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Tidal Containment System in Belgium: Innovation and Sustainability

Amanda Peña Navarro[1,*], Lidia Paola Padilla Cruz[1]

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ABSTRACT

In response to the growing challenges posed by climate change, Belgium has implemented a tidal containment system on its coastline, which was pioneering at the time and is undergoing continuous study, analysis and transformation with a view to improving it. This system combines advanced hydraulic technologies, principles of environmental sustainability and ecological integration. In this article, we will analyse the development, implementation, operation and evaluation of the Belgian tide containment system, with a special focus on the Flanders region. We will address the historical evolution of coastal policies in Belgium, the legal and administrative framework regulating hydraulic infrastructure, evaluate the socio-economic and environmental impact of the system in Belgium, and examine its possible implementation in similar geographical and climatic contexts. This research presents a contribution that brings together the fields of coastal engineering, climate resilience, environmental impact and integrated water management.

1. Introduction.

Climate change has significantly intensified the risks associated with sea level rise, the recent proliferation of extreme storms and the intrusion of salt water inland, critically affecting both crops and daily life in coastal regions. Belgium, with a coastline of approximately 67 kilometres, faces specific challenges arising from the high population density in some of its vulnerable coastal areas, the presence of critical infrastructure close to the coast, and an economy closely linked to seaports, among other issues, due to its logistics networks for the distribution of goods and coastal agro-industrial activities.

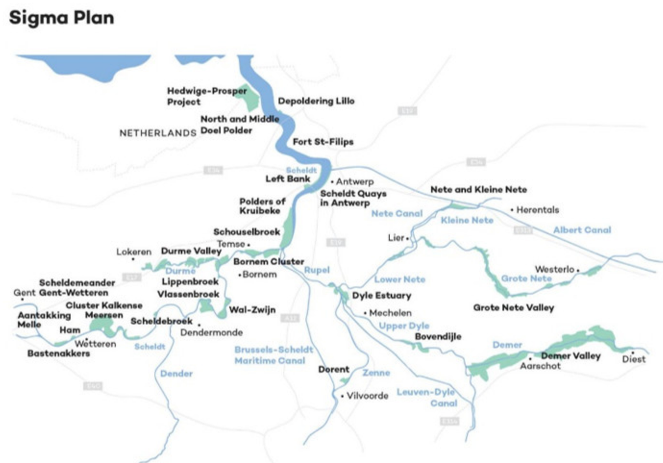
Since the mid-20th century, the country has evolved from traditional defensive strategies, based mainly on dykes, breakwaters and other hard infrastructure, towards more holistic and multifunctional approaches. The new approaches and applications of hydraulic engineering technologies seek to protect coastal areas, contributing to the restoration of ecosystems in the areas where they are implemented and promoting sustainable socio-economic development.

Belgium has been keen to implement improvement policies, such as the Sigma Plan, one of the most advanced in Europe, promoting public, advertised and participatory competitions for ideas, as well as adequate funding for the implementation of improvements to hybrid infrastructure systems for tide containment and coastal protection. Throughout the text, we will outline the conceptualisation, design and operation of this system. We will also emphasise the technological innovation involved in this new hybrid system and how it promotes environmental sustainability, economic sustainability and integration with territorial planning policies.

No less important is the proposal for the projection, development and possibility of replicating this innovative system in other parts of the world where similar conditions of coastal vulnerability exist due to climate change and where geophysical situations similar to those on the Belgian coast exist and whose governments apply policies and economic funds that allow for its implementation.

[1]Departamento de Ingeniería Civil, Náutica y Marítima. Universidad de La Laguna.
[*]Corresponding author: A. Peña-Navarro. E-mail Address: apenanav@ull.edu.es.

Figure 1: Sigma Plan diagram.



Source: sigmaplan.be.

2. Historical context and regulatory framework for coastal management in Belgium.

The evolution of coastal management in Belgium is an example of the shift towards resilient and integrated approaches to coastal areas. Throughout the 20th century and so far in the 21st century, the country has undergone a transformation in its public policies, coastal infrastructure and regulatory frameworks, driven both by catastrophic events and by growing institutional capacity and the evolution and increase in accumulated scientific knowledge and technology.

A crucial event took place in 1953, namely the great North Sea storm. It caused devastating flooding in the Zeeland region (Netherlands) and significantly affected the Flemish coast in northern Belgium. Although the damage to the rest of Belgium's coastline was minor compared to neighbouring countries, this event became a catalyst for renewing the formula for national coastal defence strategies. From that moment on, a strategic planning process began, in which the Belgian state, in collaboration with the Netherlands, academic institutions and international agencies, began to develop medium- and long-term studies and policy initiatives based on risk assessment and advanced hydrodynamic models. [2]

In 1977, the Sigma Plan was implemented, a Belgian state project whose main strategy was focused on protecting the coastline against flooding and restoring the ecosystem of the Scheldt estuary, among other things. This plan combined hydraulic engineering interventions with ecological solutions, including the expansion of intertidal zones and the rehabilitation of brackish wetlands. Brackish wetlands were expanded in both the coastal areas of Belgium and the Netherlands, and due to the presence of rocks and clays, marshes are created that prevent water infiltration. It is a system that not only respects the ecosystem of the area, but has also allowed it to provide habitats for migratory species and even the recovery of species that were in danger of extinction. This system is important for water purification and controlled storage, which prevents flooding in nearby towns. Currently, there are more than 42,000 hectares of protected wetlands, but they are not free from danger due to the overexploitation of resources, the use of these areas for urban development, and drainage for agriculture.

Figure 2: Escalda quay.

Source: sigmaplan.be.

In terms of the evolution of Belgian coastal policy and management, we can distinguish three stages: the period from 1950 to 1990, from 1990 to 2010, and from 2010 to the present.

During the initial stage, farmers frequently expanded their fields by reclaiming land from rivers or the sea, creating what are known as "polders", which have greatly contributed to the structural problems that cause flooding. Until 1990, the flood protection strategy was based on the construction of infrastructure such as regulating reservoirs, bypasses between less hydraulically congested areas, storm drains, dykes and breakwaters. Decisions were made centrally. However, it was during this period that federalisation began (culminating in the mid-1990s with the amendment of the constitution) and led to the transfer of powers to the newly created regions. The region of Flanders became primarily responsible for the planning and implementation of coastal policies, as it was the most affected by these phenomena.

Efforts were intensified to clean up rivers to ensure their navigability and prevent flooding of the coastal strip by building dykes and reservoirs to protect agricultural areas and neighbouring towns. Although these measures reduced immediate exposure to risk, they had negative consequences for coastal and riverine ecosystems. [3]

In 2005, an update was made to incorporate adaptive measures to address new climate challenges, such as sea level rise and the intensification of extreme weather events. Land use planning was carried out to promote more sustainable agricultural policies on riverbanks and to control construction and its location in areas that were not at high risk of flooding. Monitoring systems were also implemented in the areas most affected by flooding. [4]

Two key entities stand out:

- Flemish Government Coastal Agency (MDK - Maritieme Dienstverlening en Kust): responsible for the planning, design and maintenance of coastal infrastructure. [5]

- indent Flanders Hydraulics Research: unit specialising in modelling, monitoring and scientific advice in hydraulic engineering. [6]

This series of measures brings us to what we have called the second stage, from 1990 to 2010, which, given the aforementioned background, adopted a model more focused on risk assessment, analysis and the creation of specialised multidisciplinary units to provide solutions to the problems that arose.

The implementation of European Union regulations was key to water cycle management. Among other measures, water collection systems had to be modified, as the sewerage system was inadequate and obsolete, largely due to urban expansion in coastal areas and riverbanks, which exacerbated the problems of vulnerability to flooding. The European Union took action on behalf of all its member states, drafting mandatory regulations. Some of these regulations were: the Water Framework Directive (2000/60/EC) and the Floods Directive (2007/60/EC), which aimed to encourage the incorporation of ecosystems into infrastructure and the environmental and social assessment of large projects.

In the third and most recent stage, which brings us to the present, the Flanders Coastal Safety Master Plan (2011) was proposed and developed. Over the last 15 years, quays and dykes have been built and/or reinforced. A policy of expropriating farmland reclaimed from the sea or rivers (polders) has been implemented, removing inland dykes in order to create controllable flood zones and nature reserves in harmony with the environment. This comprehensive plan also includes other measures, which are set out in a more recent revision of the previous plan and which include the raising of beaches or smart floodgates that can be adjusted to the different tide levels (included in the new Flanders Master Plan, 2020). [7]

Currently, and looking to the future, it has been essential to combine public and private efforts to improve flood protection conditions.

We should also mention the collaboration of public entities such as the Flemish Environment Agency (VMM) and environmental non-governmental organisations, within collaborative governance schemes that seek to integrate public, private and social actors.

As for the legal basis for actions on the Belgian coast, there are several national and European regulations:

- Flemish Coastal Protection Act (2002): regulates rights and responsibilities regarding maritime defence infrastructure and flood zones. Specific Belgian regulation. [8]

- Water Framework Directive (2000/60/EC): aims to ensure the protection of inland waters, transitional waters, coastal waters and groundwater, seeking to promote sustainable water use and ensure the long-term availability of this resource. [9]

- Floods Directive (2007/60/EC): requires Member States to draw up flood risk maps and flood management plans in order to reduce the consequences of flooding. [10]

- European Strategy on Adaptation to Climate Change (COM / 2013 / 216): promotes nature-based solutions and long-term resilience. [11]

This regulatory framework allows tidal containment strategies to be aligned with principles of sustainability, climate adaptation and ecological conservation.

3. Coastal flood prevention management in Belgium. Masterplan Kustveiligheid.

In line with what we have been discussing regarding the creation of multidisciplinary teams, the universities of Ghent and Antwerp have been key to the development of tools that enable them to manage these improvements, from computational tools to risk monitoring and simulation systems. This, together with the work of the Maritime and Coastal Agency (MDK) and the Flemish Institute for Technology and Research (VITO), has led to progress in the integration of science, technology, public participation and ecological sustainability.

The methodology that has been implemented since the beginning of this century is based on three complementary pillars and a mixed approach, which we will break down in this section. The basis had to be, necessarily, rigorous scientific research principles and conceptually deep models that could be applied to coastal situations and phenomena in relation to tidal containment.

The exhaustive review and analysis of the documentation already available, both scientific and technical, as well as the regulations published since the 1990s on coastal management, hydraulic infrastructure, tidal containment and climate resilience, served as the basis for discussion and debate for the following phases of the project. To this end, recognised academic databases such as Scopus, Web of Science and ScienceDirect were used. Combinations of key terms such as ‘coastal flood defence’, ‘tidal barrier Belgium’, ‘nature-based solutions’, ‘Sigma Plan’ and ‘climate adaptation in estuaries’ were used. The results of the queries made on combinations of terms provided by the databases were used to include and/or exclude elements recommended by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Only peer-reviewed publications and official technical documents issued by official Belgian bodies of recognised prestige such as the MDK, VITO and the University of Ghent were considered [12].

The empirical research focused mainly on studies carried out in the Flanders region and the Scheldt estuary region, as these had traditionally been the areas most affected by flooding. It was necessary to start from one area in order to analyse and contextualise the containment infrastructures and their interaction with the territory. For this analysis, the geographic information system (GIS) was used, based on data provided by the Flemish Environment Agency (VMM) and the Flemish Cartographic Institute (AGIV). In the case of the Flanders region, the data obtained was combined with possible projections. Thus, the layers used included terrain elevation data (LiDAR), land use, flood risk maps and administrative boundaries. In addition, hydrodynamic simulations were implemented using the

Delft3D model to analyse storm surge and progressive sea level rise scenarios, comparing the performance of traditional infrastructure versus hybrid ecological solutions [13].

For the analysis and research of the Scheldt estuary area, the central section of the estuary was selected, as it has been the main setting for the implementation of the Sigma Plan and multiple contemporary interventions. For this area, in addition to the documentary analysis of regulations and projects, field data was collected on containment structures, including mobile floodgates, buffer zones, restored polders and dyke reinforcements. Of particular interest in this regard is the data provided by the participation and interviews carried out with technicians from the Coastal Agency, researchers from the Marine Research Institute (VLIZ) and local residents, which complemented the observations and scientific studies carried out. These interviews were semi-structured and aimed at specific agents whose activity and attitude in these processes was highly participatory and enriched the research.

The next phase was the interdisciplinary validation of simulations applied to specific designed models, with their corresponding comparative analysis and including the possibility of carrying out a multi-criteria evaluation, which we will explain below. Based on what had already been analysed and the tidal containment simulations for the aforementioned areas of Belgium, we moved on to the analysis of the international framework. It was necessary to compare the findings and international reference studies on sustainable coastal defence systems, including the Thames Barrier (United Kingdom), Oosterschelde Storm Surge Barrier (Netherlands) and MOSE system in Venice (Italy) projects. Validation was carried out using a Delphi approach (which allowed specialists and observers to contribute ideas to the initial project proposal), with three rounds of consultation with experts in coastal engineering, environmental policy and spatial planning, ensuring consensus in the interpretation of the results [14].

Finally, for the integrated assessment of the Belgian containment system, a multi-criteria evaluation (MCE) matrix was applied, adapted from the conceptual framework of the European Environmental Agency (EEA, 2013). The criteria considered included: hydraulic efficiency, ecological sustainability, socio-economic viability, climate adaptability and political acceptability. Weights were assigned to each criterion using hierarchical analysis (AHP), which made it possible to establish a comparative score between management alternatives and validate the replicability of the Belgian model in other vulnerable contexts.

Like any project that is carried out, and despite the proposed advances, this project is not free from criticism regarding the Belgian legal framework and faces certain challenges that must be addressed: Institutional fragmentation, due in part to federations and the existence of multiple actors and institutions with competences in certain areas, which can lead to overlaps or gaps in coordination; Legislation must be updated periodically in Belgium in order to regulate and incorporate emerging scientific evidence and innovative proposals; Citizen participation mechanisms must be strengthened and continuously incorporated into debates on what is to be done on land, in coastal areas and on riverbanks in order to incorporate viable proposals for improvement and avoid the rejection of proposals that are made. These criticisms have been partially addressed in recent revisions of the master plan and in the integration of social impact assessments.

With all this background information, the Master Plan for Coastal Safety in Belgium was developed in 2011, which became the main tool for long-term planning. Its main objective is to guarantee coastal safety between now and 2050, taking into account projections of sea level rise of between 60 and 100 cm. This plan identifies critical points of vulnerability, proposes specific solutions (hard infrastructure, controlled polders, artificial dunes) and is periodically updated by the Coastal Monitoring Committee. [2]

The plan has enabled staggered investments, with more than €400 million earmarked until 2022 for physical protection measures, environmental impact studies and institutional strengthening [5].

4. Belgian flood defence system: technical and operational components and their environmental and social impact.

Coastal flood prevention management in Belgium is set out in the Kustveiligheid Master Plan, which is reviewed periodically by a multidisciplinary team, as mentioned above. This holistic design allows for the control of excess water in certain areas and its redistribution to safer areas and subsequent drainage. The optimal basis on which this system rests is articulated in three main interconnected components of natural and artificial hydraulic infrastructures:

- Reinforced dykes. Traditional dykes, some of which are over a century old, have been reinforced with modern materials such as reinforced concrete, geotextiles and digital monitoring systems. At critical points such as Zeebrugge, Ostend and Nieuwpoort, taller 'super dykes' with a gentle slope have been implemented, integrating urban accesses, cycle paths and coastal vegetation.

A prime example is the reinforcement of the Ostend dyke, which includes pressure and humidity sensors connected to an early warning system managed by Flanders Hydraulics [15].

- Mobile floodgates. The central technical component of the system is the mobile hydraulic gates, articulated metal structures that close during intense storms and remain open under normal conditions to maintain hydrodynamic flow. Inspired by Dutch models such as the Maeslantkering, they have been adapted to the Belgian scale and topography.

The IJzer river gate complex in Nieuwpoort, built between 2008 and 2014, includes three mobile arms capable of blocking flows of more than 2,000 m^3/s, incorporating self-regulating mechanisms activated by sensors and satellite monitoring [6].

- Controlled flood zones, dynamic polders. One of the notable innovations of the Belgian system is the integration of dynamic polders: controlled areas of temporary flooding that cushion the impact of excess water. These areas combine engineering with ecological restoration, promoting the recovery of wetland habitats and mitigating soil salinisation.

In the Hedwige-Prosperpolder, shared with the Netherlands, a binational management model has been implemented that combines hydraulic gates with marsh restoration, in accordance with the Habitats Directive [16].

Figure 3: Escalda quay.

Source: sigmaplan.be.

Since 2013, based on the conclusions of the European Commission, it has been verified that the Masterplan Kustveiligheid system meets ecological and energy sustainability criteria, in addition to fulfilling its defensive mission, having integrated renewable energies and ICT into its programme and the consequent monitoring and maintenance of the system, which is constantly being updated. Hydraulic turbines have been incorporated into drainage channels, solar panels into floodgates and IoT sensors that feed real-time prediction platforms.

This entire complex system of mixed components requires significant maintenance. Maintenance is carried out from several perspectives, combining traditional systems, such as periodic inspections (visual, instrumental and underwater) that follow the protocols established in the Comprehensive Coastal Infrastructure Management Plan (PGIIC), as well as technological systems such as drones for aerial surveillance, bathymetric probes for floodgates and SCADA systems for remote control. The technological part of the system's monitoring has been designed with an ecological engineering approach, prioritising the protection of human infrastructure without compromising the resilience of coastal ecosystems.

Natural buffer zones and polders allow for the controlled intrusion of brackish water, favouring halophytic species and migratory birds, which contributes to the objectives of the Natura 2000 Network. An improvement in water quality and biological productivity has also been observed. Land use has been optimised through temporary retention areas and multifunctional polders, reconciling agricultural activities with hydraulic functions. There are incentives for farmers who adapt their crops to variable salinity conditions.

It is important to mention here the 'HydroAnticipator' system, developed by Flanders Hydraulics, which allows the simulation of multiple scenarios of high tide combined with extreme rainfall, generating automatic orders to activate floodgates using machine learning algorithms (Wang & Oumeraci, 2020). In addition, digital twins have been implemented to simulate structural behaviour under extreme conditions, enabling proactive decisions on rehabilitation or expansion. Since the implementation of these systems, Flemish coastal urban areas have significantly reduced catastrophic flooding events. The Vlaamse Baaien 2100 plan projects a reduction of up to 85% in the risk of structural damage in cities such as Ostend, Blankenberge and Knokke-Heist by 2050. The implementation of the system has been accompanied by participatory processes. Between 2010 and 2020, more than 250 public consultations and workshops were held with high citizen participation. [17][18]

According to surveys conducted by the Flemish Environment Agency (VMM) in 2021, 74% of coastal residents believe that the system has improved their safety, and 62% support its expansion. However, there are also risks of eutrophication in closed water bodies, alteration of sedimentary patterns, and some protests against the loss of agricultural land in favour of the dynamic polders incorporated into the plan. The proliferation of invasive species in altered habitats has also been detected. It is true that transparency in decision-making and access to real-time data have strengthened public confidence. Urban resilience has been strengthened through nature-based solutions, such as the reconfiguration of dunes and floodable parks, integrated into land use planning and resilient urban development. Studies have documented the recovery of marshes, estuaries and intertidal habitats in areas such as the Western Scheldt and the Hedwige-Prosperpolder environment. It is important to highlight the positive socio-economic impact, reflected in the increase in property values near resilient infrastructure and the creation of more than 2,500 green jobs linked to environmental monitoring, technical maintenance and ecotourism (OECD, 2021). [19][20][21]

5. Possible replication and technological adaptability of Belgium's tidal containment system in other countries.

The Belgian experience fits into a context that could well be shared with other estuaries and densely populated coastal areas subject to storm surges and sea level rise. The LIFE SPARC project, for example, has analysed the applicability of the "Room for the River" (CRT) concept, with controlled reduced tidal flow. International studies and technical workshops on the CRT system have also been carried out with European colleagues (LIFE SPARC, 2022). These collaborations involve hydraulic institutes (Flanders Hydraulics, Deltares) and universities (such as the University of Antwerp) that calibrate models at various sites, facilitating methodological standardisation, such as those carried out on the estuaries of northern and western Europe and the assessment of basins such as the Seine and Loire in France, the Elbe, Weser and Embs in Germany and the Humber in the United Kingdom. These scenarios share some similar features in terms of tides and risks from extreme rainfall, although there are variations in hydrodynamics: their tidal ranges, river drainage and sedimentation.

Areas of Asia such as the Mekong River delta and the Ganges-Brahmaputra also experience heavy coastal storm surges, as do some Pacific islands. The idea would be to replicate and combine hard and soft approaches and implement mobile barriers in these areas, as envisaged in the Belgian system, with the realignment of the Hedwige-Prosperpolder polders in the estuaries of these other rivers offering useful parallels. In most of these other areas, traditional defences such as mangroves and coastal wetlands have been chosen, which are not proving as effective and are not subject to monitoring, periodic review and systematic maintenance. When the decision is made to implement the Belgian holistic system, all the elements and particularities of the Belgian plan in its entirety must be taken into consideration, as well as the geophysical, social, political, environmental and regulatory conditions of each of the areas where it is to be implemented. In other words, the Belgian system cannot be automatically exported and implemented as an exact replica. The implementation of the Belgian plan will require adjusting the design to the conditions of the area or zone and to local conditions. [22][23]

The Flemish project is part of the Belgian National Climate Change Strategy (action 1.34 of the National Adaptation Plan) and complies with the European Floods Directive. The same would have to be done in the country or area where action is to be taken. To give an example, the CRT system mentioned above is based on gates calibrated to the tidal cycle and sediment dynamics, to brackish marshes to dissipate wave energy, where studies have been carried out on local species, biodiversity and salinity levels, environmental and social impact, and where advanced numerical models (such as the 3D SCALDIS model of the Scheldt estuary) have been designed, which must be adapted to the local conditions of the new estuaries and areas where they are to be installed. [22][23]

In Europe, the European Environment Agency's (EEA) Climate - ADAPT platform shares case studies and methodological guidelines on this topic. Academic networks and community projects, as well as multilateral forums, disseminate knowledge and, among other things, promote the Belgian model of tidal containment. There are programmes dedicated to dissemination through the funding of transnational pilot projects such as LIFE, Horizon Europe and the European Water Partnership. Countries must assess the costs of adapting the construction and operations required to implement the Belgian mixed system to their respective conditions and whether the amount of investment is justified in view of the damage that can be avoided. In the case of the European Union, losses quantified between 1980 and 2021 exceeded €560 billion due to climate change, which justifies the inclusion of investments in resilient infrastructure in the policies of different countries. In Flanders, the Coastal Safety Master Plan required an initial public investment of approximately €300 million. Added to this are maintenance costs (approximately €8 million/year for the conservation of nourished beaches) and local architectural expenses borne by the municipalities. These expenditures are justified by the high level of protection (1000-year return period storm surges and +30 cm sea level rise by 2050) that safeguards coastal assets (residences, tourism, port and industrial infrastructure). Beach expansion and wall improvements can generate economic co-benefits in the tourism sector, illustrating the 'triple dividend' of adaptation (threat reduction, economic benefits and environmental improvements). [22]

Globally, the UN forecasts investments of approximately $94 trillion in infrastructure over the next 20 years; however, it warns that without adequate climate policies, these resources could reinforce the unsustainable status quo. Therefore, tidal containment projects must be aligned with national adaptation strategies and leverage instruments such as green recovery funds, climate credits and public-private partnerships. Additionally, the political dimension requires cross-sectoral and regional consensus. The integration of the system into official plans (such as Belgium's Action 1.34) demonstrates the role of political will; in other countries, equivalent legal support would be needed to mobilise resources. In summary, replicability requires a solid economic case (cost-benefit analysis), financial incentives (such as European co-financing and multilateral funds) and a political-economic framework that overcomes institutional barriers. At the global level, organisations such as the UNFCCC and the IUCN promote the integration of adaptive technologies with nature-based solutions. The UNFCCC has convened specialised events highlighting hybrid "techno-eco" approaches to resilient coasts. The UN Technology Executive Committee (TEC) emphasises that the Paris Agreement requires cooperative action to improve climate technology transfer. Similarly, international scientific conferences (e.g. Climate Adaptation Congresses) and indexed publications (such as the Hydraulic Engineering Journal or Climatic Change) act as forums for disseminating results. Academic cooperation through networks such as PIANC (on ports and canals) or Working with Nature, and bilateral agreements (such as memoranda between Belgian agencies and those in the Mississippi or Mekong deltas) also facilitate knowledge transfer. Together, these knowledge instruments—shared data platforms, workshops, research partnerships, and international policies—form the basis for adapting Belgian lessons to other coastal contexts. [24]

Conclusions & Future prospects.

The flood defence system implemented in Belgium is a dream-like expression of cutting-edge hydraulic technology converging with ecological sustainability applied to comprehensive coastal management. Through a multifactorial plan, meticulous planning and implementation based on principles of climate resilience, Belgium has developed a complex and adaptive infrastructure capable not only of reducing vulnerability to hydrometeorological threats, but also of enhancing the ecosystem services of the coastal environment. It is worth highlighting the government's efforts to involve civil society and public and private entities through interviews and coastal project dissemination systems, always with a view to achieving acceptance of the ultimate goal of implementing the new measures. This is a key point to be exported to other similar implementation projects.

This study has shown how the synergistic interaction between structural elements (such as reinforced dykes and smart hydraulic gates) and nature-based solutions (NbS), such as restored wetlands and ecological buffer zones, together with the involvement of state and social actors, can optimise the functionality of the system without compromising environmental integrity. This systemic approach has generated tangible results, such as reducing exposure to flood risk in critical areas, protecting agricultural soils from salinisation and promoting coastal ecological corridors that strengthen regional biodiversity. At the same time, educational work has been carried out with local farmers on how to optimise wetlands and dynamic polder areas. From an academic point of view, the Belgian case has contributed to the enrichment of the theoretical body of knowledge related to coastal climate governance, hybrid infrastructures, and resilient design. The application of three-dimensional hydrodynamic modelling methodologies, cyber-physical systems for remote gate operation and distributed sensor technologies has facilitated the advancement of predictive monitoring and early response practices. All this has been accompanied by physical and manual supervision with other drone-based technologies, which allow for proper maintenance of the facilities. Recent research in hydraulic engineering, wetland ecology and climate science has nurtured the development of the system, forming a robust scientific basis that supports its effectiveness and viability.

The latest climate projections warn that phenomena such as sea level rise, catastrophic storms and intensified rainfall will continue to pose risks to coastal areas in Europe. Against this backdrop, the replicability of the Belgian model will depend not only on the transfer of technology and knowledge, but also on the correct analysis of all the multidisciplinary elements to be considered for the possible implementation of this project. Similarly, the availability of high-resolution geospatial data, digital governance platforms and the active inclusion of local communities will be key factors for its success in other territories. In terms of public policy, the Belgian experience highlights the importance of articulating a national adaptation strategy based on empirical data, cross-sectoral governance and sustainable financing mechanisms. Alignment with European guidelines such as the EU Climate Change Adaptation Strategy, the Water Framework Directive and the commitments of the Paris Agreement has made it possible to consolidate coherent regulatory frameworks, guarantee transparency in decision-making processes and ensure the continuity of financing through structural funds, green bonds and public-private partnerships. This, accompanied by the strengthening of interdisciplinary scientific networks with open data exchange platforms, promotes environmental awareness among young people in general and new farmers, as well as coastal communities exposed to the risk of tidal flooding. [25][22]

In conclusion, Belgium's tidal containment system stands as a paradigmatic model of structural innovation and applied sustainability, with transformative potential for other coastal regions facing the challenges of global climate change, based, as we have already mentioned, on a multifactorial dream system. We can summarise that among the strategic lines projected, the following are worth highlighting:

- Public policies prior to any transformation, based on multicriteria assessment to measure the socio-environmental and ecological impacts of the area and community participation in the area where the intervention will take place.

- Study of existing ecological buffer zones, as well as the study of the incorporation of salt marshes, wetlands, stabilised dune ridges, or reforestation of embankments.

- The incorporation of mobile containment locks or floodgates, dykes that can be monitored automatically for more effective control of their use, opening and closing remotely thanks to the use of new technologies.

- Manual and technological monitoring systems on the status and situation of the different elements, to carry out proper maintenance work.

- Integration of artificial intelligence to provide prediction models for possible water disasters, enabling effective and rapid forecasting and intervention in affected areas through analysis using data models.

- Through multidisciplinary scientific networks, strengthening information and data with open and shared platforms for data exchange and possible application to other areas.

- Finally, programmes to raise funds, increase environmental awareness among the general population, and inform and educate farmers affected by the transformation processes on how to act.

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