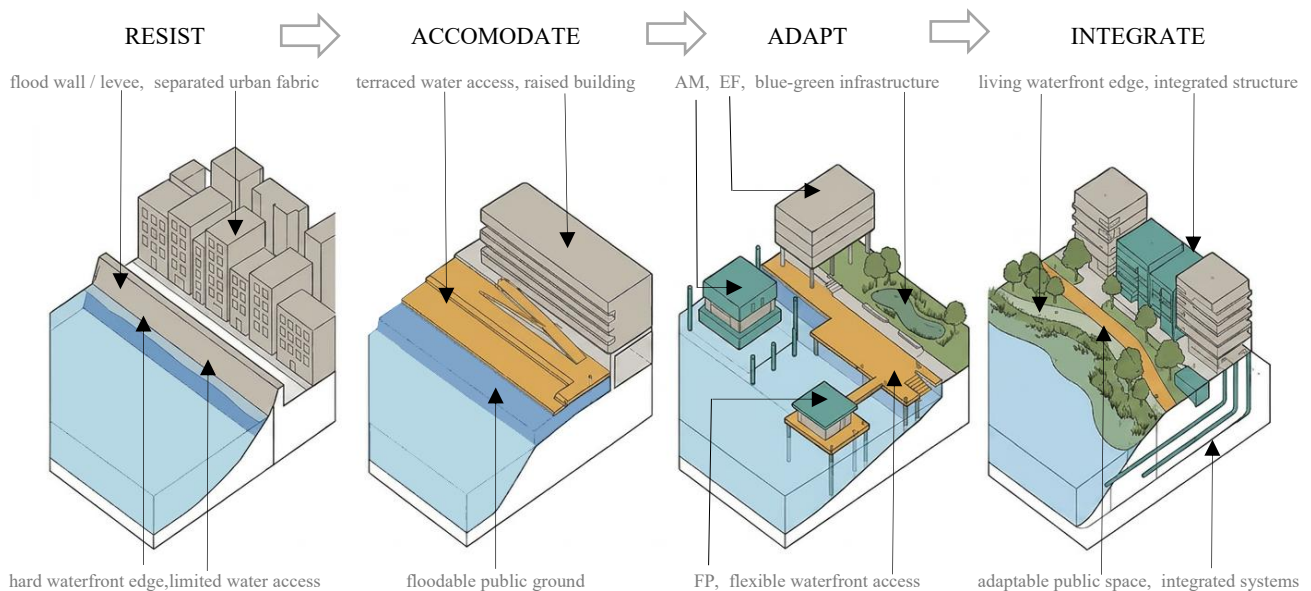
The evolving concepts of flood control and resilience are affecting how waterfront areas are planned and understood. Waterfront areas combine hydrological processes with development pressure, ecological systems, cultural identity, mobility, recreation, and public access. Protective infrastructure may reduce exposure while creating barriers between settlements and water (Burda et al., 2017). Adaptive planning therefore increasingly examines whether flood-risk measures can also enhance spatial continuity and the quality of everyday use (Burda and Nyka, 2023). For instance, Southworth (2005) provides an established framework for understanding walkability through connectivity, access to destinations, safety, comfort, and the spatial quality of pedestrian routes. These dimensions remain central to contemporary walkability research (De Vos et al., 2023; Westenhöfer et al., 2023; Venerandi et al., 2024). In flood-prone waterfronts, these properties may be affected by embankments, elevated paths, temporary closures, floodable surfaces, floating structures, and new water-based connections.

One response to these challenges has been the growing integration of blue-green infrastructure and nature-based solutions into waterfront planning and flood adaptation strategies (Aghaloo et al., 2024; Marzio et al., 2026). At the interface between water and land, growing attention is being given to wetlands, floodable parks, bioswales, and various kinds of retention landscapes. Notably, they are increasingly understood not only as drainage components, but as parts of the public realm and urban life (Ferrario et al., 2024). This shift reflects the broader scholarly interest in the role of nature-based solutions (Aghaloo et al., 2024). Raymond et al. (2017) argue that their assessment should include ecological, social, cultural, and economic co-benefits. Nesshöver et al. (2017) position nature-based solutions between science, policy, and practice, while Frantzeskaki (2019) demonstrates that their implementation also depends on aesthetics, trust, co-creation, collaborative governance, and institutional learning. Together, these studies suggest that hydro-adaptive solutions can form an integral part of broader nature-based adaptation strategies.

Beyond landscape-based adaptation measures, recent research has increasingly examined the role of buildings and architectural responses to flooding as important components of waterfront adaptation (Vanelli et al., 2024; Veloso, 2026). However, buildings should not be considered in isolation, as their adaptive capacity depends on their relationship with the wider urban and hydrological context (Vanelli et al., 2024; Tasnia and Growe, 2025). Barker and Coutts (2016) introduced the concept of aquitecture, which connects flood-resistant and flood-adaptive buildings with waterspace planning, landscape design, infrastructure, and urban development. Their work presents designing with water as an

architectural and urban process operating across multiple scales, from individual buildings to neighbourhoods and entire cities. Furthermore, they highlight the limitations of approaches based solely on excluding water from the built environment. Instead, they advocate integrated strategies that accommodate water within the urban system, including wet-proofing measures, flood-storage areas, rain gardens, and coordinated waterfront planning. This contribution is significant because it positions architectural responses to flooding within a broader spatial and infrastructural framework, reinforcing the need to consider buildings as part of interconnected urban-water systems (Vanelli et al., 2024; Tasnia and Growe, 2025).

This body of knowledge demonstrates that flood adaptation has evolved from a predominantly engineering-based approach towards a multi-scalar spatial and socio-ecological process (Figure 2.1) (Liao, 2012; Meerow et al., 2016; Tasnia and Growe, 2025). Contemporary waterfront adaptation increasingly integrates resilience, public-space quality, blue-green infrastructure, and architectural responses within broader urban-water systems (Raymond et al., 2017; Tasnia and Growe, 2025; Marzio et al., 2026). However, despite growing interest in flood-adaptive buildings and aquitecture, architectural structures capable of changing their relationship with water remain only weakly connected to wider analyses of urban morphology, public-space systems, and spatial planning. This gap has contributed to the emergence of hydro-adaptive architecture as a distinct field of research, which seeks to integrate architectural, spatial, and environmental perspectives in flood-prone environments.



Source: Author's elaboration.

Figure 2.1. Evolution of approaches to flood-prone waterfront development: from defensive separation of the city and water (resist), through the accommodation of periodic inundation, towards adaptive building and public-space strategies, and finally the integrated coordination of ecological, spatial, technical and governance systems.

2.2 Hydro-adaptive architecture as an emerging architectural field

The relationship between buildings and changing water levels has a long history. Archaeological research on pile dwellings, lake settlements, and wetland occupation shows that human settlement has repeatedly adapted to fluctuating environmental conditions through elevation, seasonal access, local materials, and forms of collective water management (Menotti and O'Sullivan, 2012). These examples differ from contemporary construction in terms of technology, infrastructure, regulation, and patterns of use, but they demonstrate that permanent separation between land and water is not the only basis for settlement.

Modern water-based structures developed partly from converted vessels, houseboats or harbour structures. During the late twentieth and early twenty-first centuries, purpose-designed floating and amphibious buildings began to constitute a more distinct architectural field. Dutch practice played an

important role in this development. Olthuis and Keuning (2010) presented floating architecture as a response to land scarcity, urban expansion, and climate change, while Nillesen and Singelenberg (2011) examined amphibious environments as planned settlements combining water management with housing and public space. More recent research has extended this discussion towards site-specific floating urban development and the integration of floating structures with broader waterfront adaptation strategies (Calcagni et al., 2025). Together, these contributions helped establish hydro-adaptive architecture as a distinct area of architectural and urban research.

Recent research has increasingly sought to classify hydro-adaptive architecture according to the way buildings interact with floodwater. A frequently adopted distinction separates dry-proof and wet-proof approaches (Rehan et al., 2024; Endendijk et al., 2024). Within hydro-adaptive architecture, three principal mechanisms can be distinguished: elevated, amphibious, and floating structures (Piątek and Wojnowska-Heciak, 2020). Elevated buildings maintain habitable floors above a defined flood level through piles, stilts, or raised ground (Pasquier et al., 2024). Amphibious buildings normally rest on or close to the ground and become buoyant during a flood, moving vertically along guidance systems (Ameh et al., 2024; Piątek et al., 2024). Floating buildings remain continuously buoyant and respond to water-level change through mooring or guidance arrangements (Storbjörk and Hjerpe, 2022; Hadi et al., 2026). Despite their different operating principles, these typologies share a common adaptive logic: modifying the relationship between the building and changing water levels in order to reduce flood damage and maintain functional use (Pasquier et al., 2024; Ameh et al., 2024; Hadi et al., 2026). In contrast, wet-proofing accepts the temporary presence of water within designated parts of a building. Such solutions seek to minimise damage through water-resistant materials, adaptable interior arrangements, and controlled inundation (Rehan et al., 2024; Endendijk et al., 2024). They may be particularly relevant in locations where complete exclusion of water is impractical or economically unjustified (Rehan et al., 2024).

Elevated construction is the most established of the three approaches. It uses a fixed vertical separation between the building and the projected flood level and is widely recognised in flood-resistant construction guidance (ASCE, 2025; Al Assi et al., 2023). Its architectural consequences extend beyond structural height. Elevation may change entrances, street relationships, accessibility, privacy, and the connection between buildings and neighbourhood space (García et al., 2025; McCall et al., 2024). Its effectiveness also depends on the selected protection level and the continuity of access and services during the flood event (ASCE, 2025).

Amphibious architecture introduces a dual operational state. English et al. (2016) describe it as a non-defensive strategy that allows buildings to remain grounded during normal conditions and rise with floodwater. This approach may preserve the established scale and street relationship of low-rise communities more effectively than permanent elevation. Research led by English also connects amphibious retrofitting with the protection of existing and historic buildings, showing how buoyant foundations may support continuity of place and cultural identity (English et al., 2021). Its applicability depends on buoyancy, vertical guidance, flexible services, suitable flow conditions, maintenance, emergency procedures, and regulatory acceptance.

Floating architecture represents continuous occupation on water. Stopp and Strangfeld (2010) discuss its potential together with problems of buoyancy, stability, thermal comfort, exposure, energy use, access, and technical infrastructure. Moon (2014) extends this discussion towards the environmental, social, and economic dimensions of floating architecture. El-Shihy and Ezquiaga (2019) focus on architectural design principles, spatial organisation, and the development of floating communities in response to sea-level rise. Together, these studies show the movement of floating architecture from individual recreational objects towards permanent buildings and possible urban structures (Li et al., 2026; Rombach et al., 2026).

Recent studies have placed more emphasis on systematisation. Piątek et al. (2024) compare European amphibious buildings through architectural, technical, functional, and implementation criteria. Ameh et al. (2024) interpret amphibious architecture as a biomimetic response and highlight the relationship between buoyancy mechanisms, passive operation, and structural guidance. At the urban scale, El-Shihy

(2024) develops a systematic approach to the assessment and configuration of modular floating platforms, extending typological analysis towards floating-city development.

The current state of knowledge therefore supports the recognition of elevated, amphibious, and floating forms as related hydro-adaptive mechanisms. However, it remains less developed in explaining how particular typologies should be selected under specific combinations of flood depth, duration, velocity, recurrence, site morphology, infrastructure, access, and regulatory conditions. Moreover, much of the literature continues to focus on individual buildings rather than their interaction with wider spatial, technical, and institutional systems. Recent studies of floating development have begun to address these broader environmental, regulatory, socio-economic, and planning dimensions, although their integration remains uneven and strongly context-dependent (Jaćović Maksimović, 2025; Ruzzo et al., 2026). This limitation has prompted increasing attention towards understanding hydro-adaptive architecture as part of broader urban-water assemblages, which is discussed in the following section.

2.3 From architectural objects to spatial, technical, and institutional systems

Research on hydro-adaptive architecture initially focused on built precedents, technical novelty, and the formal possibilities of living on or near water. The field has since expanded towards several connected research directions. These directions increasingly treat adaptive buildings as parts of public-space networks, environmental systems, technical infrastructure, and governance arrangements (Dal Bo Zanon et al., 2025).

The first important research trajectory concerns the spatial effects of adaptation. Urban-design and nature-based-solution research show that flood measures can provide recreation, ecological restoration, cooling, water retention, and new pedestrian connections (Burda and Nyka, 2017; Raymond et al., 2017; Istrate and Madfors, 2024). Raymond et al. (2017) emphasise that such co-benefits should be assessed together, while Frantzeskaki (2019) links their long-term success with co-creation and public acceptance. This body of work shifts attention from the survival of individual buildings towards the performance of the wider waterfront system. However, public-space research is still dominated by landscape interventions, floodable parks, retention areas, and blue-green networks. The direct relationship between elevated, amphibious, or floating buildings and pedestrian networks remains less developed. Architectural adaptation and public-space adaptation are still often assessed through separate concepts and indicators. A second trajectory concerns hydraulic and structural performance. Hydraulic modelling describes flood depth, extent, duration, velocity, and recurrence. Structural and marine-engineering studies examine buoyancy, displacement, freeboard, stability, wind loading, mooring, vertical guidance, flexible utilities, and material resistance. These studies establish the physical conditions under which a building may remain stable and functional. Flood-damage research provides an additional connection between hazard and building performance. Merz et al. (2010) show that damage assessment has often received less attention than hazard modelling and that its results depend on data quality, model assumptions, spatial boundaries, and uncertainty. Pistrika and Jonkman (2010) relate residential damage to flood characteristics and building conditions, illustrating the need to connect water exposure with the vulnerability of particular construction systems. This body of research supports comparative assessment of flood impacts and building performance, but architectural typologies are rarely incorporated into common damage and operability frameworks.

The development of performance-based research represents a movement from general claims of resilience towards measurable relationships between hazard and building response (Calcagni et al., 2024). It also reveals an important disciplinary separation. Hydraulic studies may accurately describe water conditions without identifying an appropriate architectural response. Structural studies may confirm buoyancy or stability without examining urban morphology, public-space access, or planning feasibility. Architectural studies may propose adaptive forms without testing them under comparable flood scenarios.

A third trajectory concerns research-by-design. It allows alternative spatial relationships to be developed and compared before implementation (Istrate and Madfors, 2024). International laboratories and living-lab formats extend this process through interdisciplinary work, local knowledge, stakeholder contact, scenario building, and comparative evaluation (Hadfield et al., 2024). The principal contribution of these

approaches lies in problem framing, spatial integration, and the generation of propositions that can subsequently be examined through technical or empirical methods.

A fourth trajectory concerns infrastructural autonomy. Floating and amphibious buildings may require flexible or decentralised systems for energy, freshwater, wastewater, waste management, communication, access, and maintenance. Schuetze et al. (2013) interpret buildings as integrated resource systems in which energy, water, and organic waste should be considered together. This approach is especially relevant to floating buildings, where conventional fixed connections may be difficult, vulnerable, or incompatible with movement. Research in this area increasingly examines photovoltaics, battery storage, heat pumps, rainwater harvesting, water purification, greywater reuse, decentralised wastewater treatment, and ecological filtration (Zheng et al., 2025). The literature also demonstrates that autonomy is relational. Its feasibility depends on climate, occupancy, energy demand, water quality, salinity, storage, maintenance, local infrastructure, and regulation.

The environmental assessment of floating development remains comparatively less mature. Floating structures may create new habitats, support ecological filtration, or reduce land consumption. They may also affect shading, circulation, sediment, water quality, and aquatic ecosystems (de Lima et al., 2022). Claims of regenerative or eco-positive performance are therefore strongest when supported by life-cycle analysis, environmental monitoring, and post-occupancy evidence. Such evidence remains less common than conceptual and simulation-based work.

The final trajectory concerns implementation. Hydro-adaptive architecture operates across spatial planning, construction law, floodplain regulation, navigation, environmental permitting, insurance, infrastructure provision, ownership, and maintenance (Lin et al., 2022). Floating buildings are particularly complex because they may be classified as buildings, vessels, floating objects, or hybrid structures. A technically effective solution therefore depends on institutional responsibilities and regulatory pathways. Dieperink et al. (2018) describe urban flood resilience as a multilevel governance challenge. Their comparison of European cases shows the importance of policy entrepreneurs, bridging concepts, clear rules, resources, and coordination across administrative levels. More recent studies similarly emphasise the importance of intergovernmental coordination, institutional integration, and cross-sectoral collaboration in governing climate adaptation and flood resilience across multiple administrative scales (Chantilas et al., 2023; Punt et al., 2023). Frantzeskaki (2019) reaches a related conclusion in the field of nature-based solutions, where implementation requires trust, collaborative governance, shared learning, and an inclusive urban narrative.

Digital technologies add a further layer to these spatial, technical, and governance challenges. Predictive models, sensor networks, digital twins, dashboards, and interactive platforms can support forecasting, scenario analysis, infrastructure management, and risk communication (Chen et al., 2025). Shneiderman (2020) argues that Human-Centred Artificial Intelligence should combine high levels of computational support with meaningful human control, reliability, safety, trust, and responsibility. Applied to flood-resilient planning, this approach directs attention towards transparency, interpretability, participation, and institutional accountability.

Taken together, these research trajectories demonstrate that hydro-adaptive architecture extends beyond the scale of individual buildings and increasingly operates through interactions with spatial, technical, environmental, infrastructural, and institutional systems. However, these dimensions are often investigated separately, using different concepts, methods, and evaluation criteria. As a result, limited attention has been devoted to integrative approaches capable of linking architectural typologies with flood conditions, public-space systems, technical performance, infrastructural autonomy, and governance contexts. The following sections synthesise these findings and identify the principal gaps that emerge from the current state of knowledge.

2.4 State-of-knowledge synthesis

The reviewed literature demonstrates a substantial evolution in approaches to flood adaptation, moving from traditional flood-control paradigms towards more adaptive, resilience-oriented, and spatially integrated strategies. Contemporary research increasingly recognises that flood-prone waterfronts cannot be understood solely through hydraulic risk or protective infrastructure. Instead, they are

interpreted as complex socio-ecological and urban systems in which environmental processes, public space, infrastructure, governance, and the built environment interact across multiple scales (Liao, 2012; Tempels and Hartmann, 2014; Meerow et al., 2016; Dodman et al., 2022; Aerts et al., 2024).

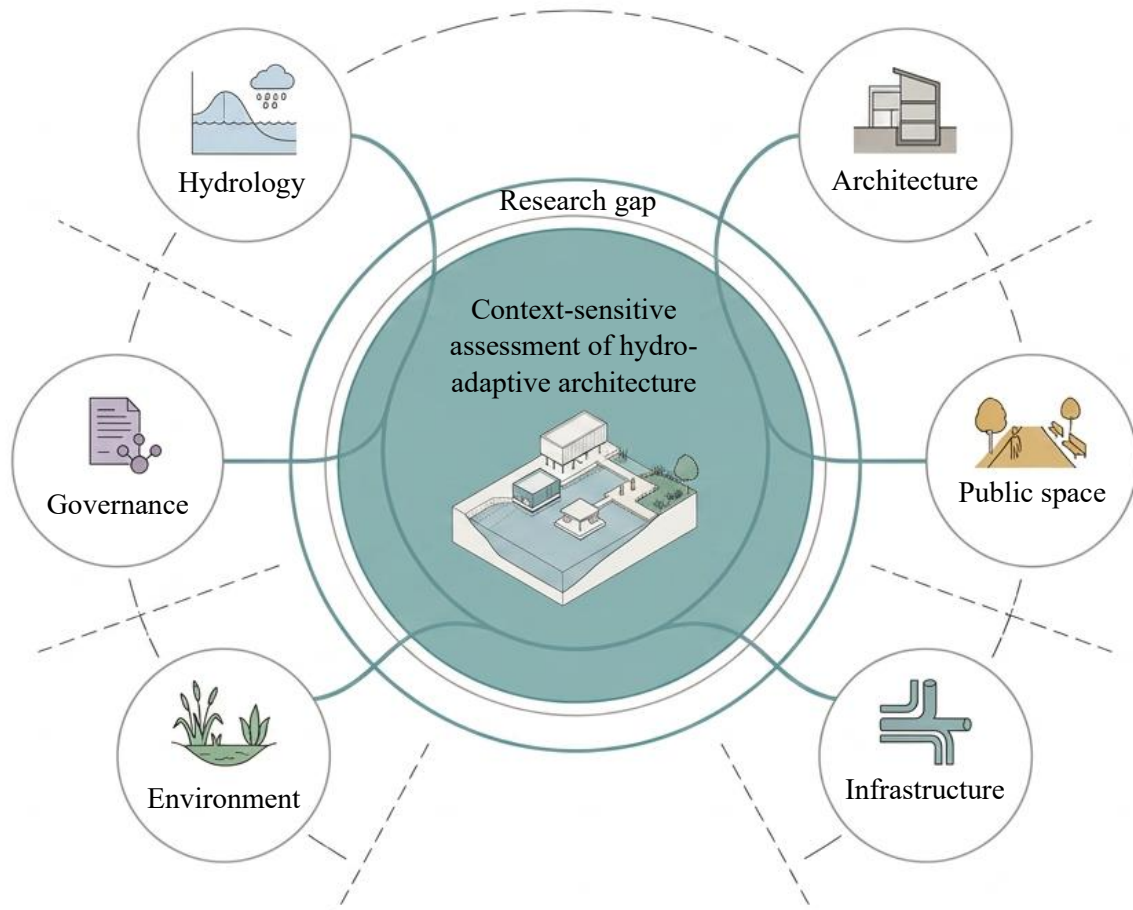
Within this broader transition, hydro-adaptive architecture has emerged as a distinct field of research concerned with the relationship between buildings and dynamic water conditions. Elevated, amphibious, and floating structures are now widely recognised as the principal hydro-adaptive typologies. Existing studies have established their technical feasibility and demonstrated their potential contribution to flood resilience under different hydrological conditions (Olthuis and Keuning, 2010; Nillesen and Singelenberg, 2011; English et al., 2016; Piątek et al., 2024). At the same time, research increasingly acknowledges that adaptive architecture should not be understood as an isolated technological response but as part of wider urban-water systems connecting buildings, public space, infrastructure, and environmental processes (Barker and Coutts, 2016).

The literature further demonstrates a growing interest in the spatial dimension of flood adaptation. Adaptive planning, urban design, and nature-based solutions have expanded the understanding of resilience beyond risk reduction towards broader objectives such as urban liveability, environmental quality, accessibility, ecological restoration, and public-space continuity (Southworth, 2005; Raymond et al., 2017; Frantzeskaki, 2019). Consequently, waterfront adaptation is increasingly evaluated not only through its protective capacity but also through its contribution to everyday urban life and the quality of the built environment. Research on blue-green infrastructure, floodable landscapes, and nature-based solutions has shown that flood adaptation can generate multiple ecological, social, cultural, and economic co-benefits while strengthening the relationship between cities and water (Raymond et al., 2017; Nesshöver et al., 2017; Marzio et al., 2026).

Parallel developments can be observed in engineering, infrastructural, environmental, and governance research. Hydraulic and structural studies have significantly improved understanding of flood processes and building performance under various hazard conditions (Merz et al., 2010; Pistrika and Jonkman, 2010). Research on infrastructural autonomy of conventional ground-based buildings has examined alternative systems for energy supply, water management, wastewater treatment, and resource efficiency (Schuetze et al., 2013), with more recent work extending these questions to floating structures (Zheng et al., 2025). Environmental research has also begun to examine the effects of floating development on water quality and aquatic ecosystems (de Lima et al., 2022). At the same time, governance studies have highlighted the importance of institutional capacity, stakeholder participation, regulatory frameworks, implementation pathways, and collaborative decision-making processes in achieving long-term resilience (Dieperink et al., 2018; Frantzeskaki, 2019). More recently, digital technologies have further expanded this discussion through predictive modelling, digital twins, sensor systems, and human-centred forms of decision support (Chen et al., 2025; Shneiderman, 2020).

Taken together, these research streams provide a substantial foundation for understanding flood adaptation as a multi-scalar challenge involving interactions between buildings, public space, infrastructure, and governance structures. However, the literature remains characterised by strong disciplinary specialisation. Research addressing hydrological hazards, architectural typologies, spatial quality, technical performance, infrastructural systems, and governance arrangements has advanced considerably within individual domains, yet these domains often employ different concepts, scales of analysis, evaluation criteria, and methodological approaches. As a result, knowledge is frequently generated within parallel research streams rather than through integrated frameworks capable of supporting comprehensive planning and design decisions.

Overall, the current state of knowledge confirms that hydro-adaptive architecture possesses considerable potential as a component of contemporary flood adaptation and waterfront transformation. Nevertheless, important questions remain concerning the integration of hydrological, architectural, spatial, infrastructural, operational, and governance-related evidence within coherent planning-oriented approaches (Figure 2.2). The following section synthesises these limitations and formulates the principal research gaps addressed by the dissertation.



Source: Author's elaboration.

Figure 2.2. Fragmented state of knowledge and the integrated research gap addressed by the dissertation.

2.5 Identification of research gaps

The overarching research gap concerns the limited integration of complementary evidence within a coherent, cross-scale framework for the context-sensitive assessment and planning integration of hydro-adaptive architecture in flood-prone waterfront environments.

Despite the substantial body of literature in the field, its principal research streams continue to develop largely in parallel. Hydraulic studies characterise hazard, engineering studies verify particular systems, architectural studies examine typologies and existing case studies, urban-design studies address public space, environmental research assesses blue-green systems, and governance literature considers implementation. Each stream contributes relevant evidence, but these forms of knowledge are rarely connected within a common architectural and planning framework.

The unresolved task is therefore to determine how complementary forms of evidence can be integrated to assess hydro-adaptive architecture across building, public-space, infrastructural, and governance scales, while also supporting typology selection and implementation appropriate to local conditions.

This overarching gap contains five interrelated research gaps, designated G1–G5.

G1. Knowledge-integration gap

Knowledge on hydro-adaptive architecture remains fragmented across hydraulic, architectural, technical, spatial, environmental, infrastructural, and governance-related research. Although these research streams provide substantial evidence on flood resilience, typologies, structural performance, public-space adaptation, blue-green systems, autonomous infrastructure, and governance, they use different concepts, scales, criteria, and forms of evidence and are rarely integrated within a common architectural and planning framework.

The resulting gap is the absence of a coherent evidence chain through which hydro-adaptive architecture can be assessed across architectural, spatial, infrastructural, environmental, and planning dimensions..

G2. Comparative typological assessment and applicability gap

The principal elevated, amphibious, and floating typologies are well recognised and extensively described in the international literature. The remaining gap concerns their comparative assessment through shared hydrological, spatial, structural, operational, infrastructural, and implementation criteria. Although existing studies provide substantial evidence on individual adaptive mechanisms and technical feasibility, they offer less support for determining the conditions under which one typology should be preferred over another in a specific flood-prone waterfront context.

The research gap therefore concerns the development of common criteria through which the relative suitability of established hydro-adaptive typologies can be assessed under differentiated flood regimes, site conditions, spatial configurations, infrastructural requirements, and implementation contexts. Such criteria are necessary to support comparative and context-sensitive planning decisions.

G3. Spatial and liveability integration gap

The third gap concerns the limited integration of building-level flood adaptation with the wider spatial and liveability objectives of waterfront development.

The architectural value of hydro-adaptive typologies is often reduced to technical feasibility or visual innovation. Their role in supporting walkability, public-space continuity, land-water accessibility, urban morphology, settlement continuity, and climate-responsive waterfront transformation remains insufficiently investigated. Building adaptation, public-space adaptation, and blue-green infrastructure are usually examined as separate fields. For example, a floodable park may provide retention, recreation, and ecological benefits while building-level vulnerability remains unresolved. A technically resilient building may remain isolated from the public-space system, restrict waterfront access, or contribute little to the continuity and walkability of the urban fabric.

The spatial research gap concerns the lack of a cross-scale framework connecting hydro-adaptive architectural typologies with public space, mobility, accessibility, urban form, landscape systems, and wider spatial co-benefits. Flood adaptation should therefore be assessed in relation to structural performance, continued use, accessibility, and waterfront liveability.

G4. Infrastructural and operational gap

The fourth gap concerns the infrastructural and operational conditions that determine the applicability of hydro-adaptive typologies.

Existing research often focuses on structural or buoyancy-related feasibility. Less attention has been given to the systems required for long-term operation. Hydro-adaptive buildings may require flexible or autonomous systems for energy, water supply, wastewater, waste management, access, evacuation, and maintenance. These requirements differ between elevated, amphibious, and floating typologies. They may strongly influence technical, environmental, economic, and planning suitability. An autonomous utility system may be technically possible but economically inefficient, environmentally inappropriate, difficult to maintain, or incompatible with local regulations and service networks. Off-grid and hybrid systems are often presented as means of increasing autonomy and resilience. Their effectiveness depends on local infrastructure, occupancy, service continuity, environmental impact, or operational capacity.

The literature provides limited evidence connecting infrastructural autonomy and operational requirements with the comparative selection of hydro-adaptive typologies.

G5. Transferability, implementation, and governance gap

The fifth gap concerns the transfer of hydro-adaptive architecture from individual projects and technical solutions into planning procedures, regulatory frameworks, institutional arrangements, and implementation pathways.

Geographical concentration of case studies is an important limitation. A substantial proportion of documented examples are located in countries with strong water-management institutions, developed construction sectors, navigable urban waters, and supportive regulatory environments. The transfer of these approaches to Central European riverine and lowland contexts cannot be assumed. Flood regimes, infrastructure, property relations, ownership patterns, construction practices, local law, climate, and planning cultures differ. A typology that performs successfully in one context may be unsuitable in another. Transferability depends on technical conditions and on the presence of adequate infrastructural, regulatory, financial, administrative, and institutional capacity.

Existing research also provides limited integration of architectural and engineering assessment with institutional arrangements, stakeholder participation, regulatory procedures, and decision-support processes. Hydro-adaptive architecture is often presented as a promising adaptation approach, while its incorporation into planning practice remains incomplete. A hydraulic or digital model may have limited practical influence when its assumptions are not transparent, its results are not understood or trusted, or it is not embedded within planning and approval procedures.

The governance gap therefore concerns the lack of a coherent pathway linking evidence, typological assessment, stakeholder interpretation, institutional capacity, regulation, and planning decisions.

Taken together, G1–G5 show that existing studies seldom combine hazard modelling, comparative typological assessment, spatial co-benefit evaluation, infrastructural operability, empirical verification, transferability analysis, and governance interpretation within one coherent evidence chain. **They therefore define the integrated research problem addressed by the dissertation:**

How can waterfront cities reconcile flood adaptation with liveability through the implementation of hydro-adaptive architecture operating at the scales of architectural typology, public space, infrastructure, and institutional decision-making?

A related question concerns the comparative assessment and selection of elevated, amphibious, and floating solutions under context-specific hydrological, spatial, operational, and governance conditions.

The dissertation addresses these gaps through a cross-scale and multi-method research in which the six component publications perform complementary functions. The public-space and walkability study examines spatial co-benefits, accessibility, and waterfront liveability (P1). The systematic review establishes the state of knowledge, identifies conceptual and typological fragmentation, and examines the available evidence on hydro-adaptive architecture (P2). The empirical and modelling-based study assesses the performance and applicability of elevated, amphibious, and floating typologies under different hazard conditions (P3). The research-by-design study provides an interpretative and validation-oriented perspective on the transferability of hydro-adaptive typologies across diverse waterfront contexts (P4). The off-grid houseboat study addresses infrastructural autonomy and operational requirements (P5). The P6 study extends the analysis towards governance, stakeholder interpretation, and digitally supported decision-making. The comprehensive dissertation-level synthesis connects these strands within one architectural and planning framework.

For analytical clarity, the five interrelated research gaps and the publications addressing them are summarised in Table 2.1.

The identified research gaps provide the foundation for the dissertation objectives, research questions, dissertation theses, methodological design, and scientific contributions. Addressing these interrelated challenges requires a cross-scale and multi-method research strategy that combines evidence synthesis, typological analysis, research-by-design, empirical assessment, modelling, and governance-oriented inquiry. The relationships between the identified research gaps, research questions, dissertation theses, methodological components, and publications P1–P6 are presented in Chapter 3.

Table 2.1. Summary of research gaps and publications addressing them.

Gap	Description	Publications addressing the gap
G1	Fragmentation of knowledge on hydro-adaptive architecture across hydraulic, architectural, technical, spatial, environmental, infrastructural, and governance-related research. Lack of a coherent evidence chain connecting these dimensions for architectural and planning assessment.	P2 Systematic review, P4 Hydro-adaptive research-by-design laboratory
G2	Limited comparative and context-sensitive assessment of established elevated, amphibious, and floating typologies through shared hydrological, spatial, structural, operational, infrastructural, and implementation criteria. Limited long-term and comparative empirical evidence concerning performance and transferability.	P2 Systematic review, P3 Hydro-adaptive typologies
G3	Limited integration of building-level flood adaptation with walkability, public-space continuity, land–water accessibility, urban morphology, settlement continuity, and waterfront liveability.	P1 walkability and flood resilience, P4 Hydro-adaptive research-by-design laboratory
G4	Insufficient consideration of the infrastructural and operational conditions governing typological applicability, including autonomous, off-grid, and hybrid service systems.	P3 Hydro-adaptive typologies, P5 Off-grid autonomous houseboat
G5	Limited understanding of geographical and institutional transferability. Insufficient integration with regulatory frameworks, stakeholder participation, institutional arrangements, implementation pathways, and digitally supported planning processes.	P2 Systematic review, P6 Governance-supported hydro-adaptive implementation

Source: Author's elaboration.

3 Chapter 3. Methodology

3.1 The overall methodological and narrative framework

Methodologically, the dissertation adopts a sequential multi-method research design in which complementary methods are applied across successive analytical scales to generate convergent evidence concerning hydro-adaptive architecture. In response to the identified research gaps and research questions, the dissertation is structured as an integrated research programme comprising six interrelated publications. Together, these publications address different analytical scales and perform distinct methodological and narrative functions. Collectively, they form a progression from resilient waterfront planning and urban morphology, through evidence synthesis, typological assessment, and research-by-design exploration, towards engineering verification and governance-supported implementation.

Publication 1 (P1): public space and walkability under flood risk

Walkability and flood resilience: Public space design in climate-sensitive urban environments study (Urban Planning, 2025) (Gorzka et al., 2025) analyses nine Baltic Sea Region waterfront cities (Stockholm, Jönköping, Gothenburg, Copenhagen, Vejle, Gdańsk, Pärnu, Helsinki, Turku) using spatial mapping, morphological metrics, and comparative case analysis. The study demonstrates how flood-adaptation measures, including the introduction of floating buildings and platforms, can simultaneously support pedestrian connectivity (route-network increases of 6–28%), waterfront accessibility (link–node increases of 24–39% and direct water-access-node increases of 150–1900%), and flood resilience. This paper establishes the spatial premise that flood resilience and urban liveability need not be treated as competing objectives. The analysis evaluates urban-morphology features and spatial-performance indicators across a sample comprising realised interventions and conceptual proposals, leaving building-level typology selection, technical verification, and governance conditions for subsequent studies.

Publication 2 (P2): systematic mapping of architectural typologies and their regenerative potential (review)

Floating and amphibious architecture in waterfront built environments: A systematic review of climate adaptation and regenerative potential (Sustainability, 2026) (Gorzka et al., 2026a) responds to these

gaps by synthesising the global evidence base on water-adaptive building typologies. Following PRISMA 2020 guidance, it screens 8,423 records down to a core evidence base of 63 studies (from an initial screened landscape of 1,410 relevant publications). It distinguishes floating architecture (continuously buoyant, water-based) from amphibious architecture (land-based, episodically buoyant during flood events) across dimensions including buoyancy condition, structural interfaces, hydrological context, infrastructure, environmental performance, and implementation conditions. Crucially, the review shows that the principal hydro-adaptive typologies are already well recognised, while several important research needs remain unresolved. These include limited comparative assessment through shared hydrological, spatial, structural, and operational criteria; insufficient evidence concerning applicability across contrasting contexts and transferability; underdeveloped integration of infrastructural and operational requirements with architectural assessment; and limited incorporation of hydro-adaptive solutions into broader governance and planning frameworks. P2 therefore provides the systematic evidence base for the dissertation and identifies the principal questions subsequently examined through the comparative typological analysis in P3, research-by-design exploration in P4, technical and infrastructural assessment in P5, and governance-oriented analysis in P6.

Publication 3 (P3): site-specific feasibility testing

Hydro-adaptive housing for flood-resilient planning: Elevated, amphibious and floating solutions (Buildings, 2026) (Gorzka et al., 2026b) operationalises the gaps identified by the systematic review through a planning-oriented comparative framework applied to three contrasting flood-prone settings along the Lower Vistula River corridor in northern Poland: a coastal delta/brownfield context (Gdańsk–Polski Hak), a peri-urban river-confluence context (Toruń–Kaszczorek), and a lower-river terrace context with documented historical deep inundation (Tczew). The methodology integrates GIS/LiDAR hazard mapping, one-dimensional unsteady-flow HEC-RAS hydraulic modelling for 50-, 100-, and 500-year design events, and parametric structural modelling to test the feasibility of elevated, amphibious, and floating housing typologies. The analysis demonstrates differentiated applicability of elevated, amphibious, and floating typologies under contrasting flood conditions. Results show that floating platforms are the only consistently feasible option in deep, permanently inundated zones, while elevated and amphibious forms suit land-dominated settings with episodic flooding; complementary blue-green infrastructure reduces surface-water retention time by 18–31%, with the strongest effects in Toruń and more limited gains in Gdańsk and Tczew due to existing drainage buffering. This paper transforms the review's abstract typology gaps into a transferable, quantitative, site-specific decision-support tool for planners.

Publication 4 (P4): cross-contextual research-by-design exploration and knowledge transfer

A Laboratory for Adaptation of Urban Areas to Climate Change: Flooding Resilience and Climate-Sensitive Waterfronts (World Transactions on Engineering and Technology Education, 2024) (Gorzka & Nyka, 2024) shifts the narrative from the performance-based, site-specific assessment developed in P3 towards a research-by-design exploration of transferability in a broader European context. Conducted through an international collaboration (Horizon 2020 project: SOS Climate Waterfront) among six universities (KTH Stockholm, Sapienza University of Rome, Lusófona University Lisbon, Aristotle University of Thessaloniki, TOBB University Ankara, and Gdańsk Tech), the laboratory combined workshops, case-study analysis, data-informed research-by-design, and comparative evaluation using the Target-Applied Interventions Assessment (TAIA) method.

The detailed investigations in Rome, addressing public access to a flood-exposed riverfront, and Gdańsk, representing a low-lying post-industrial heritage waterfront, were supported by 3D terrain and water-level simulations. The comparative evaluation indicated that amphibious foundations had the strongest adaptive potential among the assessed solutions for urban extensions under the analysed conditions. Floating structures and associated green infrastructure were also identified as potentially contributing to

water-retention and shallow-water biodiversity objectives, while the study identified opportunities for adapting heritage buildings through buoyant foundation concepts.

P4 contributes the research-by-design and transferability component of the evidence chain. It provides exploratory evidence that similar hydro-adaptive principles can be interpreted and adapted across contrasting European spatial, environmental, and cultural contexts, while demonstrating how water-level change, architectural form, public space, heritage, ecology, and urban development can be considered within a common design process. The study also identified further questions concerning continuity and walkability at the land-water interface and the off-grid operation of floating structures. The latter provides a direct transition to the technical and infrastructural assessment undertaken in P5, while the broader implementation questions anticipate the governance-supported implementation perspective developed later in P6.

Publication 5 (P5): Engineering verification of floating habitation

Zero-Emissions, Off-grid, Autonomous Houseboat: A Case Study of Selected Locations in Europe (Polish Maritime Research, 2024) (Gorzka et al., 2024), examines the floating dwelling as an integrated architectural, structural, and infrastructural system. The study compares three hull configurations - ship-type, cuboid, and catamaran - and assesses displacement, draft, metacentric height, stability, and the effects of wind and occupant movement. These analyses establish the structural and operational conditions required for safe floating habitation. The study also examines how technical systems influence architectural form and everyday use. Energy generation and storage, freshwater supply, wastewater treatment, hull geometry, spatial layout, usable area, and user comfort are considered together within one design model. The climatic and energy-performance assessment compares the operation of the same floating-dwelling model under conditions representative of Rome, Lisbon, Gdańsk, and Stockholm. At dissertation level, P5 provides the principal evidence concerning the technical and infrastructural operability of floating habitation. Its architectural significance lies in demonstrating that floating architecture cannot be assessed through buoyancy or structural stability alone: its feasibility also depends on the integration of spatial form, energy, water, wastewater, access, and operational requirements. P5 therefore complements the typological assessment developed in P3 by defining the building- and system-level conditions that must be considered when floating architecture is evaluated as a viable hydro-adaptive solution.

Publication 6 (P6): Institutional and AI-enabled governance

Revolutionizing flood resilience: Human-centred AI for adaptive and regenerative urban design (Land Use Policy, 2026) (Gorzka, Burda, Józekowski, & Nyka, 2026) paper elevates the narrative from physical, technical, and research-by-design solutions to governance. The study develops a four-pillar analytical framework comprising technical integration, institutional arrangements, stakeholder engagement, and land-use innovation. It applies this framework through a document-based comparative analysis of nine cities representing diverse flood typologies and governance regimes, including Rotterdam, Copenhagen, Bangkok, Venice, and Sydney. It argues that AI tools such as Machine Learning, Deep Learning, and Graph Neural Networks can support flood-risk prediction and response coordination, but their planning relevance depends on inclusive decision-making, ethical safeguards, and institutional embedding within adaptive regulatory systems – cities like Rotterdam, Copenhagen, and Bangkok show clearer planning-policy pathways, whereas Venice and Sydney's fragmented, project-based deployments show limited continuity. This paper extends the dissertation from architectural, technical, and spatial assessment towards governance and implementation-related considerations. Rather than evaluating hydro-adaptive architecture directly, it identifies institutional arrangements, stakeholder-engagement mechanisms, planning-policy pathways, and Human-Centred AI conditions that may support the integration of adaptive solutions into planning practice. The study therefore contributes governance-related evidence concerning implementation capacity, transferability,

and decision-support processes, complementing the architectural and technical findings generated by the preceding publications.

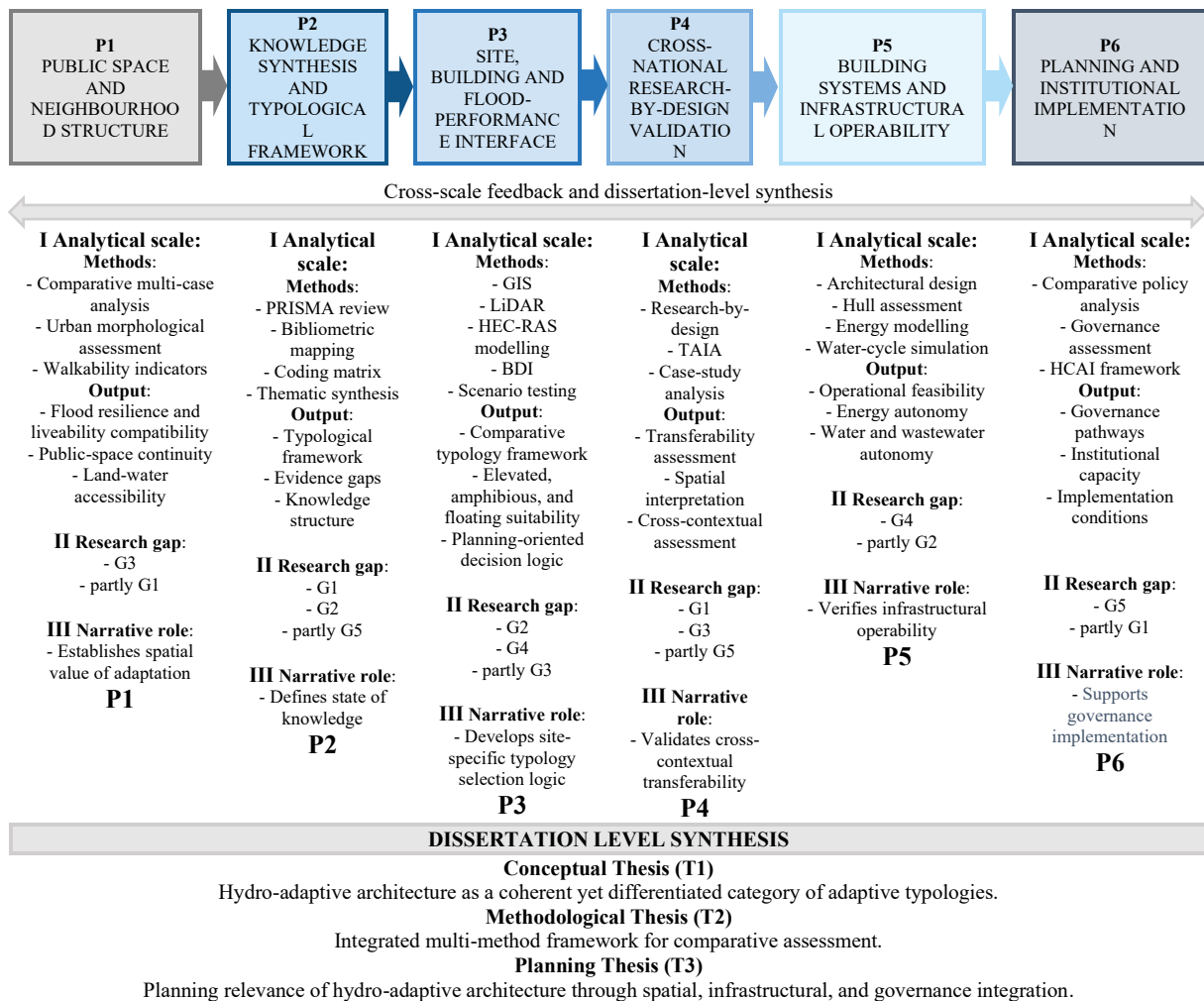
Figure 3.1 illustrates how the six publications connect analytical scales and complementary evidence strands within the dissertation-level research sequence. Table 3.1 specifies their relationship with the identified research gaps, dissertation theses, and narrative roles, while detailed methodological characteristics are consolidated separately in Section 3.3 and Table 3.3.

Table 3.1. Dissertation-level alignment of Publications P1–P6 with analytical scales, research gaps, theses, and narrative roles.

Publication	Analytical scale	Research gap addressed	Thesis Linkage	Narrative role
P1 – Walkability and Flood Resilience	Public space and neighbourhood structure	G3 – Spatial and liveability integration gap; partly G1 – Knowledge-integration gap	T3	Establishes the premise that resilience and urban liveability need not be treated as opposing objectives
P2 – Systematic Review	Disciplinary knowledge and building typology	G1 – Knowledge-integration gap; G2 – Typological, comparative, and evidential gap; partly G5 – Transferability, implementation, and governance gap	T1 + T2	Defines the state of knowledge and justifies the need for applied typological and site-based investigation
P3 – Hydro-adaptive typologies	Site, building, and flood-performance interface	G2 – Typological, comparative, and evidential gap; G4 – Infrastructural and operational gap; partly G3 – Spatial and liveability integration gap	T1 + T2	Translates the literature gaps into a planning-oriented, site-specific typology-selection logic
P4 – Hydro-adaptive research-by-design laboratory	Cross-national research-by-design and knowledge transfer	G1 – Knowledge-integration gap; G3 – Spatial and liveability integration gap; partly G5 – Transferability, implementation, and governance gap	T2 + T3	Provides a research-by-design perspective on transferability, validates hydro-adaptive strategies across contrasting contexts, and identifies new spatial and implementation challenges.
P5 – Off-grid autonomous houseboat	Building systems and infrastructural operability	G4 – Infrastructural and operational gap; partly G2 – Typological,	T2	Tests whether the floating typology identified at the planning level can function as a viable

		comparative, and evidential gap		and autonomous residential environment.
P6 – Governance- supported hydro- adaptive implementation	Planning and institutional implementation	G5 – Transferability, implementation , and governance gap; partly G1 – Knowledge- integration gap	T3	Provides the institutional framework through which technical and spatial evidence can be translated into legitimate and scalable planning practice.

Source: Author's elaboration based on publications P1–P6 and their dissertation-level methodological synthesis.



Data source: Author's elaboration based on publications P1–P6 and the dissertation-level methodological synthesis.

Figure 3.1. Sequential cross-scale multi-method research framework of the dissertation.

Each publication contributes evidence addressing a specific dimension of the research problem, while the dissertation integrates these partial findings into a coherent architectural and planning framework.

3.2 Case-study design and selection criteria

The dissertation applies a multi-level case-study design. Case selection was aligned with the methodological role of each publication and the type of evidence required at each analytical stage. The cases form four complementary case-study scopes: (1) the Baltic Sea Region cases, used to assess how flood-adaptive waterfront interventions and hydro-adaptive structures contribute to urban morphology, liveability, and enhance walkability of urban waterfronts (P1); (2) the Lower Vistula cases, which provide the principal empirical basis for the comparative assessment of hydro-adaptive typologies (amphibious, floating and elevated buildings) under consistent flood scenarios and harmonised datasets (P3); (3) the European cross-contextual cases, used to explore the design transferability, engineering feasibility, and operational autonomy of hydro-adaptive solutions (P4 and P5); and (4) nine globally distributed cities, used to analyse how digitally supported flood-adaptation approaches are embedded within different governance and planning contexts (P6).

This structure combines focused empirical testing with broader comparative interpretation. The Lower Vistula cases support detailed assessment under comparable lowland river conditions, while the international cases introduce spatial, cultural, climatic, technical, and institutional variation. The resulting framework is therefore intended to support planning and preliminary typological screening in flood-prone waterfront contexts characterised by comparable hydrological, spatial, infrastructural, and institutional conditions.

3.2.1 Baltic Sea Region (BSR) walkability cases

The Baltic Sea Region cases were selected in P1 to examine the spatial co-benefits of flood-adaptive waterfront interventions where floating architecture and structures were implemented. The comparative sample includes nine waterfront areas:

1. Stockholm;
2. Jönköping;
3. Gothenburg;
4. Copenhagen;
5. Vejle;
6. Gdańsk;
7. Pärnu;
8. Helsinki;
9. Turku.

The cases share a broad Baltic regional context and exposure to climate-related water risks. At the same time, they differ in city size, urban form, waterfront morphology, project scale, governance structure, socio-economic conditions, and adaptation strategy. The sample includes major metropolitan centres and smaller urban areas, as well as coastal, estuarine, riverine, and lakefront settings. This variation enabled a comparative assessment of how different flood-adaptive interventions affect pedestrian connectivity, public-space continuity, and access to water across diverse waterfront conditions.

The main selection criteria were:

- location within the Baltic Sea Region;
- a direct relationship with an urban waterfront;
- exposure to flood risk or climate-related water variability;

- availability of flood-risk or adaptation documentation;
- the presence of an identifiable waterfront intervention or proposal;
- variation in project scale and urban form;
- sufficient spatial material for mapping paths, nodes, and access to water.

The cases were selected to provide a regional comparative sample characterised by a broadly shared geographical and environmental context, but by visible differences in spatial responses to flood risk. The interventions examined include floating structures, blue-green infrastructure, elevated routes, public-space interventions, modular housing, floating gardens, and water-access platforms. To assess changes in public-space morphology and walkability, the comparative analysis considered pedestrian-route length, the link-node ratio, and the number of nodes located near or on the water before and after each intervention. The cases provided the empirical basis for assessing whether flood-adaptive waterfront interventions and hydro-adaptive structures can generate spatial co-benefits, strengthen public-space continuity, enhance pedestrian connectivity, and facilitate access to water.

3.2.2 Lower Vistula case studies

The Lower Vistula case studies were selected to investigate which hydro-adaptive typologies are applicable under different hydrological, morphological, and planning conditions. Three flood-prone urban settings in northern Poland were selected to represent contrasting hydro-morphological and planning conditions relevant to hydro-adaptive housing:

1. Gdańsk–Polski Hak – a coastal delta and brownfield waterfront context;
2. Toruń–Kaszczorek – a peri-urban inner-meander setting near the confluence of the Vistula and Drwęca rivers;
3. Tczew–Nadwiślańskie terraces – a lower-river terrace context with documented deep inundation during historical flood events.

The cases represent a differentiated spectrum of deltaic, confluence, and lower-river terrace conditions within one river system. This structure allows the comparison of typological applicability under different forms of flood exposure while maintaining regional and methodological coherence.

The selection criteria included:

- recurrent flood exposure;
- contrasting hydro-morphological and urban conditions;
- availability of consistent LiDAR, topographic, and hydrometric data;
- planning relevance for possible housing deployment;
- suitability for comparative hydraulic interpretation;
- the possibility of delineating the analysed reaches according to the same principles.

The selected areas were analysed using harmonised data and the same Q50, Q100, and Q500 flood-event scenarios. The analysed reaches were defined to include valley geometry, floodplain connectivity, and key hydraulic controls affecting urban exposure. This common procedure supports cross-site comparison of flood depth, inundated area, surface-water retention time, building damage, and the operability of elevated, amphibious, and floating typologies.

The three cases were selected using a maximum-variation sampling strategy within a common lowland river corridor. Their purpose was to test how differences in hydrological and morphological conditions

influence typological performance and planning applicability. The cases were not intended to represent all flood-prone areas in Poland or Central Europe. Rather, they provide evidence applicable to contexts characterised by sufficiently similar hydrological, spatial, and data conditions.

3.2.3 European case studies for validation and transferability

The European case studies were selected in P4 and P5 to examine the transferability, engineering feasibility, and operational performance of hydro-adaptive solutions in a broader European context. This part of the doctoral research was associated with participation of the author of this dissertation in the EU Horizon 2020 SOS Climate Waterfront project, which involved such institutions as; KTH Royal Institute of Technology in Stockholm, Sapienza University of Rome, Lusófona University in Lisbon, Aristotle University of Thessaloniki, TOBB University of Economics and Technology in Ankara, and Gdańsk University of Technology. The collaboration facilitated access to diverse climatic, hydrological, cultural, spatial, and planning contexts, thereby supporting the comparative analyses conducted as part of the dissertation.

Publication P4 employs research-by-design and cross-contextual case-study analysis to explore the transferability of the adaptive principles examined in the dissertation. The principal analytical focus of P4 is placed on cases in Rome and Gdańsk. The design simulations analysed in P4 were developed by the author specifically for the purposes of this dissertation.

The cases addressed different local challenges:

- in Rome, the principal challenge concerned public access to riverfront areas exposed to flood risk;
- in Gdańsk, the principal challenge concerned built heritage and waterfront development under scenarios of rising water levels.

The cases were selected because they:

- represented vulnerable waterfront areas;
- contained clearly identifiable architectural and urban adaptation challenges;
- represented different relationships between built heritage, waterscapes, urban form, and public-space accessibility;
- provided access to maps, plans, master plans, site observations, and photographic documentation;
- enabled engagement with academic experts, users, local communities, public authorities, and other relevant stakeholders.

The term *validation* is used here in relation to design exploration and methodological comparison. The study cases examine whether similar adaptive principles can be interpreted across different spatial and cultural contexts. They do not provide independent hydraulic, structural, or long-term performance validation. Their principal function is formative and interpretative: they establish the research-by-design component of the dissertation, identify cross-scale adaptation questions, and explore the conceptual and spatial transferability of floating, amphibious, blue-green, and public-space interventions.

The subsequent article, publication P5 examines four locations also associated with the EU Horizon 2020 SOS Climate Waterfront project, namely Rome, Lisbon, Gdańsk, and Stockholm representing contrasting climatic, environmental, and operational conditions. The cases are used to assess the feasibility and operational performance of floating residential architecture under different climatic conditions and assumptions of off-grid autonomy. The analysis considers architectural design,

scalability of the floating structure, hull characteristics, energy performance, and water and wastewater systems.

3.2.4 Nine globally distributed cities

To investigate the deployment of hydro-adaptive solutions across diverse spatial, planning, and governance contexts, nine globally distributed cities were selected (P6). As digital and AI-based tools are increasingly embedded in governance, planning, and flood-adaptation systems, cities utilising such technologies were chosen for analysis. The cases were identified through a two-stage maximum-variation sampling procedure. The aim was to compare how AI-enabled and digitally supported flood-resilience tools are integrated into technical infrastructures, institutional frameworks, stakeholder engagement processes, and land-use planning systems.

In the first stage, 25 flood-prone cities were screened. The initial set covered different:

- flood typologies;
- geographical regions;
- income contexts;
- governance models;
- levels of documented AI-enabled or digital activity;
- forms of planning-policy integration;
- participatory approaches.

In the second stage, nine cities were retained:

1. Rotterdam;
2. New York;
3. Bangkok;
4. Venice;
5. Tokyo;
6. Copenhagen;
7. Sydney;
8. Kolkata;
9. London.

The final selection was based on:

- sufficient documentary availability;
- relevance to flood-resilient land-use planning;
- documented use of AI-enabled or digital flood-resilience tools;
- availability of institutional and governance information;
- evidence concerning planning-policy links;
- information on stakeholder or participatory components;
- variation in the maturity of AI and digital implementation.

The sample includes cases with stronger and weaker institutional integration, planning-policy linkages, stakeholder participation, and governance uptake. This approach reduces positive-case bias and preserves analytical contrast.

The global cases demonstrate how digital and AI-supported flood-resilience approaches are integrated into planning and governance. They identify conditions under which technical knowledge and digital decision-support tools may be embedded effectively within planning processes. The cases also highlight implementation barriers, including weak institutional anchoring, limited public participation, low interoperability, fragmented project delivery, and insufficient regulatory integration.

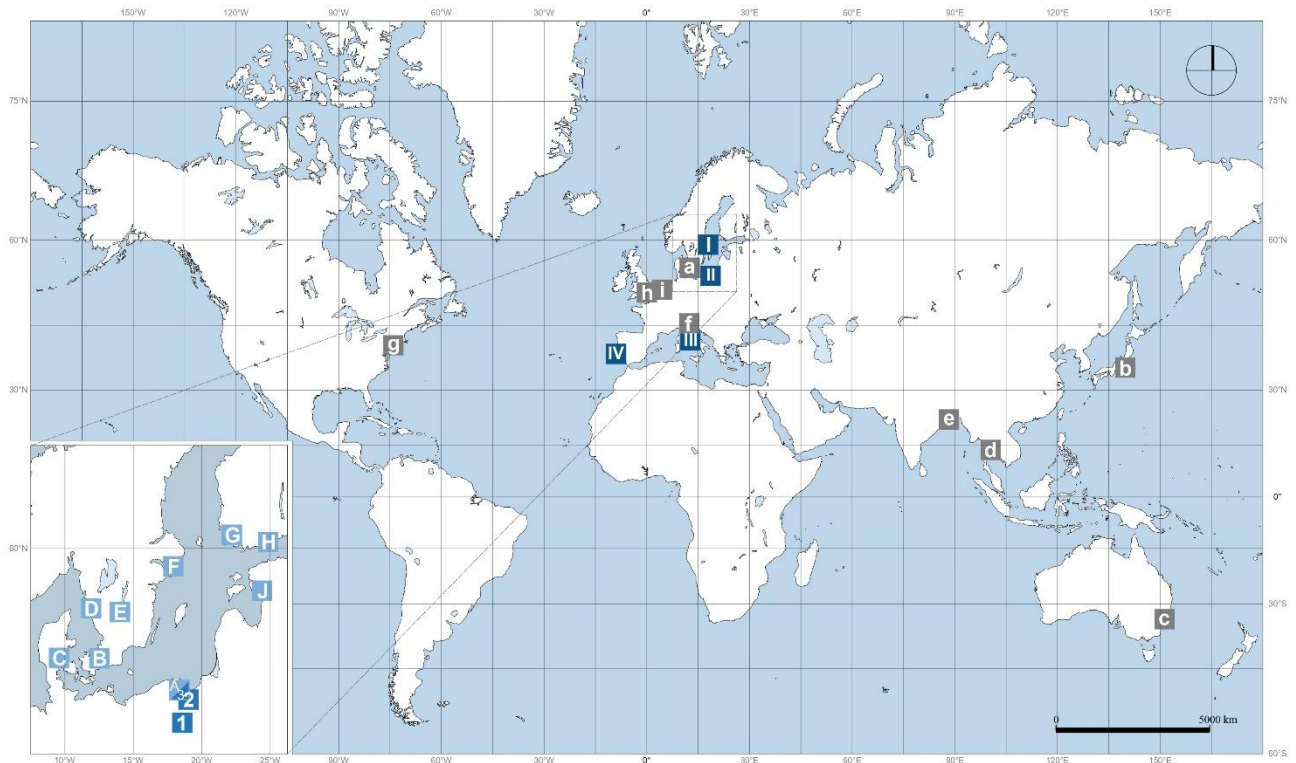
3.2.5 Integration of the four case-study scopes

The four case-study scopes fulfil complementary methodological functions within the dissertation. The Baltic Sea Region cases examine the spatial and liveability implications of flood-adaptive interventions, while the Lower Vistula cases provide the principal empirical basis for typological comparison under controlled hydrological conditions. The European cases extend the analysis through research-by-design exploration, transferability assessment, and engineering-related investigation of operational performance. Finally, the globally distributed cities broaden the analysis towards governance, implementation, and digitally supported decision-making as a broader context for applicability of hydro-adaptive architecture. Together, these case-study scopes create a multi-scalar evidence structure linking public space, architectural typologies, technical performance, infrastructural operability, and institutional implementation. Their relationships are summarised in Table 3.2.

Table 3.2. Multi-level case-study design, selection logic, and methodological functions within the dissertation research programme.

Case-study scope	Spatial level	Selection logic	Main methodological function
Baltic Sea Region walkability cases, P1	Public-space and neighbourhood scale	Regional purposive comparison of varied waterfront interventions	Assessment of how resilient waterfront interventions and hydro-adaptive structures contribute to walkability, connectivity, public-space continuity, and access to water.
Lower Vistula cases, P3	Site, building, and river corridor	Maximum contrast within a comparable regional and hydrological setting	Comparative assessment of elevated, amphibious, and floating typologies under differentiated flood scenarios.
European cross-contextual cases (P4)	Architectural and urban-design scale	Purposive selection within an international research network	Research-by-design exploration and cross-contextual interpretation, transferability assessment, and design-based validation
European engineering and operational cases (P5)	Building-system and engineering scales	Climatic and technical comparison	Assessment of the engineering feasibility and operational autonomy of floating housing
Globally distributed governance cases, P6	City, institutional, and planning-system levels	Two-stage maximum-variation documentary sampling	Comparison of governance, stakeholder participation, AI integration, and planning-policy pathways

Source: Author's elaboration based on publications P1–P6.



■ Baltic Sea Region (BSR) walkability cases (A-Gdańsk, B-Copenhagen, C-Vejle, D-Gothenburg, E-Jönköping, F-Stockholm, G-Turku, H-Helsinki, J-Parnu)
■ Lower Vistula case studies (1-Toruń, 2-Tczew, 3-Gdańsk)
■ European case studies for validation and transferability (I-Stockholm, II-Gdańsk, III-Rome, IV-Lisbon)
■ Nine globally distributed cities (a-Copenhagen, b-Tokyo, c-Sydney, d-Bangkok, e-Kolkata, f-Venice, g-New York, h-London, i-Rotterdam)

Source: Author's elaboration.

Figure 3.2. Case-study geography of the dissertation.

The map (Figure 3.2) illustrates the geographical distribution of the four case-study scopes: the Baltic Sea Region walkability cases, the Lower Vistula case studies, the European cross-contextual cases, and the globally distributed governance and HCAI cases. Together, these case-study scopes provide the empirical basis for the multi-level case-study design presented in Section 3.2.

3.3 Research methods

This section outlines the principal research methods employed in the dissertation and explains how they address different dimensions of the research problem. It also describes how evidence generated at different analytical scales is integrated within the dissertation-level synthesis.

The methods used in the dissertation can be grouped into six complementary categories corresponding to the analytical roles of Publications P1–P6. They are presented in the analytical order of the publications. Each methodological group addresses a different component of the research problem and generates a distinct type of evidence, which is subsequently integrated at the dissertation level.

1. Spatial and morphological methods (P1).

Publication P1 employed a comparative multi-case mixed-method approach to examine the spatial and walkability effects of flood-adaptive waterfront interventions across nine Baltic Sea Region cities. The procedure combined geospatial mapping, urban-morphology analysis, quantitative measurement of pedestrian networks, and qualitative comparative assessment. Existing and proposed or transformed spatial configurations were reconstructed using municipal and national geoportals, planning documentation, and project materials. Quantitative analysis focused on three principal indicators: pedestrian-route length, the number and location of nodes near or on the water, and the link–node ratio. AutoCAD 2024 was used to measure pedestrian routes and calculate network indicators, while the results were standardised to support cross-

case comparison. A qualitative assessment was then used to interpret changes in public-space structure and the role of floating structures, blue-green infrastructure, and other flood-adaptive interventions. This methodological combination generated spatial and morphological evidence concerning pedestrian connectivity, public-space continuity, land–water accessibility, and wider spatial co-benefits.

2. Knowledge-synthesis methods (P2).

Publication P2 used a systematic literature review reported in accordance with the PRISMA 2020 framework and complemented by bibliometric mapping, structured coding, and qualitative thematic synthesis. Peer-reviewed publications indexed in Scopus and Web of Science Core Collection for the period January 2015–August 2025 constituted the principal evidence base. The review procedure distinguished between the initial retrieval set, the screened publication landscape used for bibliometric analysis, and the smaller qualitative core used for in-depth evidence synthesis. Bibliometric mapping using VOSviewer 1.6.20 was applied to identify dominant thematic clusters and relationships within the research field, while structured coding and thematic synthesis were used to compare typologies, hydrological contexts, infrastructure, environmental claims, governance conditions, and implementation evidence. The method therefore established both the international state of knowledge and the conceptual, comparative, and implementation gaps subsequently examined in P3–P6.

3. Hydraulic and typological methods (P3).

Publication P3 combined GIS and LiDAR-based terrain analysis, hydraulic modelling, and parametric typological assessment to compare elevated, amphibious, and floating solutions under differentiated flood conditions. GIS processing and hazard mapping were performed in ArcGIS Pro 3.5 using terrain, hydrometric, and spatial data for the Lower Vistula case studies. Hydraulic conditions were modelled in HEC-RAS 6.0 using one-dimensional unsteady-flow simulations for Q50, Q100, and Q500 design events. In this study, HEC-RAS modelling was used to convert hydrological boundary conditions into spatially explicit information on water-surface elevations and inundation depths, which provided the hydraulic basis for evaluating typological applicability. The hydraulic results were subsequently linked with parametric models of elevated, amphibious, and floating typologies developed in Rhinoceros–Grasshopper. Their performance was assessed using the Building Damage Index (BDI), operability criteria, hydrostatic feasibility checks, and scenario-based comparison. Sensitivity testing was used to assess the consistency of the results under changing hydraulic conditions, while additional blue-green infrastructure scenarios examined the effects of bioretention and related measures on surface-water retention. The combined procedure generated comparative hydraulic, damage, operability, and typological evidence and formed the principal performance-based basis for site-specific typology assessment in the dissertation.

4. Research-by-design methods (P4).

Publication P4 employed research-by-design as an exploratory method for examining how hydro-adaptive principles can be interpreted and transferred across contrasting European waterfront contexts. The methodological framework comprised four stages: workshops and interdisciplinary knowledge exchange, case-study analysis, research-by-design exploration, and comparative evaluation using the Target-Applied Interventions Assessment (TAIA) method. Case-study work combined site visits, photographic documentation, maps, plans and master plans with design scenarios, modelling, visualisation, and multidisciplinary discussion. The detailed investigations in Rome and Gdańsk additionally used 3D terrain and water-level simulations prepared in AutoCAD LT 2021 and SketchUp Pro 2022; successive water levels were visualised at one-metre intervals to examine relationships between topography, architectural form, public space, and changing water conditions. TAIA provided a structured graphical basis for comparing proposed interventions according to common site-related criteria. P4 therefore generated exploratory research-by-design evidence concerning spatial interpretation, cross-contextual transferability, heritage, ecology, and public-space adaptation.

5. Technical and infrastructural methods (P5).

Publication P5 combined architectural design with naval-architectural, energy, water, and wastewater analyses to assess the feasibility of an autonomous floating dwelling. The research was organised as a model simulation of a self-sufficient houseboat under defined assumptions concerning occupancy, spatial dimensions, location, and climatic conditions. Three principal hull configurations – ship-type, cuboid, and catamaran – were compared in relation to displacement, draft, stability, and the capacity to accommodate the required technical systems. The analysis also considered static stability parameters, including metacentric height, together with the effects of wind and load distribution. Energy autonomy was examined through electricity-demand calculations, photovoltaic-energy potential, battery storage, and climatic comparison for Gdańsk, Lisbon, Rome, and Stockholm. Water and wastewater assessment considered alternative freshwater sources, including rainwater and treated external water, together with wastewater treatment and storage options. These technical analyses were integrated with the architectural programme and spatial configuration of the houseboat to evaluate operational feasibility and possibilities for scaling the concept. P5 therefore generated technical and infrastructural evidence concerning the conditions under which floating habitation can operate autonomously or semi-autonomously.

6. Governance and implementation methods (P6).

Publication P6 employed a comparative document-based multi-case methodology to investigate the institutional, participatory, regulatory, and decision-support conditions associated with flood-resilient planning. Case selection followed a two-stage maximum-variation procedure: an initial set of 25 flood-prone cities was screened and nine cases were retained to represent contrasting flood typologies, geographical contexts, governance systems, and levels of documented digital or AI-supported flood-resilience activity. Documentary evidence was assembled through source triangulation combining technical documents, spatial and land-use policy materials, scientific literature, institutional reports, and documented participatory evidence. The material was analysed through thematic coding structured around four analytical pillars: technical integration, institutional arrangements, stakeholder engagement, and land-use innovation. Planning-policy pathway analysis was then used to examine how digital or AI-supported flood-risk information is translated into planning and land-use processes. The method generated governance and decision-support evidence concerning governance and institutional conditions for the implementation of hydro-adaptive solutions.

Together, these six methodological groups form a complementary cross-scale research design in which each method generates evidence appropriate to a specific analytical scale and research problem. Their integration provides the methodological basis for answering the research questions and evaluating Theses T1–T3.

Cross-scale research design

The research is carried out at three main scales.

1. At the **building scale**, the dissertation examines typological mechanisms, flood exposure, potential damage, technical feasibility, and infrastructural autonomy.
2. At the **site and neighbourhood scale**, it examines public-space continuity, pedestrian accessibility, land–water connections, urban morphology, and blue-green infrastructure.
3. At the **city and planning scale**, it examines regulation, institutional capacity, stakeholder participation, digital decision support, and land-use policy.

Although these scales are analysed separately, they remain interconnected within the overall research framework. Building performance affects typological suitability. Spatial structure affects access and public-space quality. Infrastructure affects long-term operation. Governance affects implementation.

Integration of findings

The research design combines complementary methods that together support conclusions regarding which hydro-adaptive typologies may be suitable, under which hydrological and spatial conditions, and with which technical, infrastructural, environmental, and institutional requirements.

The final conclusions are based on:

- the scale of analysis;
- the type and quality of data;
- the assumptions used;
- the limits of the case studies;
- the role of each method;
- the level of agreement between different evidence sources.

Table 3.3. Methodological structure, evidence base, and analytical roles of publications P1–P6.

Publication	Research design and main method	Supporting methods and tools	Evidence base / cases	Analytical scale	Main output	Dissertation -level role
P1 Walkability and Flood Resilience	Comparative multi-case spatial and walkability analysis	Spatial mapping; urban morphology; pedestrian-route measurement; node-link analysis; link-node ratio; water-access nodes; qualitative public-space evaluation; AutoCAD 2024	9 BSR cities: Stockholm, Jönköping, Gothenburg, Copenhagen, Vejle, Gdańsk, Pärnu, Helsinki, Turku	Neighbourhood; public space; waterfront network	Walkability and spatial co-benefit indicators	Defines the spatial and liveability value of flood adaptation
P2 Systematic review	PRISMA 2020-guided systematic literature review	Scopus and Web of Science databases; screening; coding matrix; bibliometric mapping; thematic synthesis; evidence appraisal; VOSviewer 1.6.20; Microsoft Excel 2016	8,853 records identified; 8,423 records screened after deduplication; 1,410-record bibliometric landscape; 63-study qualitative core	International literature; disciplinary knowledge	Typological synthesis; research trends; evidence and implementation gaps	Establishes the conceptual and methodological basis for P3–P6
P3 Hydro-adaptive typologies	GIS and hydraulic modelling with parametric typological assessment	LiDAR and GIS analysis; Q50, Q100, Q500 scenarios; BDI; operability; hydrostatic checks; Monte Carlo sensitivity analysis; BGI scenarios; ArcGIS Pro 3.5; HEC-RAS 6.0; Rhinoceros-Grasshopper	Gdańsk-Polski Hak; Toruń-Kaszczorek; Tczew	Building; site; neighbourhood; river corridor	Comparative performance and selection framework for elevated, amphibious, and floating typologies	Provides the main empirical basis for typology selection
P4 Hydro-adaptive research-by-design laboratory	Research-by-design	Site analysis; case studies; design scenarios; visualisation; comparative	International laboratory involving 6 universities; detailed cases in	Architecture; urban design; waterfront; design research	Adaptive design strategies and TAIA-based assessment	Provides a research-by-design perspective on transferability, cross-contextual

		evaluation; TAIA; AutoCAD LT 2021; SketchUp Pro 2022	Rome and Gdańsk			interpretation, and knowledge transfer.
P5 Off-grid autonomous houseboat	Architectural, technical and infrastructural feasibility assessment	Architectural programme; hull comparison; buoyancy and stability; energy balance; PV potential; storage; water and wastewater systems; climatic comparison; scalability assessment; SketchUp Pro 2022	Gdańsk; Lisbon; Rome; Stockholm	Building; hull; infrastructure; operation	Integrated floating- dwelling autonomy model	Defines the operational and infrastructural conditions governing the applicability of floating typologies.
P6 Governance- supported hydro- adaptive implementation	Comparative document-based multi-case analysis	Two-stage case screening; maximum- variation sampling; source triangulation; thematic coding; planning-policy pathway analysis; four- pillar HCAI framework	25 cities screened; 9 selected: Rotterdam, New York, Bangkok, Venice, Tokyo, Copenhagen, Sydney, Kolkata, London	City; planning; governance; land-use policy	HCAI analytical framework covering technical integration, institutional arrangements, stakeholder engagement, and land-use innovation.	Defines governance and decision- support conditions for implementation

Source: Author's elaboration based on publications P1–P6.

Table 3.3 consolidates the methodological design, supporting methods and tools, evidence bases, analytical scales, outputs, and dissertation-level roles of Publications P1–P6. It complements Table 3.1 and Figure 3.1 by documenting methodological detail without restating the narrative sequence of the publications. Collectively, these studies provide the empirical and analytical foundation for addressing the identified research gaps and evaluating the dissertation theses. Their methodological characteristics, evidence bases, and principal findings are presented in greater detail in Chapter 4.

Data sources and evidence base

The dissertation draws upon multiple data sources and forms of evidence, selected according to the methodological requirements of the individual studies:

- Scopus - <https://www.scopus.com/>
- Web of Science Core Collection - <https://www.webofscience.com/wos/woscc/basic-search>
Bibliographic records and peer-reviewed publications used in P2.
- Official municipal geoportals, planning portals and project documentation of Stockholm, Jönköping, Gothenburg, Copenhagen, Vejle, Gdańsk, Pärnu, Helsinki and Turku – spatial and public-space data used in P1.
- Geoportal.gov.pl - Digital Terrain Model - <https://www.geoportal.gov.pl/pl/dane/numeryczny-model-terenu-nmt/>
LiDAR and terrain data used in P3.
- IMGW-PIB Public Data - <https://danepubliczne.imgw.pl/>
Historical hydrometric and meteorological observations used in P3.
- MG Hydro - Global Watersheds - <https://mghydro.com/watersheds/>
Catchment, land-cover, precipitation and environmental baseline data used in P3.
- NASA JPL PO.DAAC - GRACE and GRACE-FO - <https://podaac.jpl.nasa.gov/>
Terrestrial water-storage data used in the Lower Vistula case descriptions.
- Cadmapper - <https://cadmapper.com/>
- OpenStreetMap - <https://www.openstreetmap.org/>

- NASA - <https://www.nasa.gov/>
- USGS - <https://www.usgs.gov/>
Maps, terrain data, and visual reference materials used in the research-by-design study (P4).
- Climatic datasets, technical literature, and equipment specifications used in P5 for energy, photovoltaic, water, and wastewater assessment.
- UNDRR - <https://www.undrr.org/>
- OECD - <https://www.oecd.org/>
- C40 Cities - <https://www.c40.org/>
- World Bank - <https://www.worldbank.org/>
International resilience, governance and policy sources used in P6.
- Municipal planning documents, climate-adaptation strategies, technical reports and institutional publications for Rotterdam, New York, Bangkok, Venice, Tokyo, Copenhagen, Sydney, Kolkata and London - documentary evidence used in P6.

Each data type supports a specific research task. Bibliographic data support the literature review and identification of research gaps. Spatial data support morphological and walkability analysis. Hydrological data support flood modelling and scenario assessment. Technical and climatic data support analysis of building operation and autonomy. Planning documents and institutional reports support governance analysis.

Methodological status of evidence

The dissertation relies on multiple forms of evidence, including exploratory, conceptual, quantitative, spatial, technical, governance-related, and synthetic evidence. Systematic review and bibliometric data support the description of the state of knowledge and research gaps. Workshop and research-by-design materials support the development and comparison of spatial solutions. Climatic and technical data support assessment under defined assumptions. Walkability and morphological indicators support analysis of access, route continuity, and public-space structure. Hydraulic and damage data support comparison under modelled flood scenarios. Governance documents support analysis of institutions, implementation, participation, and policy conditions. Each source of evidence serves a specific analytical purpose and is subject to recognised methodological limitations.

Together, these sources provide the empirical and analytical foundation for the six component publications. The following chapter presents the publications individually and discusses the evidence generated through each study in relation to the dissertation's research gaps, theses, and methodological framework.

4 Chapter 4. Results - Summary of the appended articles

This chapter presents the six appended publications. While each article addresses a specific dimension of the research problem and employs its own methodological approach, together they form an integrated evidence base for evaluating hydro-adaptive architecture in flood-prone waterfront contexts. Each sub-chapter summarises the background, objectives, methods, principal findings, limitations, and contributions of each publication. Particular attention is given to the relationships between the publications and their collective role in addressing the research gaps identified in Chapter 2 and evaluating the dissertation theses introduced in Chapter 1.

4.1 Publication P1 – Walkability and Flood Resilience

Gorzka, J., Burda, I. M., and Nyka, L. (2025). Walkability and Flood Resilience: Public Space Design in Climate-Sensitive Urban Environments. *Urban Planning*, 10, Article 9561.

4.1.1 Background, aim, and methodology

Walkability is an important feature of sustainable, healthy, and liveable cities. In waterfront areas, it is increasingly connected with flood resilience because public spaces should remain accessible and usable under changing water conditions. Flood adaptation is often assessed through its protective or technical function. Less attention has been given to its effects on pedestrian routes, public-space continuity, and access to water, particularly where these outcomes are influenced by hydro-adaptive architecture and

infrastructure. Publication P1 examines the relationship between flood-adaptation measures and the spatial performance of waterfront public spaces. Its main aim is to determine whether climate-adaptive interventions can improve walkability while reducing flood risk. The study uses a comparative multi-case design covering nine cities in the Baltic Sea Region: Stockholm, Jönköping, Gothenburg, Copenhagen, Vejle, Gdańsk, Pärnu, Helsinki, and Turku. The methodology combines spatial mapping, quantitative indicators, qualitative interpretation, urban morphological analysis, and comparative case studies.

The same analytical structure was applied to all cases. The main indicators included:

- pedestrian-route length;
- route continuity;
- the number and arrangement of nodes and links;
- link–node ratio;
- public-space integration;
- the number of nodes with direct access to water.

Walkability was used as an operational indicator of pedestrian connectivity, accessibility, liveability, route choice, and the relationship between public-space systems and the waterfront edge. Walkability was treated as an indicator of spatial connectivity and accessibility at the neighbourhood scale.

The use of a common analytical framework across all cases enabled the identification of recurrent tendencies while preserving differences in urban morphology, planning context, and adaptation strategy.



Source: Author's elaboration.

Figure 4.1. Reconnecting the urban pedestrian network: A panoramic visualisation of an adaptive waterfront.

4.1.2 Summary and main findings

The analysed cases included realised interventions and conceptual proposals involving floating structures, blue-green infrastructure, elevated routes, public-space interventions, modular housing, floating gardens, and water-access platforms. These cases provided the empirical basis for assessing whether flood-adaptive waterfront interventions, including hydro-adaptive structures, can generate measurable spatial co-benefits at the public-space and neighbourhood scales. The comparative analysis

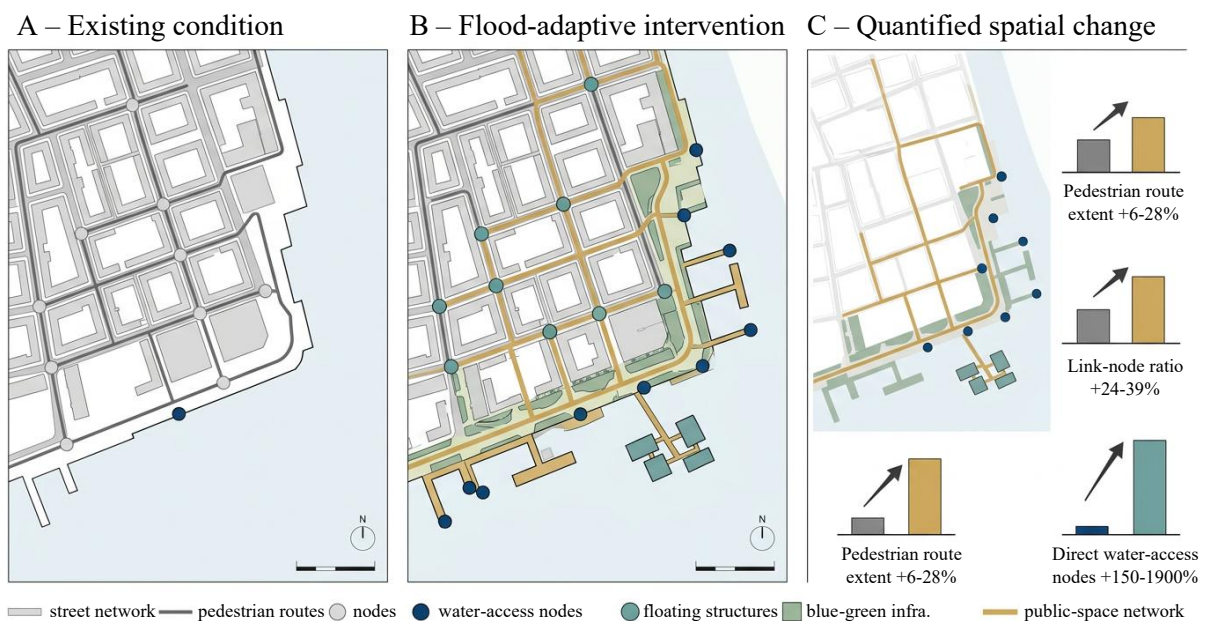
showed that interventions introducing new pedestrian routes, nodes, public-space connections, and direct relationships with the water can strengthen the spatial structure of waterfront areas.

Across the analysed cases, pedestrian-route networks increased by 6–28%, link–node ratios by 24–39%, and direct water-access nodes by 150–1900% (Figure 4.2). These changes indicate that the principal spatial co-benefits of the analysed interventions concern increased network permeability, a greater number of alternative pedestrian connections, stronger public-space continuity, and improved land–water accessibility. Their magnitude depended on the existing urban morphology, the type of intervention, and the relationship between the waterfront and the surrounding street network. The indicators describe changes in spatial configuration and should not be interpreted as direct observations of pedestrian behaviour.

The results indicate that adaptation at the land–water interface can:

- extend public-space networks;
- improve pedestrian connectivity and route choice;
- strengthen direct access to water;
- connect previously separated waterfront areas;
- support the spatial integration and usability of climate-sensitive public spaces.

P1 establishes the public-space and neighbourhood-scale dimension of hydro-adaptive adaptation. It shows that the spatial value of flood-adaptive interventions depends on how they extend and reconnect pedestrian networks and land–water interfaces. This evidence provides the principal spatial basis for the planning thesis developed across the subsequent publications.



Source: Author's elaboration.

Figure 4.2. Spatial transformation of a flood-prone waterfront: connectivity, water access and adaptive and liveable public space – theoretical example.

4.1.3 Limitations, research gaps, and future directions

The analysed indicators describe selected aspects of spatial structure. The sample includes realised projects and conceptual proposals. Their evidence status is therefore different. Realised projects provide information on implemented change, while conceptual projects show possible design directions. The study does not directly assess how the depth, duration, or frequency of flooding affects actual walking behaviour. It also does not evaluate the hydraulic or structural performance of individual building typologies. These limitations show that spatial co-benefits is only one aspect of hydro-adaptive solutions. Building typology, how different hydro-adaptive solutions can be applied in different

contexts, technical performance, infrastructure, and implementation conditions require separate analysis.

To sum up, the publication P1 shows that hydro-adaptive interventions may improve public-space continuity, walkability, and access to water. At the same time, the study reveals that knowledge concerning adaptive buildings, technical systems, environmental performance, and planning implementation remains dispersed. This creates the need for a systematic synthesis of the international literature capable of identifying the principal concepts, typologies, evidence gaps, and research directions within the field. This task is undertaken in Publication P2.

4.2 Publication P2 – Systematic Review

Gorzka, J., Burda, I. M., and Nyka, L. (2026b). Floating and Amphibious Architecture in Waterfront Built Environments: A Systematic Review of Climate Adaptation and Regenerative Potential. *Sustainability*, 18(12), 5966.

4.2.1 Background, aim, and methodology

Floating and amphibious architecture has become increasingly visible in research on climate adaptation, flood resilience, sustainability, and waterfront transformation. Existing studies provide valuable information on individual projects, technical systems, environmental concepts, and design strategies. This evidence remains divided across architecture, engineering, urban design, infrastructure, and governance. Publication P2 establishes the international state of knowledge and identifies the principal conceptual, typological, methodological, and implementation gaps within the field. Its broader purpose is to advance understanding of how hydro-adaptive architecture, applied across multiple scales, can reconcile flood adaptation with sustainable urban development in waterfront cities.

The study followed the PRISMA 2020 process of:

1. identification;
2. screening;
3. eligibility assessment;
4. inclusion.

The evidence base was derived from Scopus and Web of Science databases. After deduplication, 8,423 records were screened. A set of 1,410 records formed the wider publication landscape used for bibliometric profiling and detailed relevance assessment. The final evidence base included 63 studies used for qualitative synthesis. The search strategy covered floating architecture, amphibious buildings, waterfront built environments, climate adaptation, flood resilience, and regenerative potential.

The retained studies were examined through:

- bibliometric mapping and VOSviewer bibliometric visualisation,
- a coding matrix;
- thematic synthesis;
- typological classification;
- interpretation of the status of evidence.

The coding categories included architectural typology, geographical distribution, research method, hydrological context, technical focus, infrastructure, environmental claims, governance, regulation, and implementation evidence.

4.2.2 Summary and main findings

The review confirms that floating and amphibious architecture has developed into a growing international research field, with a marked increase in publications during the most recent part of the

analysed period. Within the qualitative core of 63 studies, floating typologies constituted the dominant group ($n = 39$), while amphibious approaches formed a smaller but distinct subset ($n = 5$); the remaining studies addressed other water-adapted typologies and waterfront or infrastructural interfaces. Floating architecture was most frequently associated with technological development, water-based urban expansion, housing, and multifunctional waterfront uses. Amphibious architecture appeared less frequently, but was more directly associated with in-place flood adaptation, retrofit strategies, continuity of use, and reduced displacement under episodic inundation.

The qualitative synthesis showed that the field is progressively moving from concept-led demonstrations of technical feasibility towards implementation-oriented assessment. Technical performance remains important, but the applicability of water-adapted architecture is increasingly evaluated in relation to site conditions, safety, comfort, regulatory compliance, operational requirements, infrastructure interfaces, and institutional acceptance. The review therefore shows that floating and amphibious solutions function not only as architectural objects or structural systems, but as components of wider socio-technical and urban systems.

Several recurring patterns were identified across the evidence base. Site suitability is strongly context-dependent and influenced by exposure, hydrography, shoreline morphology, access, and the relationship with existing urban structures. Water-adapted solutions located within established waterfronts may also contribute to public-space continuity and civic uses, while amphibious approaches provide a distinct pathway for adapting existing settlements without permanent relocation. The reviewed studies further associate floating structures with potential ecological co-benefits, including habitat provision, water-quality improvement, and blue-green integration, although such regenerative claims require explicit performance-based evidence.

At the implementation level, the review indicates that the scalability of water-adapted solutions depends on more than technical feasibility. Institutional permission, regulatory approval, tenure arrangements, infrastructure interfaces, operational stewardship, and verifiable environmental performance increasingly determine whether floating and amphibious solutions can move from individual prototypes or design concepts towards replicable urban applications. P2 therefore establishes the international evidence base concerning typology, adaptive performance, spatial integration, infrastructure, and implementation. The limitations and unresolved research needs arising from this evidence are discussed separately in Section 4.2.3.

4.2.3 Limitations, research gaps, and future directions

The review is bounded by the selected databases, search strategy, eligibility criteria, and the characteristics of the published evidence base. The study was restricted to peer-reviewed publications indexed in Scopus and Web of Science. This provides a transparent and reproducible basis for evidence synthesis.

The evidence base is also methodologically heterogeneous. The included studies differ in research design, analytical scale, evidence type, performance indicators, and evaluation frameworks. This diversity broadens the range of architectural, technical, environmental, spatial, and governance evidence represented in the review, but limits direct quantitative comparison between individual studies and does not support statistical meta-analysis of intervention effects. The findings should therefore be interpreted as evidence patterns, recurrent implementation conditions, and knowledge gaps identified across the published literature

Within these methodological boundaries, the review identifies several interrelated research gaps. The principal floating and amphibious typologies are well recognised and extensively described, while their comparative and context-sensitive applicability remains less consistently assessed through shared criteria. Existing studies provide substantial evidence on individual technological and architectural solutions, but less frequently integrate flood exposure, architectural performance, spatial relationships, infrastructure interfaces, operational requirements, and implementation conditions within a common analytical structure.

Future research should therefore focus on:

- shared comparative criteria and performance indicators for assessing established hydro-adaptive typologies under different hydrological and spatial conditions;
- applicability criteria linking flood exposure, site characteristics, architectural performance, infrastructure, and operational requirements;
- the integration of hydro-adaptive architecture into broader flood-resilient governance and planning frameworks, including regulatory approval, institutional responsibilities, stakeholder participation, infrastructure coordination, and land-use planning procedures;
- comparative studies examining the transferability of hydro-adaptive solutions across different hydrological, regulatory, and institutional contexts;
- additional evidence from underrepresented riverine and lowland contexts, including Central Europe.

Taken together, these limitations and research gaps indicate that the principal unresolved task is not the identification of hydro-adaptive typologies themselves, but the development of integrated evidence capable of supporting their comparative assessment, application under differentiated local conditions, and governance-supported implementation. These unresolved questions provide the basis for the subsequent analytical stages: P3 addresses comparative applicability, P4 cross-contextual transferability, P5 operational and infrastructural feasibility, and P6 examines the institutional and planning conditions required for implementation.

4.3 Publication P3 – Hydro-Adaptive Typologies

Gorzka, J., Burda, I. M., and Nyka, L. (2026a). Hydro-Adaptive Housing for Flood-Resilient Planning: Elevated, Amphibious and Floating Solutions. *Buildings*, 16(10), 1880.

4.3.1 Background, aim, and methodology

Existing studies often confirm the feasibility of individual elevated, amphibious, or floating solutions. They provide less support for deciding when one typology should be selected in a specific flood-prone context. Publication P3 forms the main empirical and quantitative part of the dissertation. Its aim is to develop a planning-oriented comparative framework for three hydro-adaptive typologies:

- elevated foundations – EF;
- amphibious dwellings – AM;
- floating platforms – FP.

The framework was applied to three contrasting Lower Vistula settings:

- Gdańsk–Polski Hak, representing a coastal delta and brownfield context;
- Toruń–Kaszczorek, representing a peri-urban river-confluence context;
- Tczew, representing a lower-river terrace context.

The methodology combines:

- GIS and LiDAR terrain analysis;
- hydrometric data;
- one-dimensional unsteady-flow HEC-RAS modelling;
- Q50, Q100, and Q500 flood scenarios;
- parametric typological assessment;

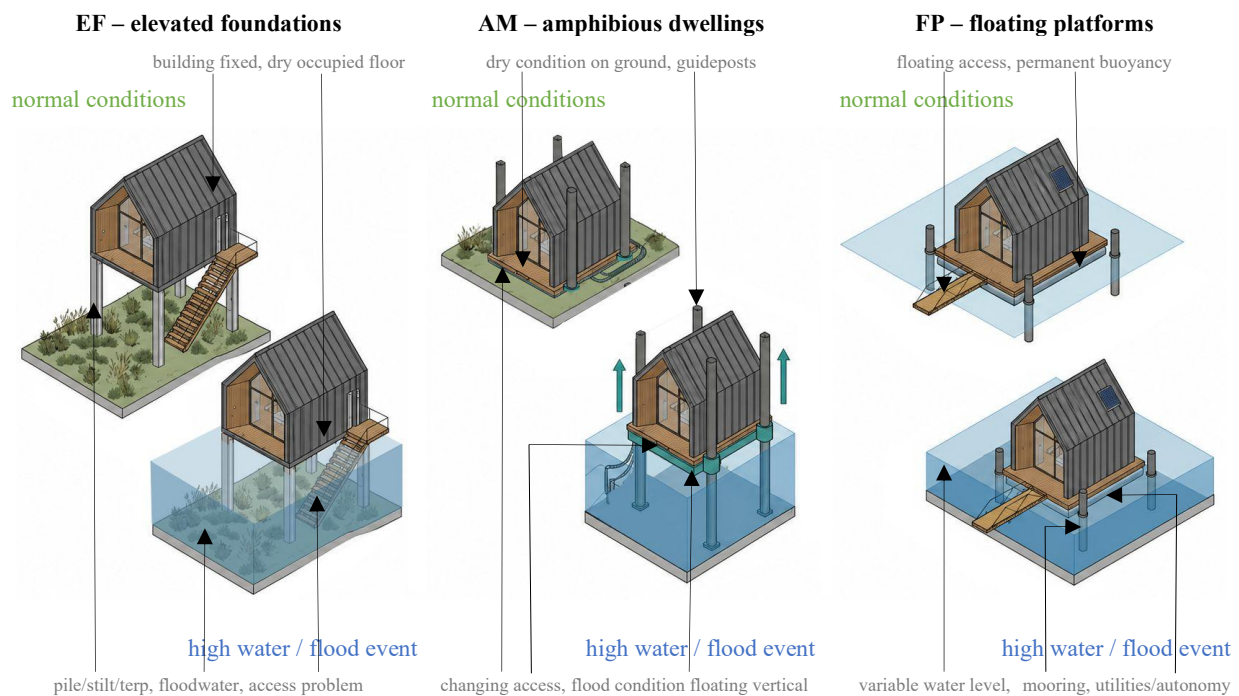
- hydrostatic feasibility checks;
- Building Damage Index (BDI) assessment;
- operability analysis;
- sensitivity testing;
- blue-green infrastructure scenarios.

The hydraulic modelling provided comparative information on inundation extent, maximum water depth, retention time, and recession conditions across the three case-study settings. The three typologies were assessed through a common analytical structure based on adaptive mechanism, water-depth range, ground relation, structural requirements, damage, and functional operability. Parametric modelling enabled all three typologies to be evaluated within a common analytical framework while preserving their distinct relationships with land and water (Figure 4.3).

For comparative purposes, the study adopted functional modelling ranges of approximately:

- 0–2 m for EF;
- 0–4 m for AM;
- 1–5 m for FP.

These ranges represent analytical performance envelopes adopted for comparative assessment and should not be interpreted as universal design limits.



Source: Author's elaboration

Figure 4.3. Hydro-adaptive typologies under normal and flood conditions.

4.3.2 Summary and main findings

Elevated, amphibious, and floating typologies form a coherent group of hydro-adaptive solutions, but they are not interchangeable. Elevated foundations provide a relatively simple static response. They are most suitable under shallow or moderate flood exposure where land-based occupation remains possible. Amphibious dwellings operate in two states. They rest on the ground under normal conditions and rise during a flood. They provide a transitional response to episodic and variable inundation. Floating platforms remain permanently buoyant. Under the analysed conditions, they provide the greatest

operational continuity in areas exposed to deeper or more persistent water. They also require more complex access, mooring, infrastructure, regulation, and maintenance.

The Building Damage Index analysis indicates that hydro-adaptive typologies can reduce relative component damage when their operating range corresponds with the local hazard profile. Operability analysis shows that limited physical damage alone is not sufficient. A building must also retain safe access, services, stability, and use.

The blue-green infrastructure scenarios indicate possible reductions in surface-water retention time of approximately 18–31%. The strongest effects were observed in Toruń, while the effects in Gdańsk and Tczew were more limited because of local drainage and terrain conditions.

P3 therefore establishes a conditional decision logic:

- EF is most suitable for limited and mainly land-based exposure;
- AM is most suitable for intermittent and variable flooding;
- FP is most suitable for deeper or persistent water conditions.

The final choice also depends on flood duration, access, infrastructure, site morphology, ground conditions, regulation, and implementation capacity. P3 transforms hydro-adaptive architecture (Figure 4.4) from a general design concept into a planning-oriented comparative framework.



A.



B.

Source: Authors own elaboration, based on P3, Figure 10.

Figure 4.4. Visualisation of the three hydro-adaptive typologies evaluated in this study under normal conditions (row A) and flood conditions (row B): elevated foundations (EF) - stilt-supported structures and terp-based configurations, amphibious dwellings (AM), and floating platforms (FP).

4.3.3 Limitations, research gaps, and future directions

The hydraulic analysis uses one-dimensional modelling. It is suitable for comparative planning-level assessment, but it does not reproduce every local lateral-flow process, microtopographic interaction, wave effect, or compound flood mechanism.

The typological parameters are simplified. The functional water-depth ranges, BDI values, and operability criteria support early-stage screening. They cannot replace structural design, geotechnical analysis, detailed hydraulic modelling, or project-level engineering.

The study covers three Lower Vistula settings. The results support interpretation in comparable lowland contexts. Their transfer to other locations requires local calibration.

The Building Damage Index provides a relative basis for comparison and should not be interpreted as a detailed economic-loss model.

The framework should therefore be used as a planning-support tool for initial assessment and typological comparison.

To sum up, P3 provides the main performance-based framework for comparing EF, AM, and FP. It explains how hazard conditions can be connected with typological suitability. This quantitative framework does not fully explain how adaptive strategies can be developed through design, interpreted across different cultural and geographical contexts, or connected with heritage, ecology, and public space. The following publication (P4) addresses these questions through a research-by-design approach, providing an exploratory environment in which adaptive strategies can be generated, discussed, and comparatively evaluated across different waterfront settings.

4.4 Publication P4 – Hydro-adaptive research-by-design laboratory

Gorzka, J., and Nyka, L. (2024). A Laboratory for Adaptation of Urban Areas to Climate Change: Flooding Resilience and Climate-Sensitive Waterfronts. *World Transactions on Engineering and Technology Education*, 22(4), 261–266.

4.4.1 Background, aim, and methodology

P4 moves beyond the site-specific applicability assessment presented in Publication P3 by employing a research-by-design approach to explore how hydro-adaptive strategies and infrastructure can support liveable waterfront development in different European contexts. The research emerged from an international academic collaboration involving six universities: KTH Stockholm, Sapienza University of Rome, Lusófona University Lisbon, Aristotle University of Thessaloniki, TOBB University Ankara, and Gdańsk Tech, within the framework of the Horizon 2020 *SOS Climate Waterfront* project. The study adopts research-by-design as a method of inquiry, whereby knowledge is generated and tested through spatial proposals, visualisation, reflection, and comparative evaluation (Schön, 1983; Frayling, 1994; Cross, 2001).

The methodology comprised four main stages:

1. preliminary investigation;
2. case-study analysis;
3. research-by-design;
4. comparative evaluation using the Target-Applied Interventions Assessment (TAIA) method.

The preliminary investigation and workshops established the interdisciplinary knowledge base for the design process and included lectures, stakeholder engagement, discussions, and the interpretation of local climatic, spatial, environmental, social, and planning conditions. Case-study analysis was then used to identify site-specific challenges and existing adaptation approaches in the investigated

waterfront settings. Research-by-design translated this evidence into alternative architectural, public-space, and landscape interventions.

In addition to these four methodological stages, the detailed case studies in Rome and Gdańsk employed 3D terrain and water-level simulation as a supporting research-by-design method. Situational and elevation data were integrated with three-dimensional terrain models to examine how successive water levels interacted with existing and proposed topography, buildings, and public spaces. The models were developed using AutoCAD LT 2021 and SketchUp Pro 2022, and changing water levels were visualised at one-metre intervals. This procedure enabled the spatial consequences of rising water levels to be examined in relation to terrain configuration and proposed hydro-adaptive interventions.

The Rome and Gdańsk case studies represented contrasting waterfront conditions. In Rome, the principal challenge concerned maintaining public access and functionality along a flood-exposed riverfront, whereas in Gdańsk the analysis addressed low-lying post-industrial and heritage waterfront areas under scenarios of rising water levels. The simulations supported the exploration of how floating, amphibious, elevated, and landscape-based interventions could respond to these changing conditions.

TAIA was co-developed during the SOS Climate Waterfront workshops by an interdisciplinary team including the author of this dissertation. The method provided a structured graphical basis for assessing the relevance and applicability of proposed interventions and for comparing design responses across different case-study contexts. The investigated sites therefore functioned as research settings for examining relationships between changing water levels, architectural form, public space, heritage, ecology, and urban development. P4 combines architectural and planning perspectives with wider interdisciplinary and stakeholder knowledge and provides an exploratory research-by-design assessment of the transferability of hydro-adaptive principles across contrasting waterfront contexts.

4.4.2 Summary and main findings

P4 shows that adaptive waterfront design requires a broad and interdisciplinary perspective. Environmental, economic, social, cultural, and legal conditions are closely connected and cannot be analysed as isolated issues. The results indicate that development in flood-prone areas may be possible when the form of development responds to changing water conditions. Amphibious foundations were assessed as having strong potential for urban extensions under the analysed conditions. Floating buildings and floating public spaces were also identified as possible climate-resilient solutions, both for Gdańsk and Rome. The study also identified the potential for adaptation of heritage buildings through buoyant foundation concepts, in both case studies. It showed that flood barriers and other hard-engineering structures are only one part of the possible response. Nature-based solutions, water-retention systems, green infrastructure, floating structures, and amphibious technologies can form a wider adaptive repertoire, even in the dense urban context. Research-by-design provided insight into changing urban morphologies under different water conditions in Rome (Figure 4.5, Figure 4.6) and Gdańsk (Figure 4.7), and indicated how these morphologies can be reconfigured while maintaining the operational continuity of public space through the application of hydro-adaptive solutions, such as floating architecture, piers or amphibious buildings. It allowed water-level change, architectural form, public space, heritage, ecology, and urban development to be considered together.

In this part of the research, the Target Applied Interventions Assessment (TAIA) method was designed, which supports structured comparison of the interventions applied in the analysed case studies. Within the dissertation, P4 provides exploratory evidence. Its main contribution lies in the development of hydro-adaptive designs through a research-by-design process. It also demonstrates how international collaboration can support knowledge generation through the interpretation of adaptive design concepts across different spatial and cultural contexts. The strength of the approach lies in its ability to consider hydrological conditions, urban morphology, cultural context, architectural form, and public-space relationships within a single analytical framework.



Source: Authors elaboration, based on P4, Figure 3.

a) Regular water level.



Source: Authors elaboration, based on P4, Figure 3.

b) Higher water level – full functionality of the waterfront facilities and buildings maintained.



Source: Authors elaboration, based on P4, Figure 3.

c) The highest water level – full functionality of the waterfront facilities and buildings maintained.

Figure 4.5. Visualisation of the Tiber's waterfront under different water levels - a) b), and c), case study Rome, Quartiere I Flaminio.



Source: Authors elaboration, based on P4.
a) Regular water level.



Source: Authors elaboration, based on P4.
b) Higher water level – full functionality of the waterfront facilities and buildings maintained.



Source: Authors elaboration, based on P4.
c) The highest water level – full functionality of the waterfront facilities and buildings maintained.

Figure 4.6. Visualisation of the Tiber's waterfront under different water levels - a) b), and c), case study Rome, Quartiere I Flaminio - eye level view.



Source: Authors elaboration, based on P4, Figure 4.

a) Regular water level.



Source: Authors elaboration, based on P4, Figure 4.

b) Higher water level (+2m) – full functionality of the waterfront facilities and buildings maintained.



Source: Authors elaboration, based on P4, Figure 4.

c) Higher water level (+4m) – full functionality of the waterfront facilities and buildings maintained.

Figure 4.7. Visualisation of the waterfront under different water levels - a) b), and c), case study Gdańsk.

4.4.3 Limitations, research gaps, and future directions

P4 is based on case-study interpretation, design exploration, comparative evaluation, and research-by-design inquiry. Its results are exploratory. The proposed designs are not construction-ready projects and do not provide confirmatory hydraulic or structural validation. Target Applied Interventions Assessment (TAIA) supports structured comparison, although the assessment still depends partly on expert and evaluator judgement.

The Publication 4 identified several directions for further research:

- continuity of public space at the land–water interface and walkability in flood-prone waterfront areas;
- off-grid operation under conditions of disconnection from municipal utility networks;

These questions show that design exploration must be supported by technical, spatial, and governance evidence.

One of the clearest research needs identified by P4 concerns the energy and service autonomy of floating structures. The research asked how a floating structure could operate during disconnection from energy, water, and wastewater infrastructure. This question provided a direct basis for P5. The next publication examines the floating building as an integrated technical system and evaluates its potential for autonomous operation under different European climatic conditions.

4.5 Publication P5 – Off-grid Autonomous Houseboat

Gorzka, J., Karczewski, A., Litwin, W., Matej-Łukowicz, K., Nawrot, N., Nyka, L., and Piątek, Ł. (2024). Zero-Emissions, Off-grid, Autonomous Houseboat: A Case Study of Selected Locations in Europe. *Polish Maritime Research*, 31(3), 42–60.

4.5.1 Background, aim, and methodology

Previous research indicates that floating architecture is increasingly being considered as a potential response to flood risk. However, questions remain regarding whether floating buildings can continue to operate when disconnected from external infrastructure, electricity supplies, and freshwater sources. To investigate this issue, an interdisciplinary team of specialists in hydraulic and maritime engineering, environmental engineering, chemistry, and legislative regulations was invited to this publication to assess, in collaboration with architects the feasibility of an autonomous floating structure and develop an original prototype concept. As a hybrid structure, a floating building must satisfy architectural, building-services, environmental and marine-engineering requirements. Accordingly, the aim of P5 was to assess the feasibility of a self-sufficient houseboat capable of operating independently of the electricity grid and freshwater supply systems for extended periods. Comparative scenarios were developed for four European locations with contrasting climatic conditions. The analysis examined how solar exposure, heating and cooling demand, energy storage capacity, water availability, and user requirements influence the duration and degree of autonomous operation.

The study was based on a model simulation of a fully self-sufficient object. Four locations were selected:

- Gdańsk;
- Lisbon;
- Rome;
- Stockholm.

These cities represent different European climatic conditions and were previously used as living laboratories, also within the EU Horizon 2020 *SOS Climate Waterfront* project.

The main design assumptions of a floating house included:

- a length of 14.7 m;
- a width of 5 m;
- a height of up to 2.7 m above the water;
- approximately 40 m² of living space;
- accommodation for two to four people.

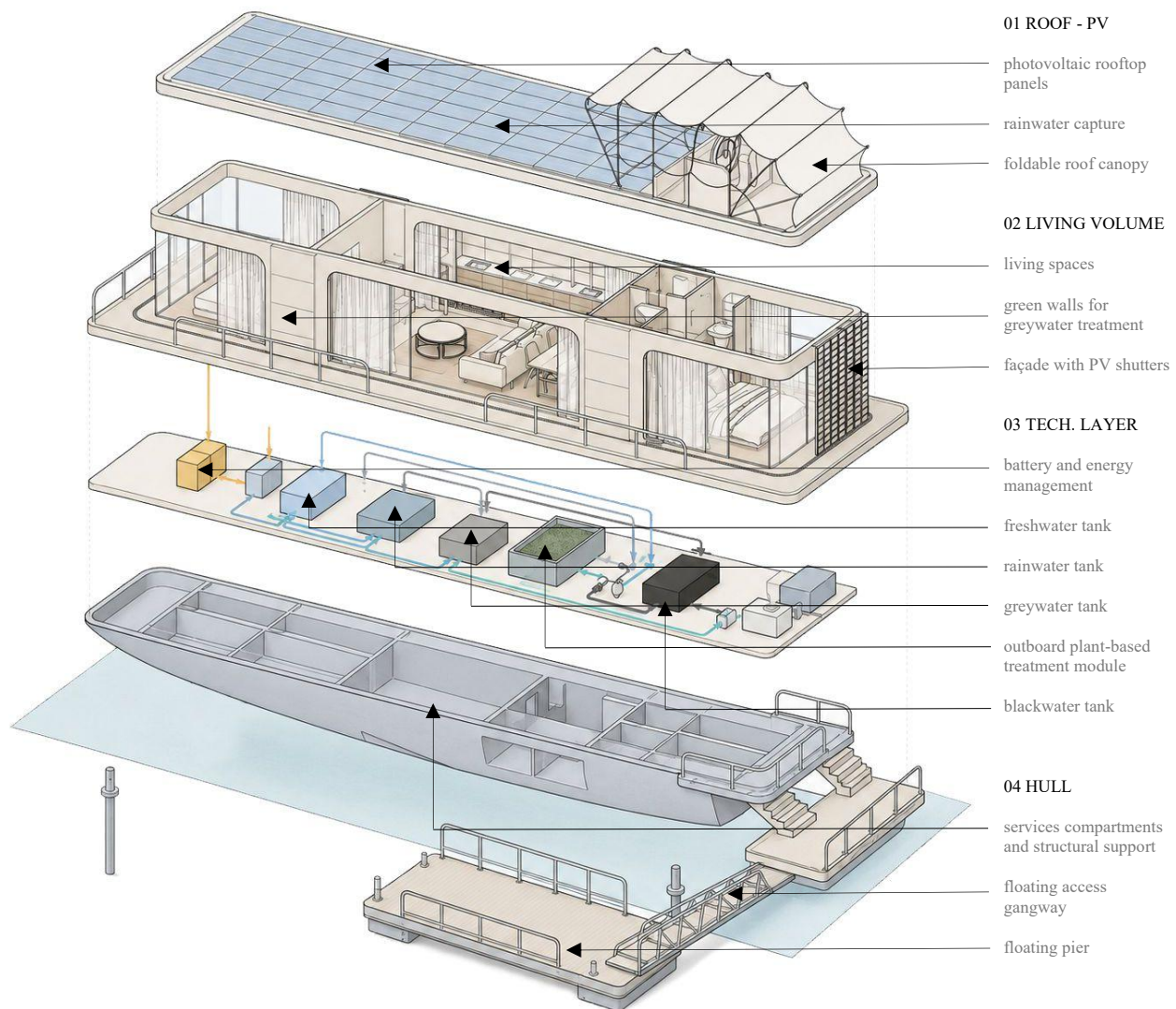
Three hull forms were considered:

- ship-type hull;
- cuboid hull;
- catamaran hull.

The analysis included:

- hull stability and the influence of hull form on architectural capacity and mobility;
- displacement and draft;
- photovoltaic energy production;
- battery storage;
- heating and cooling demand;
- water consumption;
- rainwater collection;
- purification of external water;
- desalination;
- wastewater treatment;
- ventilation and air conditioning;
- waste management.
- the relationship between usable area and the external dimensions of the unit;
- the integration of living and technical spaces;
- modularity and the possibility of adapting the concept to different locations;

The houseboat was therefore analysed as an integrated resource and service system (Figure 4.8). Energy, water, and waste were treated as interconnected components of overall building performance (Schuetze et al., 2013).



Source: Author's elaboration, based on P5.

Figure 4.8. Integrated system axonometry of the autonomous floating dwelling.

4.5.2 Summary and main findings

The study confirms that an autonomous, zero-emission floating dwelling is technically feasible under defined architectural, climatic, and operational assumptions. The proposed prototype provided approximately 40 m² of usable living space for four permanent users within a floating structure approximately 14.7 m long and 5.0 m wide. Three hull configurations – ship-type, cuboid, and catamaran – were assessed in relation to buoyancy, stability, mobility, and the accommodation of the technical systems required for autonomous operation (Figure 4.9, Figure 4.10).

The main architectural contribution of P5 is the development of an integrated design model in which spatial form, hull configuration, user comfort, mobility, energy production and storage, water management, and wastewater treatment are considered as interdependent components of the floating dwelling. The analysis shows that off-grid autonomy must be addressed from the beginning of the architectural design process because the technical systems directly influence the dimensions, layout, envelope, weight, usable area, stability, and operational characteristics of the building.

The energy analysis demonstrated a clear climatic dependency. Under the assumed photovoltaic system and energy-demand profile, the model achieved year-round independence from external energy sources in Rome and Lisbon, whereas in Gdańsk and Stockholm energy autonomy was achievable for more than nine months of the year. The results therefore indicate that full off-grid operation in northern European conditions may require supplementary renewable-energy systems or alternative heating solutions.

The water and wastewater system provided a second measurable dimension of autonomy. The proposed system comprised seven water and wastewater tanks, including an outboard tank, and reduced drinking-water consumption by up to 25% and the volume of wastewater requiring complex treatment by up to 66%. A 280 L outboard water-storage system provided a 14-day reserve for non-drinking-water purposes under the assumed four-person occupancy scenario.

The study also examined the architectural scalability of the concept. Because photovoltaic generation and water-treatment capacity depend partly on the available external surface of the building, increasing occupancy cannot be achieved solely by adding usable floor area. Under the adopted scaling assumptions, the greatest relative increase in required external envelope area occurred when occupancy increased from one to two users, reaching approximately 25%, while the corresponding increase in building height remained below approximately 30%. This finding demonstrates that energy and water autonomy impose measurable architectural constraints on the scaling of floating dwellings.

P5 therefore provides the principal technical and infrastructural evidence concerning the operational feasibility of floating habitation. It shows that the applicability of floating architecture depends not only on buoyancy and structural stability, but also on the capacity to integrate architectural form with energy generation, storage, water supply, wastewater treatment, climatic conditions, and user demand. These findings extend the typological assessment developed in P3 by defining the infrastructural conditions required for operational autonomy and provide an implementation-oriented bridge towards the governance and planning conditions examined in P6.



Source: Author's elaboration, based on P5, Figure 5.

Figure 4.9. Side view of proposed houseboat.



Source: Author's elaboration, based on P5, Figure 7.

Figure 4.10. Deck-level plan of proposed houseboat.

4.5.3 Limitations, research gaps, and future directions

The results depend on model assumptions concerning building size, number of occupants, equipment, system efficiency, and climatic data. Different user patterns or system dimensions would change the results. The findings support feasibility assessment under defined assumptions and should not be interpreted as evidence of universal performance across all floating buildings and environmental contexts. The analysis covers four European locations. It does not establish universal autonomy for all climates and water environments. The photovoltaic system alone does not provide full year-round autonomy in every location. Less favourable locations may require:

- heat pumps;
- wind turbines;
- additional energy storage;
- temporary connection to the grid;
- bidirectional energy exchange;
- other supplementary energy sources.

The environmental impact of a houseboat on the local aquatic ecosystem also requires further study. Onboard water and wastewater systems may reduce direct pollution, but the effects of shading, mooring, water circulation, construction materials, and groups of floating buildings require ecological assessment.

The study also identifies regulatory uncertainty. A floating object may be classified as a building, vessel, or hybrid structure. This affects approval, water use, wastewater discharge, grid connection, and planning status.

P5 confirms that a technically feasible floating building remains dependent on local infrastructure, environmental rules, legal classification, and administrative procedures. The study therefore leads from technical feasibility to institutional implementation. Energy, water, and wastewater systems can support autonomy only when regulations, authorities, operators, and planning systems allow their use.

Publication P6 addresses this wider implementation problem. It examines how technical and spatial evidence can be translated into institutional, participatory, and land-use planning processes.

4.6 Publication P6 – Governance-supported hydro-adaptive implementation

Gorzka, J., Burda, I. M., Józekowski, J., and Nyka, L. (2026a). Revolutionizing Flood Resilience: Human-Centred AI for Adaptive and Regenerative Urban Design. *Land Use Policy*, Article 108218.

4.6.1 Background, aim, and methodology

Hydro-adaptive architecture cannot be considered in isolation from the wider governance and planning systems within which adaptation measures are implemented. Its practical application depends not only on architectural and technical feasibility, but also on how flood-risk information is interpreted, land and water use is regulated, infrastructure is coordinated, institutional responsibilities are distributed, and stakeholders participate in decision-making. Publications P1–P5 provide complementary spatial, typological, hydraulic, research-by-design, and infrastructural evidence concerning hydro-adaptive development. P6 extends this analysis towards the institutional, participatory, regulatory, and decision-support conditions through which such evidence may enrich flood-resilient planning practice.

Within this wider governance context, digital and AI-enabled tools are increasingly used to support flood-risk prediction, modelling, scenario assessment, communication, warning, and response coordination. Their planning relevance depends on interpretability, institutional uptake, stakeholder access, transparency, accountability, and their connection with land-use and spatial-planning procedures. P6 therefore examines Human-Centred Artificial Intelligence (HCAI) as a form of human-centred digital decision support embedded within broader flood-resilient governance and planning systems. In accordance with the HCAI approach, computational capacity is considered together with human control, safety, trust, responsibility, and institutional accountability (Shneiderman, 2020).

The aim of P6 is to examine the conditions under which digital and AI-enabled flood-resilience tools can move beyond technological application and become meaningfully integrated into governance, stakeholder participation, and land-use planning. This extends the preceding architectural and technical investigations towards the wider implementation environment of adaptive spatial strategies, including hydro-adaptive architecture.

Accordingly, at the dissertation level P6 addresses the following governance-oriented research question:

How can governance and planning systems integrate technical evidence, institutional coordination, stakeholder participation, and human-centred digital decision support to facilitate the implementation of adaptive spatial strategies, including hydro-adaptive architecture?

The study employed a comparative document-based multi-case research design. Case selection followed a two-stage screening procedure based on maximum-variation principles. An initial set of 25 flood-prone cities was considered in order to capture variation in flood typology, geographical setting, governance context, documented digital activity, planning-policy integration, and participatory approaches. Nine cities were retained for detailed comparative analysis: Rotterdam, New York, Bangkok, Venice, Tokyo, Copenhagen, Sydney, Kolkata, and London. The final sample included cases with different levels of institutional integration, planning-policy linkage, stakeholder participation, and documented digital implementation, allowing both more advanced and more fragmented governance configurations to be compared.

The documentary evidence included municipal and spatial-planning documents, flood-resilience and climate-adaptation strategies, policy reports, institutional materials, technical documentation, scientific literature, and documented implementation experience. Source triangulation was used to compare evidence originating from different institutional and technical sources. The material was subsequently organised through thematic coding and planning-policy pathway analysis in order to examine how flood-risk information, digital tools, institutional arrangements, participation, and land-use mechanisms were connected within each case.

The comparative analysis was structured around four interrelated analytical pillars:

1. technical integration – the relationship between digital or AI-enabled flood-risk tools, data systems, modelling, communication, and their interoperability with existing planning and decision-making procedures;
2. institutional arrangements – the distribution of responsibilities, inter-agency coordination, regulatory pathways, accountability, and institutional capacity required to translate technical evidence into action;
3. stakeholder engagement – the role of participation, accessible information, feedback, inclusion, and human oversight in increasing the legitimacy and usability of flood-resilience decision support;
4. land-use innovation – the translation of flood-risk knowledge into spatial-planning mechanisms, including land-use regulation, zoning, development guidance, blue-green infrastructure, and adaptive planning procedures.

The analysis distinguished between the mere presence of digital or AI-enabled technologies and their effective integration into governance and planning practice. Machine learning, deep learning, graph neural networks, digital twins, dashboards, warning systems, and related tools were therefore examined not as autonomous solutions, but in relation to human interpretation, institutional uptake, stakeholder participation, transparency, accountability, and planning procedures. From this perspective, HCAI represents a decision-support approach in which computational capabilities remain embedded within human-centred and institutionally accountable processes.

The methodological role of P6 is to identify the wider governance and implementation conditions through which technical and spatial evidence can become usable in planning decisions. P6 consequently

provides the final governance-supported implementation component of the integrated dissertation's cross-scale analytical sequence.

4.6.2 Summary and main findings

The findings show that flood-resilient planning requires the coordination of technical knowledge with institutional capacity, stakeholder participation, and land-use planning. Digital and AI-enabled tools may support flood-risk prediction, modelling, monitoring, communication, and scenario assessment, but their planning relevance depends on how their outputs are interpreted, institutionally embedded, communicated to stakeholders, and translated into spatial and policy decisions. The study therefore indicates that technological capacity alone is insufficient to support resilient urban development.

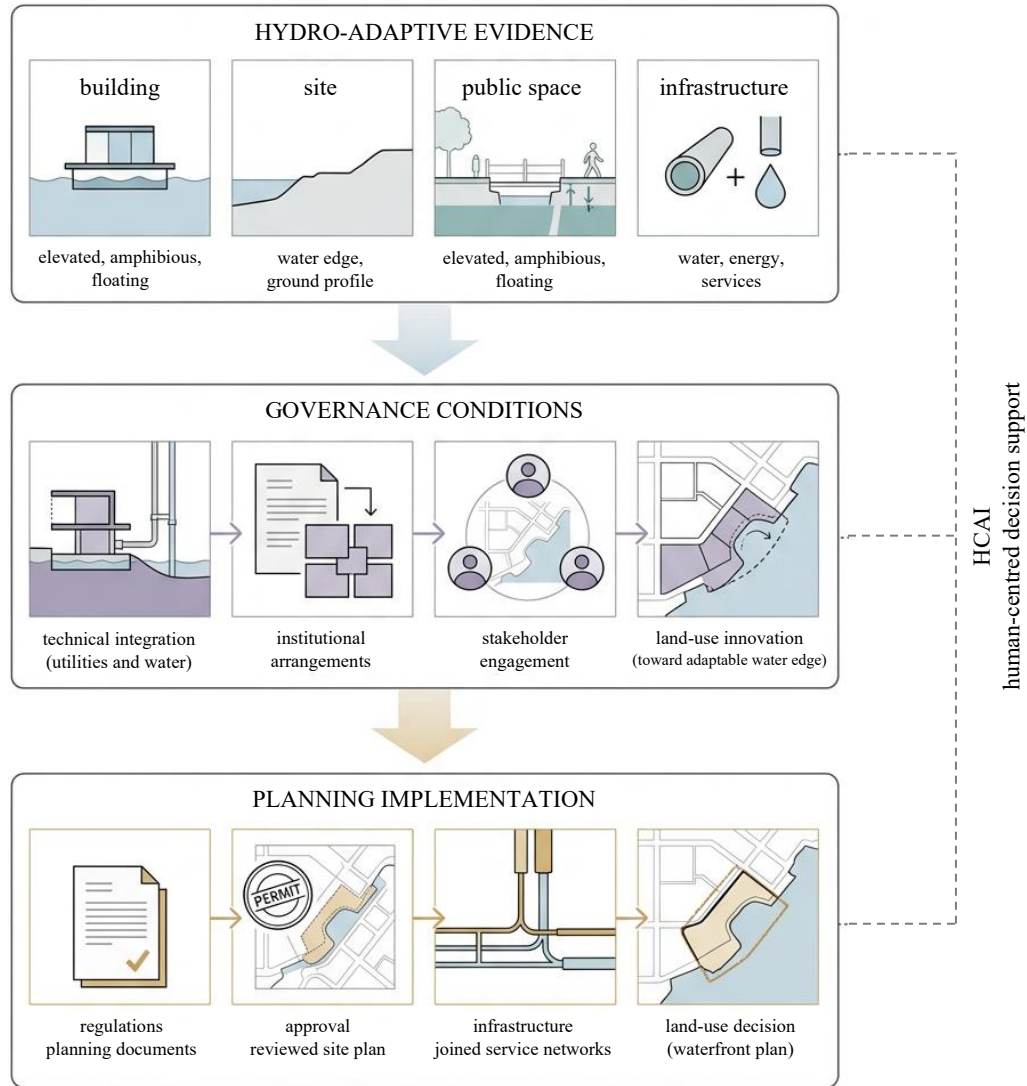
The comparative analysis revealed substantial differences in the degree to which digital flood-resilience tools are connected with governance and planning systems. Among the nine analysed cities, Rotterdam and Copenhagen ($n = 2$) showed strong documented planning-policy linkage and institutional embedding; New York, Bangkok, Tokyo, Kolkata, and London ($n = 5$) showed partial integration; and Venice and Sydney ($n = 2$) showed limited integration. The classification reflects the strength of documentary evidence concerning planning-policy linkage and institutional embedding, rather than the technological quality or effectiveness of the digital or AI-enabled tools themselves.

The four analytical pillars identify complementary conditions for implementation:

- Technical integration: flood-risk information and digital decision-support tools need to be interpretable, transparent, and interoperable with existing planning systems. Their value depends on whether technical outputs can be translated into information usable by planners, institutions, and other decision-makers.
- Institutional arrangements: effective implementation requires clear mandates, coordination between public authorities and infrastructure actors, regulatory pathways, institutional capacity, and accountability. Technical evidence becomes operational only when institutions are able to interpret it and assign responsibility for subsequent action.
- Stakeholder engagement: resilient planning also depends on accessible information, participation, feedback mechanisms, and the inclusion of communities exposed to flood risk. Human-centred decision support therefore requires communication and participatory processes that connect technical knowledge with local needs and civic legitimacy.
- Land-use innovation: flood-risk knowledge becomes spatially operative through its integration into zoning, development guidance, blue-green infrastructure strategies, land-use regulation, and other adaptive planning mechanisms. This pillar provides the direct connection between technical and governance evidence and decisions concerning the future development of flood-prone areas.

Taken together, the findings indicate that resilient design and flood adaptation cannot be reduced to the performance of individual technological solutions. Their implementation depends on relationships between technical evidence, institutional structures, stakeholder participation, regulatory procedures, and land-use policy. AI-enabled and digital tools can support these relationships, but they become planning-relevant only when embedded within transparent, accountable, participatory, and institutionally supported decision-making processes (Figure 4.11).

This finding extends the analysis beyond the building and public-space scales addressed in the preceding publications. Hydro-adaptive solutions may be technically feasible, spatially beneficial, and operationally viable, yet their practical implementation also depends on institutional coordination, regulatory acceptance, infrastructure responsibilities, stakeholder participation, and their integration into wider flood-resilient planning systems. P6 provides the governance-related evidence required to connect the architectural, spatial, hydraulic, and infrastructural findings of P1–P5 with the conditions of planning implementation. Rather than assessing hydro-adaptive architecture directly, the study identifies institutional, participatory, and planning-policy arrangements that may support the integration of adaptive solutions into planning practice.



Source: Author's elaboration.

Figure 4.11. Architecture-centred decision framework for hydro-adaptive development.

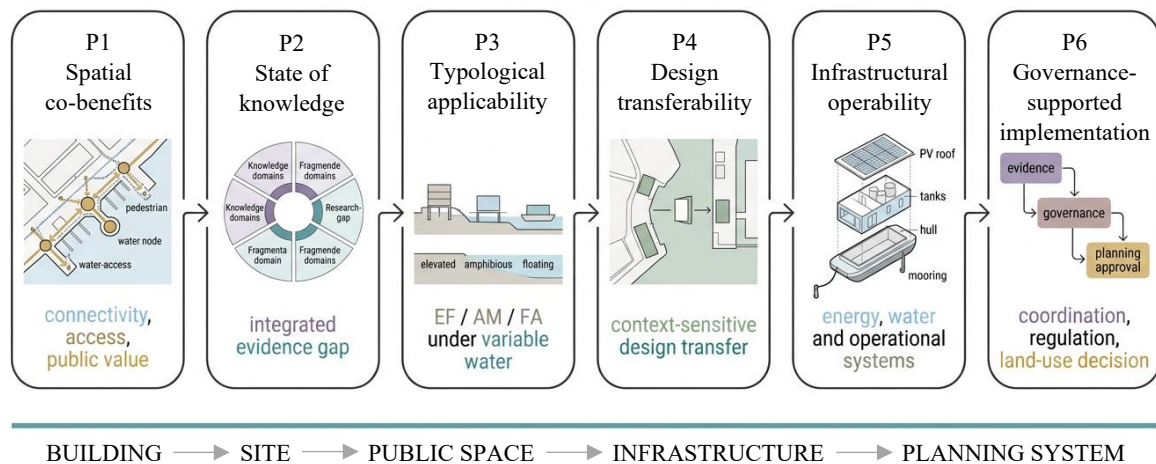
4.6.3 Limitations, research gaps, and future directions

The main limitation is the document-based character of the study. P6 analyses available municipal, institutional, technical, and policy documents. The findings represent documentary evidence of governance configurations. A second limitation concerns documentary availability. Cities with strong institutions, extensive reporting, international visibility, and English-language documentation are more likely to provide sufficient material. The sample supports comparative interpretation, but it is not statistically representative of all planning systems. The study relies on interpretative and documentary comparison and does not test causal relationships between specific technologies and planning outcomes. The findings support the interpretation of governance systems and implementation pathways, but they do not independently validate AI performance or permit statistical generalisation across all planning contexts. Future work should address institutional reflexivity together with algorithmic development. HCAI must remain transparent, accountable, participatory, and connected with the societies it serves. These limitations do not diminish the value of AI-enabled tools but highlight the importance of embedding technological innovation within institutional, participatory, and planning frameworks. This broader perspective provides the final component of the dissertation-level synthesis presented in the following section.

4.7 Synthesis of the six publications

The synthesis follows the dissertation-level analytical order of Publications P1–P6. P1 establishes the spatial premise of the dissertation by showing that flood-adaptive waterfront interventions – including floating structures, blue-green infrastructure, elevated routes, public-space interventions, floating gardens, and water-access platforms – can generate measurable spatial co-benefits related to pedestrian connectivity, public-space continuity, and land–water accessibility. P2 structures the international state of knowledge and identifies the principal comparative, infrastructural, and implementation-related research needs. P3 provides performance-based evidence on how the applicability of elevated, amphibious, and floating typologies varies differentiated flood conditions. P4 explores how hydro-adaptive principles can be interpreted and adapted across contrasting waterfront contexts through research-by-design. P5 examines the technical and infrastructural conditions required for floating habitation to operate through integrated energy, water, wastewater, hull, and spatial systems. Finally, P6 identifies the institutional, participatory, regulatory, and planning-policy conditions through which technical and spatial evidence can inform planning decisions and support the governance-supported implementation of adaptive solutions.

Together, the six publications establish a cross-scale evidence chain extending from spatial value and the state of knowledge to typological applicability, design transferability, infrastructural operability, and governance-supported implementation (Figure 4.12, Table 4.1).



Source: Author's elaboration.

Figure 4.12. Dissertation-level evidence chain from spatial value to governance-supported implementation.

Table 4.1. Complementary evidence strands and dissertation-level roles of Publications P1–P6.

Publication	Main evidence strand	Main role in the dissertation
P1 Walkability and flood resilience	Spatial and morphological evidence	Establishes measurable spatial co-benefits related to pedestrian connectivity, public-space continuity, and land–water accessibility
P2 Systematic Review	Systematic knowledge-synthesis evidence	Establishes the state of knowledge and identifies comparative, infrastructural, and implementation-related research needs
P3 Hydro-adaptive typologies	Hydraulic, damage, operability, and typological evidence	Defines the applicability of elevated, amphibious, and floating typologies under differentiated flood conditions
P4 Hydro-adaptive research-by-design laboratory	Exploratory and research-by-design evidence	Examines the cross-contextual interpretation and transferability of hydro-adaptive principles
P5 Off-grid autonomous houseboat	Technical and infrastructural evidence	Defines the architectural, technical, and infrastructural conditions of autonomous and semi-autonomous floating habitation
P6 Governance-supported hydro-adaptive implementation	Governance and planning-policy evidence	Identifies institutional, participatory, regulatory, and planning-policy conditions supporting the implementation of adaptive solutions

Source: Author's elaboration based on publications P1–P6.

Together, the publications show that the assessment of **hydro-adaptive architecture for flood-prone waterfronts requires the integration of six complementary dimensions**:

1. **hydrological conditions and flood exposure** – including flood regime, water depth, duration, and site-specific hazard conditions;
2. **typological and performance conditions** – including adaptive mechanism, potential damage, structural feasibility, and functional operability;
3. **spatial and public-space conditions** – including pedestrian connectivity, public-space continuity, land–water accessibility, and relationships with the surrounding urban fabric;
4. **technical and infrastructural conditions** – including energy supply, water and wastewater systems, storage, servicing, access, and operational autonomy;
5. **environmental and blue-green conditions** – including retention, blue-green infrastructure, ecological interfaces, and site-specific environmental requirements;
6. **governance and planning conditions** – including regulatory approval, institutional responsibilities, stakeholder participation, infrastructure coordination, and land-use planning.

The integration of these evidence strands provides the basis for the dissertation-level planning-support framework. Elevated foundations, amphibious, and floating architecture form a coherent but differentiated hydro-adaptive repertoire whose applicability depends on the alignment of hydrological, spatial, technical, infrastructural, environmental, regulatory, and institutional conditions. The contribution of the synthesis lies in connecting these conditions within a single cross-scale architectural and planning argument and in translating them into a structured basis for early-stage assessment and decision support.

The combined evidence also allows the four research questions to be answered at a dissertation level. Table 4.2 summarises these answers and indicates the publications that provide the principal supporting evidence and their relationship with Theses T1–T3.

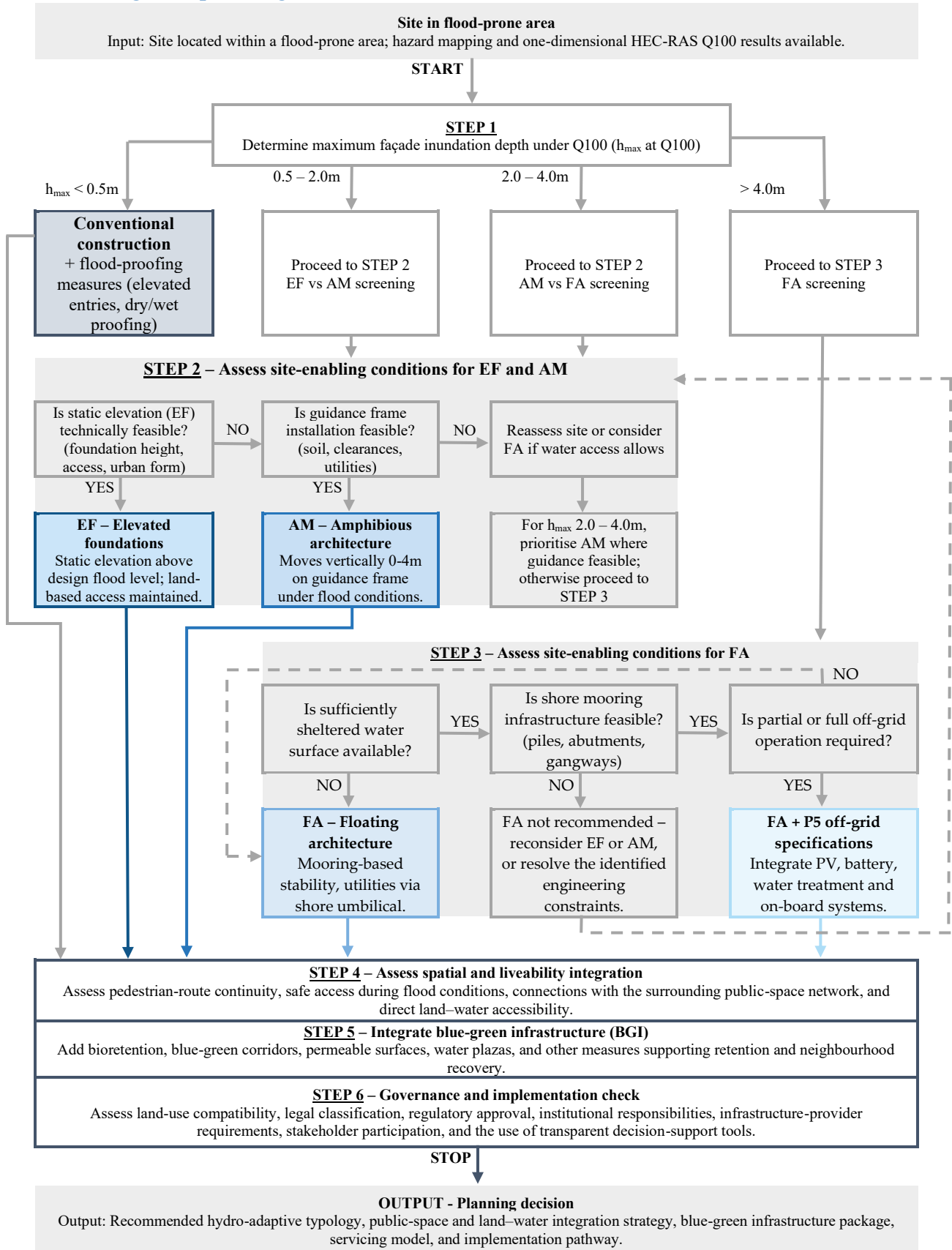
Table 4.2. Dissertation-level answers to the research questions.

Research question	Integrative dissertation-level answer	Principal evidence	Thesis linkage
RQ1 - spatial and liveability contribution	Flood-adaptive waterfront interventions can generate measurable spatial co-benefits by extending pedestrian networks, improving connectivity and public-space continuity, and increasing land–water accessibility when appropriately integrated with the existing urban structure.	P1; supporting evidence P4	T3
RQ2 - typological applicability	Elevated, amphibious, and floating typologies form an established hydro-adaptive repertoire, but their applicability differs according to flood regime, site conditions, adaptive mechanism, spatial context, infrastructure, and implementation requirements.	P2, P3; supporting evidence P4	T1, T2, T3
RQ3 - technical and operational performance	Typological feasibility requires compatibility between hydraulic conditions, structural and damage performance, access, servicing, and infrastructure; for floating habitation, operational feasibility additionally depends on energy, water, wastewater, storage, stability, and climatic conditions.	P3, P5	T1, T2
RQ4 - governance-supported implementation	Implementation requires institutional coordination, regulatory pathways, stakeholder participation, infrastructure responsibilities, land-use integration, and transparent decision support capable of translating adaptation evidence into planning practice.	P6; P5 as infrastructural bridge	T3

Source: Author's elaboration based on publications P1–P6.

Together, these findings provide direct answers to RQ1–RQ4 and establish the evidence base subsequently used for the formal verification of Theses T1–T3 in Chapter 5. These integrated findings are operationalised in the planning-support framework presented in Section 4.8.

4.8 Integrated planning framework



Data source: P3 Tab. 8 (decision matrix); P3 §4 (planning synthesis).

Figure 4.13. Integrated planning framework linking flood-hazard conditions, hydro-adaptive typology selection, spatial integration, infrastructural operability, and governance requirements.

The framework operationalises the integrated evidence established in Section 4.7 as an early-stage planning-support procedure. Its typological screening logic is derived primarily from the comparative assessment developed in P3 and is complemented by spatial, infrastructural, environmental, and implementation criteria established across the dissertation.

Figure 4.13 begins with flood-hazard characterisation and proceeds through typology screening and site-enabling conditions. The selected alternatives are then assessed in relation to spatial and liveability integration, blue-green infrastructure, servicing requirements, and governance and implementation conditions before a planning recommendation is formulated.

The framework is intended for early-stage screening and decision support. It does not replace project-specific hydraulic, geotechnical, structural, environmental, infrastructural, or regulatory verification. Its purpose is to identify potentially appropriate typologies, indicate supporting spatial and servicing strategies, and specify the additional analyses required before implementation. Chapter 5 subsequently evaluates whether the evidence underlying this framework supports the three dissertation theses.

5 Chapter 5. Verification of the dissertation theses

The three dissertation theses were verified through the combined evidence presented in Publications P1–P6. Chapter 5 evaluates the three dissertation theses against the evidence synthesised in Chapter 4. Its purpose is not to restate the analytical sequence of Publications P1–P6, but to determine whether their combined findings provide sufficient support for the conceptual, methodological, and planning propositions formulated in Chapter 1. Each subsection therefore links the relevant evidence directly to Theses T1–T3.

5.1 Verification of T1 – Conceptual thesis

T1.

Hydro-adaptive architecture constitutes a coherent architectural and planning category comprising elevated foundations, amphibious architecture, and floating architecture; however, these typologies represent differentiated adaptive strategies whose suitability depends on the interaction between flood regime, site characteristics, adaptive mechanism, infrastructural conditions, and planning constraints.

The research findings confirm T1. P2 establishes the typological basis for this grouping, while P3 provides the principal comparative evidence concerning differentiated applicability under defined flood conditions. P5 further demonstrates that floating habitation has distinct operational and infrastructural requirements. Together, this evidence supports the conceptual unity of the hydro-adaptive category while confirming that the selection of an individual typology remains conditional on local hydrological, spatial, technical, and infrastructural conditions.

5.2 Verification of T2 – Methodological thesis

T2.

The comparative assessment of hydro-adaptive architecture requires an integrated, multi-method research framework that combines systematic evidence synthesis, typological analysis, research-by-design, hydraulic modelling, engineering verification, spatial-performance assessment, and governance analysis.

T2 is confirmed. As detailed in Section 3.3, the comparative assessment of hydro-adaptive architecture required complementary methods operating at different analytical scales and generating different forms of evidence. Spatial and morphological analysis addressed public-space effects; systematic evidence synthesis established the state of knowledge and research needs; hydraulic and typological assessment examined performance under defined flood conditions; research-by-design explored cross-contextual interpretation and transferability; technical analysis examined operational and infrastructural feasibility; and governance analysis addressed implementation conditions.

The methodological significance lies in the complementarity of these approaches. None of the individual methods provides sufficient evidence across all relevant architectural, spatial, hydraulic, infrastructural, and implementation dimensions. Their integration therefore enables the cross-scale assessment required by T2.

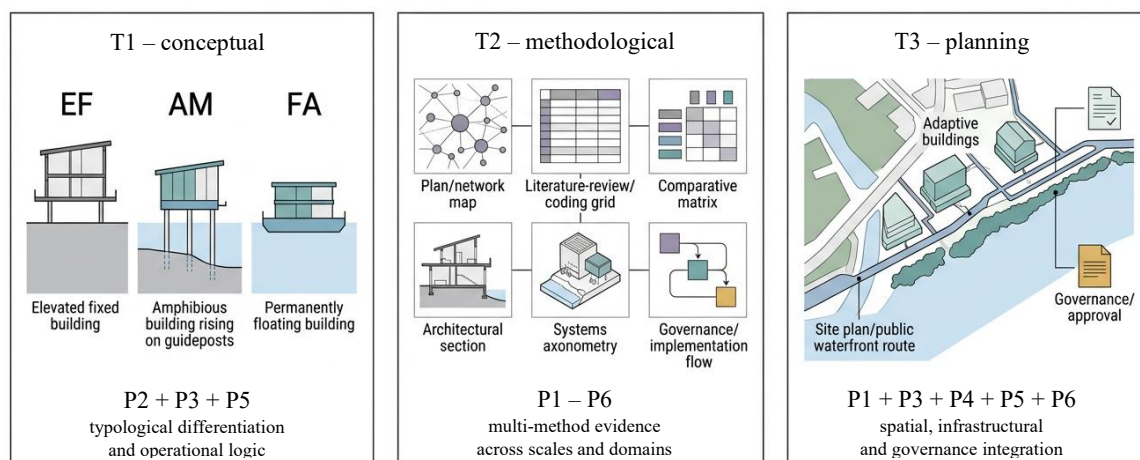
5.3 Verification of T3 – Planning thesis

T3.

The planning value of hydro-adaptive architecture depends on its capacity to integrate building-level flood adaptation with public-space continuity, land–water accessibility, blue-green infrastructure, infrastructural operability, and governance-supported decision-making, thereby supporting resilient and liveable waterfront development.

T3 is confirmed. P1 demonstrated that flood-adaptive waterfront interventions including hydro-adaptive buildings and structures, can strengthen spatial quality by improving the configuration and connectivity of pedestrian networks. Across the analysed Baltic Sea Region cases, the interventions increased the number and concentration of pedestrian nodes, created additional route alternatives, and strengthened direct connections between public spaces and the waterfront. These changes are important morphological determinants of walkability because greater network permeability and route choice improve accessibility and continuity of pedestrian movement. In this sense, improved walkability supports waterfront liveability by strengthening everyday access, public-space continuity, and interaction with the water. P3 connected building-level adaptation with site and neighbourhood conditions. Amphibious and floating solutions reduced damage or maintained habitability within their respective operating ranges, while bioretention measures and blue-green corridors reduced surface-water retention time by 18–31%. P4 provided research-by-design evidence concerning the integration of architecture, public space, heritage, ecology, and waterfront transformation. P5 demonstrated that continuous habitation depends on energy, water, wastewater, storage capacity, hull form, and climatic conditions. Finally, P6 identified four implementation conditions for resilient and hydro-adaptive strategies: technical integration, institutional arrangements, stakeholder engagement, and land-use innovation. Together, this evidence confirms T3 by showing that the planning relevance of hydro-adaptive architecture emerges when building-level adaptation is coordinated with public-space continuity, land–water accessibility, blue-green infrastructure, infrastructural operability, and governance-supported implementation.

Taken together, the evidence supports T1–T3 within the defined research scope (Figure 5.1). Chapter 6 therefore turns from thesis verification to the broader conclusions, disciplinary contribution, limitations, and future research directions arising from these findings.



integrated planning–support framework

Source: Author's elaboration.

Figure 5.1. Evidence supporting the verification of Theses T1-T3.

6 Chapter 6. Conclusions and future research directions

6.1 Conclusions

The research demonstrates that flood-resilient waterfront development requires more than a single protective, architectural, ecological, or technological intervention. Flood risk results from the interaction of hydrological processes, urban morphology, building vulnerability, infrastructure, patterns of use, and governance. The relevance of hydro-adaptive architecture therefore depends on the relationship between the adaptive mechanism, local flood exposure, spatial integration, infrastructural requirements, environmental conditions, and institutional feasibility.

The principal conclusion is that hydro-adaptive architecture should be evaluated not only as a building-scale response to flood risk, but also in relation to its role within integrated planning strategies capable of supporting resilient waterfront transformation under changing climatic conditions. Its applicability remains conditional on local hazard conditions, adaptive mechanisms, spatial relationships, infrastructural requirements, environmental conditions, and institutional capacity.

Elevated, amphibious, and floating typologies respond to changing water conditions through fundamentally different relationships between built form, ground, and water. Their adaptive mechanisms are intended to maintain habitability or functional continuity during flood exposure, while generating different spatial, structural, access, and infrastructural requirements under both normal and flood conditions. Their suitability must therefore be evaluated in relation to the complete operating context of the site, rather than to flood performance alone. The planning-support framework developed in Chapter 4 translates these relationships into a structured basis for comparing typological alternatives under defined local conditions.

These conclusions provide the basis for identifying the theoretical, methodological, and planning-oriented contributions of the dissertation to the discipline of architecture, discussed in the following section.

6.2 Contribution to the discipline of architecture

The contribution of the dissertation to the discipline of architecture can be considered at three complementary levels: theoretical, methodological, and planning-oriented. The theoretical contribution concerns the way hydro-adaptive architecture is conceptualised and understood as an architectural field of inquiry. The methodological contribution concerns the integration of complementary forms of evidence across scales. The planning contribution concerns the translation of this knowledge into a locally adaptable framework supporting early-stage assessment and decision-making in flood-prone waterfronts.

6.2.1 Theoretical contribution to architectural knowledge

The principal theoretical contribution of the dissertation lies in developing a relational and multi-scalar understanding of hydro-adaptive architecture as a field of architectural knowledge. The research does not propose elevated, amphibious, and floating solutions as newly identified typologies; these are already well recognised in the international literature. Instead, it demonstrates that they can be understood as a coherent yet differentiated hydro-adaptive architectural category whose individual typologies respond to changing water conditions through distinct relationships between built form, ground, and water. Their architectural significance therefore lies not only in their technical mechanism of adaptation, but also in the spatial, functional, infrastructural, and urban consequences generated by that mechanism.

A second theoretical contribution concerns the shift from typology understood as an isolated building solution towards typology understood through relationships and conditions of applicability. The dissertation shows that the suitability of elevated, amphibious, and floating architecture cannot be explained by typological characteristics alone. It emerges from the relationship between flood regime, adaptive mechanism, site morphology, spatial organisation, access, infrastructure, environmental conditions, and intended patterns of occupation. This establishes context-sensitive applicability as a

central theoretical principle of hydro-adaptive architecture: the typologies form a common architectural repertoire, but their relevance remains conditional rather than universal.

A third contribution is the extension of architectural performance beyond building-scale resistance to water. The findings show that hydro-adaptive architecture can also be evaluated through its relationships with public space, pedestrian connectivity, land–water accessibility, and waterfront morphology. Architecture is therefore interpreted as part of a wider land–water spatial system in which building form, public realm, infrastructure, and changing hydrological conditions interact. This extends the conceptual scope of hydro-adaptive architecture from the protection or adaptation of an individual object towards the transformation of relationships between buildings, water, ground, and urban space.

The dissertation consequently contributes to architectural theory by positioning hydro-adaptive architecture as a relational, conditional, and multi-scalar category of the built environment. Its theoretical value lies in connecting three levels that are often examined separately: the adaptive mechanism of the building, the spatial consequences of its relationship with the waterfront, and the infrastructural and environmental conditions required to maintain habitation and functionality. In this interpretation, architecture acts as a mediating discipline between environmental dynamics and the organisation and use of built space, while retaining architectural form, typology, inhabitation, and spatial quality as its central concerns.

6.2.2 Methodological contribution

The methodological contribution of the dissertation lies in integrating complementary evidence generated at different analytical scales without treating the methods as interchangeable. Spatial and morphological analysis, systematic evidence synthesis, hydraulic and typological assessment, research-by-design, technical and infrastructural analysis, and governance-oriented comparative analysis each address a distinct component of the research problem. Their integration enables hydro-adaptive architecture to be assessed simultaneously as an architectural typology, a response to hydrological conditions, a component of public-space systems, an infrastructural system, and an element operating within wider implementation conditions.

This cross-scale methodological structure provides a means of connecting evidence that is usually produced separately. Its contribution lies in establishing how different forms of architectural, spatial, hydraulic, technical, and governance evidence can be combined to achieve a coherent, multi-scalar assessment framework for hydro-adaptive architecture.

6.2.3 Planning relevance and practical applicability

The planning relevance of the dissertation lies in its focus on a holistic understanding of how hydro-adaptive architecture can be designed, evaluated, and implemented within diverse urban contexts. Hydro-adaptive architecture is presented as one component of wider adaptation strategies, alongside flood protection, blue-green infrastructure, development control, land-use change, and retreat where necessary. The proposed approach can support the initial assessment of flood-prone waterfronts by structuring the following questions:

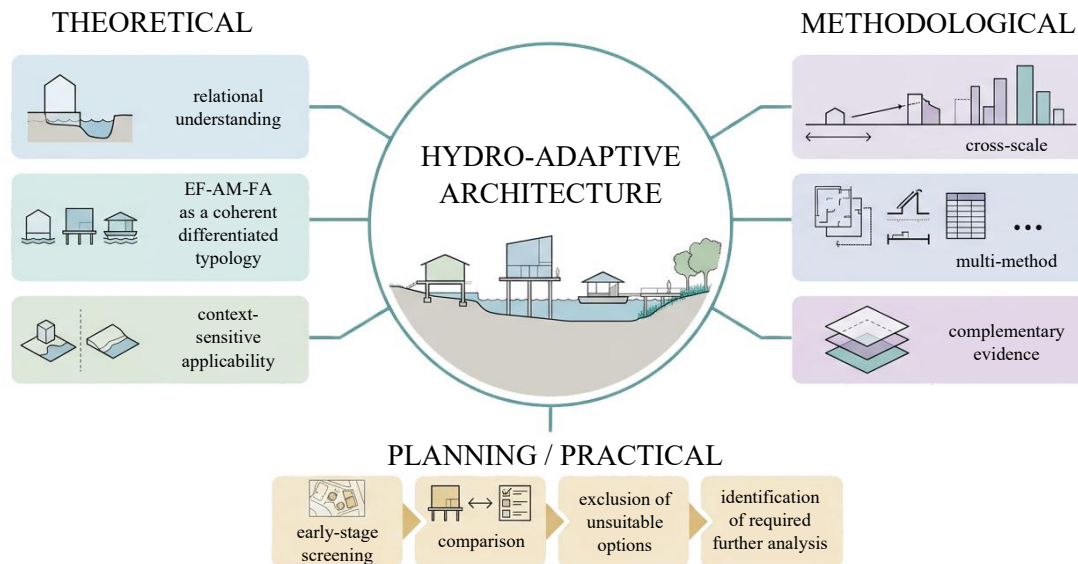
- What type, depth, duration, and recurrence of water exposure characterise the site?
- Which forms of occupation and functional continuity are expected?
- How will the intervention relate to streets, public spaces, and access to water?
- What energy, water, wastewater, access, and maintenance systems are required?
- Which environmental, legal, and institutional conditions affect implementation?
- What further site-specific verification is needed?

This structure is particularly relevant to Polish and broader Central European lowland and riverine contexts, where international examples require adaptation to different flood regimes, legal classifications, infrastructure systems, ownership patterns, and planning cultures.

Boundaries of applicability

The applicability of the dissertation findings is bounded by the environmental, spatial, climatic, and institutional conditions represented by the selected case studies. The international cases provide comparative variation rather than statistical representation, and transfer to other waterfront contexts therefore requires local calibration and project-specific assessment. Further hydraulic, geotechnical, structural, environmental, infrastructural, and statutory verification remains necessary before implementation.

The dissertation reframes hydro-adaptive architecture as part of a wider architectural response to environmental uncertainty. Its contribution lies in connecting the adaptation of buildings with the transformation of waterfront space and with the systems required for long-term occupation and implementation. The final outcome is a planning-oriented architectural framework that supports the transition from the question of whether hydro-adaptive solutions are conceivable to the more relevant question of when, where, and under what conditions they can become appropriate components of resilient waterfront development.



Source: Author's elaboration.

Figure 6.1. Three levels of the dissertation's contribution to architecture.

6.3 Future research directions

The remaining uncertainties concerning empirical validation, long-term performance, transferability, environmental effects, and implementation provide the basis for the future research directions presented below. The dissertation opens several directions for further research.

The first direction concerns hydraulic and spatial modelling. Future studies should test the framework using 2D or coupled 1D–2D hydraulic models, especially in complex urban floodplains where lateral flow redistribution and microtopography strongly influence inundation patterns.

The second direction concerns full-scale technical assessment and pilot implementation. EF, AM and FA should be examined through structural, geotechnical, utility, cost and maintenance studies in specific implementation contexts. This would allow the planning-support framework developed in the dissertation to be extended toward project-level feasibility assessment.

The third direction concerns post-occupancy and user-centred research. The dissertation identifies spatial co-benefits such as walkability and public-space continuity, but future work should examine how users experience hydro-adaptive waterfront environments over time.

The fourth direction concerns long-term environmental performance. Floating and amphibious architecture should be studied in relation to water quality, aquatic ecosystems, material durability, life-cycle impacts and maintenance responsibilities.

The fifth direction concerns governance and regulatory implementation. Future research should examine how hydro-adaptive typologies can be incorporated into local plans, building regulations, insurance systems, ownership structures and public procurement procedures.

The sixth direction concerns comparative international testing. The framework should be tested in other lowland, deltaic, coastal and riverine contexts in order to refine its transferability and identify region-specific adaptation pathways.

A seventh direction concerns social and economic feasibility. Future research should address affordability, tenure, equity, insurance and financing mechanisms, accessibility for vulnerable groups and the distributive effects of waterfront adaptation.

An eighth direction concerns deeper cross-scalar integration through district-scale pilot studies and implementation-oriented demonstrators linking typological choice, blue-green infrastructure, utilities, access systems and regulatory instruments.

Collectively, these research directions form a structured progression from technical verification to implementation-oriented planning research. The first set of directions (FR1–FR2) concentrates on technical validation, pilot implementation, and environmental performance assessment. The second set (FR7–FR8) extends the framework towards social, spatial, environmental, and district-scale integration. The third set (FR3–FR6) addresses governance, regulation, transferability, and digitally supported implementation pathways. The future research agenda demonstrates that hydro-adaptive architecture remains an emerging field requiring further empirical validation, technical development, environmental assessment, and governance integration. At the same time, the results of the dissertation indicate that sufficient evidence already exists to support its use as a planning-oriented adaptation strategy. Continued research should therefore focus not only on improving individual solutions but also on strengthening the connections between architectural design, infrastructure, environmental systems, and institutional implementation. In this sense, the dissertation provides both a synthesis of current knowledge and a foundation for future investigations into resilient and liveable waterfront development.

To clarify how the dissertation may be extended beyond its current empirical and methodological boundaries, Figure 6.2 organises the principal future research directions into a sequenced roadmap structured by time horizon, methodological dependency, and expected outputs.

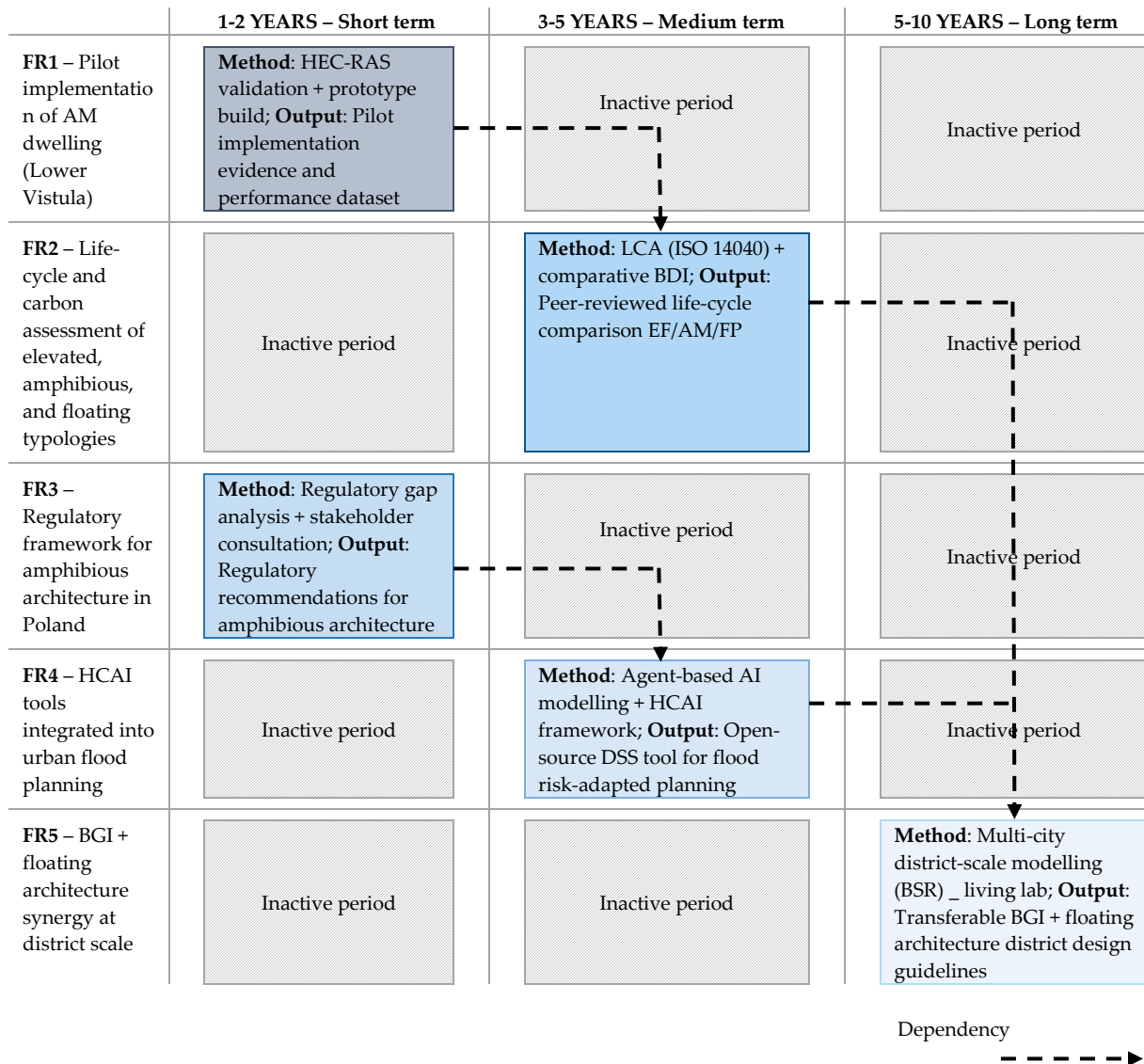


Figure 6.2. Future research roadmap for the Hydro-Adaptive Architecture Framework.

6.4 Final synthesis

The dissertation began with the question of how waterfront cities can reconcile flood adaptation with liveability through hydro-adaptive architecture. The answer emerging from the research is that architecture can play a mediating role in adaptation at the land–water interface by organising relationships between changing water levels, built form, public space, infrastructure, and everyday urban life. In this sense, hydro-adaptive architecture represents not only a response to flood risk but also an opportunity to redefine how waterfront cities coexist with changing environmental conditions.

The dissertation therefore contributes to the emerging shift from resisting water towards designing and planning with water. It provides an architectural basis for considering adaptation across building, public-space, infrastructural, and implementation scales and establishes a foundation for future research and planning practice aimed at creating resilient and liveable waterfront environments.

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Papers

Paper 1

Gorzka, J., Burda, I. M., & Nyka, L. (2025). Walkability and flood resilience: Public space design in climate-sensitive urban environments. *Urban Planning*, 10, Article 9561.
<https://doi.org/10.17645/up.9561>

Paper 2

Gorzka, J., Burda, I. M., & Nyka, L. (2026). Floating and amphibious architecture in waterfront built environments: A systematic review of climate adaptation and regenerative potential. *Sustainability*, 18(12), Article 5966. <https://doi.org/10.3390/su18125966>

Paper 3

Gorzka, J., Burda, I. M., & Nyka, L. (2026). Hydro-adaptive housing for flood-resilient planning: Elevated, amphibious and floating solutions. *Buildings*, 16(10), Article 1880.
<https://doi.org/10.3390/buildings16101880>

Paper 4

Gorzka, J., & Nyka, L. (2024). A laboratory for adaptation of urban areas to climate change: Flooding resilience and climate-sensitive waterfronts. *World Transactions on Engineering and Technology Education*, 22(4), 261–266. <https://doi.org/10.5281/zenodo.14711488>

Paper 5

Gorzka, J., Karczewski, A., Litwin, W., Matej-Łukowicz, K., Nawrot, N., Nyka, L., & Piątek, Ł. (2024). Zero-emissions, off-grid, autonomous houseboat: A case study of selected locations in Europe. *Polish Maritime Research*, 31(3), 42–60. <https://doi.org/10.2478/pomr-2024-0035>

Paper 6

Gorzka, J., Burda, I. M., Józekowski, J., & Nyka, L. (2026). Revolutionizing flood resilience: Human-centred AI for adaptive and regenerative urban design. *Land Use Policy*, 170, Article 108218.
<https://doi.org/10.1016/j.landusepol.2026.108218>

Appendices

Appendix A. Statements of co-authors

This appendix contains formal statements of co-authors concerning publications P1-P6 included in the doctoral dissertation.

Statement concerning publication P1

Publication identifier: P1

Title: Walkability and Flood Resilience: Public Space Design in Climate-Sensitive Urban Environments

Authors: Gorzka, J., Burda, I., and Nyka, L.

Source: *Urban Planning*, 2025, 10, 9561. <https://doi.org/10.17645/up.9561>

Contribution shares: Gorzka, J. 60%, Burda, I. 35%, and Nyka, L. 5%

Declaration text: I, the undersigned, confirm that I am a co-author of the publication identified above and consent to its inclusion in the doctoral dissertation of Jakub Gorzka. I confirm that Jakub Gorzka's individual contribution to the publication comprised the activities specified below and that this description accurately reflects the actual division of work among the authors.

- Conceptualisation;
- Methodology;
- Comparative framework / indicator development;
- Case-study analysis;
- Formal analysis;
- Visualisation / figures;
- Writing - original draft preparation;
- Writing - review and editing;

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Place and date:


Gdańsk, 07.09.2026


Gdańsk, 09.09.2026

Statement concerning publication P2

Publication identifier: P2

Title: Floating and Amphibious Architecture in Waterfront Built Environments: A Systematic Review of Climate Adaptation and Regenerative Potential

Authors: Gorzka, J., Burda, I., and Nyka, L.

Source: *Sustainability*, 2026, 18, 5966. <https://doi.org/10.3390/su18125966>

Contribution shares: Gorzka, J. 60%, Burda, I. 35%, and Nyka, L. 5%

Declaration text: I, the undersigned, confirm that I am a co-author of the publication identified above and consent to its inclusion in the doctoral dissertation of Jakub Gorzka. I confirm that Jakub Gorzka's individual contribution to the publication comprised the activities specified below and that this description accurately reflects the actual division of work among the authors.

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Statement concerning publication P3

Publication identifier: P3

Title: Hydro-Adaptive Housing for Flood-Resilient Planning: Elevated, Amphibious and Floating Solutions

Authors: Gorzka, J., Burda, I., and Nyka, L.

Source: *Buildings*, 2026, 16, 1880. <https://doi.org/10.3390/buildings16101880>

Contribution shares: Gorzka, J. 60%, Burda, I. 35%, and Nyka, L. 5%

Declaration text: I, the undersigned, confirm that I am a co-author of the publication identified above and consent to its inclusion in the doctoral dissertation of Jakub Gorzka. I confirm that Jakub Gorzka's individual contribution to the publication comprised the activities specified below and that this description accurately reflects the actual division of work among the authors.

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- Formal analysis;
- Visualisation / figures;
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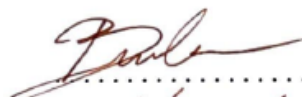
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Gdańsk, 09.09.2026

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Publication identifier: P4

Title: A Laboratory for Adaptation of Urban Areas to Climate Change: Flooding Resilience and Climate-Sensitive Waterfronts

Authors: Gorzka, J., and Nyka, L.

Source: *World Transactions on Engineering and Technology Education (WTETE)*, 2024, 22(4), <https://doi.org/10.5281/zenodo.14711488>

Contribution shares: Gorzka, J. 80%, Nyka, L. 20%

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Publication identifier: P5

Title: Zero-Emissions, Off-grid, Autonomous Houseboat: A Case Study of Selected Locations in Europe

Authors: Gorzka, J., Karczewski, A., Litwin, W., Matej-Lukowicz, K., Nawrot, N., Nyka, L., and Piątek, Ł.

Source: *Polish Maritime Research*, 2024, 31(Issue 3 (September 2024)).

<https://doi.org/10.2478/pomr-2024-0035>

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- Methodology;
- Technical / design input: architectural design and description;
- Visualisation / figures: visualization, architectural schemes and scalability;
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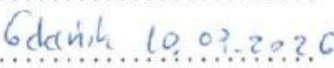
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Authors: Gorzka, J., Karczewski, A., Litwin, W., Matej-Łukowicz, K., Nawrot, N., Nyka, L., and Piątek, Ł.

Source: *Polish Maritime Research*, 2024, 31(Issue 3 (September 2024)).
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Contribution shares: Gorzka, J. 20%, Karczewski, A. 16%, Litwin, W. 16%, Matej-Łukowicz, K. 16%, Nawrot, N. 16%, Nyka, L. 16%, Piątek, Ł. 16%

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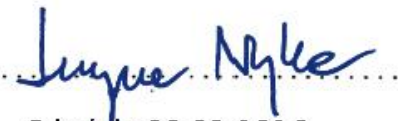
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- Technical / design input: architectural design and description;
- Visualisation / figures: visualization, architectural schemes and scalability;
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- Writing - review and editing: final manuscript redaction;

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Place and date:

WARSAW, 10/09/2026

Statement concerning publication P6

Publication identifier: P6

Title: Revolutionizing Flood Resilience: Human-Centred AI for Adaptive and Regenerative Urban Design

Authors: Gorzka, J., Burda, I., Józekowski, J., and Nyka, L.

Source: *Land Use Policy*, 2026, 170, 108218. <https://doi.org/10.1016/j.landusepol.2026.108218>

Contribution shares: Gorzka, J. 50%, Burda, I. 23%, Józekowski, J. 23%, and Nyka, L. 4%

Declaration text: I, the undersigned, confirm that I am a co-author of the publication identified above and consent to its inclusion in the doctoral dissertation of Jakub Gorzka. I confirm that Jakub Gorzka's individual contribution to the publication comprised the activities specified below and that this description accurately reflects the actual division of work among the authors.

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- Methodology;
- Comparative governance framework;
- Documentary analysis / case analysis;
- Formal analysis;
- Visualisation / figures;
- Writing - original draft preparation;
- Writing - review and editing;

Name and surname of co-author:	Izabela Burda	Jacek Józekowski	Lucyna Nyka
Academic title / degree:	dr inż. arch.	mgr inż. arch.	prof. dr hab. inż. arch.
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Place and date:

