Book of Abstracts

ECSA Focus Meeting 2025

Estuarine Restoration: From theory to practice

University of Antwerp
Antwerp, Belgium
19-23 May 2025

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BOOK OF ABSTRACTS

ECSA FOCUS MEETING 2025

ESTUARINE RESTORATION: FROM THEORY TO PRACTICE

UNIVERSITY OF ANTWERP

ANTWERP, BELGIUM

19-23 MAY 2025

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PART I

CONFERENCE INFORMATION

Sponsors

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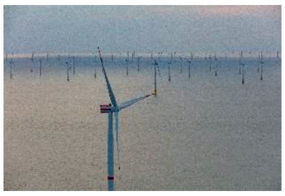
About DEME

DEME (Euronext Brussels: DEME) is a leading contractor in the fields of offshore energy, environmental remediation, dredging and marine infrastructure.

DEME also engages in concessions activities in offshore wind, marine infrastructure, green hydrogen, and deep-sea mineral harvesting. The company can build on nearly 150 years of experience and is a front runner in innovation and new technologies.

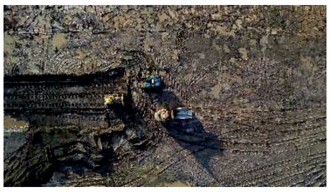


DEME's vision is to work towards a sustainable future by offering solutions for global challenges: climate change, a growing population and urbanization, increasing maritime trade and environmental issues. With a team of more than 5,800 highly skilled professionals and one of the most advanced fleets in the world, DEME is well-positioned to tackle even the most complex projects. DEME realized a turnover of 4.1 billion euro with an EBITDA of 764 million euro in 2024.

For more information, please visit www.deme-group.com.

In the context of climate change and biodiversity loss, DEME explores the potential of Nature based Solutions to harness the power of natural processes to address a myriad of environmental challenges while also providing social and economic benefits.
Bringing together a traditional environmental mitigation approach of undesired effects with a proactive ecosystem-based design facilitating a wider sustainable growth reflects our courage to move from analysis to action.

Everything we do is driven by our vision for a better, more sustainable world. We are dedicated to ensuring that our planet thrives for generations to come.
Our three core values – We Care, We Dare, We Deliver – embody this spirit.

JAN DE NUL

World Builders

Jan De Nul shapes water, land and energy around the world, addressing some of the most important challenges of our time. From the rising sea level to the energy transition, from polluted soil to sustainable construction: we engineer solutions that future-proof our world, known for their complexity and high stakes. Our Can-Do people focus on **four areas of expertise**: Offshore Energy, Dredging Solutions, Construction Projects and Planet Redevelopment. Together, we all work towards one shared goal: to improve the global quality of life for generations to come.

Nature-based solutions to boost biodiversity

We have the ambition to **support and increase biodiversity** throughout our activities, to support new ecosystems and enrich existing ones. We always look for opportunities to create a win-win situation: design and execute efficient projects for our clients that benefit biodiversity as well. We want to prosper with nature, be a financially sound company that manages biodiversity sustainably in its activities.

How are we getting there?

- We develop scalable solutions to **restore nature**.
- We work on **nature-based solutions** to protect our coastlines.
- We **monitor and minimise our impact** throughout our projects.

Projects to discover

Mangrove restoration AquaForest, Ecuador

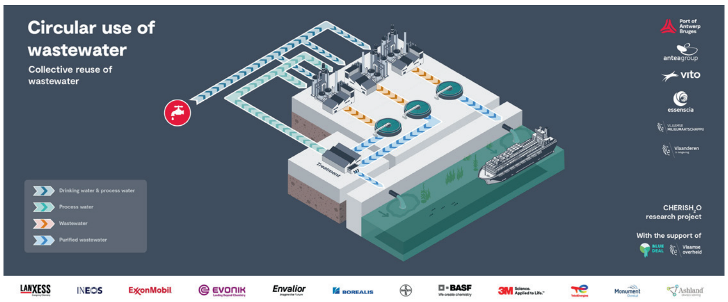
Prince Hendrik Sand Dike, Netherlands

New measuring station investigates impact of nature restoration on greenhouse gases in Hedwige-Prosperpolder, Belgium

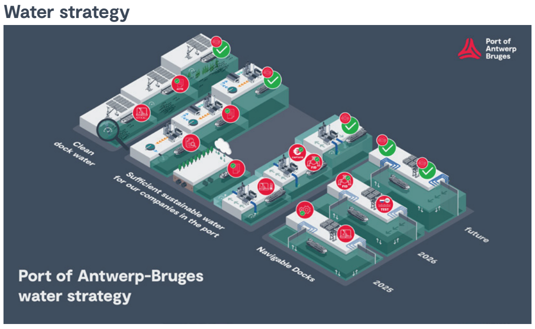
Port of Antwerp-Bruges is a vital hub in global trade and industry. The port facilitates efficient container handling, breakbulk traffic, and vehicle transshipment, and is home to 1,400 companies, including Europe's largest integrated chemical cluster.

Port of Antwerp-Bruges has a clear mission: to become the world's first port that brings economy, people, and climate together. The port is actively committed to nature restoration by integrating innovative and sustainable measures into its development. This includes not only promoting circular and low-carbon industries (CHERISH2O) but also implementing large-scale ecological initiatives such as the restoration of intertidal areas (Bankbusters), improving water quality (Water strategy and actions to reduce and avoid floating waste), and preserving biodiversity within the port territory (creation of fish nursery ponds and low dynamic shores).

CHERISH2O



Water strategy



Bankbusters

Floating waste actions

Fish nursery

Together with the port community, customers, and partners, Port of Antwerp-Bruges seeks pioneering solutions to minimize its ecological footprint and create a positive impact for future generations. Social responsibility and ecological awareness are central to its strategy.
The port locations in Antwerp and Zeebrugge are managed by Port of Antwerp-Bruges, a publicly regulated corporation with the City of Antwerp and the City of Bruges as shareholders. With 1,800 employees, the Port Authority is committed to the sustainable and innovative growth of the port.

Scientific Committee

Conference chairman

Prof. Dr. Patrick Meire, Emeritus ECOSPHERE Research Group, Department of Biology, University of Antwerp, Belgium.

Scientific Committee

- Prof. Dr. Mike Elliott, Emeritus Professor in Estuarine & Coastal Sciences, School of Environmental Sciences, The University of Hull, United Kingdom.
- Prof. Dr. ir. Tom de Mulder, Hydraulics Laboratory, Department of Civil engineering, Ghent University, Belgium.
- Prof. Dr. Wim Vyverman, Research Group Protistology & Aquatic Ecology, Department of Biology, Ghent University, Belgium.
- Prof. Dr. Natacha Brion, Archaeology, Environmental changes & Geo-chemistry, Vrije Universiteit Brussel, Belgium.
- Dr. Karline Soetaert, Department of Estuarine and Delta Systems, Royal Institute for Sea Research (NIOZ), Yerseke, The Netherlands.
- Jelle Rondelez, Flanders Marine Institute (VLIZ), Ostend, Belgium.
- Dr. Gunther Van Ryckegem, Research Institute for Nature and Forest, Brussels, Belgium.
- Dr. Roeland Adams, Water Resources Management, IMDC, Antwerp, Belgium.
- Dr. Vicky Stratigaki, Project Development & Conceptual Design, Jan De Nul Group, Hofstade, Belgium.
- Dr. Marc Huygens, DEME dredging, Environmental & Marine Engineering, Zwijndrecht, Belgium.
- Ir. Mario Lepage, French National Institute for Agriculture Food, and Environment (INRAE), Department of Waters, Bordeaux, France.
- Prof. Dr. Iris Möller, Department of Geography, Trinity College Dublin, Ireland.
- Prof. Dr. Michèle Tackx, Centre de Recherche sur la Biodiversité et l'Environnement (CRBE), Toulouse, France
- Prof. Dr. Todd Bridges, Practice, Resilient and Sustainable Systems, College of Engineering, University of Georgia, USA.
- Ir. Tom Maris, ECOSPHERE Research Group, Department of Biology, University of Antwerp, Belgium.
- Lotte Oosterlee, ECOSPHERE Research Group, Department of Biology, University of Antwerp, Belgium.

Program

Monday 19 May

9:00 Registration desk open

12:00 Lunch

12:50 Welcome word ECSA

General introduction

13:00 P. Meire
Restoring the Scheldt – from theory to practice

Pelagic restoration

13:45 K. Sabbe *et al.*
Plankton research in the Scheldt estuary: an overview of 3 decades of change

14:15 A. Bernard *et al.*
Zooplankton community changes in a restoring estuary

14:30 M. Tackx *et al.*
Plankton resting stages and meiofauna of the Scheldt marshes

14:45 *Poster session*

R. Debeer *et al.*
Long-term phytoplankton dynamics in the Belgian part of the Schelde estuary

J. Vanlede & M. Nazarali
Modelling the Scheldt estuary: the SCALDIS model and its applications

A. Bernard *et al.*
Zooplankton, suprabenthos and fish in the restoring Scheldt

D. Bas *et al.*
Microphytobenthos biomass in high temporal resolution

15:00 Coffee Break

15:30 F. Azémar *et al.*
Pelagic communities and functioning of the upper part of the Seine estuary

15:45 C. Mouth *et al.*
Environmental factors as drivers of the spatial distribution of the copepods *Eurytemora affinis* and *Eurytemora velox* in the Scheldt tributaries and estuary

16:00 I. Tulp
Comparison of fish communities between the last two remaining (natural) estuaries in the Netherlands and Belgium

16:15 L. Amadei Martínez *et al.*
Phytoplankton enhances the flocculation of suspended particulate matter in a tidal, turbid estuary

16:30 M. Olamide Idowu *et al.*
Capturing salinity profile across the Schelde Estuary: A hybrid modelling approach

16:45 L. Yuan & D. Giu
The tidal front dynamic process and ecological environment impact in an estuary crossroads formed by cape and island

18:30 Symposium dinner

Tuesday 20 May

Intertidal restoration

9:00	I. Möller 'What comes first, the 'geo' or the 'bio'?: Estuarine bio-geomorphological restoration and the importance of acknowledging time, space, and uncertainty through observation-based action'
9:30	V. Mason *et al.* Restoring sufficiently wide marshes for coastal defence: identifying early indicators of cliff initiation and marsh retreat
9:45	J. Graham *et al.* Increasing hydrological connectivity to facilitate ecological engineering and landscape transformation within a managed dyke realignment site in the Bay of Fundy
10:00	N. Van Putte *et al.* Improving groundwater dynamics: a crucial factor for successful tidal marsh restoration
10:15	*Poster session* O. Geunens *et al.* Managed Realignment of Lillo's Potpolder B. Walles *et al.* Thermal dynamics in intertidal sediments: the role of grain size and water content H. Bard *et al.* Cyclical Dynamics of Tidal Flats and Saltmarshes: Implications for Sustainable Management Practices S. Battaglia *et al.* Making Room for Wetlands 2.0: Managed realignment and tidal wetland restoration in Nova Scotia's dykelands L. Bataille *et al.* Tides, Vegetation, and CO_2, Fluxes: Insights from 1.5 Years of Eddy Covariance Monitoring in a Brackish Coastal Wetland
10:30	Coffee Break
11:00	G. Van Ryckegem *et al.* Tracking 25 Years of Change: Ecosystem Shifts and Food Web Dynamics in the Sea Scheldt Estuary
11:15	E. de Froe *et al.* Ecological development of benthic communities in nature restoration measures along the Western Scheldt
11:30	S. van Donk *et al.* Sediment nourishments to preserve foraging habitat for shorebirds in an erosive system
11:45	J. van Belzen *et al.* Priming Nourishments with Local Sediment to Accelerate Recovery: A Large-Scale In Situ Experiment
12:00	T. Grandjean *et al.* Ecological consequences of estuarine dredging
12:15	B. Verheyen *et al.* Sustainable Sediment Reuse for Ecological Island Development in the Scheldt Estuary: A Case Study
12:30	Lunch
13:30	D. Van Proosdij *et al.* Re-imagining Resilience of Dykeland Communities in a Changing Climate

14:00 J. Bootsma *et al.*
Assessing the role of intertidal habitats on estuarine hydrodynamics

14:15 G. Panique Casso presents L. Ho
Drivers of Greenhouse Gas Emissions in Estuarine Systems: Insights from the Scheldt Estuary

14:30 J. Feng *et al.*
Geomorphic dynamics and climate change effects on the spatiotemporal patterns of estuarine saltmarsh phenology

14:45 N. Ligot
AquaForest: Nature-based-Solutions for restoring and developing new mangrove habitats through eco-engineering

15:00 H. De Preter
SIGMAplan introduction

15:30 Visit Antwerp Quays Sigmaplan
Workshop Navigating tomorrow: Stakeholder engagement for a sustainable port future

Wednesday 21 May

How to plan for restoration, define objectives, goals?

9:00 M. Elliott
Marine, coastal and estuarine restoration as an integral component of Ecosystem-based Management.

9:30 J. Dale
Is unmanaged realignment an appropriate saltmarsh restoration approach?

9:45 J. Ollerhead et al.
Recovery of salt marshes in the Bay of Fundy after restoration: What does recovery really mean?

10:00 V. Méléder
REWRITE project: Addressing the Climate-Biodiversity-Society Crisis in Coastal Zones using Rewilding approach

10:15 *Poster session*

A. Hamer *et al.*
Small scale variability of thermal stress patterns in intertidal sediments: drivers and ecological implications.

D. Meire *et al.*
Tidal propagation in an estuary under sea level rise and morphological evolutions: a sensitivity analysis.

G. Panique Casso presents L. Ho & M. Barthel
Biogeochemical Drivers and Microbial Pathways of Greenhouse Gas Emissions from Tidal Wetlands

N. Vanermen *et al.*
ECOTIDE: a package designed for ecological modelling of the tidal Scheldt

A. Boerema *et al.*
Increasing complexity of project objectives results in a search for smart solutions

10:30 Coffee Break

11:00 M. De Beuckelaer – Dossche & R. Adams
Development of a vision on future-proof management of an estuary: the Integrated Plan of the Upper Sea Scheldt

11:15 D. Vrebos & T. Maris
A model for evaluating ecosystem services in tidal restoration for enhanced flood protection.

11:30 B. Verheyen *et al.*
Assess the spatial design of flood areas and local depoldering for proper ecological functioning, case studies along the Durme River

11:45 M. Lejeune *et al.*
Analysis of biting midges *Culicoides riethi* in the Schelde basin

12:00 L. Mignien *et al.*
Enhancing Estuarine and Coastal Resilience to Climate Change with Nature-Based Solutions: A Systematic Review

12:15 Lunch

13:30 Excursion KBR

18:00 Conclusion & BBQ

Thursday 22 May

Evaluation and monitoring

9:00 L. Carassou & M. LePage
From ecological theories to restoration practices in estuaries

9:30 S. Little
Linking the catchment and the seascape: nature-based solutions in tidal freshwaters

9:45 S. Cerisier
Evaluation of an ambitious program to restore Loire estuary : key question of spatial and temporal scales

10:00 V. Méléder *et al.*
Enhancing knowledge and management of Seine estuary mudflats

10:15 Coffee Break

10:45 B. Weigel *et al.*
Assessing restoration success – fish community response to an incidental restoration event in the Gironde estuary (France)

11:00 T. Maris & P. Meire
Does the Sigmaplan ensure a healthy phytoplankton population in the Schelde estuary?

11:15 R. Münstermann *et al.*
Does a recently restored intertidal wetland already contribute to water quality improvement? A case study of the Hedwige-Prosperproject.

11:30 D. Meire *et al.*
The effect of Hedwige-Prosperpolder on the tidal propgation in the Scheldt estuary

11:45 P. Gelsomini *et al.*
Unveiling Full-Spatial Seasonal Dynamics in the Sea Scheldt Estuary: Integrating Satellite Remote Sensing with Long-Term Monitoring

12:00 G. Verreydt *et al.*
iFLUX: an innovative method to measure groundwater flow in newly restored tidal marsh areas

12:15 Lunch

Dynamic ecosystems versus static regulation

13:15	A. Cliquet The EU Nature Restoration Regulation and estuarine ecosystems: moving towards recovery
13:45	R. Blust Challenges in setting environmental quality standards for chemical stressors in estuarine gradients
14:00	M. Taal Balancing towards a resilient Scheldt estuary
14:15	*Poster session* J. Vanoverbeke *et al.* Defining the upper boundary of the marsh ecotope in the brackish and freshwater stretches of the Sea Scheldt G. Van Holland *et al.* Supporting Fairway Management and Flexible Disposal in the Western Scheldt N. Reinhold On possibilities and limitations of predictions in estuarine systems B. De Maerschalck AMORAS sediment treatment: Estimate of sediment import through lock exchange at the right-bank port of Antwerp A. Mackay *et al.* Restoring tidal freshwater zones: The use of environmental DNA to monitor fish communities
14:30	Coffee Break
15:00	R. Adams *et al.* System evaluation based on an integrated model approach: the model train of the Upper Sea Scheldt
15:15	H. Schoukens From static to adaptive: how case law can influence the regulation of dynamic estuarine ecosystems in the context of nitrogen, PFAS, and climate change.
15:30	N. van der Burgt & H. Schoukens Stakeholder dynamics and the role of legal instruments in transboundary biodiversity governance. Can the Nature Restoration Law play a role in facilitating consensus?
15:45	P. Meire **Closing word + announcements**
16:15	Closing reception
19:30	Cultural excursion KMKA

Friday 23 May

9:00	Optional excursions (timing and planning are different between the three excursions)

Background information

Several presentations at the conference refer to the **Sigmaplan**.

We suggest reading the next introductory text beforehand. It will give you some additional background and will make the attendance of the presentations even more pleasant and instructive.

Curious about the **Integrated Study and Plan**? Two presentations are dedicated to detailing them. A couple of other presentations refer to models or results built and obtained during the integrated study. Watch out for them, you'll find them in the program looking for the following stamp:

Tidal nature of the freshwater part of the Schelde river @Melle © Vilda

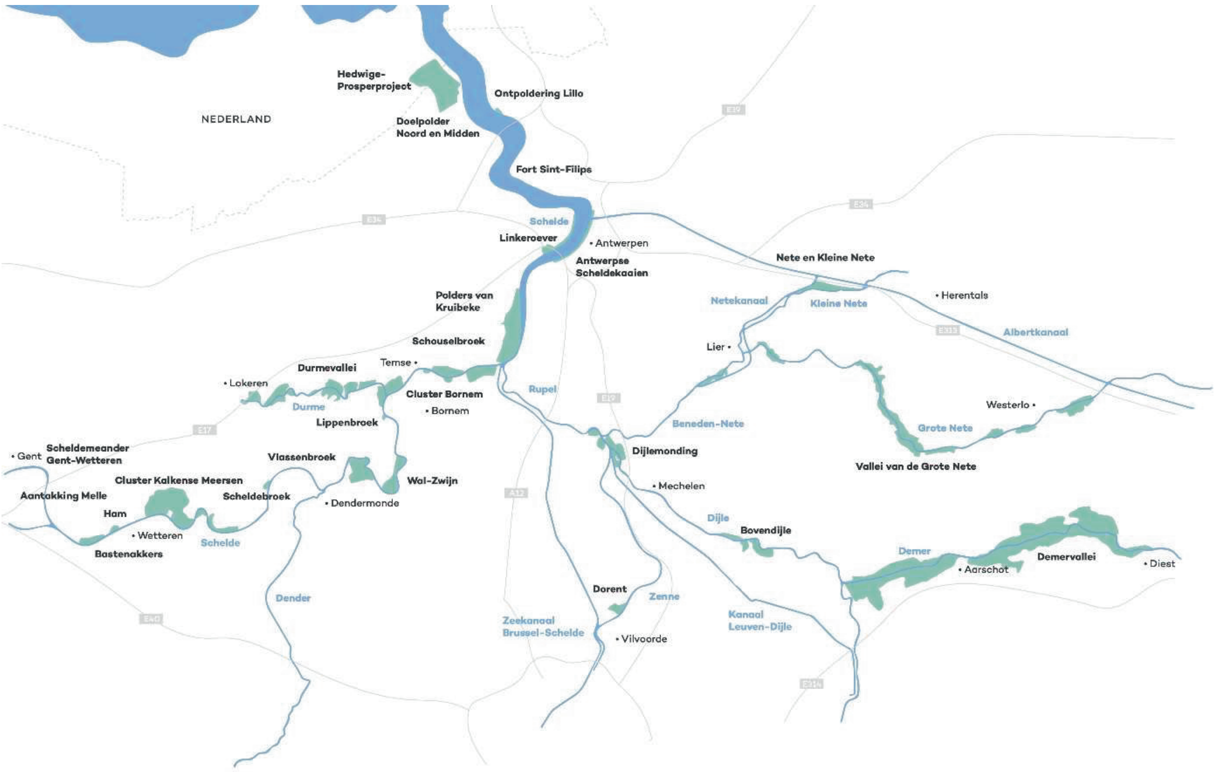
The Sigmaplan, better flood safety and estuarine nature in Flanders

To better protect Flanders from flooding on the Scheldt and its tributaries and boost valuable river nature at the same time: these are the objectives of the Sigmaplan, which is implemented by De Vlaamse Waterweg nv and the Flemish Agency for Nature and Forest. The plan also considers the development of recreational activities on and along the water and the river's accessibility for inland navigation.

A large part of the Scheldt is a tidal river. The gravitational forces of the sun and moon result in two spring tides a month. Combined with a north-westerly storm in the North Sea, this may lead to a storm tide in the Scheldt estuary as water is pushed to an extremely high tide. The gales of 1953 and 1976 are well-known examples of storm surges. They caused tremendous damage, so the government launched the Sigmaplan in 1977 to better protect Flanders from floodings of the Scheldt and its tributaries. This ambitious plan had three pillars: raising dikes, building flood control areas (FCAs) and finally a huge storm surge barrier. At the start of the new millennium, dike works were nearly finished and 12 of the 13 FCAs were operational. The last and largest FCA in Kruibeke however, was not built yet, neither was the extremely expensive storm surge barrier.

In the meantime, ideas on water management evolved. Creating more FCAs with both a safety and a nature function appears to provide more benefits than building a storm surge barrier. Also the plans for Kruibeke changed from an FCA with only safety purposes towards a project with a focus on safety and nature restoration. For this, compensation requirements for the expansion of the Antwerp harbor were an important driver.

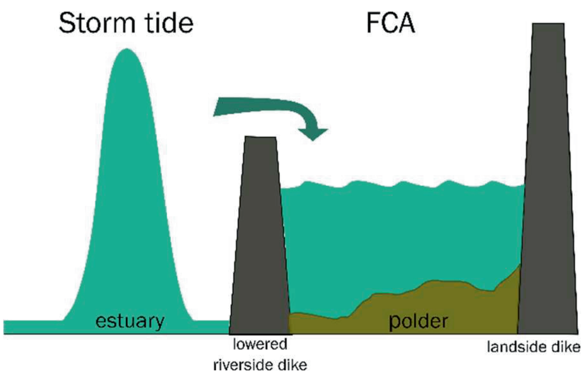
Since 2005, the plan has focused on water safety and restoration and creation of estuarine habitats along the rivers. The Sigmaplan counters flooding and aridification by raising and widening dikes, creating controlled flood areas, depoldering, and restoring natural river bends. This promotes the creation of unique tidal and intertidal habitats, and achieves the conservation objectives of Natura2000, the European network of nature reserves.



Overview of all Sigmaplan projects ©Sigmaplan.be – De Vlaamse Waterweg nv

Flood control area (FCA)

A flood control area is an area of flat land alongside a river that buffers water during storm surges. At dangerously high highwater levels, the water flows over the overflow dike onto the plain. This causes the tidal wave in the estuary to lose strength. The overflow dike is the original dike, which has been lowered and reinforced to withstand river water flowing over. When the water lowers again in the reiver, a culvert system in the embankment allows the water to flow back into the Scheldt. A ring dike always protects the hinterland to prevent any residential areas from being flooded during storm surges.



FCA scheme © Lotte Oosterlee

Storm Corrie in the Polders of Kruibe © Vilda

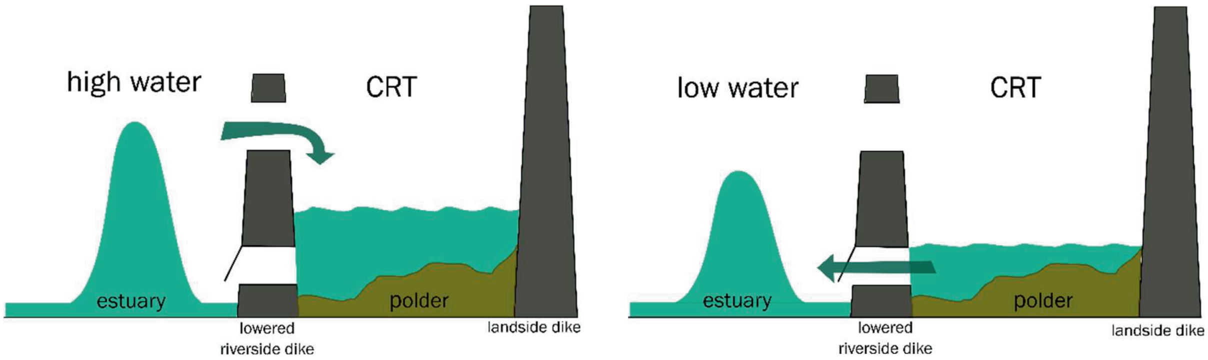
Flood control area with controlled reduced tides (FCA-CRT)

When water flows in and out of an area twice a day, a tidal nature area develops with mudflats and salt marshes. Tidal areas sparkle with diversity. To create this tidal nature within a flood control area, a new technique can be implemented: controlled reduced tide (CRT).

A flood control area with controlled reduced tide is similar to the above-mentioned FCA but combined with the purpose of creating estuarine habitat using a smart designed culvert system in the overflow dike. At high tide, a high inlet culvert lets in a limited quantity of water, just enough to trigger the development of tidal mudflats and tidal marshes. At low tide, the water slowly flows back through a low outlet culvert into the river.

Although the tidal amplitude is strongly reduced, the newly created marsh faces flooding characteristics similar to the macrotidal natural marsh in the Scheldt, showing a range of inundation frequencies. Most RTE techniques reduce this essential inundation gradient by minimizing the springtide-neap tide differences. In a CRT however, the high positioned inlet culverts allow a lot of water during spring tide, but nearly nothing during neap tide, to flow into the area.

In a FCA-CRT water buffering during storm surges and the creation of tidal nature are combined.



CRT schemes © Lotte Oosterlee

Depoldering by managed realignment

Depoldering means giving back land to the river. First, we construct a new dike inland. Subsequently we remove the old dike either partially or entirely and make deeper breaches, creating additional room between the old and the new dike where the river can (over)flow. This lowers the water level in the river and reduces the force of the water, thereby decreasing the risk of flooding. As the tides are given free rein again, this also gives rise to valuable tidal nature.

Wetlands

Wetlands within the Sigmaplan are marshy areas that are unaffected by the tide. In wetlands groundwater levels are high in winter and drop in summer. The landscape varies from open water and reed beds across alluvial forests to wet grasslands.

The Integrated Plan, a vision on future management of the Scheldt

The Integrated Plan seeks a way to link the safety and nature functions of the Sigmaplan with sustainable management of the waterway and its valley to safeguard its functions for the future. The plan is committed to creating hydrodynamic conditions that support healthy ecosystem functioning.

Integrated study of the Upper Sea Scheldt

The Scheldt estuary extends from the North-Sea in the Netherlands to the shipping locks in Ghent with a total length of 160 km. The Upper Sea Scheldt (Flanders, Belgium) is the navigable upstream part of the estuary.

While challenges on flood protection and nature development in this unique fresh water estuarine system are addressed in the Sigmaplan, the increase of tidal dynamics and turbidity as a result of the cumulated effect of processes such as i) the autonomous morphological development of the estuary, the further morphological evolution as a consequence of ii) past realignments and dredging works for navigation, and iii) the sea level rise, are not.

There are signs that the increased dynamics and sediment load affect both habitat and light climate, and that may lead to a disruption of the ecosystem functions in this part of the estuary. In order to understand how to deal with this challenge an integrated study has been launched by De Vlaamse Waterweg nv: the Integrated Study of the Upper Sea Scheldt.

Understanding the estuary system functioning

In order to better understand the system functioning and to prepare for counteracting these undesired evolutions the study program aimed at investigating solutions in order to prepare a vision for the future management of the river. An extensive modelling instrument was developed coupling different state of the art models into one modeling chain. The developed instrument proved to be highly effective to study (i) the interdependencies between the different river functions which allowed for an integrated analysis and evaluation of potential measures, and (ii) the robustness of the measures for climate change and allowing the selection of a set of measures providing a desired level of system resilience.

An Integrated Plan for future management

As such the results of the study formed the backbone for the development of a future vision on estuary management, while the model instrument will continue to be used to study design alternatives and finetune measures for implementation.

Conference Excursions & workshops

Tuesday 20 May

Visit of the SIGMAPLAN Quays by De Vlaamse Waterweg nv

For this visit we walk from the conference venue to the quays. We will be walking along these quays for about 1 hour, guided by engineers from *De Vlaamse Waterweg nv*. They will focus on the technical challenges encountered with this remake of the quays.

Along a stretch of more than 7 kilometers, the Scheldt quays in Antwerp are undergoing a thorough makeover. While *De Vlaamse Waterweg nv* focuses on water safety, the city of Antwerp is turning the quays into an inviting waterside location.

Flood protection, including stabilization and restoration of unstable, centuries-old quay wall
As early as 1883, engineers noticed that parts of the quay wall were subsiding towards the Scheldt. This precarious balance was caused by the Boom clay beneath the wall's foundation and the pressure of the groundwater. Over the past 130 years, engineers have developed various solutions, all of which proved inadequate. *De Vlaamse Waterweg nv* worked on a permanent solution to the unstable quay wall as part of the SigmaPlan.

The Scheldt quays always flood during heavy storm surges. Antwerp is very prone to flooding due to its location on the Scheldt. In the wake of the Gale of January 1976, a water barrier was built: a concrete wall 5.5 kilometers long and 1.35 meters high. Climate change and sea level rises have made it necessary to raise that water barrier by 90 centimeters. This will be done once the quay wall has been stabilized. The primary function of the water barrier is flood protection, but it obviously also affects the aesthetics of the quays. We are therefore combining these works as much as possible with the redevelopment of the quay plain.

Workshop Port of Antwerp-Bruges

Navigating Tomorrow: Stakeholder engagement for a sustainable port future

This workshop features three dynamic roundtable discussions, each tackling the themes below. You are invited for a thought-provoking exchange at the crossroads of regulation, sustainability, and collaboration—where collective action shapes a resilient and environmentally responsible port system.

The Port of Antwerp stands as a powerhouse of international trade and regional development. However, safeguarding its future demands a unified effort from all stakeholders. Together with port users, NGOs, and governmental institutions, we are driving forward sustainable strategies to minimize environmental impact and boost climate resilience.

This workshop will deliver insights into the legal complexities of the Scheldt riverbanks, the Antwerp port's water strategy, and real-world case studies of nature projects—both triumphant and challenged—along the banks of the Scheldt.

Key focus area's:

- **Legal framework of the Scheldt Riverbanks** – An interactive high-level discussion about Environmental legislation along the Scheldt.
- **Water strategy in the Antwerp Port area** – With clear ambitions for water quality and quantity, the Port of Antwerp-Bruges is implementing decisive measures to achieve sustainable water use while protecting vital aquatic ecosystems.
- **Integrating Port development with ecological conservation**– A deep dive into our achievements along the Scheldt, highlighting completed and ongoing projects that thrived and those that faced legal or technical hurdles.

Wednesday 21 May

Polders Van Kruibeke

The Scheldt makes two capricious bends at Kruibeke, first north, then eastward. At this strategically chosen location Waterwegen & Zeekanaal (administration for waterways and seacanal - now called De Vlaamse Waterweg nv) has built the flood control area Kruibeke-Bazel-Rupelmonde. The largest of 13 flood control areas in the Scheldt basin became operational in 2015, providing a fivefold increase in the protection of Flanders against floods from the Scheldt and its tributaries.

In the 600 ha FCA at Kruibeke several types of nature were created and restored. Part of the FCA was set up as an FCA with reduced tides, another part as a wetland. The project provides a boost to the nature of the Scheldt region: no less than 300 hectares of mudflats and marshes, 150 hectares of meadow bird area and 92 hectares of alder marsh forest were added.

On site we will receive information from various speakers on planning, design and construction. Also monitoring results concerning e.g. hydro- and morphodynamics, water quality and biota will be explained.

Friday 23 May

FRESHWATER excursion

The Schelde still has a full tidal gradient from salt over brackish to freshwater marshes. In the Schelde and its tidal tributaries more than 100 km of tidal freshwater estuary can be found, with a tidal range going up to 6 m, creating a risk for floodings. In the past century, tidal nature dramatically declined due to habitat loss and poor water quality. The Sigmaplan aims for a healthy, sustainable estuary, focusing on both safety and nature restoration. It uses a 'building with nature approach', using techniques such as managed realignment, flood control areas and the novel technique of controlled reduced tide. In this excursion you will visit several restoration sites that demonstrate these restoration measures. You will be guided by experts and project engineers from University of Antwerp, De Vlaamse Waterweg (Flemish Waterways) and Agentschap voor Natuur en Bos (Agency for Nature and forestry) that can give insight into the planning and construction of these sites. The following sites will be visited:

Ham: a flood control area, under construction, to protect the surrounding area from flooding. In this site, a controlled reduced tide will be introduced using a system with high inlet and low outlet sluices. This will allow the introduction of tidal nature in this embanked site.

Bastenakkers: this flood control area, also under construction, is designed in such a way that it will only flood during extreme storm events, on average once every 50 years. Therefore, in this area safety against floodings can be combined with agriculture.

Clusters Kalkense Meersen: In this area, 950 ha of nature has been restored. Several key elements of the Sigmaplan can be found here. You will see wetlands in a flood control area, but also a managed realignment site (Wymeers) or a site with a controlled reduced tide (Bergenmeersen). Monitoring results and lessons learned will be shared.

BRACKISH WATER excursion

In the brackish part of the Schelde estuary, the largest tidal marshes can be found. We will visit the 3500 ha marsh 'Verdronken land van Saeftinge' and the adjacent 'Hedwige-Prosperpolder'. The latter is a 450 ha managed realignment site, created in 2021, and intensively monitored nowadays. A bit more upstream, in the harbor area, only small fringing marshes are left. These marshes are often subjected to severe lateral erosion due to the high hydrodynamics they are exposed to. The Bankbusters research project aims to restore such an eroding bank and create a functional marsh providing several ecosystem services. In this excursion you will visit all of these locations.

PART II

ABSTRACTS

ORAL PRESENTATIONS

Restoring the Scheldt estuary– from theory to practice

Patrick Meire

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The Scheldt estuary is one of the few estuaries still having an entire gradient from marine to fresh water tidal areas. Due to pollution and habitat loss, however, the estuary was heavily degraded. In the seventies and eighties of the last century the entire fresh and part of the brackish zone of the estuary were completely anoxic for most of the year, with major impact on biodiversity. Morphological changes also impacted the hydrodynamics leading to an amplification of the tides in the upper part of the estuary causing serious safety issues.

In the beginning of the nineties new insights into integrated water management gradually changed the management, which developed from a very sectorial approach only oriented towards economic development and safety towards a more holistic approach taking into account the functioning of the ecosystem.

Since then, water quality improved enormously, and large-scale restoration projects were realized. In this presentation I gave an overview of how the estuary changed over the last 30 years and what were the most important triggers to expand the management to the restoration of the estuary. A detailed monitoring project, OMES, started in 1995 and covered both water quality and plankton, later extended within MONEOS with benthos, fish, vegetation, morphology and hydrodynamics. This integrated monitoring combined with targeted research projects increased our understanding of the functioning of the system. Based on this conservation objectives were derived that were based both on biodiversity and ecosystem functioning. For the last, the concept of ecosystem services was crucially important as it focusses on the different aspects of the system and links ecology and economy.

A whole series of restoration projects were designed and implemented going from alternative bank protection to managed retreat of large areas. However, as the competition for space is intense, it was important to combine as many functions as possible at the same place. Therefor the concept of controlled reduced tide was developed that allows both safety against inundation and ecological functioning.

Plankton research in the Scheldt estuary: an overview of 3 decades of change

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The Scheldt estuary, a macrotidal estuary in Belgium/SW Netherlands, is one of the only NW European estuaries with extensive freshwater and brackish tidal reaches. Located in a very densely populated region and heavily impacted by harbour, industrial and agricultural activities, the estuary has undergone marked changes during the past decades. Until the early 2000s, the estuary was highly eutrophic, with frequent episodes of anoxia. This was followed by a period of de-eutrophication, which saw the re-establishment of zooplankton and fish communities. At the same time, the estuary underwent important changes in hydrodynamics and geomorphology as a result of enhanced dredging activities and the commissioning of new docks, but also because of an important increase in tidal wetlands as a result of depoldering for flood protection. Last but not least, climate change affects the ecosystem through changes in temperature and (often extreme) fluctuations in discharge. In the framework of the OMES project, during the past three decades, we have been monitoring the response of phyto- and zooplankton, and more recently the whole microbial planktonic community using omics approaches, to this recent period in the history of the estuary. The main trends, and how these relate to the above-mentioned environmental and anthropogenic changes, will be presented.

Zooplankton community changes in a restoring estuary

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This study investigates the relationship between crustacean (copepods and cladocerans) and rotifer abundance, diversity and community composition in the Scheldt estuary, during the 1996-2022 period of improving water quality.

Two-monthly samples taken at stations Grens (G) and Antwerpen (A) situated in the brackish water Lower Sea Scheldt (LSS) and at Dendermonde (D) and Uitbergen (U) in the freshwater Upper Sea Scheldt (USS) in 1996, 2002, 2009, 2016 and 2022 were used. Taxa were analyzed at the highest possible taxonomic level. A multiple factor analysis (MFA) correlated the zooplankton characteristics (total abundance, α diversity and Pielou index) to environmental parameters and a decision tree was used to test whether environmental factors could significantly segregate Bray-Curtis dissimilarity-based homogeneous community clusters.

Both crustacean and rotifer communities showed a clear chlorinity-induced separation between the LSS and the USS, slightly modulated by discharge fluctuations. Major consequences of water de-eutrophication were the gradual disappearance of highly eutrophic water-resistant species *Ceriodaphnia reticulata* and *Acanthocyclops americanus* and the massive development of *Eurytemora affinis* in the USS crustacean communities since 2007. This shift was not followed by changes in crustacean α diversity. The eutrophic-water rotifer indicator *Brachionus calyciflorus* decreased in both LSS and USS, as did bacterial feeding species in the USS. Crustacean and rotifer abundances systematically decreased with Chla in the LSS. Considering the total brackish-freshwater reach, water quality improvement did result in a higher zooplankton γ diversity in the Scheldt estuary, but recent changes in community composition at some stations indicate that this might not be a stable situation.

More recently indeed, changes in phytoplankton community, including the increase of cyanobacteria, seem to be leading to new USS balance between the crustacean community dominated by *E. affinis* or by cladocerans, probably in response to human-induced chlorinity entrance into the natural freshwater reach. While a constancy in zooplankton community composition was observed in the LSS, progressing marinization was evidenced at G in 2022 with the shift from a rotifer-dominated to a eury-haline copepod-dominated zooplankton community. In addition, the emergence of the psammic rotifer *Trichotria brevidactyla* as a USS indicator species, as well as that of several benthic crustaceans, could indicate the effect of dredging activities.

Plankton resting stages and meiofauna of the Scheldt marshes

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The importance of the controlled reduced tidal area (CRT) Lippenbroek (Scheldt estuary, Belgium) to zooplankton has been investigated in three ways:

A number of zooplankton samplings at the in- and outflow of the Lippenbroek were performed during tidal cycles representing different conditions of tidal coefficient and runoff to verify if zooplankton abundance and composition changes by its stay in the CRT. Only the copepod *Acanthocyclops americanus* and the rotifer *Synchaeta bicornis* show significant differences in the abundance between in- and outgoing samples. Nevertheless, the tidal coefficient seems to have an influence of the ratio in/out of some taxa. Overall, the impact of the tidal in -and outflow through the Lippenbroek on the estuarine zooplankton populations seems small.

By incubating sediment cores of the Controlled Reduce Tidal (CRT) Scheldt pilot area 'Lippenbroek' under a 14h light/10 h dark cycle at 18 °C, the existence of quiescent forms of various zooplankton organism in the sediments was demonstrated. A second series of incubations showed that, besides quiescent forms, which can activate as soon as circumstances are favourable, the Lippenbroek sediments also contain diapause forms, which only activate after an obligatory resting period. The main organism found were copepodite stages of the cyclopoid copepod species *Eucyclops serrulatus*, cladocerans and tartigrades. The latter hatch from the sediments in high abundances at two stations: in a permanent pond within the Lippenbroek and at a higher situated station, characterised by fine sediments.

Comparison of the meiofauna communities in three Scheldt tidal marshes (Burchtse Weel, Notelaer et Lippenbroek) has shown that the presence of tardigrades is quite unique to the Lippenbroek. While meiobenthic communities showing different importance of nematodes, oligochaetes and harpacticoid copepods occur at all three marshes and are generally associated with factors such as elevation, conductivity and organic matter content of the sediments, tardigrades are specifically associated with the delta pH (the difference between the pH of the water and the potential acidity of the sediments).

Pelagic communities and functioning of the upper part of the Seine estuary

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The project 'Seine-Amont: Réseaux Trophiques Estuariens' (SARTRE, 2019-2021) studied the concentration/abundance, composition, origin and spatio-temporal distribution of suspended and dissolved matter, communities (zooplankton and suprabenthos) and the trophic functioning in the oligohaline and freshwater zones of the Seine estuary (France).

Bimonthly cruises covering 13 stations, combined with intensive measurements at 5 stations were carried out along the salinity gradient. A station upstream of the Poses Dam, out of the tidal reach, was also sampled, to characterize inflows from the riverine Seine river.

Essentially three spatial zones are distinguished: the downstream, brackish water reach, characterized by low zooplankton but important suprabenthos and fish abundances with primary production and phytoplankton biomass increasing in upstream. Particulate and dissolved matter are mainly of terrestrial origin, mixed with marine inputs. Upstream, the zooplankton communities are similar to the ones of the non-tidal Seine and more diverse than the downstream ones. There are less fish than downstream and very little suprabenthos. Both freshly produced phytoplankton and terrestrial material and constitute suspended and dissolved matter. In the middle reach, a sink in primary production and phytoplankton biomass is observed, corresponding to a transition zone between fresh- and brackish water communities. Curiously, primary production increases again upstream while phytoplankton biomass does not.

Zooplankton grazing experiments, combined with stable isotope analysis on SPM, zooplankton and suprabenthos led to the hypothesis that the downstream reach functions mainly by a grazing food chain, while the microbial loop is more important in the upstream part of the Seine estuary. To better understand the spatial and temporal distribution of both environmental conditions and communities, interdisciplinary studies including ecology, hydrology, sedimentology and ecotoxicology will be needed.

Environmental factors as drivers of the spatial distribution of the copepods *Eurytemora affinis* and *Eurytemora velox* in the Scheldt tributaries and estuary

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Estuaries and their tributaries are dynamic ecosystems where environmental factors can shape species distribution and abundance. They therefore offer an interesting setting to study the response of organisms to various environmental conditions. This study focuses on the spatial and temporal distribution of two calanoid species, *Eurytemora affinis* and *Eurytemora velox*, in the Scheldt estuary and its tributaries (Belgium, The Netherlands), investigating their spatial-temporal distribution and ecological preferences.

Species distribution and abundance data, collected in four tributaries between 2018 and 2021 and five estuarine stations between 2018 and 2022 are analyzed by Generalized Linear Models (GLMs) and Generalized Linear Mixed Models (GLMMs) and the results interpreted in the context of ecosystem functioning.

Results reveal distinct habitat preferences for the two species. *E. affinis* was predominantly found in tidal tributaries and the oligohaline zones of the estuary, where tidal turbulence leads to lower oxygen concentrations (< 10-11 mg L^{-1}) and higher POM levels. In contrast, *E. velox* was abundant in non-tidal tributaries and upstream freshwater zones of the estuary, which are characterized by higher oxygen levels (often rising above 10-11 mg L^{-1} and sometimes showing high variability) and phytoplankton biomass.

The study suggests that *E. affinis* is sensitive to hyperoxia, potentially experiencing oxidative stress under high oxygen conditions, while *E. velox* demonstrates greater tolerance to such conditions.

Comparison of fish communities between the last two remaining (natural) estuaries in the Netherlands and Belgium

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Before the construction of extensive dams, dikes, and drainage systems, the Netherlands and a large part of Belgium was a vast, flat, low-lying region where multiple rivers - including the Rhine, Meuse, Scheldt, IJssel and Ems - emptied into the North Sea through a network of open estuaries. To date, there are only two open estuaries remaining: the Western Scheldt in the south and the Ems estuary in the north. For fish, such open systems are important for various reasons: open estuaries provide sheltered environments with abundant food sources, making them ideal nursery grounds and feeding areas for many fish species and act as critical transit areas during their migrations to fulfil their life cycles. However, despite the fact that these last two estuaries are still open, they are also under various anthropogenic pressures. In the Western Scheldt, ongoing deepening and widening of the shipping channel, to safeguard the entrance to the Antwerp harbour, results in habitat loss, sediment disturbances, and water quality issues. Also, pollution caused by industrial activities along the river, agriculture, and urban development is impacting the system. In the Ems estuary, land reclamation of large parts of the estuary, channel deepening in the Ems river and lack of natural siltation have resulted in decreased sedimentation capacity of the estuary. As a consequence, turbidity levels increased, and oxygen levels decreased since the 1950s.

In two long running monitoring programs (going back to 1970 and 2006 respectively) the abundance of both pelagic and bottom dwelling fish has been monitored in both systems. For pelagic fish, a stow net is used at several locations along the salinity gradient from the mouth inland in both estuaries. Bottom-dwelling fish are sampled using a beam trawl at different locations throughout the estuary.

In this contribution, we sketch developments throughout the monitoring period and by comparing the two systems, we suggest hypotheses for observed developments and where possible test these.

Phytoplankton enhances the flocculation of suspended particulate matter in a tidal, turbid estuary

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Since 2009, suspended particulate matter (SPM) concentration in the Scheldt estuary has increased, particularly during the summer months in the freshwater tidal reaches, largely due to enhanced dredging and dumping activities. At the same time, improvements in water quality led to alterations in phytoplankton biomass and community composition. We hypothesize that this has influenced SPM dynamics by altering the stability of flocs and thus their size.

Our study investigates seasonal and spatial variability in SPM flocculation processes, using water samples collected monthly from December 2021 till December 2022 at five stations in the estuary's freshwater and brackish tidal reaches (~km 60 to km 140 from the mouth from the estuary). In a custom-made flocculation chamber, field samples were first subjected to a high turbulent shear rate (45 s^{-1}) to break the flocs, and then to a turbulent shear rate that promoted aggregation (20 s^{-1}) during 120 mins. Observed changes in the floc size distribution were used to derive several parameters, focusing on equilibrium floc size (De) and flocculation speed (Vf). We used generalized additive models to disentangle the effect of seasonal, spatial, environmental, and biotic factors on De and Vf.

Unlike brackish stations, freshwater stations exhibited significant seasonal trends, with both De and Vf increasing during spring and summer, and these trends strengthened upstream. Our results suggest that, as shown in previous studies in other turbid systems, phytoplankton influences flocculation. In the Scheldt, this is supported by strong positive correlations between De, Vf, and chlorophyll a, as well as a correlation between Vf and particulate organic carbon from phytoplankton. The link between phytoplankton and flocculation is mediated by transparent exopolymeric particles (TEPs) and their adhesive properties. However, we did not find a good correlation between flocculation and TEP, most likely because TEP stickiness depends on remineralization, age, and composition.

Capturing salinity profile across the Schelde Estuary: A hybrid modelling approach

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Three-dimensional (3-D) numerical models constitute indispensable instruments for simulating and forecasting estuarine salinity profiles, essential for developing management strategies to improve and maintain the healthy state of estuarine ecosystems. However, the effort required to run these models is significant due to prolonged computation time. In contrast, developing management strategies for estuaries often require a quick turnaround time for long-term simulations or short-term forecasts of estuarine salinity conditions that 3D models cannot meet. To bridge this gap, we established a coupled modelling framework that links the one-dimensional (1-D) OMES ecosystem model with the 3-D Scaldis hydrodynamic model, yielding rapid simulations of salinity profiles throughout the Schelde estuary. Synthetic salinity fields generated by Scaldis were used to calibrate the 1-D OMES ecosystem model. As a result, the OMES model reproduced the observed salinity profiles with high fidelity. The workflow presents a framework for projecting future salinity regimes in the dynamically evolving Schelde estuarine system.

The tidal front dynamic process and ecological environment impact in an estuary crossroads formed by cape and island

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The tidal fronts that take place off estuaries are of great importance in the converging of nutrients, nourishing local fisheries and exerting a substantial environmental influence. While it is known that topography play an important role in controlling where the front will occur and how intense and how long it will last, it remains uncertain in complex terrain conditions, such as a cape and an island coexist in an estuary mouth. thereby constituting the primary focus of this study on tidal front dynamic process and ecological environment impact in west of Pearl River Estuary, a crossroads field formed by cape and island, which relies on the analysis of (FVCOM) simulation results and in-situ investigation data. In the tidal field, islands and capes form small-scale vortices that enhance upwelling and mixing. However, the cross shaped tidal channel formed by islands and capes can create larger range convergence fronts. When the intensity of the two incoming flows is stable during the tidal process, the position of the front remains stable; when the intensity contrast changes, the position of the front shifts accordingly.

In-situ investigation data show that the chlorophyll concentration at the location where the front passes is much higher than in non-frontal zones. The red tide zone and the gathering spots for Chinese white dolphins coincide with the timing and location of the strong fronts. The impact range and duration of the front are significantly greater than those in other areas, making this region a hotspot for Chinese white dolphin gatherings.

This study reveals the reasons why the cross-shaped channel formed by capes and island can become a hot spot for Chinese white dolphins by analysing the strength and duration of the front. Due to more intense human activities in the eastern Pearl River Estuary, the western part of the Pearl River Estuary, a special terrain area with stronger fronts, is becoming an increasingly important habitat for Chinese white dolphins.

‘What comes first, the ‘geo’ or the ‘bio’?: Estuarine bio-geomorphological restoration and the importance of acknowledging time, space, and uncertainty through observation-based action

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Coastal ecosystems exist (and survive) on account of the interaction between biological, physical, and chemical processes. This interaction is particularly visible in the way in which water flows through, against, and over, the bio-physical structures but also maintains those structures with which such ecosystems are associated. The size and scale of these interactions, however, matters, and is intrinsically connected to the timescale over which restoration is envisaged. When we want to understand the degree to which coastal ecosystems (a) rely on such interactions and (b) provide benefit to humans and the adjacent natural environment through such interactions (e.g. in terms of carbon sequestration and providing coastal protection and resilience in the face of a changed climate future), we have to do so through a place-specific approach and with carefully managed expectations. This talk will illustrate the different scales of interactions of geomorphological and biological processes through the lens of bio-geomorphology, from the mm to km scale and over instantaneous to decadal time scales. It will further highlight how uncertain outcomes are an intrinsic characteristic of an inherently unpredictable coastal system. The emergence and meaning of the terms ‘nature-based solution’ and coastal ‘rewilding’ are explored and the challenge of finding ways towards coastal restoration and management in the absence of predictable outcomes will be discussed. The notion of land- and sea-scape restoration emerges from this, raising key questions around its achievability within our current governance systems?
The talk will draw particularly scientific evidence of the bio-geomorphological functioning of the heavily human modified system of Dublin Bay and on ongoing research in two EU projects, REWRITE and NATURESCAPES, focused on coastal rewilding and the added benefits of considering the connectivity of nature-based solutions in an urban (including urban coastal) context.

Restoring sufficiently wide marshes for coastal defence: identifying early indicators of cliff initiation and marsh retreat

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The flood defence capacity of a saltmarsh is often an incentive to restore coastal wetlands, however the wave attenuation capacity of a saltmarsh is a function of its width. Successfully restoring saltmarshes for flood protection therefore depends on the ability to project when and where a cliff might form, which will trigger the saltmarsh into a stage of retreat, reducing its ability to protect our coastlines. Unfortunately, the processes and conditions under which cliffs form remain unknown, making the moment of cliff initiation unpredictable. Here, we took field measurements of sediment properties and stability at comparable saltmarsh edges both with and without a cliff and combined them with direct flume measurements of sediment erodibility.

We identified that for a cliff to form under raised hydrodynamic conditions, three conditions must be present: 1) a substantial offset in sediment erodibility at the saltmarsh-mudflat interface, governed by small-scale gradients in sediment characteristics such as grain size distribution and sediment compaction; 2) a marsh edge with near-negligible erodibility and 3) site-wide sediment characteristics resulting in an erodible mudflat. Without these conditions, increased wind-wave activity is unlikely to initiate cliff formation; instead, a more gently sloping marsh edge will occur as erosion across the saltmarsh-mudflat interface is more evenly distributed.

We use these findings to provide early indicators, supported by field and flume observations, of the role of small-scale gradients in sediment stability across the saltmarsh edge in driving saltmarsh cliff initiation. Based on this, we provide practical monitoring advice for predicting cliff formation at the edge of natural and restored marshes. The inclusion of sediment characteristics at the marsh-mudflat transition zone into the projection of marsh extent will be critical for making long-term predictions, since subtle differences can lead to cliff initiation. Subsequent marsh erosion will limit wave attenuation in a system which is already increasingly threatened by climate change associated erosion and reduce the probability of successful restoration.

Increasing hydrological connectivity to facilitate ecological engineering and landscape transformation within a managed dyke realignment site in the Bay of Fundy

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Globally, the practice of re-introducing tidal flow to former dykelands and restoring tidal wetland habitat has been identified as a viable adaptation method to current and future risks associated with climate change. The Onslow-North River Marshland situated near the town of Truro in Nova Scotia, Canada provides an important opportunity to demonstrate the environmental and social benefits of a large-scale strategic dyke realignment project, as well as the benefits of a multidisciplinary and multi-stakeholder approach to tidal wetland restoration. Carried out in collaboration with the NS Department of Agriculture, NS Public Works, and the Onslow-North River Marsh Body, this project included the construction of two sections of new dyke, a new aboiteau and the restructuring of the agricultural ditch network to create a foundation for a new hybrid tidal creek network, and the hydrodynamic modelling of dyke breach scenarios. A six-year monitoring program including sediment dynamics and repeat low altitude high resolution surveys was initiated to establish baseline conditions at the site and track restoration efficacy. The old dyke was decommissioned and tidal flow re-introduced to the site in the fall of 2021 and tidal flow was re-introduced to 90 ha of a modern agricultural landscape which was reclaimed historically from natural tidal wetlands in the estuary.

The construction of two new inner dykes and the decommissioning of the old dyke has resulted in re-establishment of a more natural hydrological regime to the site, including flooding by tidal waters, the development of tidal channels; deposition of marine sediments, and the transition of vegetation communities in areas that are frequently flooded. The previous agricultural land forming (hills and dales) that occurred throughout much of the site has played a strong role in sedimentation patterns and channel development. Velocities recorded within McCurdy's brook and the channel created in the western basin are sufficiently high to mobilize and transport sediment. Although no clear flood dominance was recorded at the created channel where the instrument was located, the evidence of bedform migration and significant bank deposits and delta like sedimentary features extending inland suggests sediment import. In 2023, these deposited sediments appeared to contain coarser sediments than the surrounding environment and suggest influx from the Salmon River. The borrow pits associated with the new dykes, as well as the two pits within the central meander basin near the south-western end of the site, have continued to infill since Year 1 and to establish channel networks.

Overall, the system is evolving as anticipated, facilitated by the expanding hybrid channel network which provides tidal access to the interior of the site. Given the position of the marsh high in the tidal frame and field observations, most of the modifications in channel morphology and intertidal landscape are driven by a limited number of high spring tides. Vegetation establishment is occurring as anticipated in relation to elevation gradients. This project represents the largest and most comprehensively monitored managed dyke realignment site in Canada to date, offering valuable lessons to other hypertidal minerogenic sites globally.

Improving groundwater dynamics: a crucial factor for successful tidal marsh restoration

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Along estuaries and coasts, tidal marsh restoration projects are increasingly executed on formerly embanked agricultural land to regain the ecosystem services provided by tidal wetlands, such as their contribution to water quality improvement. However, historical agricultural soil compaction in these areas often hinders soil - groundwater interactions after restoration. We hypothesized that this relict agricultural compact soil limits biogeochemical cycling and the contribution of a restored marsh to water quality improvement. In a field study, we investigated how soil compaction affects groundwater dynamics and porewater nutrient concentrations in a restored tidal marsh. Furthermore, we set up a large scale mesocosm experiment to quantify the effect organic soil amendments as a design measure to jumpstart biogeochemical cycling in newly restored tidal marshes.

We studied porewater nutrient concentrations using porewater equilibrators in function of depth and distance from the nearest tidal creek in both a natural and a restored tidal marsh in the freshwater tidal zone in the Scheldt estuary. We then linked these concentrations to the soil saturation index (the proportion of time the soil is saturated at a certain depth), which was calculated based on groundwater level measurements. Soil aeration generally extends over a deeper portion of the soil profile in the natural marsh compared to the restored marsh. Porewater concentrations of phosphate and dissolved iron were significantly correlated to the depth of soil aeration, suggesting retention of phosphate on iron oxides in well aerated zones. Nitrate was significantly negatively correlated with the depth of soil aeration, whereas a positive correlation was found for ammonium. Since coupled nitrification – denitrification is enhanced by fluctuation of groundwater levels and consequent alternating aerobic and anaerobic conditions, impaired removal of nitrogen from the estuarine water by the marsh soil is expected where groundwater dynamics are reduced.

In the mesocosm experiment, we tested the effect of organic soil amendments on groundwater drainage depth and nutrient concentrations in seepage water. In an agricultural polder area with compacted soil, four different soil treatments were locally applied: (1) plowing, (2) plowing + adding reed cuttings, (3) plowing + adding wood chips and (4) no amendments (control treatment). In each of the treatment plots, a large undisturbed soil monolith was excavated and placed in the mesocosm construction. At high tide, the monoliths inundate, and water can infiltrate into the soil and during low tide, water can drain out of the monoliths. A conservative mass balance was calculated to quantify the sink-source function of the soil monoliths for different nutrients. Compared to the control treatment, the amended monoliths remove more total dissolved inorganic nitrogen and phosphate from the water and deliver more dissolved silica to the estuary. These results suggest that organic soil amendments are a viable method to improve nutrient cycling in newly restored tidal marshes.

In general, we conclude that soil aeration patterns and associated biogeochemical cycling are highly depending on pre-restoration land use, suggesting the need for design measures to increase groundwater dynamics and to jumpstart the contribution to water quality improvement in newly restored tidal marshes.

Tracking 25 Years of Change: Ecosystem Shifts and Food Web Dynamics in the Sea Scheldt Estuary

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The Sea Scheldt Estuary is a highly dynamic open ecosystem, characterised by pronounced seasonal and long term spatio-temporal changes in its abiotic and biotic components. It is one of the best monitored estuarine systems in Europe, harbouring a unique and valuable salt to freshwater gradient in the habitats of tidal mudflats, marshes and pelagic zones.
We provide an in-depth synthesis of more than two decades of monitoring and research on the ecosystem functioning and food web dynamics in the freshwater and oligohaline regions both in the pelagic and benthic ecosystem compartments. It highlights the spatial differences and temporal changes within this unique estuarine system, emphasizing the transformative changes in biogeochemical and ecological processes from 2000 onwards.

Three primary ecosystem states are characterized in the monitoring period:
Anoxic State: Dominated by oxygen-depleted waters, suppressing larger pelagic organisms and limiting energy transfer within the benthic and pelagic compartments.
Transition State: Characterized by alternating phases of algal blooms and hypoxic conditions, with gradual increases in aquatic fauna hindered by migration barriers and persistent summer anoxia.
Oxygen-Rich State: Marked by improved water quality and re-colonization by larger aquatic organisms, leading to seasonal algal blooms and shifts in energy flow from allochthonous to autochthonous sources.
We showcase the transition between states and its effect on the coupling of the pelagic and benthic food webs:
Pre-2007 food web: The pelagic zone is dominated by cyclopoid copepods relying on upstream detritus, while the benthic zone exhibits high Oligochaeta biomass supported by labile carbon. Anoxic barriers restrict predator diversity and complexity.
2003-2007 Spatio-temporal transitional food webs: The initial effect of water quality improvements during transition states manifests as disturbed food webs in the pelagic compartment but gives a productive boost to the benthic compartment during different periods following an upstream towards downstream pattern.
Post-2007 food web: Initial water quality improvements resulted in slight improvements in oxygen concentrations, allowing for algal growth. This was the trigger in the self-purification capacity of the ecosystem, resulting in an often oxygen-saturated ecosystem boosting local autotrophic energy sources. This enables colonization by calanoid copepods. The food web becomes increasingly complex, with rising abundance and diversity in predatory fish and crustaceans, including diadromous species. In the benthic zone, reduced detritus availability and increased predation lead to declines in *Oligochaeta* populations.
Since 2007 we highlight new seasonal differences, particularly in trophic interactions with the benthic populations. Where previously only wintering waterfowl fed on Oligochaeta in winter, the newly established fish and hyperbenthos communities also feed on Oligochaeta during summer and autumn, introducing new trophic and competitive interactions that are, among others, affected by water discharge differences between years.
We also focus on spatio-temporal changes, with recently shifted salinity intrusions in the oligohaline zone, potentially impacting sensitive benthic species.
This synthesis underscores the estuary's dynamic response to environmental changes and water quality improvements, offering vital insights for estuarine management and conservation efforts.

Ecological development of benthic communities in nature restoration measures along the Western Scheldt

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Intertidal mudflats are highly productive habitats and provide a broad range of ecosystems services. These mudflats have been declining globally over the past decades, including in the Western Scheldt.

Since 2010, the province of Zeeland has been implementing several projects to create intertidal mudflats in the Western Scheldt and promote benthic macrofauna. Groins have been modified or constructed at five sites in the Western Scheldt to reduce current velocity, enhance sediment deposition, and ultimately to create a low-dynamic habitat. Moreover, a managed realignment (depoldering) was carried out at two locations, to flood old agricultural land and thereby create new intertidal habitat (Perkpolder/Hedwige-Prosperpolder).

Here, we show how benthic communities have developed in these nature restoration areas over the years, comparing the different projects and evaluating their development in relation to low dynamic habitats in the Western Scheldt.

Sediment nourishments to preserve foraging habitat for shorebirds in an erosive system

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Estuaries world-wide are under pressure due to climate change and anthropogenic activities. To protect coastal communities from flooding these estuaries are often (semi) closed off due to construction of dams and storm search barriers. However, such structures impact the physical processes affecting morphological equilibria leading to sediment starvation and in combination with sea-level rise results in drowning estuaries. The Oosterschelde (the Netherlands) is such a drowning estuary. This tidal basin underwent large changes due to construction of a storm-surge barrier and closure of upstream branches in the 1980s. Consequently, system-wide erosion occurred resulting in loss of intertidal areas, which makes it an interesting system to study ecological consequences and the effect of mitigation measures. It is important to mitigate negative effects of erosion, as intertidal areas are significant foraging grounds for shorebirds. To preserve suitable foraging ground, sand nourishments have been conducted since 2008. In 2019, the Roggenplaat (a tidal flat of ~1440 ha) was nourished with 1.13 million m^3 sand, covering 15% (211 ha) of the tidal flat with a 30-80 cm thick layer of sand, to preserve foraging habitat for the coming 25 years. The elevated tidal flat provides foraging area for birds, but deposition of this layer of sand disturbs and kills (temporary) most of the macrobenthos underneath. The tidal flat and the sand nourishments have been monitored over time. The nourishments mainly differ from the rest of the tidal flat in sediment grain size and height. In this presentation we will show how birds use the area in response to the (developing) nourishments and how bird's spatial use are related to characteristics of the environment like the type of macrobenthos, sediment grain size and height and we reflect on whether sediment nourishments can be an effective management measure to counteract negative ecological consequences of tidal flat erosion in the Oosterschelde, and have potential for other estuaries worldwide.

Priming Nourishments with Local Sediment to Accelerate Recovery: A Large-Scale In Situ Experiment

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Estuaries worldwide face degradation due to climate change and human interventions. The Oosterschelde (Netherlands), a former estuary, has experienced system-wide erosion since the construction of a storm surge barrier in the 1980s, leading to the loss of intertidal foraging grounds for shorebirds. As barrier removal is not a near-term option, sand nourishments have been implemented since 2008 to counteract intertidal loss. However, these interventions can disrupt benthic communities, a key food source for shorebirds.

We tested whether priming nourishments with local, fauna-rich sediment enhances benthic recovery. During a 1.13 Mm^3 nourishment on the Roggenplaat (Oosterschelde) in autumn 2019, we applied a priming approach on one nourishment element by embedding relocated local sediment within standard (nonlocal) nourishment. Additionally, we tested cockle-seeding, where cockles were introduced to burrow into the sediment. The experiment consisted of 12 plots across four treatments: (1) standard nourishment, (2) sediment priming, (3) cockle-seeding, and (4) undisturbed control plots.

Sediment priming significantly accelerated benthic recovery compared to standard nourishment or cockle-seeding. Immediately after nourishment, primed plots exhibited higher biomass, suggesting partial preservation of the benthic community. One year later, primed plots were nearly fully recovered, likely due to retained sediment properties (e.g., grain size, organic matter). Faster recovery is especially beneficial for shorebirds, as thicker nourishments typically take years to regain ecological function. These findings highlight sediment priming as a promising strategy to improve tidal flat nourishment effectiveness, warranting further investigation, particularly for thicker, slow-recovering nourishments.

Ecological consequences of estuarine dredging

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Estuaries are dynamic coastal systems that act as ecological and economic lifelines for coastal populations worldwide. They support biodiversity, host large human populations, and serve as critical hubs for global maritime trade and transport. However, maintaining their role as gateways for commerce has increasingly come at an ecological cost. Embankments of tidal marshes, and activities like dredging and the construction of groynes, essential for stabilizing and deepening shipping channels, have profound and often underestimated impacts on estuarine ecological functioning. By concentrating tidal energy into narrower and deeper channels, these interventions may amplify tidal ranges, tidal currents, disrupt sediment transport, and alter patterns of erosion and deposition. This redistribution of sediments directly affects intertidal zones, such as mudflats and salt marshes—key habitats for biodiversity and ecosystem services. While localized sediment accumulation may temporarily promote salt marsh establishment, its effects on habitat diversity depend on spatial distribution and long-term sediment dynamics, which may lead to homogenization in certain areas. Meanwhile, the observed shrinking of mudflat extents compromises benthic communities vital for ecological processes and migratory shorebirds, ultimately threatening the ecological variability of estuarine systems.

The complexity and scale of human interventions in maintained estuaries often obscure the specific drivers of morphological and ecological changes, making it challenging to isolate the direct consequences of shipping lane maintenance. Despite this, clear ecological trends are evident in systems like the Western Scheldt, where steepening of the intertidal zone and an increase in high-elevation, low-dynamic intertidal habitats signal a significant shift in ecological conditions. Current management strategies frequently prioritize preserving low-dynamic intertidal areas, which provide fine sediment substrate for benthic communities, but it remains uncertain whether focusing solely on total habitat area is sufficient. A critical question is whether emphasizing diversity in elevation gradients, including variations including variations in the length of and distance between waterlines, may better support ecological resilience and biodiversity in the long term.

To address these challenges, we analyse large-scale global remote sensing datasets to identify patterns of habitat evolution in estuaries influenced by shipping lanes compared to those without. These findings are further linked to local physical processes in the Western Scheldt, enabling us to translate global observations into a more detailed understanding of estuarine-scale dynamics. This approach shifts the focus from localized studies to a broader, foundational understanding of estuarine habitat dynamics under human influences, providing actionable insights for environmental monitoring and sustainable management. Our global synthesis results demonstrate that dredging-induced changes lead to intertidal steepening, reduced mudflat extent, and shifts in sediment deposition patterns, ultimately impacting habitat diversity and ecological resilience in estuarine systems.

Sustainable Sediment Reuse for Ecological Island Development in the Scheldt Estuary: A Case Study

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The Scheldt Estuary is a dynamic tidal system influenced by natural and anthropogenic forces, where navigation channels, flood protection structures, and sediment management strategies have altered sediment transport, ecological conditions, and hydrodynamics. In response to the need for compensatory ecological measures associated with the Complex Project Extra Container Capacity in Antwerp, the Flemish government proposed the construction of a bird island near Ballastplaat. This initiative aims to create a stable breeding and foraging habitat for target avian species while enhancing sediment retention and estuarine resilience. A key component of the project is the strategic reuse of dredged sediments, reducing offshore disposal and promoting sustainable sediment management.

This study presents a multi-disciplinary approach integrating hydrodynamic and morphological modelling with ecological design criteria to optimize the island's layout and stability. Using numerical modelling, different island configurations were assessed to evaluate their impact on flow conditions, sedimentation patterns, and wave energy dissipation. Site selection was informed by historical sediment transport trends, bathymetric evolution, and existing ecological constraints. The island was designed to balance stability under extreme water levels (100-year return period) with periodic inundation outside the breeding season to maintain natural dynamics.

The island design incorporates a protective breakwater to minimize erosion, a sandy substrate to support target bird species, and gentle slopes to enhance accessibility for avian populations. Hydrodynamic simulations indicate that a well-positioned island can mitigate local flow disturbances while facilitating sediment deposition in designated areas, thus reinforcing habitat formation. Additionally, sensitivity analyses demonstrated that optimizing substrate composition and elevation reduces habitat loss due to storm surges and sea level rise.

The results suggest that strategic sediment reuse in estuarine restoration can enhance ecosystem functions while addressing sediment management challenges. The project showcases how engineering and ecological objectives can be harmonized, fostering biodiversity, improving estuarine sediment balance, and contributing to nature-based solutions for climate adaptation. Lessons from this case study are relevant for estuaries worldwide facing similar sediment management and ecological restoration challenges.

This study highlights the potential for sustainable dredged material management, demonstrating that anthropogenic sediment displacement can be converted into an ecological opportunity rather than a disposal challenge. By integrating adaptive design strategies with sediment dynamics, the study underscores the importance of interdisciplinary approaches in coastal and estuarine engineering.

Re-imagining Resilience of Dykeland Communities in a Changing Climate

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Dykes and aboiteaux have historically been used in estuaries around the world to convert low lying parcels of tidal wetlands to highly productive agricultural dykelands. However, in many areas, these dykes now increasing also protect valuable transportation and municipal infrastructure, residential or commercial development and sites of valuable cultural heritage. With rising sea levels and increased frequency of storm surges, existing dykelands are not always adequately protected given their age, dimensions, and lack of foreshore tidal wetlands. The factors involved in the decisions to reinforce or raise, realign, or abandon dykes are complex, and often involve significant trade-offs. Coastal climate change adaptation options are usually categorised based on the PARA framework- Protect, Accommodate, Retreat and/or Avoid. However, the PARA categorization lacks coverage of the psychological, social, cultural and linguistic underpinnings necessary for transformative coastal adaptation.

This presentation draws upon two decades of experience in the application of managed dyke realignments and tidal wetland restoration in the Bay of Fundy, Canada to present a reclassified framework for nature-based coastal adaptation (NBCA) based on '5 Rs': **Reimagine, Reserve, Relocate, Restore, Reinforce.** The nested nature of our framework is illustrated through three case studies of *Making Room for Wetlands* in the Upper Bay of Fundy with varying spatial scales and complexity. Our experience has shown that social-psychological and political barriers are among the strongest obstacles to NBCA and room (time and space) needs to be made for approaches to manage those. **Reimagine** therefore underpins our framework, shifting the narrative from static to dynamic, from domesticated to wild, from private amenity to public good and from government to share responsibility in order to enhanced resilience overall of dykeland communities in a changing climate.

Assessing the role of intertidal habitats on estuarine hydrodynamics

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Vegetated intertidal areas play a crucial role in estuarine ecosystems by providing key ecosystem services, including habitat provision, flood protection, and potentially mitigating salt intrusion. Both changes in intertidal areas within the current estuarine system as restoration efforts through managed realignment and thereby increasing the area of intertidal habits in an estuary, have an effect on these ecosystem services. Through a modelling study, using the depth-averaged NeVla model of the Scheldt estuary, we demonstrated that vegetation on intertidal areas within the current system significantly influences local flow velocities. By integrating bathymetry and vegetation cover snapshots from 1993 and 2016 in the hydrodynamic model, we found that changes in vegetation (species composition, extent, and distribution) affect currents to a similar magnitude as bathymetric changes. However, the spatial extent of vegetation's impact on current velocities in its surroundings was limited to an area of up to the vegetated zone. Nevertheless, over a timescale of decades, these vegetation-induced alterations in current velocities can influence estuarine biogeomorphology through changes in sediment transport, geomorphology and ecological processes.

In estuarine environments, increasing salt intrusion events pose a challenge to freshwater availability and tidal ecosystems. Nature-based solutions offer a promising approach to addressing these challenges while simultaneously supporting flood protection and biodiversity. While existing vegetated intertidal areas within current estuarine systems may have limited influence on salt intrusion mitigation, restoration efforts through managed realignment could provide a viable solution. Previous studies have shown that intertidal areas impact estuarine salt intrusion, but the direction (increase or decrease in salt intrusion length) and magnitude of this effect depends on estuarine classification (e.g., stratified vs. well-mixed systems) and the geometry, elevation and location of the intertidal area (e.g., near the estuary mouth vs. further upstream).

Although managed realignment is primarily implemented for flood protection and intertidal habitat restoration, its potential influence on estuarine salt intrusion remains poorly understood. Therefore, our study aims to assess the impact of managed realignment on estuarine salt intrusion across multiple estuary classes, considering variations in realignment site geometry, elevation and location. We employ an idealized funnel-shaped estuary geometry and integrate intertidal areas through managed realignment using the Delft3D-FM model. By adjusting river discharge and tidal range, we simulate different estuary classes. Our focus is on short estuaries, of which salt intrusion lengths are comparable to tidal excursion lengths. In such systems, the impact of managed realignment on salt intrusion is expected to be most pronounced.

Ultimately, a holistic approach to intertidal habitat restoration - incorporating ecological, flood protection, and salt intrusion mitigation perspectives - is essential for maximizing estuary-wide benefits. This research contributes to a broader understanding of how restoring intertidal habitats can serve as a multifunctional strategy in estuarine management.

Drivers of Greenhouse Gas Emissions in Estuarine Systems: Insights from the Scheldt Estuary

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Estuaries are dynamic aquatic systems that play a critical role in the global greenhouse gas (GHG) budget. Yet, their spatiotemporal dynamics and the influence of anthropogenic and natural factors on GHG emissions remain underexplored. This study investigates the emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from the Scheldt Estuary, with a focus on their drivers, including salinity gradients, nutrient enrichment, land use, and biogeochemical dynamics. Using a combination of machine learning techniques and isotopocule analyses, we reveal the interconnected impacts of salinity, water pollution, and land use on GHG fluxes.

We found that salinity negatively affected CO_2 and N_2O emissions, with stronger pollution-driven effects in freshwater sites upstream compared to saline sites downstream. Sites surrounded by urban areas exhibited significantly higher emissions, with CO_2 and N_2O fluxes nearly doubling and tripling, respectively, compared to sites surrounded by natural or industrial areas. Nutrient and organic enrichment, particularly elevated nitrate (NO_3^-) concentrations from wastewater discharges, further stimulated GHG emissions in the estuary.

Our isotopocule analysis of N_2O revealed that nutrient availability, oxygen levels, temperature, and salinity were key drivers of its emission pathways. While denitrification remained the dominant pathway (~89%), nitrification and/or fungal denitrification accounted for a consistent 11%, with little seasonal variation. Despite higher denitrification rates in summer, N_2O fluxes showed minimal seasonal differences, as winter conditions with lower temperatures and higher oxygen levels reduced the reduction of N_2O to N_2.

These findings underscore the importance of considering the interaction between salinity, nutrient loading, land use, and biogeochemical mechanisms to understand GHG emissions in estuarine systems. Our study highlights the utility of coupling advanced machine learning techniques with isotope analyses to provide a comprehensive understanding of emission pathways and their drivers in dynamic environments like the Scheldt Estuary.

Geomorphic dynamics and climate change effects on the spatiotemporal patterns of estuarine saltmarsh phenology

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Saltmarsh ecosystems are vital yet vulnerable interfaces where geomorphic processes and vegetation dynamics interact. Here, we present two interconnected studies in the Western Scheldt estuary, Netherlands, to assess these ecosystems under climate change.

The first study investigates the bio-geomorphic interplay between tidal emergence and vegetation dynamics from 1993 to 2016 (Feng et al., 2025). Using pixel-based geospatial analysis, we demonstrate that emersion duration—shaped mainly by elevation changes—critically influences plant diversity and cover, up to an optimal threshold. Spatial and temporal patterns of four dominant species (*Spartina* spec*., Salicornia* spec*., B. maritimus,* and *P. australis*) show that pioneer species thrive in lower intertidal zones, while high marsh species like P. australis expand in elevated areas. These findings highlight the tight coupling between geomorphic processes and vegetation dynamics, underscoring the need to incorporate localized sea level changes into ecosystem management frameworks.

The second study explores long-term vegetation phenology from 1993 to 2022, using satellite-derived vegetation indices and climate data. We identify phenological shifts, including earlier green-up, accelerated peak growth, and extended growing seasons, driven by seasonal climate variables such as spring warming and winter precipitation. Notably, higher intertidal areas exhibit earlier growth onset than lower areas. Pioneer species green up earlier than high marsh species. These trends align with global patterns observed in terrestrial and marine ecosystems, emphasizing the universal impacts of climate change on vegetation phenology.

By bridging geomorphic and phenological dynamics, our findings not only identify the patterns associated with ecosystem responses to climate change but also provide a framework for predicting future shifts and guiding restoration efforts.

AquaForest: Nature-based-Solutions for restoring and developing new mangrove habitats through eco-engineering

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Mangrove ecosystems are crucial for coastal resilience, biodiversity, and carbon storage. However, more than half face collapse due to human activities, sea-level rise, and severe storms, as highlighted by the IUCN Red List of Ecosystems. Meanwhile, vast volumes of dredged sediments could be repurposed to sustain mangrove habitats in tropical and subtropical regions. The AquaForest project addresses these challenges by demonstrating, for the first time, the circular reuse of dredged material to restore and create mangrove habitats.
Jan De Nul Group leads the consortium of eight partners, including private consultants, universities, and NGOs. The project is located in Ecuador's Guayas Delta, a region that has suffered severe mangrove habitat loss, heightening risks of coastal flooding and erosion. Since 2018, Jan De Nul Group has maintained the Access Channel to Guayaquil's port, providing an opportunity to reuse dredged sediments innovatively. After extensive investigations, including data collection and eco-engineering studies, the project secured permits and identified an intertidal flat near the Access Channel as the most suitable location for a new mangrove habitat.

The 50-hectare habitat comprises a J-shaped sand bund and a semi-permeable structure filled with silty sediments. Hydrodynamic modelling verified the landmass's hydraulic stability, while sediment analyses and mangrove nursing experiments confirmed its suitability for supporting mangrove growth. Construction was completed in September 2024, following four months of operations. Local workers built a 3-kilometer semi-permeable wall using natural materials to contain the sediment and protect the 1.5-kilometer sand dike. The wall's wave-breaking effect is under study with Gent University. Although the habitat is designed for natural mangrove recruitment, 10,000 propagules and 14,000 saplings spanning three local mangrove species were planted to initiate afforestation efforts. Early drone monitoring indicates good sapling survival and sediment compaction. The University of Antwerp is tracking carbon sequestration as part of the cSBO WetCoast project, using LiDAR to assess mangrove canopy architecture. Projections suggest a net negative carbon balance of 5,000 tCO_2e over ten years. Monthly biodiversity assessments by the local university, ESPOL, will refine ecosystem service evaluations, currently estimated to generate €650,000 annually upon full habitat maturation. AquaForest's biodiversity will also be showcased through a bird guide, developed with local NGOs and fishing communities, to enhance ecological awareness and support potential eco-tourism initiatives. Community engagement has been integral throughout the project. Local stakeholders, including residents and authorities, have been trained in nursery management, planting, and long-term habitat stewardship, ensuring sustainable management of the new habitat while fostering socio-economic benefits. AquaForest exemplifies a Nature-based Solution that delivers flood protection, ecosystem restoration, and climate adaptation.

This living lab provides critical insights into the practical implementation and scalability of mangrove-based Nature-based Solutions globally. AquaForest offers a replicable model to address the interconnected crises of mangrove loss and climate change.

Marine, coastal and estuarine restoration as an integral component of Ecosystem-based Management

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The overriding aim of marine, coastal and estuarine management is to protect and where necessary restore the natural system, its structure and functioning, while supporting ecosystem services from which society gathers goods and benefits. This review introduces and illustrates the theory and practice of social-ecological systems and systems analysis in relation to the dynamic nature of marine, coastal and estuarine systems, include the need to protect their connectivity with the catchment. It addresses the Ecosystem-Based Approach (EBA) and Ecosystem-Based Management (EBM) within the DAPSI(W)R(M) cause-consequence-response system and shows where active and passive restoration, rehabilitation and habitat recreation/creation play a role. In this, it describes the means of restoring systems against the major pressures on the systems. The new EU Nature Restoration Law and recent and ongoing examples will be used to illustrate the requirements and competencies of Member States and corresponding examples will be used from the UK and Canada. Finally, the review will indicate how success in restoration can be measured against both the requirements in the natural sciences and the obligations of competent authorities.

Is unmanaged realignment an appropriate saltmarsh restoration approach?

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Typically, managed realignment has been implemented at former intertidal locations that have been embanked and reclaimed, on the assumption these areas should be able to support intertidal habitats again. Despite this assumption, extensive engineering and landscaping works are often carried out during site construction. This includes the construction of drainage channels rather than utilising remnant pre-reclamation intertidal drainage channels. These engineering works are intended to encourage a range of habitat types and support the intended post site breaching land use, such as grazing. However, it has been demonstrated that managed realignment sites have more simplified creek and drainage networks, and lower topographic variability, than natural saltmarshes, which might restrict drainage, impact the plant communities that can colonise, and prevent widespread sedimentation and seed dispersal. The construction of simple linear channels may also have an impact on users of the site, such as fish, and there is evidence that constructed channels might impede morphological development post site breaching.

In contrast to managed realignment, unmanaged realignment is the natural breaching of flood defences without any costly engineering or landscaping works. Unmanaged realignment sites provide an opportunity to assess the "natural" morphological evolution of restored saltmarsh sites without the influence of extensive site design, engineering, or landscaping features. However, there remains little analysis of the evolution of "recent" unmanaged realignment sites, with most studies focusing on historic breaches. This study provides an assessment of the occurrences and the potential for future unmanaged realignment. The benefits of unmanaged realignment are discussed in the context of long-term shoreline management planning, including habitat creation, flood defence and carbon storage. The opportunities to learn from managed realignment through a sedimentary perspective are also considered. It is recommended that more data is collected from unmanaged realignment sites to improve the understanding of their development, and to enable additional comparisons with managed realignment sites. In doing so, we can evaluate further the appropriateness of unmanaged realignment as an approach to saltmarsh restoration.

Recovery of salt marshes in the Bay of Fundy after restoration: What does recovery really mean?

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Over 80% of the salt marshes around the Bay of Fundy, Canada were lost to agriculture over 250 years as dykes were built and land "reclaimed". Some marshes recovered as dykes failed and were abandoned. Over the past 20 years, we have been actively restoring salt marshes around the Bay employing evolving design and monitoring techniques. When the tide is restored to these systems recovery begins - but what does "recovery" mean in terms of coastal resilience and criteria to be considered in determining progress toward complete "recovery"?

The purpose of this presentation is to explore this question. First, we consider positional recovery, which can be thought of in three dimensions: the x-y (horizontal) position of the salt marsh relative to the coast and the z (elevation) position relative to mean sea level. Second, we consider hydraulic recovery, in which the hydrologic system is re-connected, and the tide can fully flood and drain from the marsh. Once positional and hydraulic recovery are attained, the natural protection offered by the salt marsh to the inland environment is largely reestablished. Third, we consider functional recovery, in which vegetation communities are reestablished, habitat is restored, carbon is sequestered, and the intrinsic values of the salt marsh system to society are returned to pre-reclamation conditions. Finally, using 20+ years of experience in this field, we contemplate the temporal dimension of recovery and the challenging question we are often asked – "how long will recovery take"?

REWRITE project: Addressing the Climate-Biodiversity-Society Crisis in Coastal Zones using Rewilding approach

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The climate and biodiversity crises are critical global challenges driven by increasing greenhouse gas emissions, particularly carbon dioxide (CO_2), resulting from human disruptions of biogeochemical cycles. The decade 2011-2020 was 1.1 °C warmer than pre-industrial levels, leading to biodiversity loss, extreme weather events, and rising sea levels. In European coastal zones, intertidal soft sediment seascapes (ISS) including seagrass meadows, salt marshes, and mudflats cover over 10,000 km² and provide crucial ecosystem services, such as carbon sequestration, biodiversity support, flood protection and recreative activities. However, these habitats are degrading due to fragmentation, pollution, and habitat loss, threatening their contributions to climate resilience and social equity.

REWRITE's Vision: REWRITE aims to develop nature-based solutions and innovative approaches for rewilding ISS, addressing biodiversity conservation, climate adaptation, and societal needs. It focuses on three key challenges:

1. Reducing Uncertainty in Future Trajectories: Understanding ISS ecological and social dynamics is critical for projecting future scenarios under restoration (active), rewilding (passive), "do nothing" and "business-as-usual" approaches.
2. Understanding Cascading Effects: Investigating how CO_2 increases, sea level rise, and biodiversity loss impact local and global ecosystems to enhance shoreline resilience.
3. Engaging Society in Rewilding: Identifying cultural and social drivers and barriers to navigate trade-offs and ensure broad societal support for rewilding initiatives.

Innovative Methodologies: REWRITE employs advanced tools and approaches to tackle these challenges:

- Ecosystem Services Mapping and Modelling: Remote sensing data from satellite, drone, airborne sensors, and field campaigns are combined to map biodiversity, carbon sequestration, flood protection, and cultural services. A stepwise validation process addresses ISS complexities, such as patchiness and mixing, ensuring robust scalability.
- Scenario Development: Scenarios are co-developed with stakeholders to explore the effects of restoration, rewilding, or no-intervention approaches. These scenarios incorporate multivariable constraints - environmental, economic, and societal - to evaluate trade-offs and identify cost-effective options for rewilding resilient shorelines. The scenarios are evaluated using iterative feedback from local to global scales to ensure feasibility and relevance.
- Social Innovation and Cultural Valuation: Participatory processes, focus groups, interviews, social media analyses, and historical research capture the cultural and societal values of ISS. This dual approach raises awareness among stakeholders and integrates bottom-up and top-down perspectives for transformative change.

Interdisciplinary Collaboration and Demonstrators: The project's strength lies in its interdisciplinary consortium of 25 partners spanning academia and private sectors from eight European tidal states, along with Canada, the UK, and the USA. By leveraging 10 demonstration sites across diverse environmental, societal, and coastal management contexts, REWRITE uses a "space for time" approach to analyse ISS trajectories. This strategy integrates natural and social sciences to co-develop robust scenarios that reflect diverse environmental constraints, societal uses, and stakeholder priorities.

By coupling cutting-edge methodologies, interdisciplinary expertise, and stakeholder engagement, REWRITE addresses the climate-biodiversity nexus and offers scalable solutions for rewilding ISS ecosystems. The project promotes resilient European coastlines and provides a blueprint for global restoration efforts, with proposed scenarios that can serve as actionable solutions within the framework of the European Nature Restoration Law.

Development of a vision on future-proof management of an estuary: the Integrated Plan of the Upper Sea Scheldt

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The Upper Sea Scheldt is the upstream and tidal part of the Scheldt, and is an important shipping connection in the Seine-Scheldt network. It is characterized by a freshwater tidal habitat fed by the flows of the cross-border Lys and Scheldt basins. The river and its valley provide important ecosystem services. Cumulative effects of climate change, the effects of the interaction with and interventions for shipping, and the hydrodynamic and morphological impacts, pose a possible risk of undesirable changes such as a system change as the one that took place in the river Ems.

In order to safeguard the ecosystem services and all functions of the estuary for the future, the waterway manager, De Vlaamse Waterweg, wishes to develop a vision for the management of the river and the layout of the valley. Making an estuary future-proof has a major spatial and social impact, takes a lot of time to realize and must therefore be tackled in a timely manner with the best possible available instruments and insights. An integrated study has been carried out by the waterway authority to gain knowledge about the functioning of the system, and to draw conclusions for the management and future layout on the basis of this.

Parallel to this study, a plan for adaptive waterway management (Sustainable Management Plan) was developed with immediate effect and set up in consultation with the nature partner, in order to coordinate the estuarine nature values and river maintenance for navigation.

The integrated study is based on a state-of-the-art model study in which prediction models were drawn up for all relevant disciplines. The models are linked together in a so-called model train in which each subsequent component builds on the input of the previous one (Adams et al.).

The system functioning, or interaction between water and sediment movement and the ecosystem functioning and nature is insufficiently known in this upward part of the estuary. The model allows insights to be gained about this. Subsequently, starting from model results of various design alternatives of the river and the valley, substantiation is given to an expert opinion of the multidisciplinary study team, on which measures make the system more robust against undesirable developments, and better still, how the condition of the system can be further improved.

The main conclusions are: a good distribution of measures in space and time, measures on a sufficiently large scale to prevent an increase in tides, a dynamic in which the valley is involved in the current. The spread over time allows the system to adapt and to monitor effects and adjust follow-up measures, taking into account acquired insights.

The presentation will discuss the main conclusions of the study, how they came about and how they contribute to the vision for the future management of the estuary.

A model for evaluating ecosystem services in tidal restoration for enhanced flood protection

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Nature based solutions for flood protection, such as managed realignment or flood control areas are often considered because of the additional ecosystem services they can offer. With rising sea levels and more frequent extreme weather events, the need for integrated solutions is increasing and hence the need for good tools to evaluate different scenarios.
The Sigma II Plan in Flanders aims to protect the region from flooding by enhancing flood control measures along the Zeeschelde estuary and its tributaries. This includes creating additional flood control areas, expanding and preserving riverine nature, providing recreational opportunities, and supporting the local economy. In developing Sigma areas, continuous decisions regarding location and design, impact flood safety and other ecosystem services such as agriculture and carbon storage. They also influence water-related services like oxygen delivery, nutrient cycling and foraging areas for birds. To accurately assess these services, spatial models evaluating the spatial structure and underlying processes are required.

ECOPLAN-SE, a spatial model developed for Flanders, evaluates 17 ecosystem services but cannot assess estuarine systems in its current form. For the Sigma areas, an extension to the model was developed to assess additional services, including regulating services like the delivery of dissolved silicon and oxygen to the water column and storage of suspended matter. Habitat functions include foraging areas for birds and spawning grounds for fish. Additional metrics or revised methods were sought for provisioning services like agriculture and energy crops and regulating services like nitrogen removal and carbon storage in the soil.

This model was tested on the remaining areas of the Sigma II Plan by evaluating different planning alternatives. In the future, it might be used within the Sigma III plan to better understand the effects of tidal restoration alternatives on ecosystem service delivery and thus help in the decision making.

Assess the spatial design of flood areas and local depoldering for proper ecological functioning, case studies along the Durme River

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In order to deal with the impact of climate change and sea level rise, the sigma plan was developed to protect Flanders from flooding from tidal rivers at storm tides. The plan is currently implemented and as part of the measures, a chain of flood areas and local depoldering along the Scheldt river and its tributaries are being implemented. At the same time, by giving these tidal rivers more space, estuarine ecosystems in these areas are developed and restored. Based on ecosystem visions, there is often a clear goal expressed in terms of amount of surface areas to be developed as new ecosystems. When new flood areas or depoldering are assigned, the contribution in terms of surface area is quickly assessed. However, the inherent desire for these new ecosystems to function properly once connected to the tidal river is harder to assess beforehand. A proper spatial design of these areas may be needed.

To support the assessment and spatial design for flood areas and depoldering in the Durme river, an evaluation framework was set up to assess the proper functioning of the areas in combination with hydrodynamic modelling. Different expert workshops were held to discuss the set up and results.
The proposed evaluation framework considered aspects such as the assessment of the design of breaches, sufficient flooding and subsequently drying of the area, potential for development of channels, siltation and potential habitat and nature development. For each of the areas, the flooding and drying of the mudflats was modelled showing the water level variations and flows throughout the area and the potential presence of (quasi)permanent dry or wet areas. These model results were then translated in expected morphological behaviour, and impact on fauna or flora. Finally, based on the assessment results and the discussion with the experts, several suggestions for adaptation on the spatial design of the areas have been made such as proposals for enlarging or damping certain existing channels in the areas, suggestions on levelling or introducing other topographic features, and proposals for the creation of local pools.

Although the modelling in these case studies gave a good first insight in the behaviour in the new flood areas or depoldering and showed to be useful in supporting the spatial design of the areas, there are still many uncertainties related to this approach, and it is therefore highly recommended to monitor the actual evolution after installation to allow an adequate management of the areas.

This presentation will illustrate the above approach by the case studies of flood area Groot Bunt and local depoldering Klein and Groot Broek in the Durme river.

Analysis of biting midges *Culicoides riethi* in the Schelde basin

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Wetlands are very valuable and threatened ecosystems that provide many ecosystem services such as flood mitigation, biodiversity conservation, and carbon sequestration. However, they also create favourable breeding conditions for biting midges, which can negatively impact nearby human communities. Their feeding behaviour, combined with their tendency to form swarms during the summer, can make them a significant nuisance to humans residing near their breeding sites.

Detailed knowledge about these midges, particularly in relation to specific stages and manifestations of the mudflat–tidal marsh successional evolution, remains scarce. This knowledge is especially critical in the newly created nature-based solutions projects in the Scheldt valley, where a rare and ecologically important, but little known, low dynamic type of estuarine habitat exists, in which biting midges of the genus *Culicoides* and more specifically *Culicoides riethi*, thrives.

This project therefore aims to expand the knowledge on *Culicoides riethi* and ways to predict an outbreak as well as mitigation strategies to prevent such outbreaks in newly created flood areas.

Enhancing Estuarine and Coastal Resilience to Climate Change with Nature-Based Solutions: A Systematic Review

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Estuarine and coastal ecosystems are increasingly threatened by climate change, facing sea level rise, intensified storms, and shoreline erosion. As traditional infrastructure proves increasingly inefficient, nature-based solutions (NbS) emerge as essential strategies for coastal and estuarine resilience, biodiversity conservation, and socio-economic sustainability. NbS harness natural processes to provide adaptive, cost-effective alternatives to engineered defences. Solutions such as salt marshes, seagrass meadows, and mangrove forests act as buffers against storm surges and erosion while enhancing biodiversity and water quality.

In this context, the LIFE ADAPTO+ project aims to promote adaptive coastal management by integrating NbS through scientific research, pilot projects, and policy engagement. It demonstrates NbS feasibility in estuarine and coastal settings by combining ecological restoration with socio-economic considerations. By fostering interdisciplinary collaboration, the project bridges the gap between ecological restoration and socio-economic imperatives, ensuring scientifically robust and practical adaptation.

Building on these objectives, this study conducts a systematic review of NbS for estuarine and coastal adaptation following the Collaboration for Environmental Evidence (CEE) methodology. By analysing a broad spectrum of literature, we evaluate the effectiveness, scalability, and limitations of NbS across diverse ecological and socio-economic contexts. Our review compiles best practices in NbS implementation, emphasizing their role in ecosystem resilience and biodiversity conservation. It evaluates policy integration strategies and identifies key knowledge gaps essential for advancing future implementation while considering the broader implications for coastal and estuarine ecosystem resilience. This review aims to support the broader objectives of adaptive coastal management in France and serve as a foundation within the LIFE ADAPTO+ framework, guiding pilot projects and providing evidence-based recommendations for policymakers and coastal managers.

From ecological theories to restoration practices in estuaries

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The scientific discipline of restoration ecology found itself upon theories and methodological frameworks from community ecology. However, the application of these theories and methods is particularly complex in estuaries, due to the dynamic nature of these ecosystems and their global degraded and human-mediated status worldwide. These specificities of estuarine environments induce particular challenges for the application of classical Before After Control Approaches (BACI) for example, and complexifies the formulation of simple and static objectives for the restoration of ecological functionalities of habitats and populations, and the multiple ecosystem services they provide.

Based upon diverse examples of estuarine restoration programs, we illustrate those methodological levees and theoretical challenges and envision the development of comprehensive multifunctional indicators to be used for monitoring restored habitat trajectories in estuaries and coastal systems. Such indicators are inspired by specialized scientific literature, in particular the *restoration wheels* proposed by the European Society for Ecological Restoration (SERE) and are built upon previous attempts of holistic indicators development for decision-making in specific projects where nature-based solutions are proposed as a climate change adaptation measures.

The aim is to provide management guidelines for projects pursuing the adaptation of coastal environments and associated socio-economic interests to ongoing climate change. Current research thus seeks improving available indicators to better illustrate concurrent changes in both terrestrial and aquatic components of estuarine and coastal interface habitats, impacts of those changes in terms of socio-economic dimensions and incertitude related to the future of estuarine habitat trajectories in the context of global change.

Linking the catchment and the seascape: nature-based solutions in tidal freshwaters

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Estuarine ecosystems worldwide face significant threats from climate change and changes in land use within their catchments, with upper estuarine tidal freshwater and low-salinity zones being particularly vulnerable and yet poorly understood. These zones play a crucial role as gateways, supplying and exchanging energy, matter, and organisms between the lower brackish estuary and the upper non-tidal freshwater river. Despite their importance, these areas have often been neglected in habitat restoration efforts, which have typically been employed in the fluvial catchment and lower estuary and seascape.

This presentation highlights one of the primary threats to estuarine tidal freshwater zones - estuarine squeeze. By mapping the extent of tidal freshwater and low-salinity zones across England and Wales, we identify which estuaries are at risk of losing these vital areas. Our findings demonstrate how mapping can guide the implementation of nature-based solutions, such as the creation of tidal freshwater marshes, to maximize benefits and enhance resilience against climate change and other human-induced pressures.
We propose that, when applied correctly, nature-based solutions in these tidal freshwater zones could be the key missing link that connects the catchment to the seascape, offering a holistic approach to nature-based solutions from source to sea.

Evaluation of an ambitious program to restore Loire estuary: key question of spatial and temporal scales

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Like many large European estuaries, the Loire estuary has undergone many changes since the 19th century, mainly due to the commercial navigation development and the massive sand extraction for construction and vegetable farming. These interventions have deeply altered the hydromorphological balance of the river, resulting in hydraulic disconnection of many secondary channels.

Since 2015, the Loire estuary has been the subject of an ambitious program to restore nearly 50 kilometres of river length in order to improve its hydromorphological balance, within the framework of Contrat pour la Loire et ses annexes (the Contract for the Loire and its channels). The Groupement d'Intérêt Public Loire Estuaire (Loire estuary public interest grouping) coordinates physical and biological monitoring in order to measure the effects of the restoration work invested.

The river and sea section concerned by the Contract is facing a tough hydromorphological variability. Therefore, watershed's inputs influence both monitoring results (before and after work) and the time it takes to see quantifiable effects of actions taken. As a passageway for migratory species, the Loire estuary is also dependent on external factors.

Whether from a morphological, hydraulic or biological perspective, the evaluation of the works effects leads the experts to question the spatial and temporal scales that will condition the results interpretation:
- How do you choose a reference state before starting work?
- How can we get closer to a systemic and exhaustive approach about transformations?
- Which spatial scales or geometric cutting do we choose for analysis?
- How can we program monitoring over time in a context of high seasonal and inter-annual variability?
- How can we perceive and discern the effects of our work from natural existing dynamics?
- Should we set a deadline for the monitoring, so we can confirm the success of restoration works?

Enhancing Knowledge and Management of Seine Estuary Mudflat

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Estuarine mudflats, particularly those in the Seine estuary, are critical ecosystems that deliver numerous ecological functions and services. These include primary and secondary production, nutrient cycling, carbon storage, flood risk mitigation, habitat diversity and refuge areas for fishes and birds. However, extensive anthropogenic modifications along the Seine River have significantly degraded these vital functionalities. Restoring the ecological integrity of these systems is essential to ensure their continued contribution to environmental sustainability and societal well-being.

Our projects, SUIVA and EVREST, funded by GIP Seine Aval, aim to advance our understanding of the physical, biological, and ecological dynamics of Seine estuary mudflats. These projects are focused on restoration efforts and long-term monitoring strategies, addressing key challenges while offering solutions for sustainable management. The overarching goal of the projects is to deepen knowledge of estuarine mudflat ecological functionality to inform and guide restoration efforts. By studying four lateral mudflats, the projects also aim to determine how spatial and environmental variables—such as connectivity to secondary rivers, sedimentary state, and hydrodynamic and salinity gradients—shape ecological functionality and restoration potential.

To achieve this, specific indicators are developed to assess ecological functions while identifying the key factors that influence their integrity, using a multi-scale, integrated monitoring approach to analyze the physical, biological, and ecological dynamics of the mudflats. The approach emphasizes sediment behavior, as well as the distribution, productivity, and diversity of microphytobenthos (MPB) and macrozoobenthic communities. Cutting-edge tools and techniques are central to this methodology, including:

- Satellite imagery (Sentinel and Pléiades),
- Drone-based imaging,
- Fixed cameras,
- *In situ* measurements.

These data are combined with statistical and machine learning analyses to explore the interactions between hydrodynamic processes, sediment properties, and MPB biomass, pigment composition, primary production, organic matter profiles, oxygen microprofiles, EPS contents (ExoPolymeric Substances) and photobiological parameters at the water-sediment interface. The monitoring framework also examines how mudflats respond to extrem events such as storms or fluctuations in sediment transport dynamics, or atmospheric and water heatwaves.

Both projects aim to provide actionable recommendations and a robust scientific foundation for future restoration initiatives. Key outcomes include:

- Development of scalable, automated monitoring strategies to enable long-term observation and adaptive management of estuarine mudflats.
- Integration of ecological and morphological observations to equip regional and local stakeholders with tools for evidence-based decision-making.
- Generation of insights into the drivers of mudflat functionality and resilience.

By disseminating results and raising awareness of the ecological value of mudflats, the projects emphasize their critical role in estuarine systems. This outreach ensures that stakeholders recognize the importance of preserving these ecosystems and are equipped with the knowledge and tools to implement effective conservation strategies.

The combined efforts in these projects will deliver key advancements in the understanding of mudflat dynamics, drivers of resilience, and restoration potential. Through innovative methodologies, long-term monitoring frameworks, and stakeholder engagement, these initiatives will provide a foundation for sustainable management of the Seine estuary mudflats, preserving their ecological functions benefiting for the riverine ecosystem and its potential adaptation to climate change.

Assessing restoration success - fish community response to an incidental restoration event in the Gironde estuary (France)

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Tidal marshes are vital coastal and estuarine ecosystems, providing an array of essential functions for fish and other species groups. During the past millennia, the creation of dykes and polders to reclaim land have resulted in large-scale declines of tidal marsh areas in Europe, altering their natural ecosystem functions. In the Gironde estuary, the largest macrotidal estuary in France, parts of the marshes of the Île Nouvelle island were tidally restored after an incidental dyke breach following a storm in 2010. With no clear reference state conditions available, dating to pre-dyked conditions, the assessment of restoration success remains a challenge.

Here we use a joint species distribution modelling framework to assess the fish community trajectory between 2009 and 2013 and evaluate the progressive effect of the restoration by modelling species-specific occurrence probabilities, as well as species richness over time in response to environmental change at tidally-restored and locked sites (negative reference).

We find strong spatio-temporal structuring of the ambient fish community coinciding with the breached dyke. Roughly half of the community showed strong statistical support for altered occurrence probabilities, with the majority of estuarine-associated species showing higher occurrence probabilities over time. We also observe a positive trend in total species richness.
While these results only shed light on relatively short-term effects of a restoration event, quantifying occurrence probabilities of species within a changing habitat context could help to evaluate the community trajectory at sites undergoing restoration measures and provide knowledge on its success by highlighting the development of target species.

Does the Sigmaplan ensure a healthy phytoplankton population in the Schelde estuary?

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In 2005 conservation goals have been set for the Zeeschelde estuary, on habitat, species, but also on system scale. These objectives were based on theoretical knowledge, rather than on historical or geographical references. The central concept here was carrying capacity: the minimum structural and functional conditions for sustainable biodiversity were derived.

As a basis for the estuarine food chain, maintaining a healthy, biodiverse phytoplankton community is crucial. Due to eutrophication however, dissolved silica, an essential element for diatom growth, was often limiting. As marshes are an important source of dissolved silica (DSi), the minimal surface of marshland needed to maintain a good DSi level in the estuary, has been calculated. The Sigmaplan, a major plan to combine flood protection and nature restoration in the Zeeschelde, aims to achieve this functional conservation goal.

Now, 20 years later, it is time to make a balance. Can we confirm, with more and better data, the assumptions made in 2005? Are the nature restoration projects (embankments and areas with a controlled reduced tide) able to restore a minimal DSi concentration in the estuary, and hence a healthy phytoplankton population? Or are new challenges appearing, with further anthropogenic modifications of the estuary and climate change?

Does a recently restored intertidal wetland already contribute to water quality improvement? A case study of the Hedwige-Prosperproject

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Within the Scheldt River basin, many tidal wetlands have been restored for their ecosystem service provisioning. One of these wetlands is the Hedwige-Prosper polder (HPP): 465 ha of previous agricultural land, restored in late 2022 for the realization of Grenspark Groot Saeftinghe. This area consists of an older restored part in the Sieperda marsh, and the newly restored parts in the former Hertogin Hedwigepolder and Prosperpolder Noord. Because of the sheer size of this restoration project, HPP forms an ideal opportunity to evaluate how nature restoration in brackish tidal marshes works on a landscape scale.

To now properly evaluate whether the restored wetland is transforming into functional nature, water quality is one of the key aspects that needs to be monitored. Brackish tidal marshes are known for their capacity for nutrient exchange and water quality regulation, but the contribution of recently restored brackish tidal marshes remains largely unexplored. Thus, a water quality evaluation was performed in the form of two field campaigns covering two full tidal cycles.

Key findings include the import of dissolved inorganic nitrogen in both older and newer tidal areas. The newer areas were found to export phosphate, while the older tidal area imported phosphate. The Sieperda Marsh exported dissolved silica, thereby contributing to healthier nutrient ratios in the Scheldt. Thereby, this research framework hints at a contribution of the Hedwige-Prosper polder to maintaining healthy nutrient and oxygen levels in the Scheldt. More research remains, however, needed to calculate actual nutrients and pollutant fluxes to estimate the full size of the water quality effect of this newly restored tidal marsh.

The effect of Hedwige-Prosperpolder on the tidal propagation in the Scheldt estuary

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The Hedwige-Prosperpolder is located on the border between Belgium and the Netherlands, along the Scheldt estuary. The Hedwige-Prosperpolder has an area of approximately 465 ha. The area was depoldered beginning of 2023 by excavation of the former primary dyke and an onset of a creek and gully system was excavated in the area itself.

In this study an assessment was made on the impact of the depoldered area on the tidal propagation in the Scheldt estuary itself and a comparison with previous model excercises. A data analysis was performed, based on the measured tidal data from gauges along the Western Scheldt and the lower Seascheldt.

Based on this analysis, the effect on the highwater levels at Antwerp is estimated at a reduction of about 1 - 2 cm at neap tide and 3 - 5 cm at spring tide. The largest effects are found at Liefkenshoek, just upstream Hedwige-Prosperpolder, the smallest effects at Prosperpolder, just downstream of the depoldered area.

Unveiling Full-Spatial Seasonal Dynamics in the Sea Scheldt Estuary: Integrating Satellite Remote Sensing with Long-Term Monitoring

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The Sea Scheldt Estuary is a highly dynamic and intensively utilized waterway, hosting the Port of Antwerp and serving as a crucial corridor for inland shipping. This intensive use necessitates frequent waterway modifications, making monitoring essential for effective adaptive management. Traditional in-situ water monitoring provides precise data but is limited to specific sampling points, offering only a fragmented view of the estuarine system. On the other hand, satellite remote sensing provides comprehensive spatial coverage but is hindered by Belgium's frequent cloud cover (~75%) and the lower accuracy of the method. To address these challenges, a clustering analysis was conducted on satellite imagery of the Sea Scheldt. This analysis identified regions within the estuary that exhibit similar characteristics, enabling the extrapolation of in-situ point samples to the entire estuary. This integrative approach provides a detailed spatial understanding of the seasonal dynamics of primary production and its key drivers, salinity and turbidity, thereby enhancing our ability to manage and restore the Sea Scheldt Estuary effectively.

iFLUX: an innovative method to measure groundwater flow in newly restored tidal marsh areas

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Tidally induced groundwater and soil moisture dynamics play a crucial role in tidal marsh ecosystem functioning. Groundwater dynamics regulate the flow of nutrients and soil aeration depths, hereby controlling the prevailing biogeochemical processes, vegetation development and the ability of the marsh to store carbon. In newly restored tidal marshes, altered soil structure and the limited amount of organic matter in the soil can hamper groundwater dynamics and the functioning of the marsh to improve estuarine water quality.

In the Bankbusters marsh restoration project, a new marsh was built using willow withies and filled with allochthonous soil that was mixed with wood chips in several treatment plots. Here, we quantify the effect of organic soil amendments soil moisture dynamics, groundwater dynamics and groundwater flux and we monitor the development of the newly restored tidal wetland.

We present a newly developed sensor that can measure both groundwater flow velocity and direction in real-time. The sensor probe consists of two bidirectional flow sensors that are superimposed. It is installed in a dedicated prepack filter and can measure a broad range of groundwater flow velocities from 0.5 cm/day to 2000 cm/day. With an IoT (Internet of Things) system, all measurements are wirelessly transmitted and visualized in real-time on an online dashboard.

Measurements of groundwater flux clearly show the inflow and outflow flux of water during the rising tide and falling tide, respectively. However, observed flow directions do not follow flow orientation from and towards the creeks and the main channel, suggesting that groundwater in the marsh mainly flows through macropore networks. Both groundwater flux and groundwater level fluctuations show a clear correlation with semi-diurnal tidal surface level fluctuations. Soil moisture dynamics, in contrary, are mainly correlated to longer term (spring tide – neap tide) variations and weather conditions during the non-inundated period around neap tide. No clear effect of organic soil amendments on groundwater dynamics was observed yet.

Given the importance of groundwater dynamics for the success of tidal wetland restoration, we conclude that monitoring of soil moisture dynamics, groundwater level fluctuations and groundwater flow is essential to assess the development of a restoration site towards a fully functional tidal marsh ecosystem.

The EU Nature Restoration Regulation and estuarine ecosystems: moving towards recovery

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With the adoption of the EU Nature Restoration Regulation in June 2024, new legal possibilities arise to upscale restoration in Europe. Although the Commission proposal for a nature restoration law was weakened during a tumultuous political process the finally adopted text still holds potential for restoring degraded ecosystems. The Nature Restoration Regulation complements and strengthens existing restoration obligations under EU law, including under the Habitats Directive and the Water Framework Directive. For estuarine ecosystems the law includes twofold provisions: on the one hand the obligations for Annex I listed ecosystems, which include estuaries and on the other hand additional obligations for restoring the connectivity of rivers. Restoration has been defined as the process to assist the recovery of an ecosystem. This presentation will unravel the obligations under the Nature Restoration Law for the recovery of estuarine ecosystems. Which steps need to be taken to move towards recovery? Should this lead to full recovery? What if full recovery is not possible, for instance due to climate change? Is the law strong enough to prevent moving backwards through non-deterioration obligations? Are the obligations under this law capable of dealing with dynamic ecosystems such as estuaries?

Challenges in setting environmental quality standards for chemical stressors in estuarine gradients

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Estuaries form the transition zone between the freshwater and marine environment where the mixing of fresh and seawater creates unique conditions from a physical, chemical and biological perspective. These conditions also make estuaries the habitats of a specific flora and fauna, including freshwater, estuarine, and marine species along the gradient.

The protection of the aquatic environment requires environmental quality standards (EQS) that are protective for the diversity of species occurring in a given environment. This is especially a challenge for the estuarine environment because of the strong gradient in salt concentrations (salinity) and other factors that change along the gradient. These changes are also strongly reflected in the changes in biological species diversity moving from the freshwater to the marine part of an estuary.

Nonetheless, most (inter)national environmental quality standards only distinguish between freshwater and marine guidelines. Within this framework, the estuary is divided in a freshwater and marine part. However, it is well known that the sensitivity of aquatic organisms to chemical stressors may change strongly with salinity, depending on the chemical compound and biological species. These effects are most outspoken in the fresh/brackish zones of estuaries, but are not fully accounted for in current regulations.

In this work, an overview is presented of existing (inter)national regulations and how this translates into the setting of environmental quality standards for estuaries. Which conditions and processes determine the changes in sensitivity of organisms to chemical stressors, and how they are (or are not) taken into account in setting standards for estuaries ? Examples are given of cases where the effects are small, moderate, or of critical importance. Guidelines for further development of estuarine-specific guidelines for chemical stressors are given.

Balancing towards a resilient Scheldt estuary

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Nature restoration and complying with N2000 regulation in the Scheldt estuary has been hampered for the last decades due to the difficulties to get agreements on setbacks (depolderings). The Flemish Dutch Scheldt Committee therefore decided to first try and agree with stakeholders on the perspective for the long term for 'a robust and resilient estuary'. After a period of joint fact finding, resulting in a system analysis (2019), a process started to draft such long-term perspective.

In the working process solutions were necessary to balance between the short-term conservation goals and the long-term need for a dynamic and resilient estuary (to cope with climate change). The translation of a long-term perspective to actions in the coming 15 years is more than challenging. In the presentation these solutions are discussed, especially (i) elaborating the elements of 'robustness and resilience' in agreements with the stakeholders, (ii) the development of a 'framework of ambitions' to assess both short term and long term effects of 'directions of development', (iii) using a design process to visualize these directions and facilitate the stakeholder discussions on assessments of effects and (iv) using the theory of pathway dependency to bring the short term (15 years ahead) and the long term (several decades and longer ahead) together.

Finally, the evaluation is done what this has brought for the working process (did it help getting consensus between stakeholders) and the scientific challenge to provide tools to balance between static regulation, supporting the present ecological values and giving priority to estuarine processes to enhance long term resilience and self-organization.

System evaluation based on an integrated model approach: the model train of the Upper Sea Scheldt

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The integrated study of the Upper Sea Scheldt seeks to draw up a long-term vision for the management and layout of the estuary (De Beukelaer-Dossche et al.). The vision seeks to arm the river against the cumulative effects of interventions, shipping, climate change, the morphological impact of these effects, in order to provide sufficient guarantees to sustain the various functions of the river: safety against flooding, ecosystem functioning, nature and ecosystem services, recreation, shipping.

In order to better understand the functioning of the Upper Sea Scheldt and changes in the system, a comprehensive model instrument has been built to simulate the processes in the river. A model train has been put together in which each follow-up model builds on the outputs provided by the previous models in the chain. The train starts with a hydrodynamic model, to which a sediment transport, ecosystem, habitat and two separate models for higher trophic levels are successively linked.

With the succession of models, the spatial detailing decreases and the uncertainty increases. To make the transition from one model to the other possible, comparable interpretations of bathymetry and boundary conditions are needed. This requires extensive coordination between the modelers in the different and widely divergent disciplines.

In contrast to the status assessment according to the acknowledged Scheldt Estuary Evaluation Methodology, which is based on measurements, there are no tools available for the evaluation of a future situation on which the vision wants to be based. Inspired by the Evaluation Methodology mentioned, a framework has been drawn up for the state description and evaluation of the simulated situation. The extensive monitoring carried out in the context of the Evaluation Methodology has made it possible to calibrate and validate the various models.

The process of coordination and evaluation ultimately led to an instrument and working methodology that effectively allow conclusions to be drawn about the expected state of the river after the implementation of interventions and design alternatives. The development vision for the Upper Sea Scheldt could be based on this.

The presentation will discuss the interactions between the model components, the translation into parameters for evaluation, the input of expertise in the evaluation process, how this led to design choices, and recommendations for the further use of the model instrument.

From static to adaptive: how case law can influence the regulation of dynamic estuarine ecosystems in the context of nitrogen, PFAS, and climate change

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The Scheldt estuary serves as an example of the tension between dynamic ecosystems and static regulatory frameworks. Characterised by fluctuating tidal waters, shifting sediment patterns, and diverse habitats, the estuary presents challenges in balancing conservation objectives with the natural dynamics of the environment. This natural dynamism is essential for maintaining biodiversity and the overall health of the ecosystem. Conflict can arise from attempts to maintain fixed conservation goals in the face of the constantly shifting estuarine ecosystem, raising questions about how to reconcile the natural processes of habitat change with rigid regulatory and conservation policies. A relevant aspect of this discussion is how case law can contribute to shaping a more adaptive regulatory response to the management of dynamic ecosystems, such as estuaries, and the impacts they face.

A recent series of court rulings has indicated that, while more attention has been paid to direct habitat loss when contemplating port management and expansion plans, indirect environmental stressors, such as atmospheric nitrogen deposition, persistent organic pollutants (POPs) and climate change, are often still overlooked in the current permitting procedures. This paper discusses these three areas of case law, relevant to the Scheldt estuary.

* Where it regards nitrogen, the recent INEOS ruling found that the Flemish Government failed to justify why additional nitrogen deposition was not harmful to a near Natura 2000 area. The Council stated that the reasoning for allowing a deposition below 1% of critical values did not adequately consider the conservation objectives of the nature reserve. More robust considerations of conservation objectives are required when assessing environmental impacts, like nitrogen deposition.
* There has been legal action due to the long-lasting contamination of water and soil resources with PFAS. In some cases, courts compelled authorities to take more urgent action to monitor and address PFAS pollution, acknowledging risks to human and ecological health. This broader judicial trend emphasises the need for thorough regulation and cleanup.
* Climate change impacts are becoming increasingly relevant in legal discussions. Courts started to recognise the need for adaptive management in light of shifting environmental conditions. The evolving legal framework is pushing for dynamic, responsive conservation strategies that can account for both pollution and the long-term effects of climate change on estuarine ecosystems.

This paper will explore how case law can contribute to the development of a more effective regulatory framework for dynamic ecosystems, for example by emphasizing the need for more robust considerations of conservation objectives when assessing environmental impacts in areas, like the Scheldt estuary, where conditions are constantly changing. It will demonstrate how case law can support a more dynamic approach to protection by advocating for adaptive management practices that respond to evolving environmental conditions and impacts.

Stakeholder dynamics and the role of legal instruments in transboundary biodiversity governance. Can the Nature Restoration Law play a role in facilitating consensus?

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The Scheldt estuary is one of Europe's most important ecological estuaries, also hosting one of Europe's largest ports, necessitating effective transboundary environmental governance between Flanders and the Netherlands. Bilateral treaties were concluded to ensure flood protection, accessibility, and ecosystem preservation. The Flemish-Dutch Scheldt Commission was established to implement these treaty objectives and facilitate the cooperation between the Netherlands and Flanders to achieve common policies and management in the Scheldt estuary to develop the Scheldt estuary as a multifunctional estuarine water system used sustainably for human need. In a later stage, the Scheldt Council was established as an independent advisory body to the Commission, enhancing pro-active stakeholder participation

The Commission aims at developing a long-term perspective for the nature of the Schelde estuary, in which process it considers the involvement of stakeholders an important aspect. The Council was asked to set up a stakeholder participation process to reach a common perspective.

Through a bottom-up approach, stakeholders collaboratively, with support from independent experts, defined what constitutes 'robust and resilient nature' while exploring options for achieving this. Although the findings-report did not reflect consensus on specific options, it provides valuable insights into stakeholder discussions and reveals sensitivities; for example, while ecosystem-wise de-poldering was agreed optimal, this received strong opposition from some stakeholders.

This article examines the interplay between legal obligations regarding nature, the bilateral treaties governing transboundary environmental cooperation in the Scheldt estuary, and stakeholder contributions in this process. It discusses the role of stakeholder processes in fostering a shared understanding of the ecosystem and documenting various options and their impacts. It acknowledges that the broad mandate of defining options to achieve robust and resilient nature, as well as the use of a bottom-up approach presented challenges, which to a great extent relate to a shortage of space and conflicting land-use interests.

The Sea Scheldt and Western Scheldt are both designated as Natura 2000 areas. With this designation, the Flemish and Dutch governments have to implement the legal requirements set out in the Birds and Habitats Directive for protecting and managing these areas. A legal obligation to achieve good water quality, moreover, stems from the Water Framework Directive.

Such legal obligations have been leading in this process, however, seem not to have been able to play a decisive role in the stakeholder process. Overall, the article emphasizes the complexities of transboundary environmental governance and the necessity of effectively navigating diverse stakeholder perspectives within a clear framework of legal obligations related to nature.

While not impacting on the mandate of the Commission, the article also looks at whether the Nature Restoration Law could provide additional legal guidance to this sensitive stakeholder debate on what is required in practice to achieve robust and resilient nature in the Scheldt estuary. The conclusion of this article aims to contribute to a debate on how governance – specifically through the interplay with the legal obligations from the Scheldt treaties and European nature instruments, can contribute to better protection of the estuary ecosystem.

PART III

ABSTRACTS
POSTER PRESENTATIONS

Long-term phytoplankton dynamics in the Belgian part of the Schelde estuary

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We analysed two decades of phytoplankton monitoring data from the OMES project, using pigment analysis for biomass and microscopy counts for community composition, focusing on the freshwater and brackish tidal reaches of the Belgian part of the Schelde estuary.

Our results showed that extreme flooding events and changing human activities, such as de-eutrophication during the 2000s and morphological interventions in the 2010s, have affected phytoplankton dynamics in the estuary. Since 2018, metabarcoding sequencing of V4-18S rDNA has been included in the monitoring program, allowing the detection of eukaryotic taxa that were previously undetectable using light microscopy.

These data indicated a pronounced seasonal species turnover, driven by the interaction of freshwater discharge and saltwater intrusion. The eukaryotic community composition along the estuarine gradient was more uniform during periods with high discharge, but differentiated when discharge was low, with an upstream dominance of diatoms, and downstream dominance of ciliates and fungi. Moreover, metabarcoding data suggested a previously unknown cryptic diatom diversity and confirmed regular observations of parasitic chytrids. While these fungi can cause mass mortalities in phytoplankton, their potential impact on phytoplankton dynamics is not clear and will be further investigated to improve our understanding of the aquatic ecosystem of the Schelde estuary.

Modelling the Scheldt estuary: the SCALDIS model and its applications

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The SCALDIS model serves as a reference for the tidally influenced part of the Scheldt estuary and was developed using TELEMAC-3D. Initially created and calibrated for scenario analysis in the Upper Sea Scheldt as part of the "Integrated Plan of the Upper Sea Scheldt" project, it features an unstructured mesh with a higher spatial resolution, particularly upstream, compared to its predecessor, the NEVLA model which used a structured grid.

The SCALDIS model has various applications. It provides hydrodynamic input for sediment transport calculations involving sand and mud. The hydrodynamic results are used to delineate habitats in the subtidal zone of the Sea Scheldt. Specifically, the maximum flood current velocity defines boundary values for high and low dynamic subtidal zones. The SCALDIS model is also utilized to assess the impact of flood control areas on hydrodynamics in the Scheldt estuary. Tracer dispersion experiments within the model are employed to calibrate an ecosystem model. The flow fields generated by the model are processed as a flow atlas and integrated into the shipping simulator of Flanders Hydraulics.

The first SCALDIS model was calibrated for 2013, and a re-calibration was done for 2019. Flanders Hydraulics is currently developing the next model in this series, SCALDIS 2020. This update focuses on generating an optimized unstructured mesh and revising the type and location of the open sea boundary condition. All active or planned Flood Control Areas are included in the mesh of the SCALDIS 2020 model. The model is optimized for efficient computation on the High-Performance Computing (HPC) cluster of Flanders Hydraulics.

To develop a reference model with broad applicability, it is essential to implement a comprehensive calibration strategy. For this purpose, the VIMM toolbox is employed for the hydraulic model. This toolbox is internally developed at FH and operates in MATLAB. The Scheldt estuary benefits from extensive measurements, allowing for robust calibration and validation against a rich dataset. Calibration and validation are conducted for distinct, non-overlapping periods in the year 2020, encompassing storm events, normal conditions, and high river discharge scenarios in the Scheldt estuary.

Continuous water level data are available from 55 stations, while continuous salinity data are accessible from 13 stations. Additionally, continuous deep water velocity measurements for the year 2020 are recorded at two stations: Lillo and Oosterweel. Further measurement data originate from shallow water campaigns carried out over the preceding five years (2015-2020). From the sailed ADCP data, 49 campaigns were selected spanning three years before and after the modelling year (2017-2023), ensuring an even distribution of measurements across the model domain as well as during calibration and validation phases.

Zooplankton, suprabenthos and fish in the restoring Scheldt

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Water quality improvement has given rise to the revival of zooplankton, hyperbenthos and fish populations in the brackish-freshwater reach of the Scheldt estuary. Zooplankton, hyperbenthos and fish data obtained from the OMES project and INBO monitoring at 6 six stations along the Zeeschelde over the period 2013-2023 were combined to evaluate in how far hyperbenthos and fish impact on the mesozooplankton abundance and community composition. Do they represent an important structuring factor for mesozooplankton, besides physico-chemical environmental data?
Analyses are running at present; the poster will show the results!

Microphytobenthos biomass in high temporal resolution

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Microphytobenthos (MPB), algae that inhabit the top sediment layers of intertidal flats, can form dense biofilms that contribute significantly to the primary production in estuarine ecosystems. The biomass development of these MPB biofilms is characterized by pronounced temporal variability at multiple scales, in relation to tidal and diurnal, spring-neap, seasonal and interannual cycles. On top of that, MPB community composition varies over the estuarine gradient, and different communities can show diverse biomass patterns. Field sampling but also airborne remote sensing is not able to fully capture this variability. We installed light sensors to measure Normalized Difference Vegetation Index (NDVI, as a proxy for MPB biomass) in high resolution (every ten minutes) on estuarine intertidal flats along the salinity gradient of the Schelde estuary. The sensors were installed at a freshwater tidal flat where the MPB biofilm was dominated by euglenoids, and at a brackish and marine tidal flat, where the biofilm was dominated by diatoms. We show contrasting migratory responses of the biofilm that result in different intratidal biomass patterns between communities. We also observed contrasting seasonal biomass patterns between communities. These results underline that including high-resolution temporal variation in biomass estimates could be relevant for benthic primary production modeling.

Managed Realignment of Lillo's Potpolder

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The Sea Scheldt restoration plan aims to establish 2000 hectares of new estuarine habitat in Flanders (Belgium). Managed realignment or depoldering is an effective estuarine restoration measure. In 2012, the Lillo's Potpolder was depoldered and divided into two compartments with distinct realignment designs. Lillo-West had the dike fully removed, whereas Lillo-East retained a partial dike with a single breach.

Over the first decade, sedimentation, vegetation dynamics and macrozoobenthos populations (mud scud and ragworm) were monitored. Creek development was reconstructed using aerial photographs and LiDAR data. Within one year, a dendritic creek system had formed, and after ten years both compartments showed substantial sediment accretion, with higher net sedimentation in Lillo-West. Vegetation established via two pathways: clonal expansion from higher zones (e.g. reed, bulrush) and pioneer colonization on creek ridges, starting with the algae (*Vaucheria* sp.) and followed by pioneer species (e.g. sea aster, orache). While pioneer species emerged simultaneously in both compartments, their expansion was faster in Lillo-West. Macrozoobenthos populations settled rapidly and reached similar densities in both compartments.

Estuarine habitat development processes progressed more rapidly in Lillo-West due to the complete dike removal, which maximized tidal exchange, accelerated sedimentation, and enhanced creek density. These factors contributed to a faster transition from unvegetated mudflats to vegetated tidal marshes. Ultimately, both compartments developed into fully functional estuarine environments, confirming that well-implemented managed realignment facilitates natural estuarine ecosystem restoration. Long-term monitoring has proven essential for understanding these processes and guiding future restoration efforts.

Thermal dynamics in intertidal sediments: the role of grain size and water content

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Sediment grain size and water content strongly influence thermal dynamics in intertidal environments. Coarse sands drain quickly, dry out faster, and absorb more heat under direct sunlight, potentially subjecting burrowing benthic species to thermal stress. In contrast, muddy sediments retain more water, which could buffer temperature fluctuations. However, their darker color increases absorption of solar radiation, potentially leading to higher surface temperatures. Shallow-burrowing organisms, such as bivalves, are particularly vulnerable to surface heating, as they have limited capacity to escape rising temperatures. Prolonged exposure to heat stress can disrupt survival, alter burrowing behavior, and reduce their availability as prey for higher trophic levels, such as foraging birds and fish. With climate change driving temperatures in tidal flats closer to lethal thresholds, understanding the relationship between sediment properties and temperature extremes is critical for predicting species vulnerability and ecosystem stability. We investigate how sediment grain size and water content influence thermal dynamics in intertidal sediments. This is particularly important for restoration efforts, where human interventions such as managed realignments, groins, and nourishments alter these key factors, potentially affecting species resilience and ecosystem stability.

To investigate how grain size and water content influence thermal dynamics in tidal flats, temperature sensors were deployed in 2024 at contrasting sites across the Oosterschelde, Westerschelde, and Waddenzee. These included muddy tidal flats (Bath and Paulinapolder in the Westerschelde, mainland coast in the Waddenzee) and sandy tidal flats (Oesterdam, Dortsman, and Roggenplaat in the Oosterschelde, Texel in the Waddenzee). Sensors were placed at multiple sediment depths (0, -3, -5, -10, -20, and -40 cm) to monitor temperature fluctuations across varying inundation frequencies (20%, 33%, 50%, 66%, and 80%). Additionally, sediment samples from the top 3 cm were collected to analyse grain size and water content to assess how these sediment properties influenced temperature buildup. While 2024 was not an exceptionally warm year, temperatures still exceeded 30°C for several hours at -3 cm and -5 cm, depths typically occupied by shallow burrowing benthic species, such as cockles. The rate of heating and the amplitude of temperature fluctuations within a tidal cycle varied between muddy and sandy environments. These variations suggest that sediment properties influence the extent and duration of thermal stress experienced by benthic species. The role of water content was analysed using an advanced sediment temperature simulation model developed at NIOZ (Liu et al., in prep), showing that sediment drying accounts for differences in heat accumulation.

These findings highlight the importance of understanding thermal dynamics in intertidal habitats, particularly as climate change intensifies heatwaves. Sediment composition may play a crucial role in species resilience, especially in areas where human interventions alter sediment properties, such as managed realignments, groins, and nourishments. These modifications can unintentionally change grain size, water retention, and thermal properties, potentially increasing heat stress for benthic organisms. Failing to account for these factors could lead to shifts in benthic community structure, with cascading effects through the food web, impacting higher trophic levels and the overall functioning of estuarine ecosystems.

Cyclical Dynamics of Tidal Flats and Saltmarshes: Implications for Sustainable Management Practices

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Intertidal estuarine environments, including tidal flats and saltmarshes are dynamic systems with wide ranging benefits from flood resilience to habitat biodiversity. Saltmarshes and tidal flats are eroding globally with an estimated saltmarsh loss of 0.28% per year between 2000 to 2019 [1]. This is expected to continue with rising sea levels, increased storm intensity, and human interventions that are reducing sediment supply. The protection of saltmarshes and tidal flats from erosion is therefore key to enable continued benefit realisation.

Despite many long-term erosive trends, in the short term, the same saltmarsh may retreat and expand and the same tidal flat may erode and accrete indicating they are naturally rebuilding systems. This poses an opportunity to manage these natural processes to minimise the erosion whilst maximising the expansion.
We aim to provide conceptual models to explain the processes that drive tidal flats and saltmarsh biomorphodynamics globally. For tidal flats we focus on the vertical changes in sediment, whereas at the saltmarsh edge we focus on the horizontal movement. These conceptual models are based on global literature, including management and recommendation manuals. This aims to provide an understanding of the similarities and differences in the processes occurring and the management strategies to optimise resilience.

In the short term (days), tidal flats experience fluctuations in the bed shear stress due to the hydrodynamics, which can trigger either erosion or accretion. Over the long term, the tendency towards erosion or accretion depends on the sediment supply into the system as more energy is required to keep more sediment in suspension. Once a tidal flat enters a long-term state of erosion or accretion, the shape reinforces this process, creating a self-sustaining morphological cycle.

Saltmarshes experience an expansion-retreat cycle, influenced by the sediment dynamics at the tidal flat- saltmarsh interface. The retreat stage is triggered when a height difference forms, leading to marsh cliff formation. However, short term retreat does not always indicate long term trends, as accretion on the tidal flat or a toppled marsh platform may reduce the height difference, fostering seed settlement. Since saltmarshes and tidal flats are highly interrelated, management approaches must consider the system as a whole. During the meeting I will discuss how these processes can be used to improve management of intertidal estuary environments.

Making Room for Wetlands 2.0: Managed realignment and tidal wetland restoration in Nova Scotia's dykelands

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The practice of re-introducing, where feasible, tidal flow to dykelands and the restoration of tidal wetland habitat has been identified as a viable adaptation method to current and future hazards associated with climate change.

Building upon the successful implementation of managed dyke realignment and the restoration of 30 ha of tidal wetland habitat in the first iteration of the Making Room for Wetlands (MRFW) project (2017-2022), MRFW 2.0 is being implemented in four tidal river estuaries in the Bay of Fundy, Nova Scotia, Canada. Sites for dyke realignment, habitat restoration and/or drainage improvements are being selected in collaboration with the Nova Scotia Department of Agriculture, following an estuary-scale evaluation, and comprehensive dyke vulnerability assessment, building upon over two decades of collaboration and experience in tidal wetland restoration. Many sites have historical and cultural significance to both the Mi'kmaq and Acadian peoples and are known to support culturally important species including plamu (Atlantic Salmon), punamu (Atlantic Tomcod) and ka't (American Eel).

The project will improve the resilience of communities, infrastructure, and agricultural lands surrounding each estuary by re-establishing room for the natural migration of wetlands and reducing flood and erosion risks.

This poster will provide an overview of the MRFW project and associated goals, the integration of a comprehensive estuary-wide assessment into the project framework and will describe the development of best practices for managed realignment and tidal wetland restoration in these areas.

Tides, Vegetation, and CO_2, Fluxes: Insights from 1.5 Years of Eddy Covariance Monitoring in a Brackish Coastal Wetland

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Despite their significant potential for carbon storage, coastal wetlands in the Rhine-Meuse-Scheldt Delta remain largely unmonitored regarding carbon flux dynamics, especially in mature brackish marshes.

Using the Eddy Covariance method, we measured CO_2 exchange over ~1.5 years in Verdronken Land van Saeftinghe (NL), a brackish marsh bordering the middle Scheldt River estuary. It is characterized by free-ranging cattle grazing, a dominance of reed vegetation (*Phragmites*), and the presence of wrack deposits accumulating against dykes and in higher, sheltered marsh areas. Due to the accumulation of this wrack, the soil has a high organic content reflected in the plant species and soil fauna present.

The main objective was quantifying the magnitude of vertical CO_2 emissions and uptake, their seasonality, and their relationship to tidal water levels. Additionally, flux footprint analysis was used to explore the influence of different vegetation types and land cover classes within the study area.

The data suggest relatively low uptake and emission fluxes and a weak dependence on (especially the more extreme) tides. A possible explanation is that the substantial carbon storage capacity of coastal wetlands is mainly driven by lateral sediment accumulation rather than vertical CO_2 fluxes. Additionally, the presence of cattle and wrack may suppress gross primary production, while large respiratory fluxes offset CO_2 uptake, resulting in low net exchange.

Opportunities are being explored to continue this monitoring as a longer-term study, incorporating CH_4 flux measurements and enabling comparisons with the nearby, recently restored Hedwige-Prosper Polder. In this younger marsh, researchers from Antwerp University have started similar greenhouse gas flux studies, offering a chance for comparison. These comparisons will leverage how wetland age and management influence carbon flux dynamics.

Small scale variability of thermal stress patterns in intertidal sediments: drivers and ecological implications

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Intertidal areas are among the most challenging environments for organisms due to significant fluctuations in temperature, emersion time, salinity, and oxygen levels. Temperature dynamics in particular play a crucial role in shaping species distributions and are strongly influenced by vertical positioning, which determines exposure duration. Climate change is expected to amplify these fluctuations, particularly through the increasing frequency, intensity, and duration of atmospheric and marine heatwaves, and the gradual rising of mean water and air temperatures.

Shallow intertidal habitats heat up rapidly, making them highly vulnerable to temperature fluctuations. Recent mass mortality events of infaunal species have been linked to extreme heat, where sediment temperatures exceed species tolerance thresholds, causing lethal and sub-lethal effects. However, due to small-scale environmental heterogeneity, thermal conditions vary significantly, creating diverse exposure patterns that can vary considerably between sites.

This study examines the thermal characteristics of two contrasting sites in the Oosterschelde (the Netherlands). For this, continuous measurements were taken at five emersion times (24, 36, 52, 66, 80%), from May to August 2020, an abnormally warm summer for this system with multiple heatwaves and higher temperatures throughout the summer. Measurements included temperatures at different depths within the sediment (0, 3, 10cm), UV-radiation strength and water depth.

Results revealed distinct thermal stress patterns shaped by environmental variability along a vertical gradient. Hereby emphasizing emersion time as an important factor driving heat build-up and dissipation, with sub optimal temperatures experienced throughout the intertidal zone during warmer weather events. Extreme and potentially lethal temperatures were more frequently observed at higher emersion times, whereas lower emersion times experienced prolonged periods of moderate-to-high temperatures, making the entire gradient susceptible to either lethal effects or harmful sub-lethal effects. The two study sites displayed markedly different heat build-up patterns, showing strong interaction effects between emersion time and location, suggesting these differences are driven by environmental drivers such as sediment composition and water temperature. These contrasting thermal conditions can lead to substantial differences in ecological implications, potentially altering species distributions, causing population declines, and affecting intertidal community structure and ecosystem function.

These findings highlight the importance of site-specific conditions in determining the severity and type of thermal stress experienced by infaunal communities, reinforcing that thermal exposure can vary drastically between locations within the same system.

Tidal propagation in an estuary under sea level rise and morphological evolutions: a sensitivity analysis

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Sea level rise (SLR) poses many challenges to estuaries and their functioning (e.g. safety against flooding, ecological values, …). To tackle or mitigate these challenges, the Flemish government is developing Sigmaplan 3.0. In order to do so it is necessary to better understand the impact of SLR on tidal propagation in estuaries. The tidal propagation along the estuary is mainly determined by its geometry and morphology. SLR will not only influence the tidal characteristics but will also alter the morphodynamics of the system. By hydro-morphological feedback mechanisms, these morphological evolutions will in turn alter the hydrodynamics.

Prediction of the future morphological evolution of the Scheldt estuary is extremely difficult as it depends on numerous factors (sediment availability, management options, rate of sea level rise, …). To circumvent these uncertainties, a sensitivity analysis is performed in which various potential morphological evolutions are prescribed (i.e., elevation increase of intertidal areas and/or subtidal channels as a fraction of SLR). This is done under different scenarios of SLR. The impact on tidal characteristics (i.e., evolution of high- and low water along the estuary, tidal asymmetry) is assessed for each of these scenarios using a complex 3D hydrodynamical model of the estuary (Scaldis in Telemac). Additionally, the sediment budgets of the different scenarios are compared and assessed using GIS analysis.

Biogeochemical Drivers and Microbial Pathways of Greenhouse Gas Emissions from Tidal Wetlands

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Tidal wetlands are significant sources of greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), yet the complex interplay of natural and anthropogenic factors driving their emissions remains poorly understood. This study synthesizes findings from two complementary investigations into the spatiotemporal dynamics and production pathways of GHG emissions in tidal wetlands along the Scheldt Estuary, with a focus on the interactive effects of salinity gradients, water pollution, and microbial processes.

Our findings reveal a marked increase in GHG emissions as salinity decreases and water pollution intensifies upstream. Freshwater wetlands, characterized by elevated concentrations of organic matter, nutrients, and ammonium (NH_4^+), along with reduced dissolved oxygen and pH levels, were the largest GHG emitters. These conditions promoted methanogenesis and denitrification, leading to significant CH_4 and N_2O production, while also shifting carbonate equilibria to enhance CO_2 release. As a result, the most upstream freshwater wetland exhibited a global warming potential 35 to 70 times higher than downstream meso- to polyhaline wetlands. In contrast, saline wetlands, with lower nutrient and organic carbon (OC) concentrations and higher salinity, released considerably smaller amounts of GHGs, underscoring the suppressive effect of salinity on microbial activity and organic matter decomposition.

Isotopic and functional gene analyses provided deeper insights into the microbial pathways driving CH_4 and N_2O production. Methanogenesis, indicated by the abundance and expression of the mcrA gene, was dominant in freshwater wetlands, where labile OC and nutrient availability were highest. Conversely, higher salinity inhibited methanogen activity, resulting in lower CH_4 emissions in saline wetlands. For N_2O, denitrification was the primary production pathway, contributing 80-90% of emissions, as reflected in the strong expression of denitrifier marker genes (nirS, nirK, and nosZ) and low nosZ:nir ratios. Nitrification also played a significant role in N_2O production, particularly in freshwater wetlands with high NH_4^+ concentrations and abundant nitrifier marker genes (amoA AOA and amoA AOB). Notably, methanogen and denitrifier gene expression was more pronounced in surface sediments, highlighting the presence of methane and denitrification paradoxes in tidal wetlands.

By integrating isotopic, functional gene, and biogeochemical analyses, this study advances our understanding of the drivers and pathways of GHG emissions in tidal wetlands. Our findings emphasize the importance of addressing both natural salinity gradients and human-induced water pollution through integrated management strategies, such as wetland restoration and pollution prevention, to mitigate GHG emissions from these dynamic ecosystems. This work provides a scientific basis for managing tidal wetlands in the context of global climate change and anthropogenic pressures.

ECOTIDE: a package designed for ecological modelling of the tidal Scheldt

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ECOTIDE (ECOlogical modelling of the TIDal SchEldt) is a sequence of models developed by the Research Institute for Nature and Forest (INBO) aiming to assess anthropogenic and climate change impact on the ecological functioning of the Scheldt estuary. It allows to investigate and compare multiple scenarios regarding - for example - sea level rise, morphological alterations and nature developments.

Within ECOTIDE, a habitat module predicts the distribution and quality of estuarine ecotopes. As such, the estimated areas of estuarine ecotopes can be tested against agreed conservation objectives. The ecological quality of the estuary can further be evaluated based on the (modelled) habitat suitability for Twait Shad (*Alosa fallax*) and Common Teal (*Anas crecca*). Interestingly, ECOTIDE is part of a longer 'model train' with prior modules providing predictions on hydrodynamics, sediment transport and the pelagic ecosystem, all necessary input for the ecological models.

Only recently, modules on the upper salt marsh boundary and sedimentation rates in de-embankment sites have been added to the model package. Indeed, within the framework of the Sigma³ project, ECOTIDE is currently being extended and optimized, in order to support the future decision-process on a sustainable and ecological-friendly development and management of the Scheldt estuary.

Increasing complexity of project objectives results in a search for smart solutions

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Near Ghent a historical stretch of the river Scheldt was cut off as a result of the creation of a bypass-canal (19th century). The remaining tidal channel becomes increasingly sensitive to flooding, due to increasing storm tides and siltation. With no room for extra dyke development, a conversion to a Controlled Reduced Tidal area (CRT) was chosen, implying the construction of a CRT-sluice to reduce flood risk, reduce siltation of the river meander and restore freshwater tidal habitats. This is one of the many Sigma plan projects to better protect Flanders against flooding from the Scheldt and its tributaries.

Over time, intense stakeholder surveys resulted in an extensive list of diverse goals and requirements, related to both water management, ecological restoration of freshwater mudflats and marshes, minimizing the occurrence of midges and deal with climate chaos in general.

The commitment to address all those objectives and concerns posed several challenges in the project design phase. The first challenge related to the precise definition of the many objectives and restrictions from the various stakeholders. Putting those objectives in precise criteria/indicators was needed to be able to evaluate if the project design fulfills the objectives. During the development of the project design, we came to the conclusion that some objectives lead to conflicting project design settings (e.g. low water levels are required for some objectives, while high levels are desired for others). As a consequence, it became apparent that no single fixed sluice design could cater to the needs of all stakeholders. As of then, options for smart model-based steering of the inlet and outlet settings were investigated that provide 1) a basic tidal regime, 2) optimize the water level for the different stakeholders and 3) protect against events such as exceptional rain/drought events.

Given the status of the water system (i.e. water levels in the valley, soil moisture saturation) and expected boundary conditions (rainfall, downstream water level of the Sea Scheldt), the model provides a basic tidal regime whereby inlet and outlet valves are regulated that reduce the tidal water volume, while mimicking the cycle of neap and peak tides in the Scheldt. Whenever a threshold (e.g. expected drought or expected peak runoff) is exceeded, a regulation routine is started. Through a number of simulations of valve settings, the optimal setting is deduced, taking into account the stakeholder criteria. The stakeholder criteria are translated into a decision tree that determines the objective function for the optimization. Resulting actions from the simulation are for example the closing of the inlet to improve water safety in the valley.

We finished the analysis with a multi-criterial analysis to compare the effects of each scenario for each of the evaluation indicators linked to the different stakeholder objectives. This allowed to indicate the scenario that performs best for the overarching objective to meet all objectives as good as possible. Further finetuning will remain possible during the operational phase of the project with the automated model-based steering of the inlet and outlet settings.

Defining the upper boundary of the marsh ecotope in the brackish and freshwater stretches of the Sea Scheldt

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Within the Scheldt Estuary, ecotope maps are a key instrument to evaluate trends in habitat diversity and condition. The area, distribution, and quality of each ecotope type act as a form of currency for policy and management planning and evaluation. Therefore, it is essential that all ecotope types are well characterized and delineated accurately in an ecologically meaningful way.

The outer boundary of the estuary is an important delineator, as it determines the total area of estuarine nature. This upper boundary is theoretically set at the elevation that, based on tide data, is flooded at least four times per year on average. However, the upper zone within this boundary only floods during storm surges and heavy rainfall, and it features more riverine vegetation than typical (salt) marsh vegetation. For potential assessments and scenario analyses, it is advisable to consider the true marsh boundary, dominated by typical marsh vegetation, rather than this theoretical outer boundary.

While the upper marsh boundary is relatively clear in salt marshes, definition of this boundary in freshwater marshes is much more challenging, as the transition from typical marsh vegetation to riverine vegetation in freshwater marshes is more gradual. The current delineation method relies mainly on expert judgment and is rather time consuming.

The goal of the current research is to unambiguously characterize and validate the upper boundary of the true salt and freshwater marsh ecotopes along the Sea Scheldt by examining the transition from moisture-loving (and salt-tolerant) plant species to moisture- (and salt-) avoiding plant species in relation to the inundation gradient and other abiotic environmental characteristics. This approach will allow for better substantiation and standardization of the upper marsh boundary.

In the spring of 2022, surveys were conducted along the entire Sea Scheldt and Rupel. Site characteristics and flora were examined in relation to the inundation gradient, and in the zone with a strong salinity gradient also Gray's coast snail. Flora was classified into ecological groups based on Ellenberg values for soil moisture and salinity preferences/tolerances. This enabled us to characterize the inundation frequency that defines the border between communities dominated by true marsh vegetation and those dominated by riverine vegetation, for both the brackish and freshwater stretches of the Sea Scheldt. These physical boundaries are considered as the upper boundary of the true marshes and the lower boundary of the high supralittoral zone. In the brackish zone presence of Gray's coast snail and soil conductivity (salinity) further support this boundary definition.

Supporting Fairway Management and Flexible Disposal in the Western Scheldt

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Since the third deepening program of the Scheldt fairway in 2009, IMDC has been involved in various assignments to support the Flemish Government's Maritime Access Division in fairway management and dredging activities within the Scheldt Estuary. IMDC's support focuses on obtaining and maintaining environmental permits for dredging and infrastructure projects under AMT's responsibility. These projects include the ongoing maintenance of the Western Scheldt and Low Sea Scheldt fairways. IMDC provides technical-scientific analyses, prepares project reports, and manages permit applications for dredging and fairway management.

Flexible Disposal Strategy, Reporting, and Advisory Services

Following the third deepening program a Flexible Disposal strategy for maintenance dredging in the Western Scheldt fairway has been implemented and subsequently monitored. Predetermined disposal locations have been selected in the permits that should maximize ecological benefits, contributing to the creation of valuable intertidal areas. The strategy is adaptable, with (bi)monthly evaluations based on soundings to determine if adjustments to disposal activities are required. As part of the maintenance permit requirements, an annual status report is prepared to assess the quality parameters from the Flexible Disposal Protocol and guide decisions for the following year.

Monthly reports include comprehensive analyses and validation of dredging and disposal activities. These monitoring results are discussed with the responsible authorities during a bimonthly meeting. In this meeting the disposal process is evaluated and adjusted to ensure that the dredging and disposal process is optimised, and potentially unfavourable developments are mitigated.

Every two years, a progress report has been prepared to evaluate the strategy's effectiveness and suggest necessary adjustments. This progress report analysed the effects of dredging activities and sediment disposal on hydrodynamics, morphology, water quality, ecology, and fauna, in relation to the third deepening and the Flexible Disposal process. The report offered valuable insights into the effectiveness of current strategies and provides recommendations for future monitoring and research. Following the latest permit the scope of the report will be reduced.

Beyond reporting, IMDC also provides advisory services related to Flexible Disposal and potential pilot campaigns.

Poster Outlook

The monitoring and reporting of the Flexible Disposal strategy, implemented by the Flemish Government's Maritime Access Division, is crucial for effectively managing dredging and disposal activities in the Scheldt Estuary. This poster will showcase how flexible strategies, combined with detailed monitoring and comprehensive reporting, have contributed to maintaining ecological balance while supporting fairway maintenance. Through specific examples, the poster will illustrate how monitoring and reporting have ensured sustainable dredging practices, optimizing both ecological benefits and operational efficiency.

On possibilities and limitations of predictions in estuarine systems

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Estuaries have long been systems of interest for humanity. We disproportionally settle in these regions and use the water ways as economic trade routes as well as for fishing, recreation and other activities. Accompanying land is often used for agriculture or industrial pursuits. Estuaries and their adjacent marshlands are also hotspots of carbon cycling and therefore of central relevance to our efforts at combating anthropogenic climate change. To make better decisions in these systems we need to understand their complex interactions and mechanisms not only historically, and currently, but also in regard to future scenarios.

Predictions in ecology have been increasing over the last decades and the topic has been subject to scientific discussions for most of the time this discipline existed as a science. Interestingly, our ability to forecast quantitatively and precisely in ecological systems seems to be somewhat more limited than in other natural sciences. Prediction is theoretically getting ever more unreliable the further we try to forecast through time, but in ecology predictability across ecological systems might show different patterns in stability and in the partitioning of uncertainties in forecasts. These patterns might give insight into where our efforts of understanding more about a system might be rewarded with better predictions. Estuaries are an especially interesting system to analyse in the light of prediction because they are dynamic but for the most part tidal cycles are recurring predictably which theoretically makes it easier to forecast some ecological variables.

The commentary paper I am working on tries to summarize to what extent (and why) we predict ecological variables in estuaries and analyses our current understanding of what uncertainties limit our ability to forecast in these systems. I will showcase common motivations for predictions in estuaries and what the most popular variables are as well as the most popular means of (model-driven) forecasting. I will then question and dissect the applicability of predictions over different timescales and finally I will highlight some strategies in how we might deal with limits in knowledge when it comes to planning for the future, which is especially relevant as climate change is changing the world we live in rapidly towards novel ecosystem states we have never seen before.

I think bringing attention to the way we understand and develop predictions in estuaries is crucial if we want to develop plans for restorations and define goals for the future. How much confidence should we place into a projection of carbon stocks? Or fish stocks? On what timescales should we plan? Thinking about sources of uncertainty in our predictions could help us navigate these questions.

AMORAS sediment treatment: Estimate of sediment import through lock exchange at the right-bank port of Antwerp

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Sediments that are dredged within the docks of the right-bank port of Antwerp suffer from historical contaminants and therefore cannot be disposed back into the system. Since 2011 AMORAS contributes to a sustainable treatment and storage of the dredged sediments. When dredged material is brought to the underwater cell, first the sand content is separated. The mud content is than pumped to the AMORAS dewatering installation and the dry material is stored on land for reuse as construction material in the future.

It is estimated that there is enough accommodation space for at least the next 15 years. Nevertheless, an accurate prediction of the future need for sediment treatment is required. Therefore, it is necessary to understand the different sediment sources within the port. Principal sources of dredged sediments are the removal of sediments of historical backlog of maintenance, local deepenings and construction works (limited), and through water exchange between the Lower-Sea Scheldt and docks through culverts. But the main source of sediment is the import of fresh sediment from the Lower-Sea Scheldt through lock exchange.

The exchange of water, salt and sediments is driven by the density difference due to the salinity difference between the port and the river. Every time the lock doors are open, either on the river side or on the dock side, the water starts exchanging resulting in a net import of fresh sediments into the port. Within the docks there is hardly any currents which allows the sediments to settle in the vicinity of the lock complexes. The import of fresh sediment through the lock complexes is estimated by combining and analysing different dredging registration databases of the past nine years.

Restoring tidal freshwater zones: The use of environmental DNA to monitor fish communities

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Upper estuarine tidal freshwater zones (TFZs) are unique habitats which are often overlooked in scientific literature because their distinctive characteristics exclude them from studies on non-tidal freshwater rivers or brackish estuaries (Jones et al. 2020; Little et al. 2022). TFZs are under threat from climate change and human intervention, particularly in relation to 'estuarine squeeze'. This is the loss of TFZs against in-channel, man-made barriers at an estuaries tidal limit through saline intrusion driven by rising sea levels and reduced summer river flows (Little, Lewis and Pietkiewicz, 2022; Prandle and Lane, 2015).

The unique characteristics of TFZs suggest that they could play an important role in the functioning of estuarine and riverine ecosystems by providing trophic subsidies and serving as important habitats for fish species, including those of conservation concern. Restoring these zones, particularly their intertidal marshes, could help offset losses caused by estuarine squeeze while delivering multiple ecosystem benefits.

To build a strong case for restoring these zones, it is essential to understand which fish species utilise them and for what purpose. Whilst some studies indicate that TFZs are used for foraging, breeding and migration (Pihl et al., 2002), more research is needed to determine the specific species involved and what role this habitat plays in their lifecycle.

The dynamic nature of TFZs makes monitoring fish communities and habitat use across tidal cycles challenging. Environmental DNA (eDNA) is gaining popularity for monitoring fish in aquatic ecosystems, offering a cost-effective and efficient alternative to traditional methods (Yao et al. 2022). It is a promising tool for monitoring estuaries as sampling is non-invasive and requires minimal set-up which makes it possible to identify changes in fish communities throughout the tidal cycle or before and after habitat restoration. However, factors influencing DNA transport and degradation can affect spatial resolution, so understanding tidal dynamics is crucial for designing effective sampling strategies and interpreting results accurately.

Here we present the findings of a systematic review evaluating how eDNA has been used to survey fish in estuaries, in particular TFZs and the current knowledge of fish presence and habitat use in TFZs in NW Europe. We conclude by providing recommendations for how eDNA surveys can be improved to deal with the issues arising from the transport of DNA in tidal systems.

Results show that the impact of tidal dynamics on eDNA transport is often overlooked in sampling strategies, with only a few examining the effects of the falling tide. When it is addressed, most use statistical models to determine if the communities detected are discrete between samples, but this does not deal with whether the DNA is from transport or organisms in the sampled habitat. Most research on fish in TFZs has been conducted in North America with fewer than 50 studies in Europe and only three in the UK, leaving many questions about fish use of the TFZs in NW Europe unanswered. While eDNA could help address these gaps, more robust sampling strategies and a clearer understanding of DNA transport are needed.