VIRTUAL DELTA:

towards the digital twin for real-time management of salt intrusion in the Rhine-Meuse delta

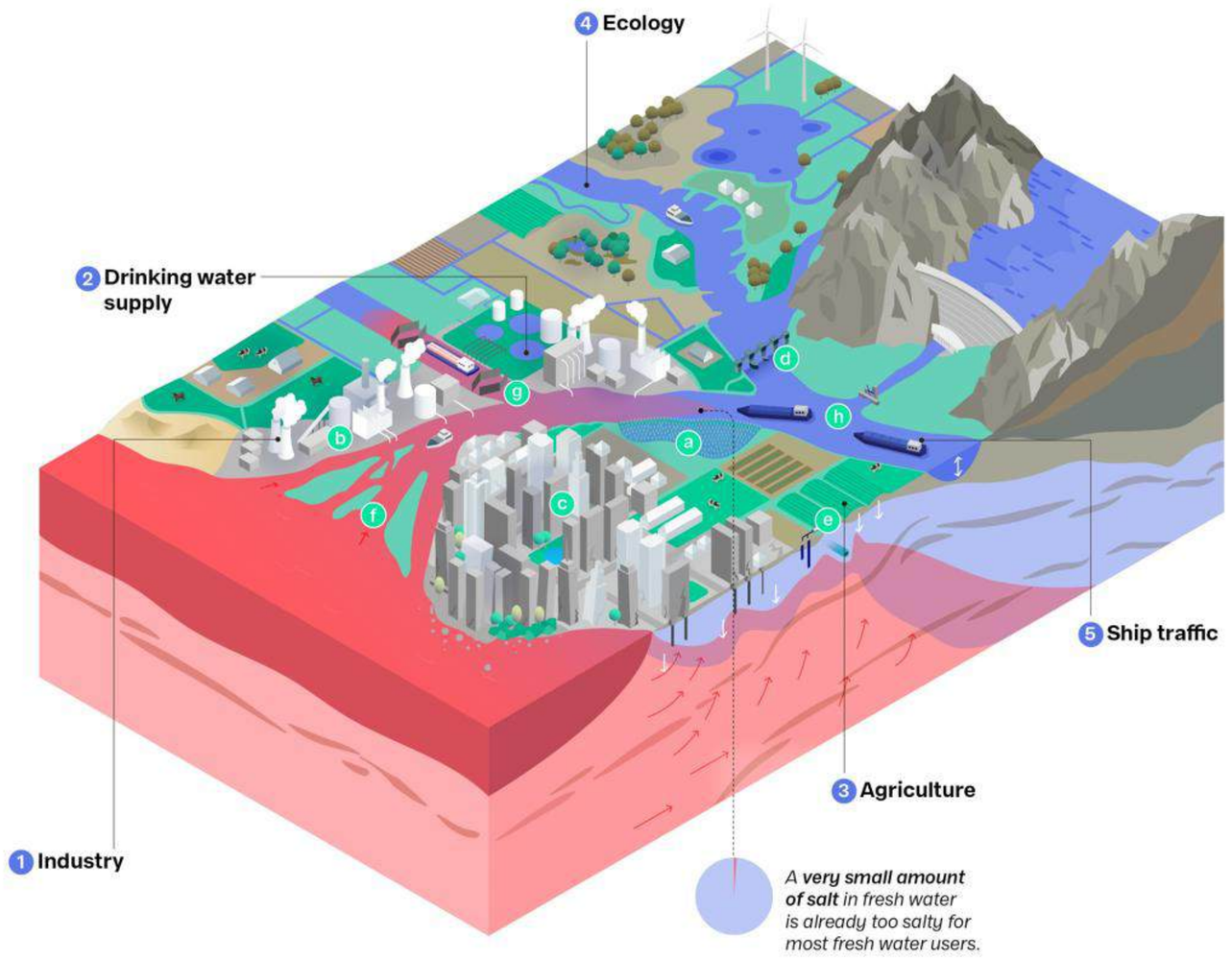
Mo Wannasin

(on behalf of Thomas Stolp, Gijs Hendricx, Meinte Blaas, Nathalie van Veen, and SALTISolutions Project 9)

DigiShape Day Digital Twins, 23 June 2025

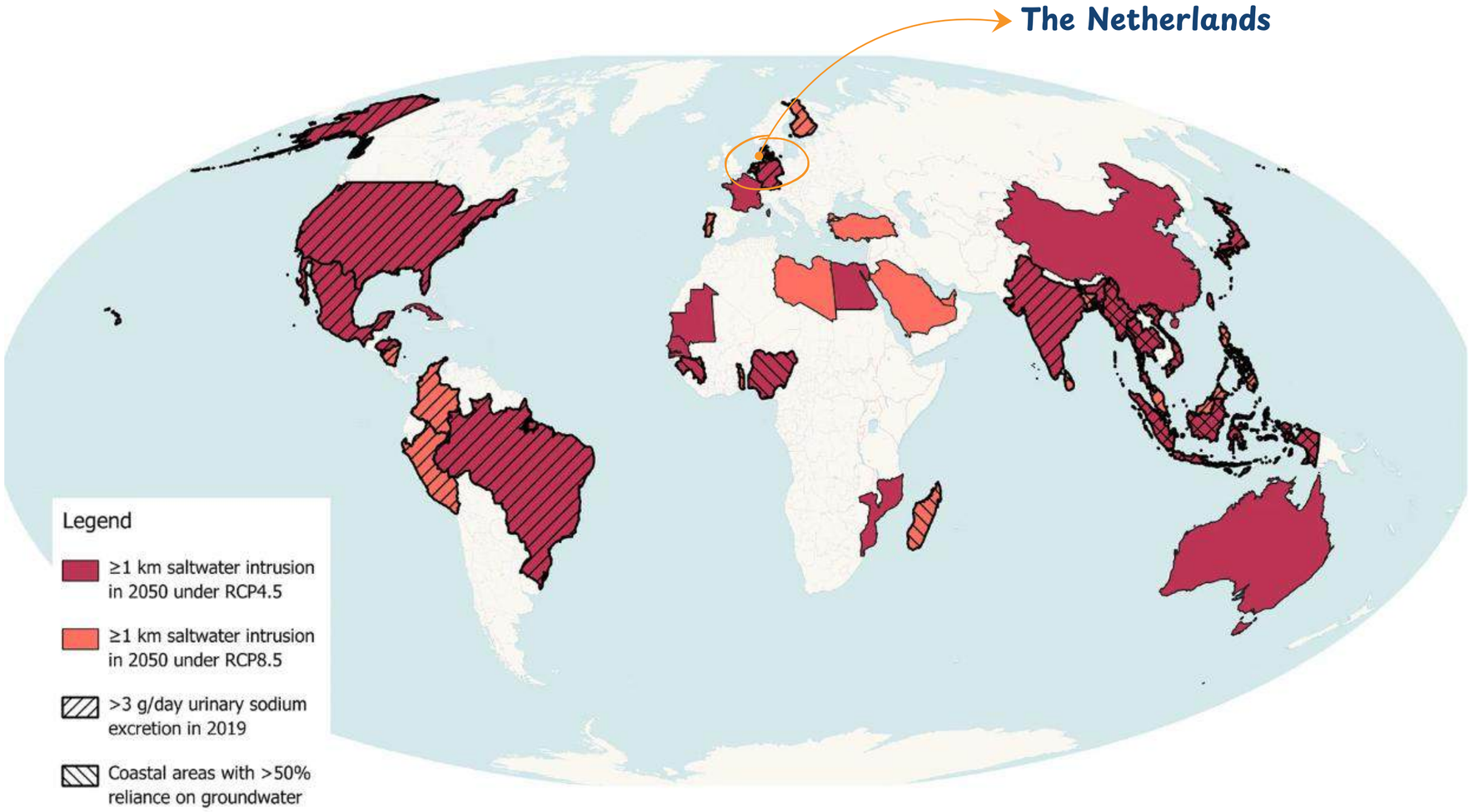
SALTISolutions Deltares UNIVERSITY OF TWENTE. Rijkswaterstaat *Ministry of Infrastructure and the Environment* HKV LIJN IN WATER

Saltwater intrusion: the slow disaster



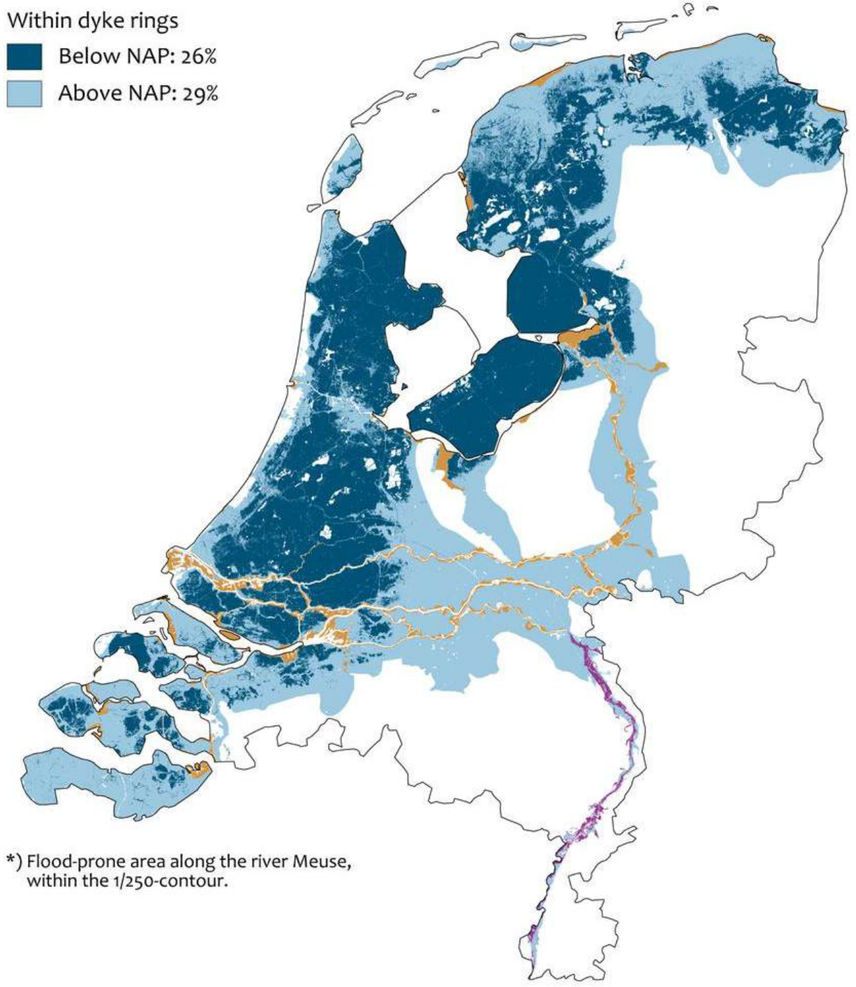
Deltares (2022)

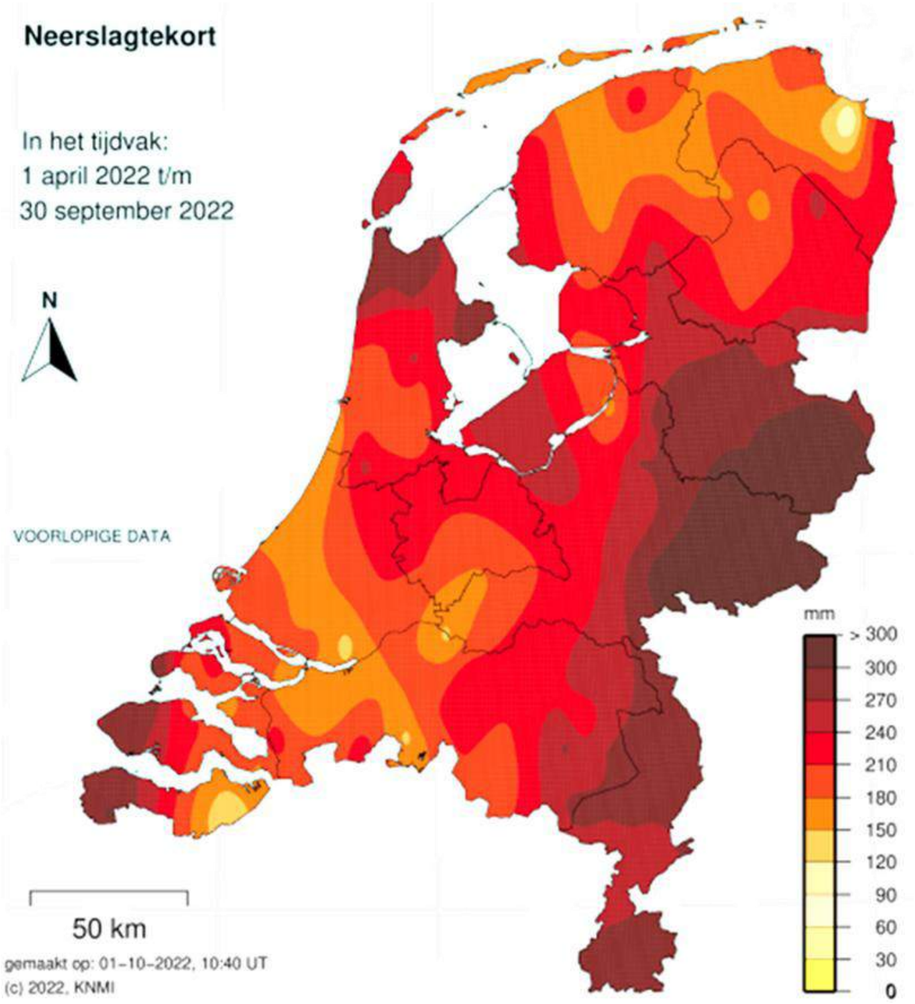
And it happens globally…



Mueller et al (2024)

The Netherlands is vulnerable

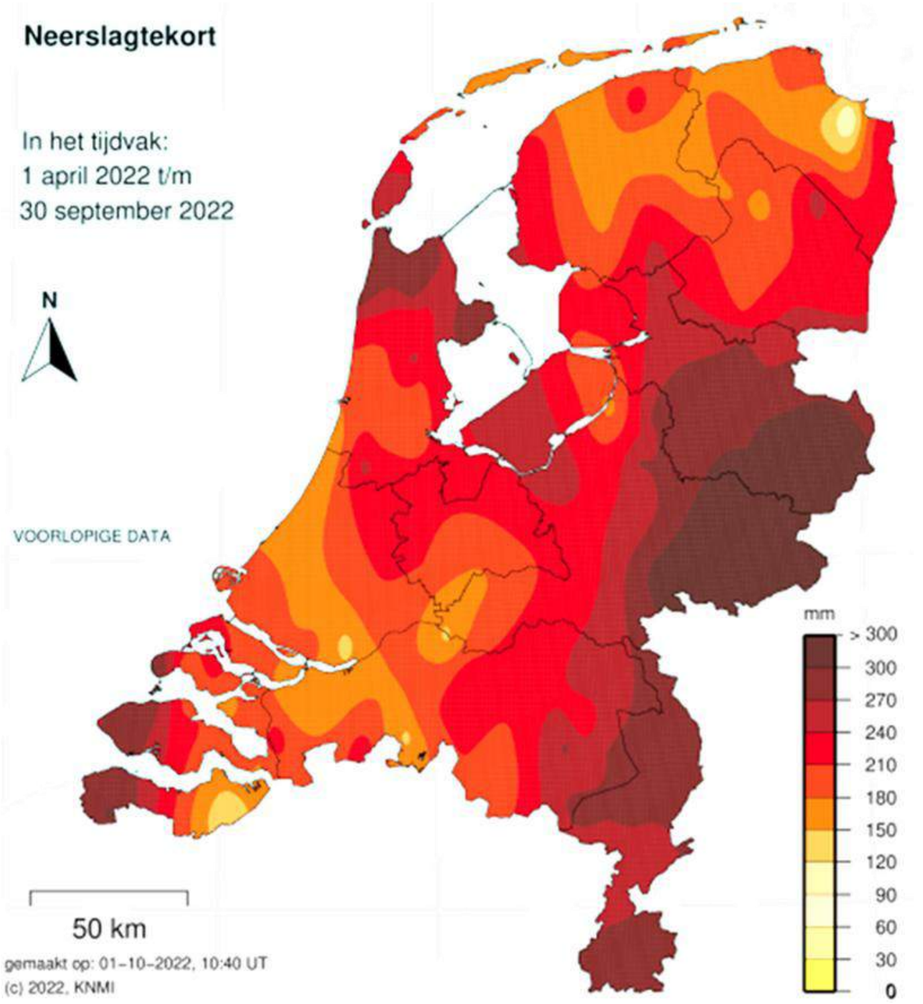




PBL; IMF (2024); KNMI (2022)

Espectially the 'Rijn-Maasmonding' (RMM)

*) Flood-prone area along the river Meuse, within the 1/250-contour.



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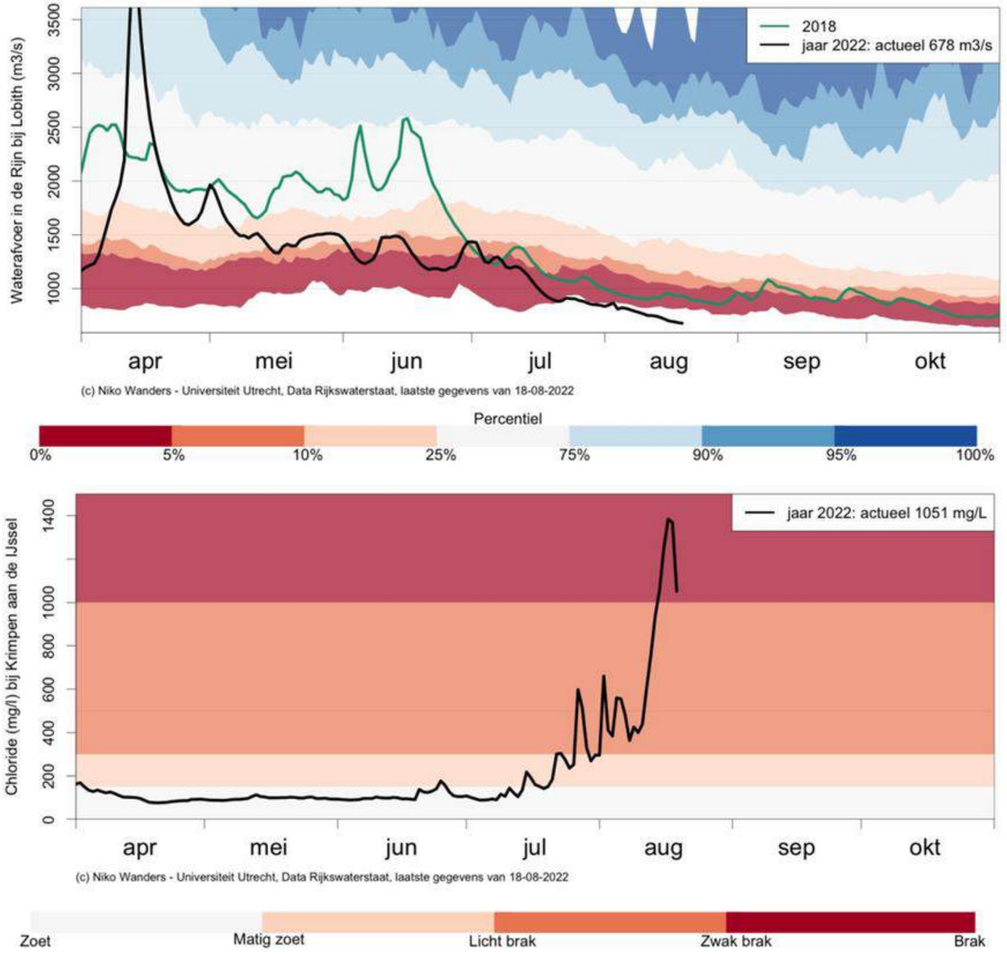
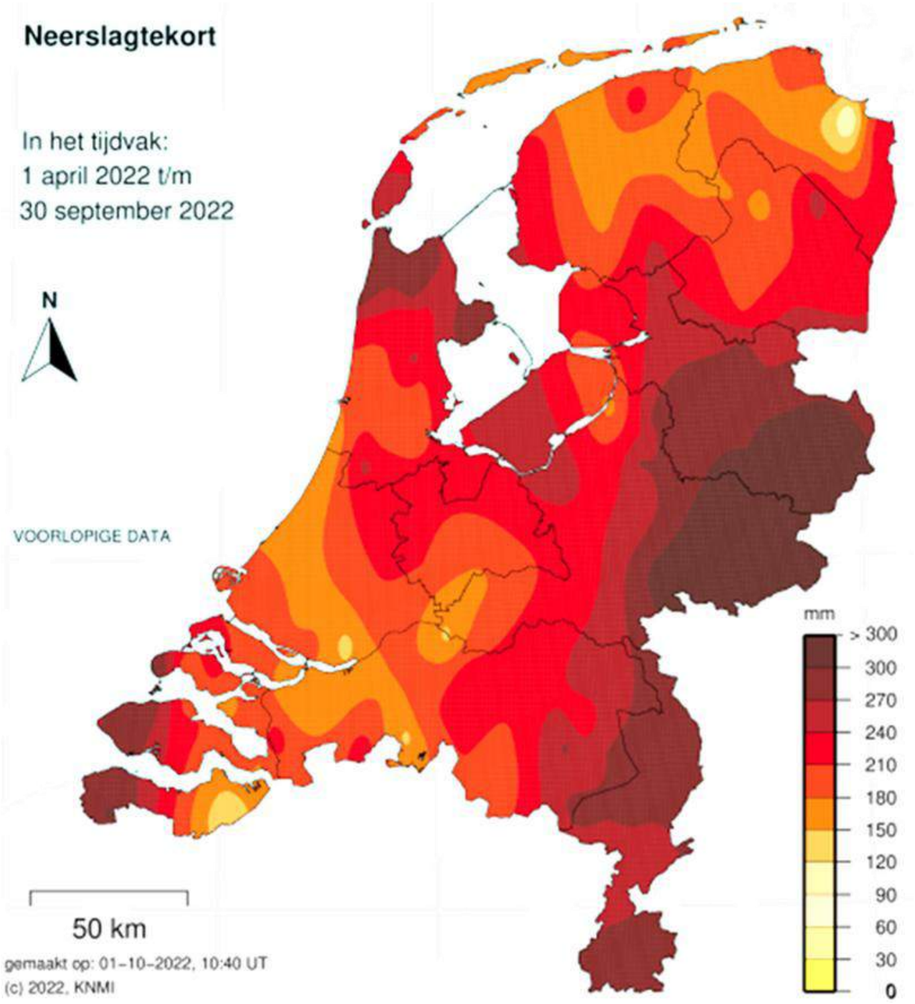
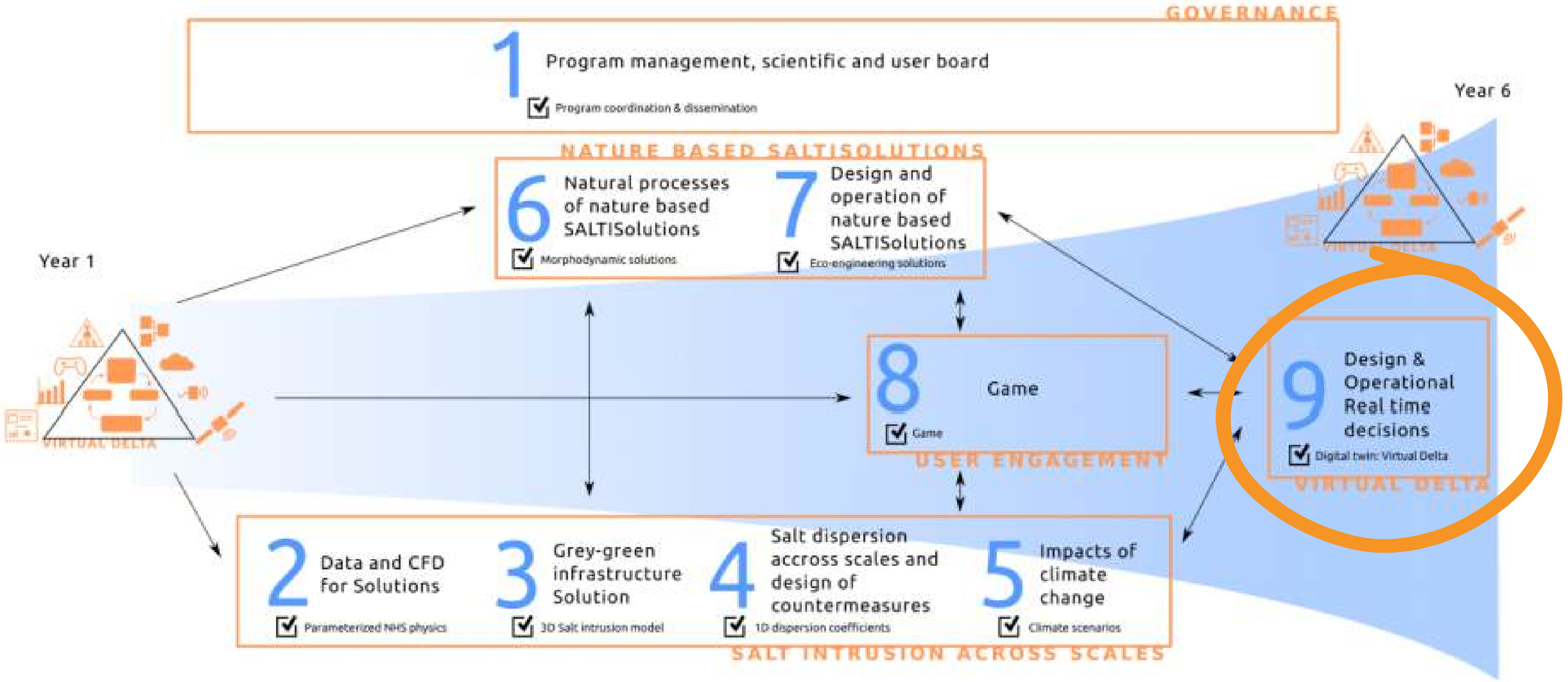


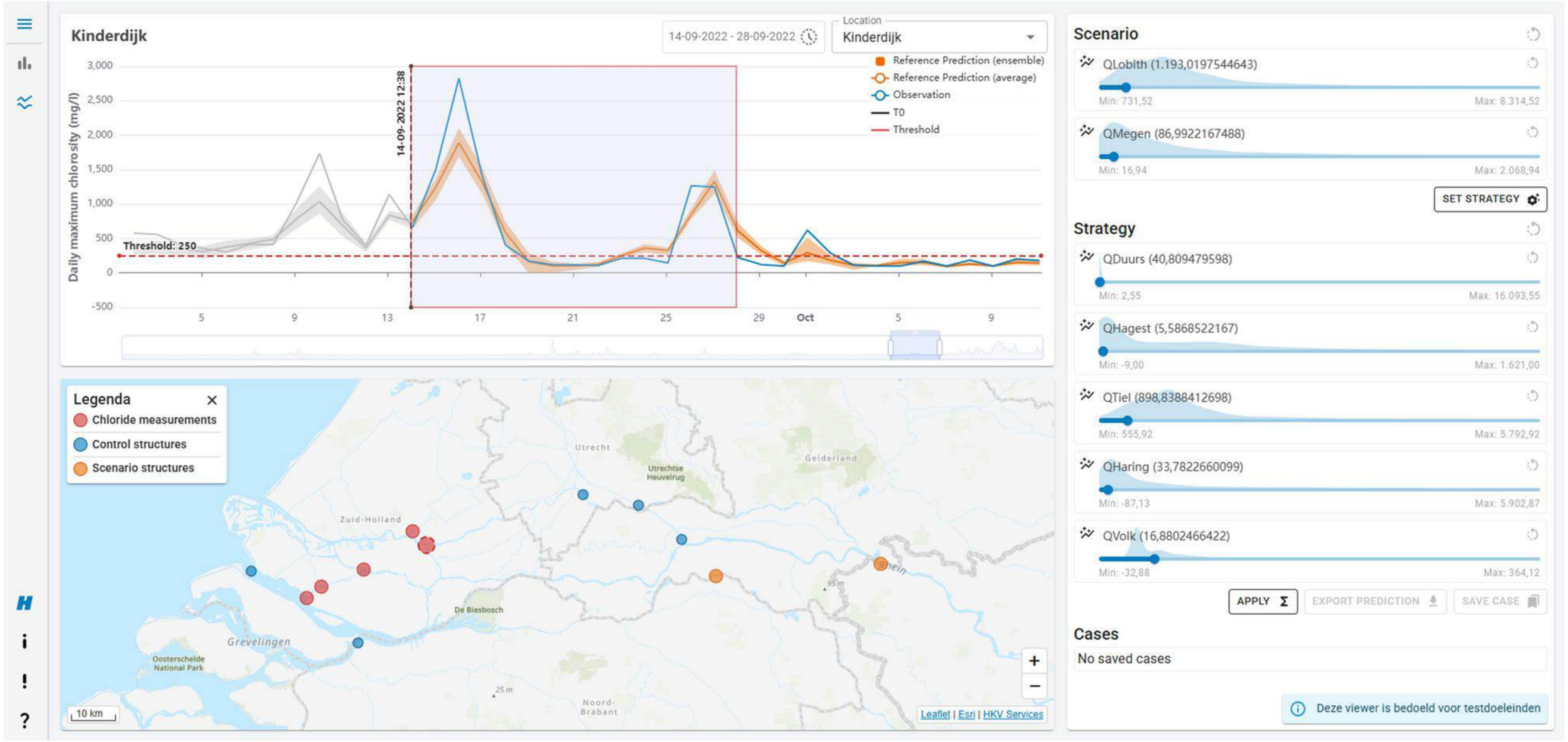


PBL; IMF (2024); KNMI (2022)

SALTISolutions: solutions for salt intrusion



(part of) the Virtual Delta



From the beginning, we set long-term visions

1 Context

What are digital twins in the context of salt intrusion management?

2 Demands

Who are the end-users and what do they need?

3 Situation

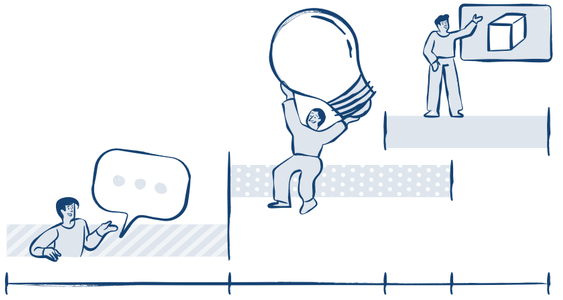
How is salt intrusion managed in real-time across scales in the RMM?

4 Supplies

What resources are available for the Virtual Delta development?

5 Development

How can we develop the Virtual Delta that users will trust and use?



Then designed the user-oriented development

IDEATION

What are digital twins in the context of salt intrusion management?

Who are the end-users and what do they need?

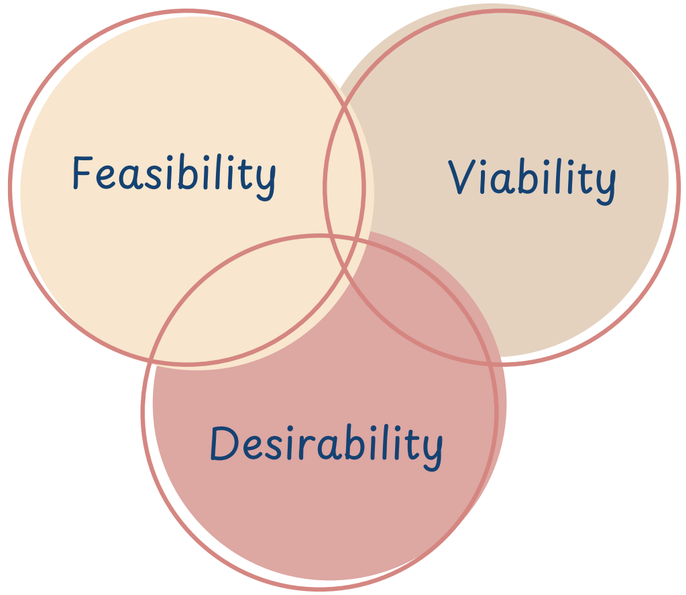
CONCEPT

How is salt intrusion managed in real-time across scales in the RMM?

What resources are available for the Virtual Delta development?

EXECUTION

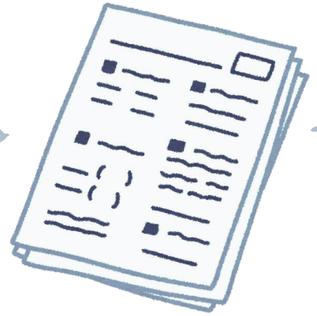
How can we develop the Virtual Delta that users will trust and use?



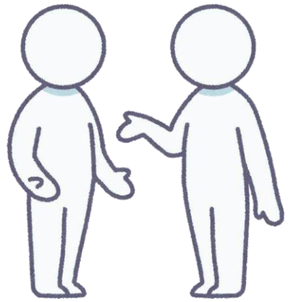
Ideation

IDEATION

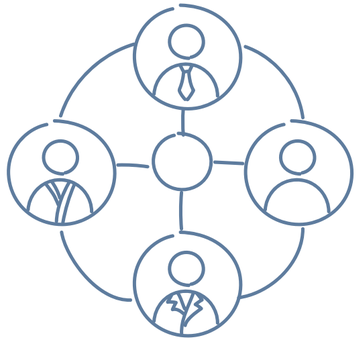
Literature review



In-depth map-based questionnaire



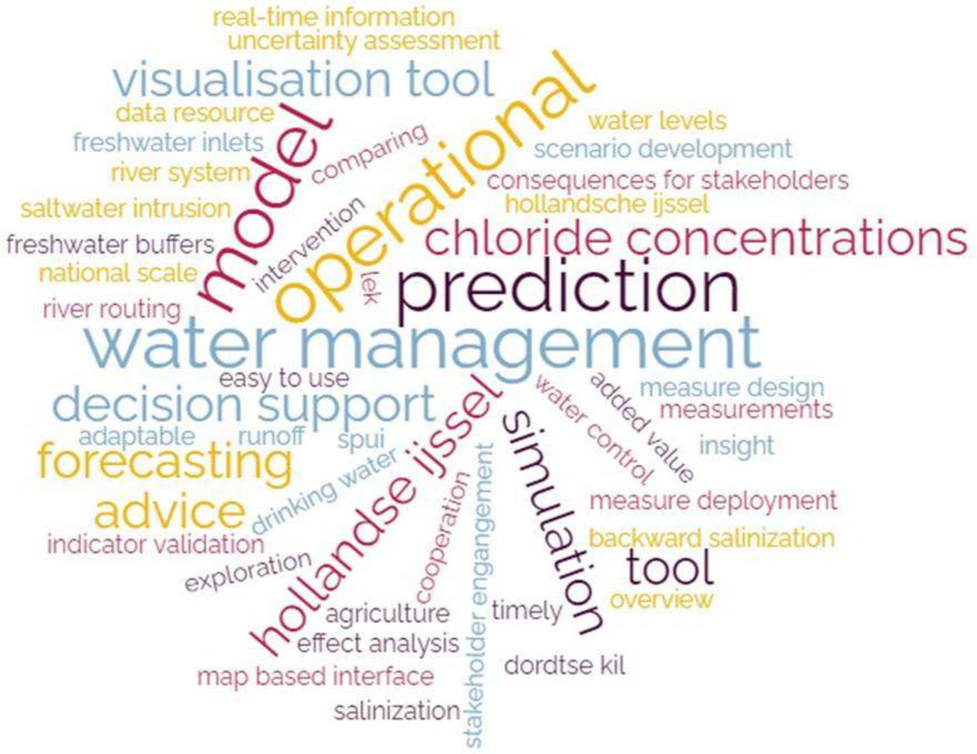
Individual stakeholder interview



Joined stakeholder disscusion

Ideation

IDEATION



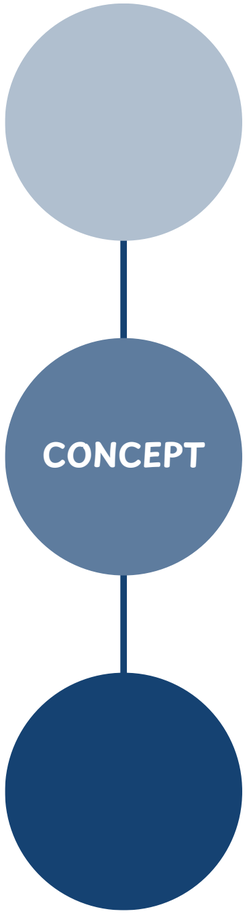
Backend

- Detailed representation
- Real-time data incorporation
- Accurate real-time prediction
- Real-time risk assessment and early warning
- Decision support with measure designs
- Exploratory simulations

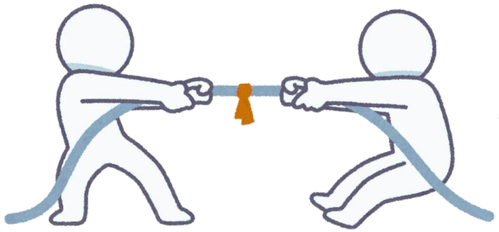
Frontend

- Visualization and interactive dashboarding
- Collaborative decision-making
- Remote access and control
- Integration with water management systems

Ideation → Concept



From information to conceptual design

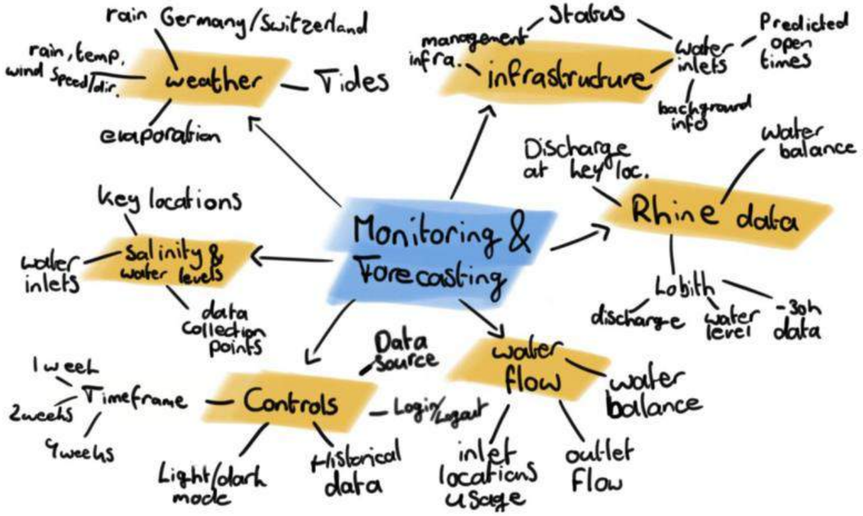


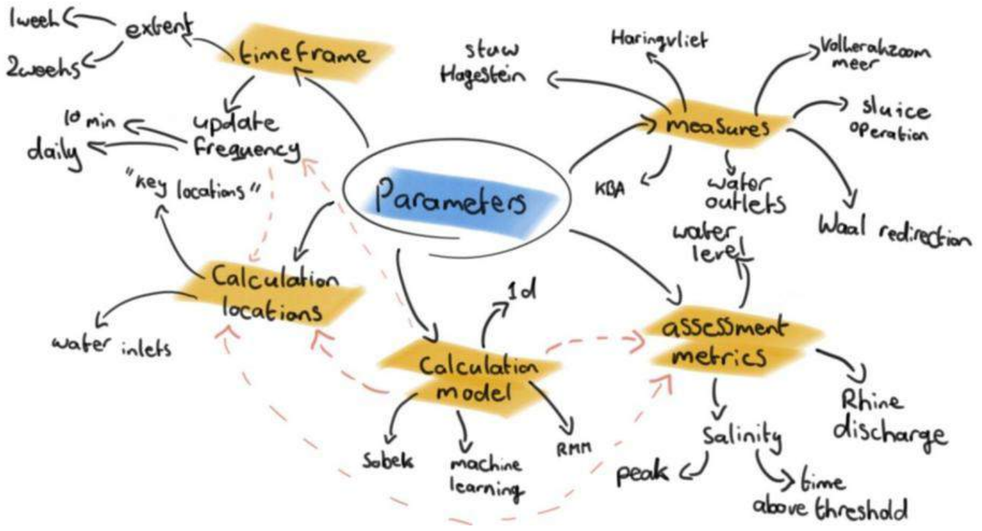
MoSCoW prioritization

Stepwise development planning

Ideation → Concept

CONCEPT

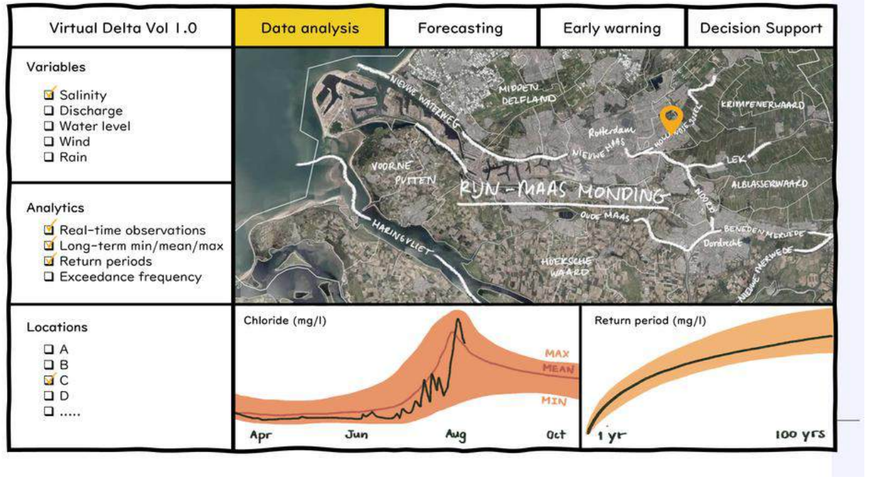


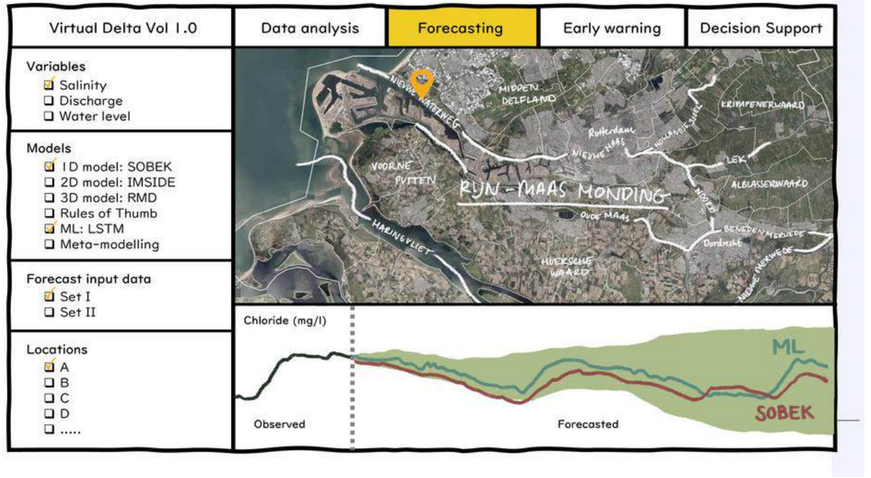


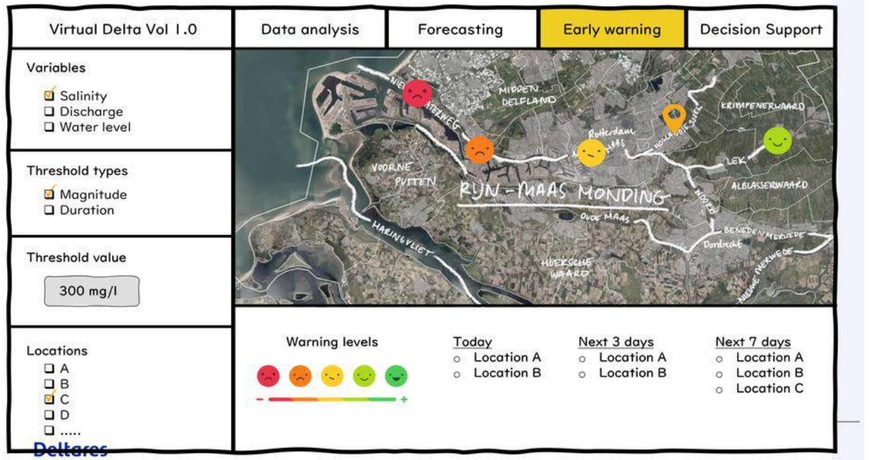
Bottenberg (2024)

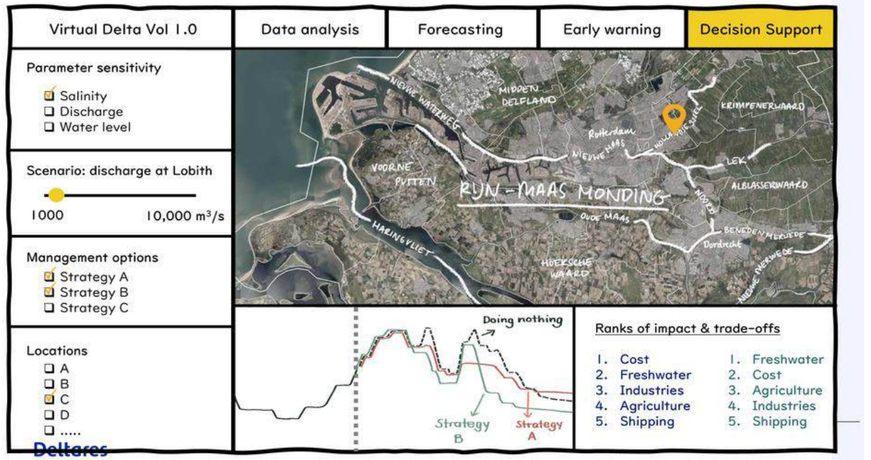
Ideation → Concept

CONCEPT

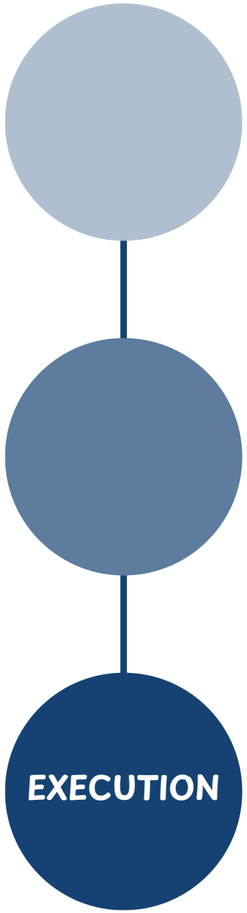


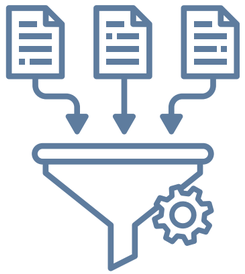






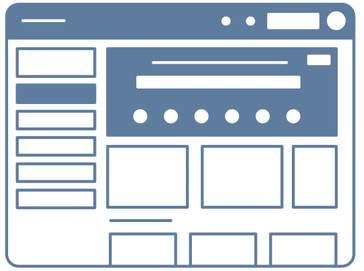
Ideation → Concept → Execution





Data collection
and integration

Modelling
(backend)



Graphical user interface
(frontend)

The Virtual Delta

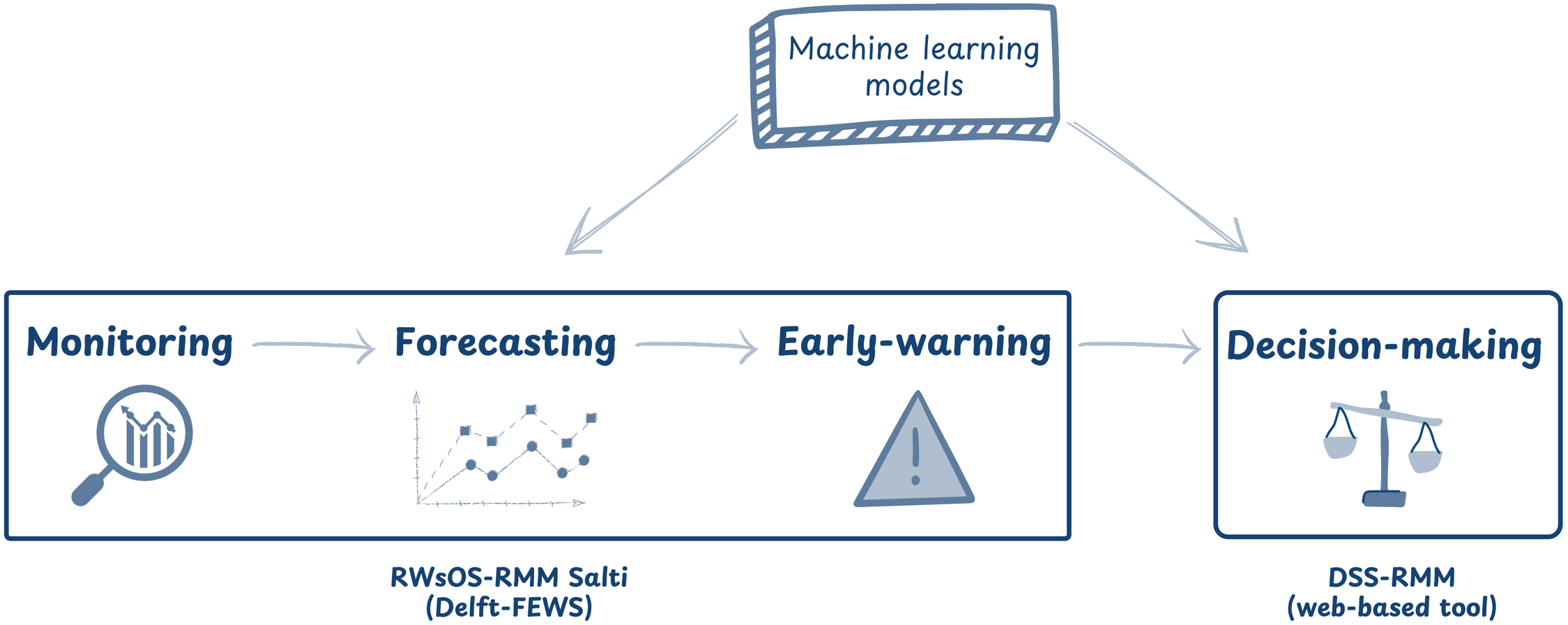
Ideal definition of the Virtual Delta:

Modelling toolbox with interactive interface for assisting real-time **monitoring**, **forecasting**, **early-warning** and **decision-making** of salt intrusion crises in the RMM

To assist RDO crisis meetings, especially during droughts

Daily chloride concentration (mg/l) at key locations

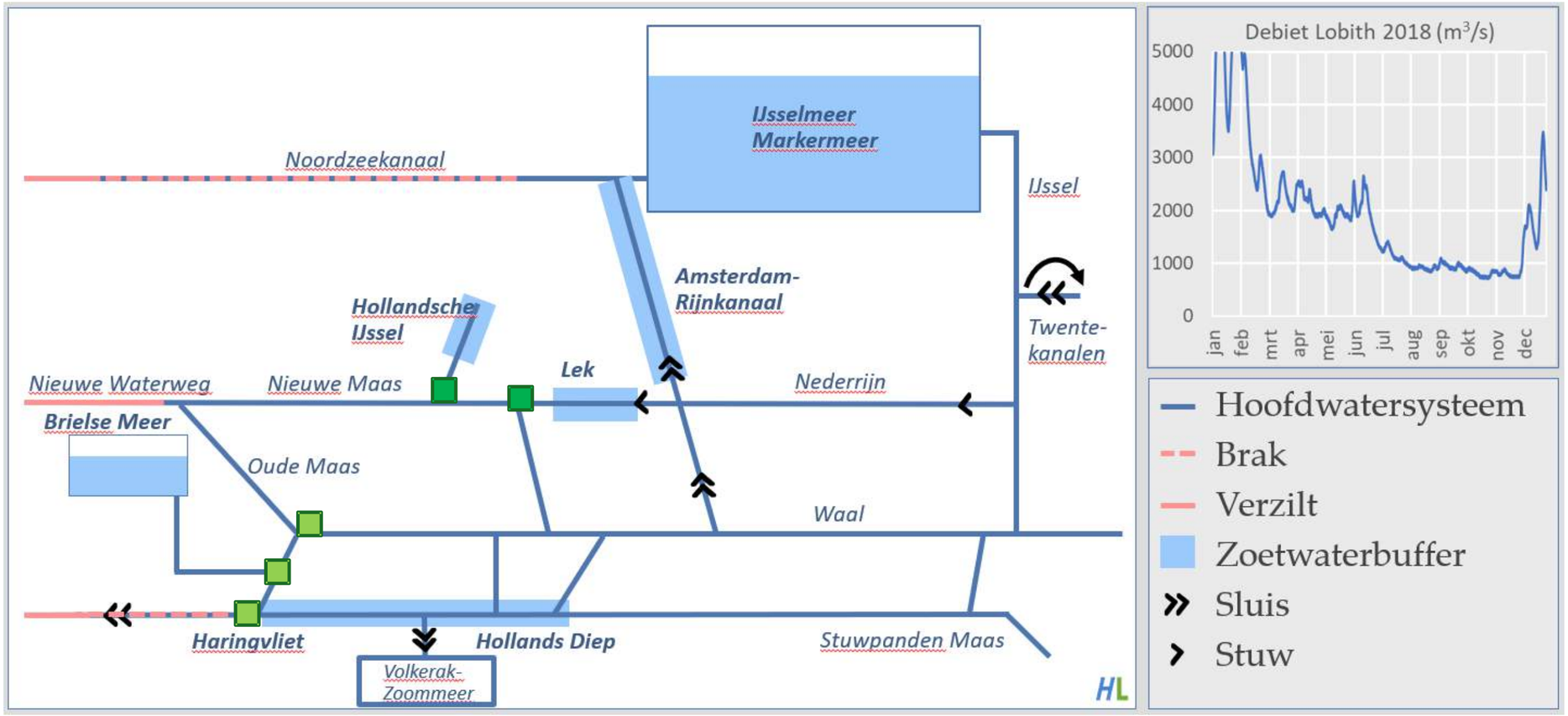
The Virtual Delta



ML model output: Chloride at 5 locations

Northern edge
- Kinderdijk (-5 m)
- Krimpen a/d IJssel (-4 m)

Southern edge
- Beerenplaat (-2 m)
- Bernisse/Zuidland (-3 m)
- Middelharnis Spui (-5 m)



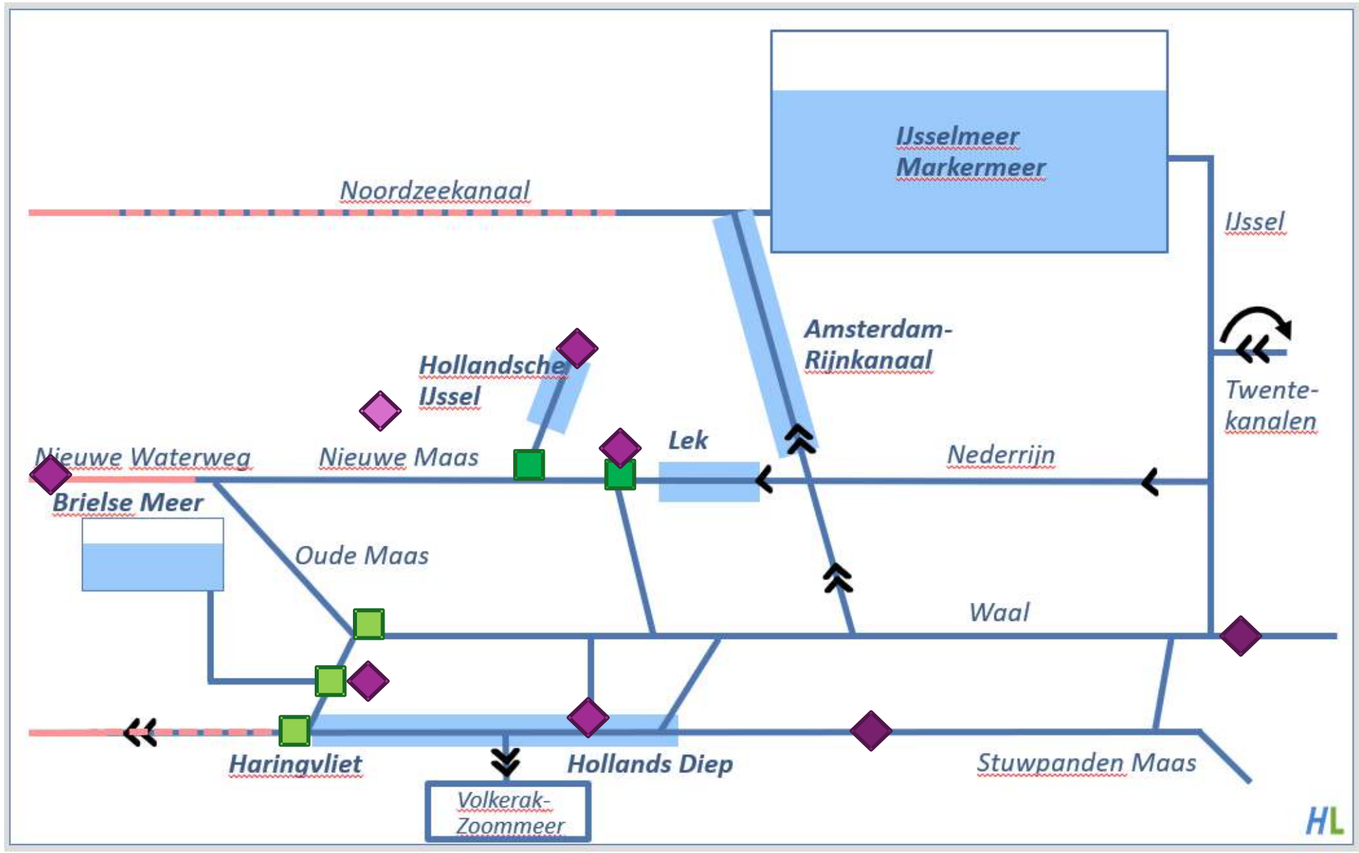
ML model input: Factors/pressures

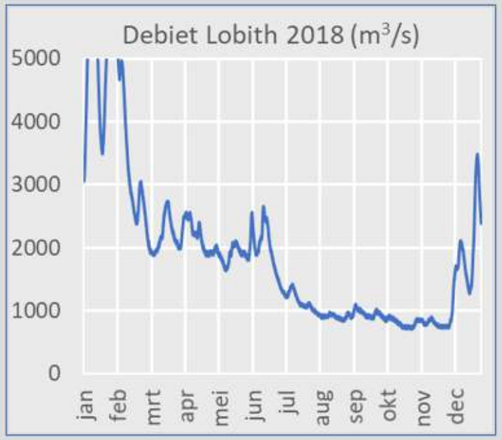
Hydrological factors

- Natural river discharge (Q)
  - Lobith (Rhine)
  - Megen (Meuse)
- Water level (H)
  - Hoek van Holland
  - Krimpen a/d Lek
  - Moerdijk
  - Gouda
  - Bernisse

Meteorological factors

- Wind setup (W)
  - Rotterdam
- Evaporation (E)
  - Rotterdam





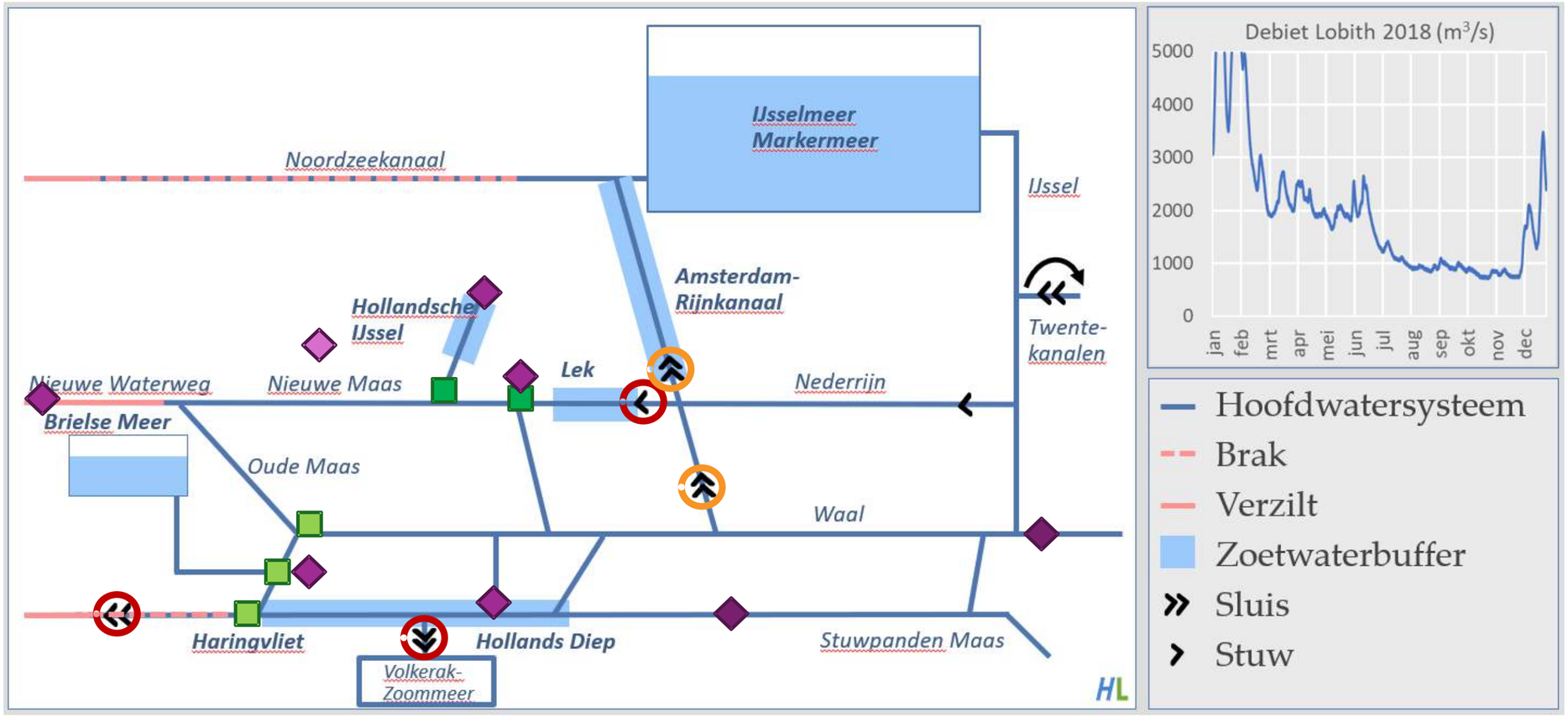
ML model input: control knobs

Primary control knobs

- Hagestein weir
- Haringvliet sluices
- Volkerak-Zoommeer sluices

Secondary control knobs

- Pr. Bernhard sluices (Tiel Waal)
- Pr. Irene sluices (Wijk bij Duurstede)



ML models: overview

Factors/pressures

- Natural river discharge (Q)
  - Lobith (Rhine)
  - Megen (Meuse)
- Water level (H)
  - Hoek van Holland
  - Krimpen a/d Lek
  - Moerdijk
  - Gouda
  - Bernisse
- Wind setup (W)
  - Rotterdam
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Primary control knobs

- Hagestein weir
- Pr. Bernhard sluices
- Pr. Irene sluices
- Haringvliet sluices
- Volkerak-Zoommeer sluices

T-4 to T+1

Data pre-processing

Model training & testing

Machine learning models

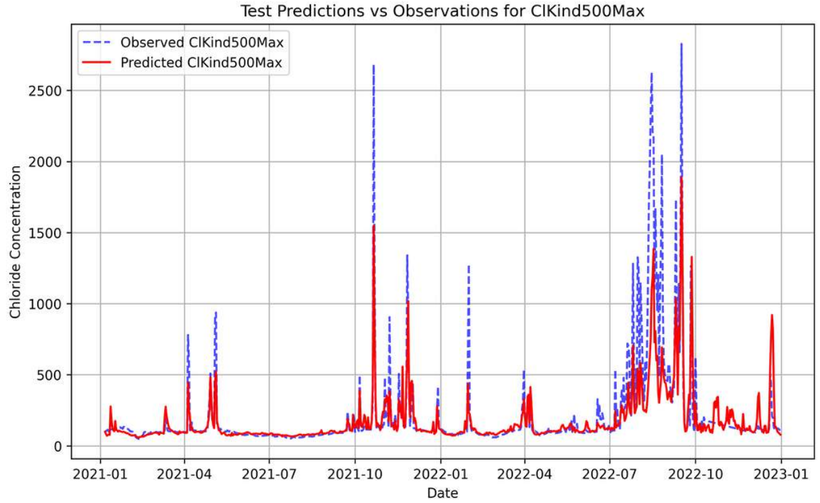
10 model ensembles

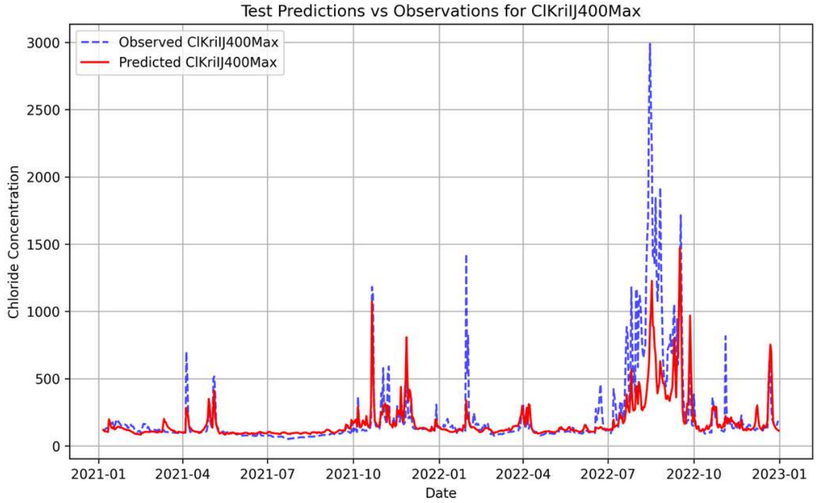
Training: 2008-2018
Validation: 2019-2020
Testing: 2021-2022

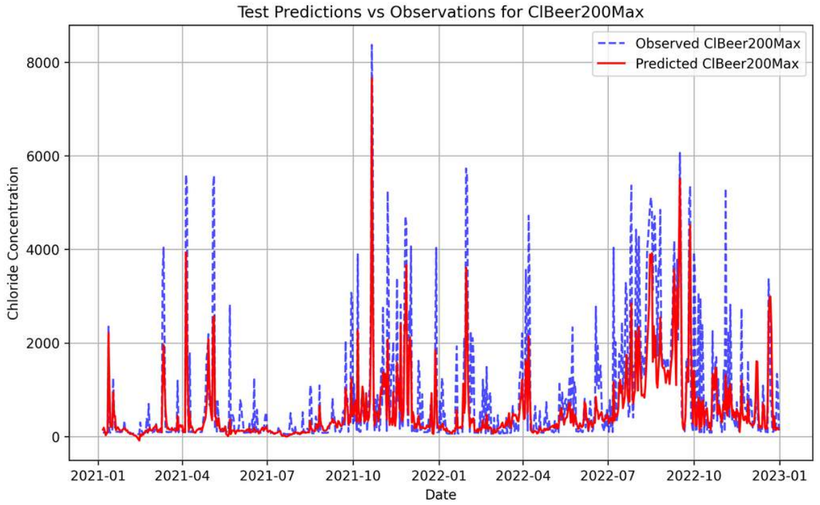
Forecast daily **maximum** and **mean** chloride concentration (mg/l) at T+1

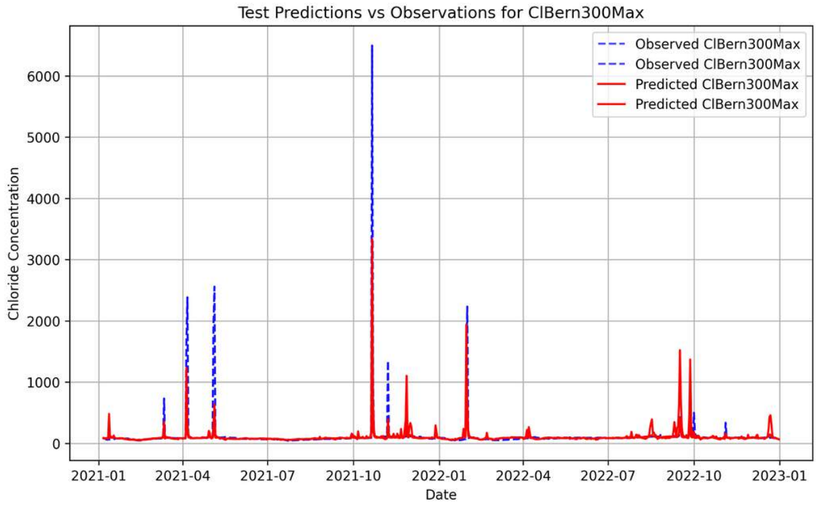
- Kinderdijk (-5 m)
- Krimpen a/d IJssel (-4 m)
- Bernisse/ Zuidland (-3 m)
- Middelharnis Spui (-5 m)

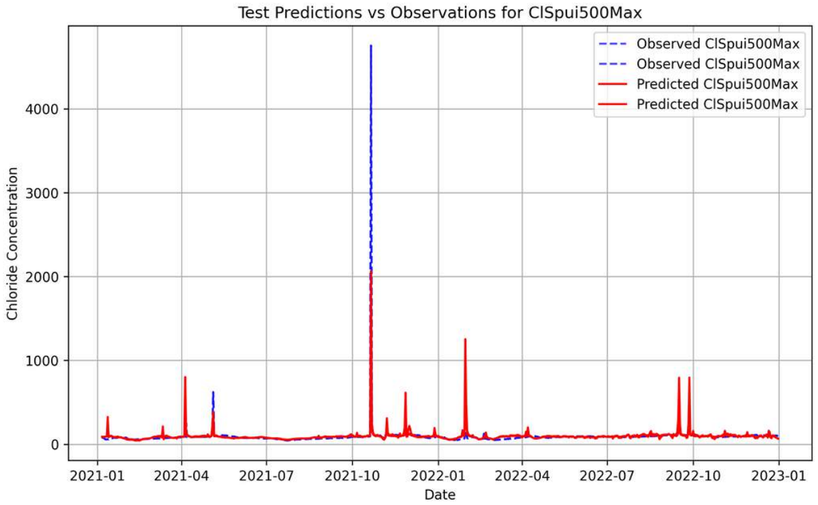
ML model output: Chloride at 5 locations











ML models → Exploratory decision-support tool

Factors/pressures
- Natural river discharge (Q)
  - Lobith (Rhine)
  - Megen (Meuse)
- Water level (H)
  - Hoek van Holland
  - Krimpen a/d Lek
  - Moerdijk
  - Gouda
  - Bernisse
- Wind setup (W)
  - Rotterdam
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Primary control knobs
- Hagestein weir
- Pr. Bernhard sluices
- Pr. Irene sluices
- Haringvliet sluices
- Volkerak-Zoommeer sluices

Scenarios

Management strategies

T-4 to T+1

Data pre-processing

Model training & testing

Machine learning models

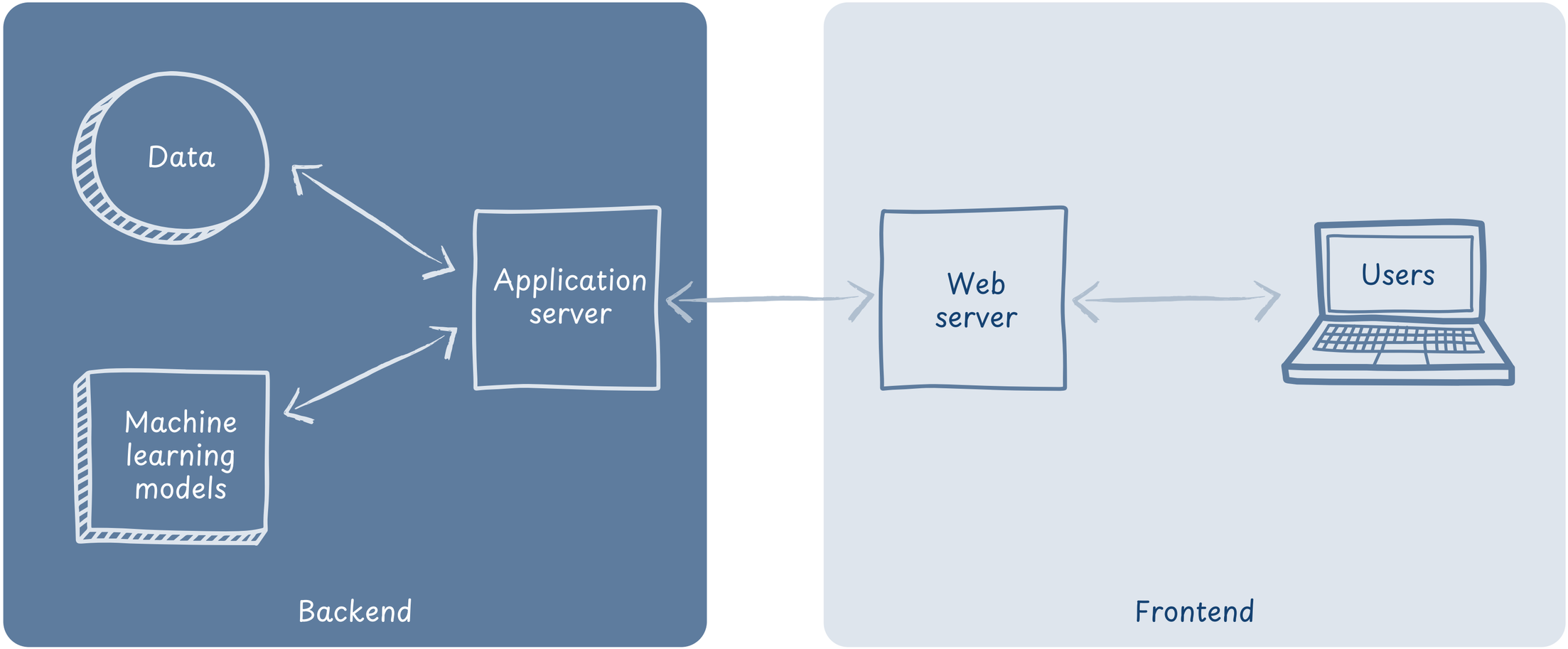
10 model ensembles

Training: 2008-2018
Validation: 2019-2020
Testing: 2021-2022

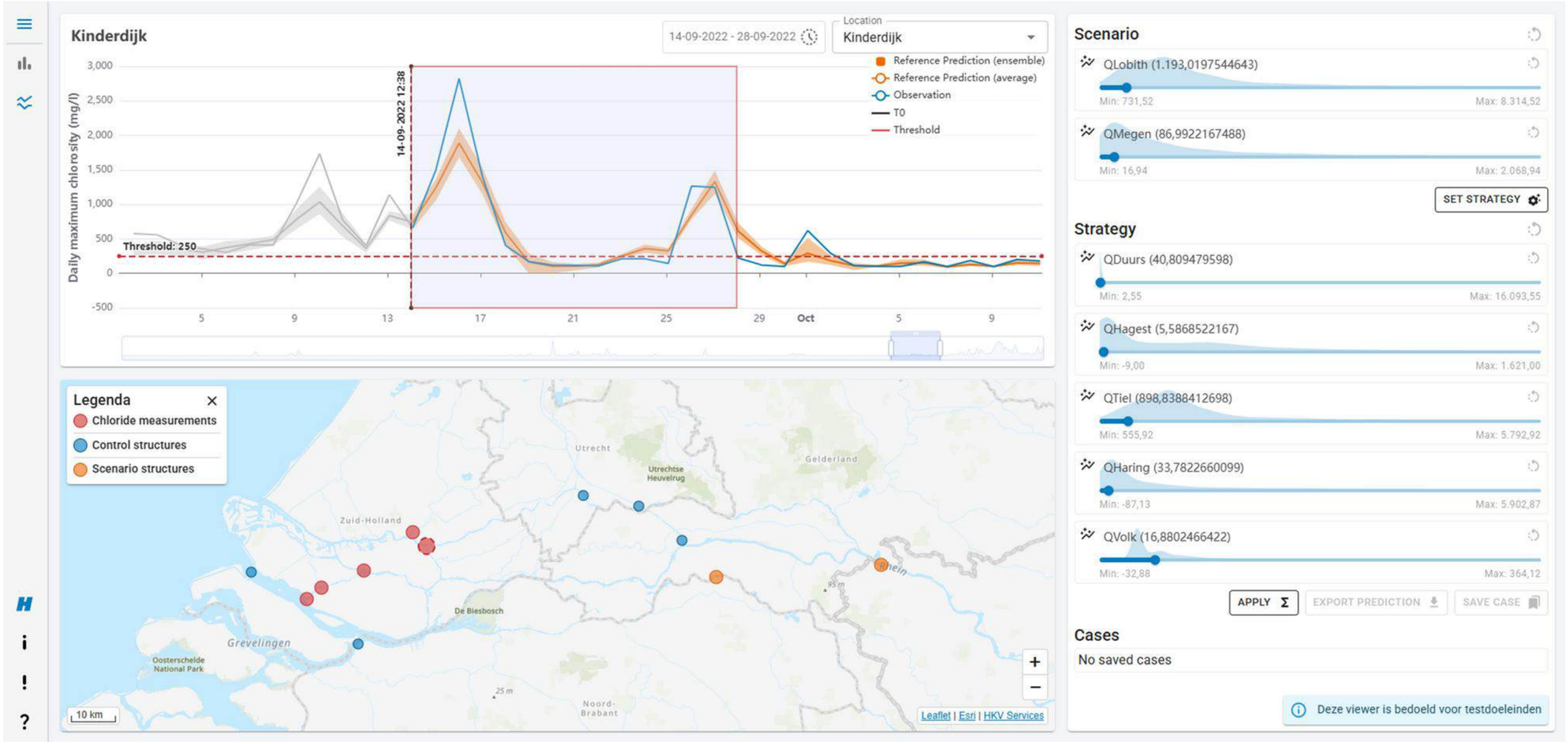
Forecast daily **maximum** and **mean** chloride concentration (mg/l) at T+1

- Kinderdijk (-5 m)
- Krimpen a/d IJssel (-4 m)
- Bernisse/ Zuidland (-3 m)
- Middelharnis Spui (-5 m)

DSS-RMM (web-based tool)

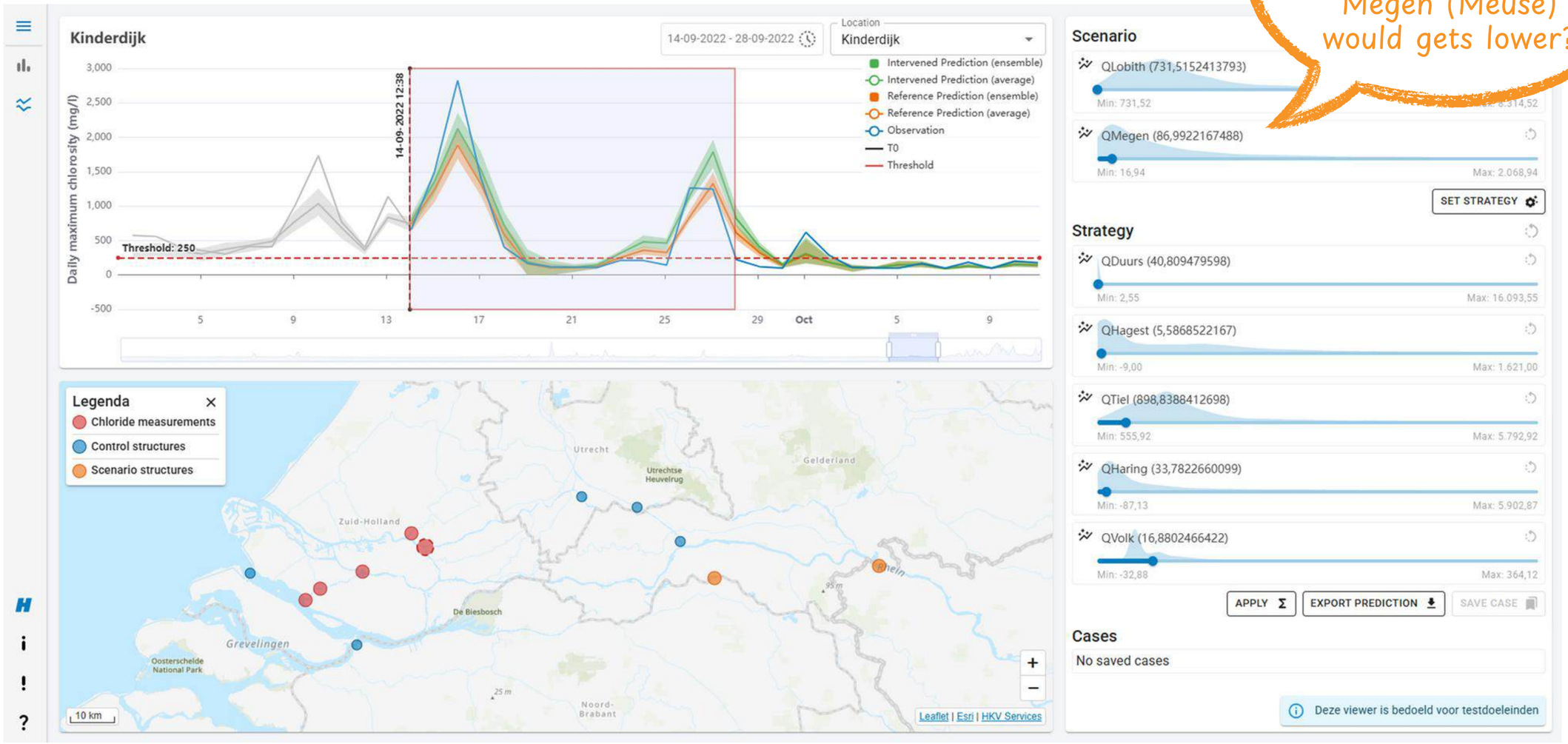


DSS-RMM (web-based tool)

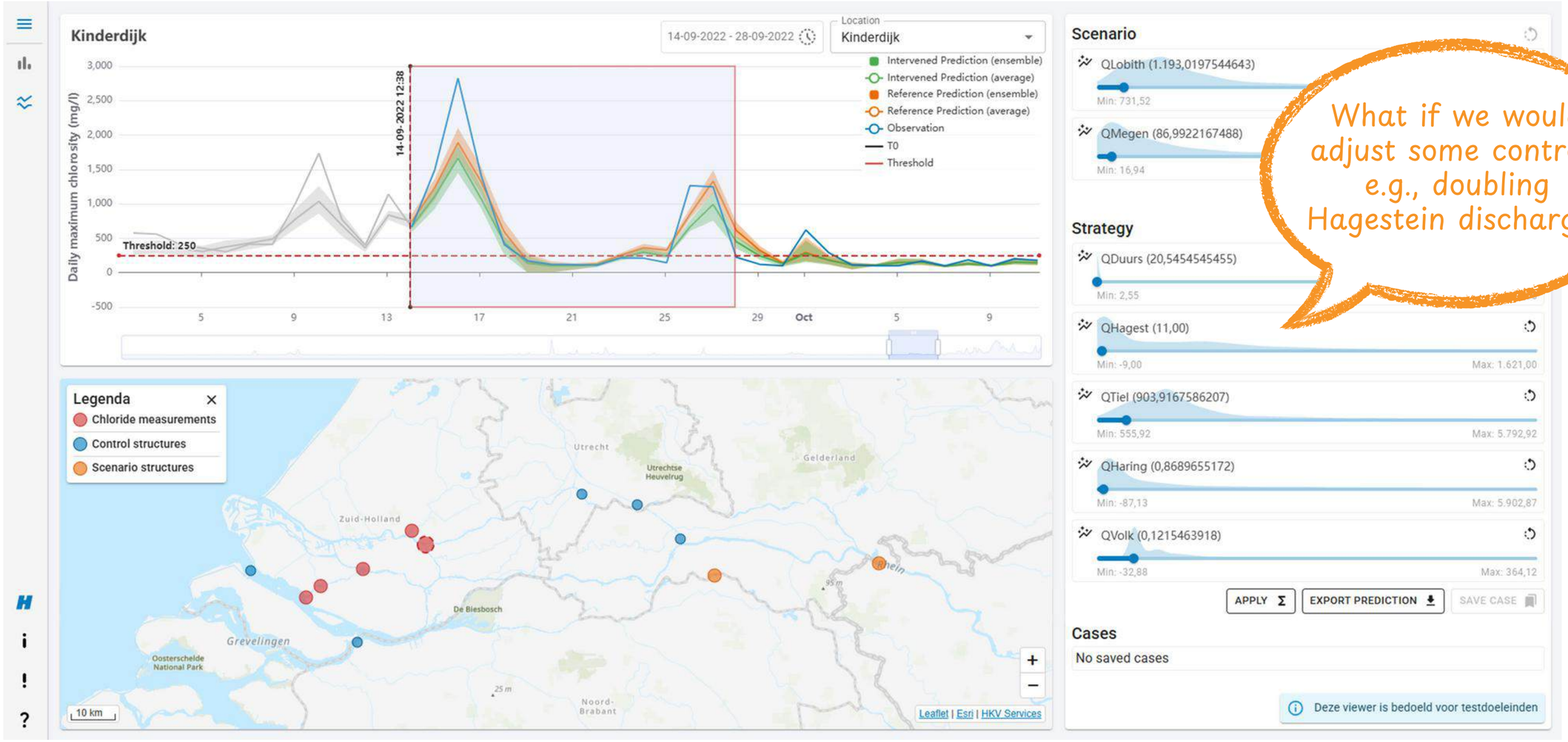


DSS-RMM (web-based tool)

Scenarios: What if the river inflow at Lobith (Rhine) and/or Megen (Meuse) would gets lower?



DSS-RMM (web-based tool)

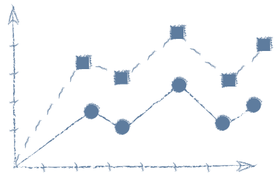


The Virtual Delta

- Make it real-time
- Provide complete evaluation
- Link to current operational systems

Machine learning models

Monitoring → **Forecasting** → **Early-warning**

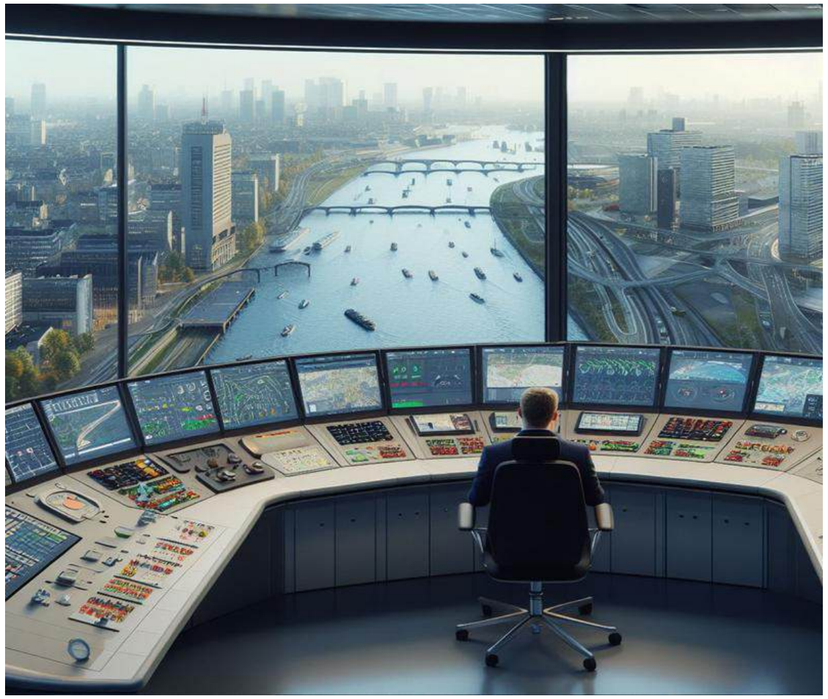


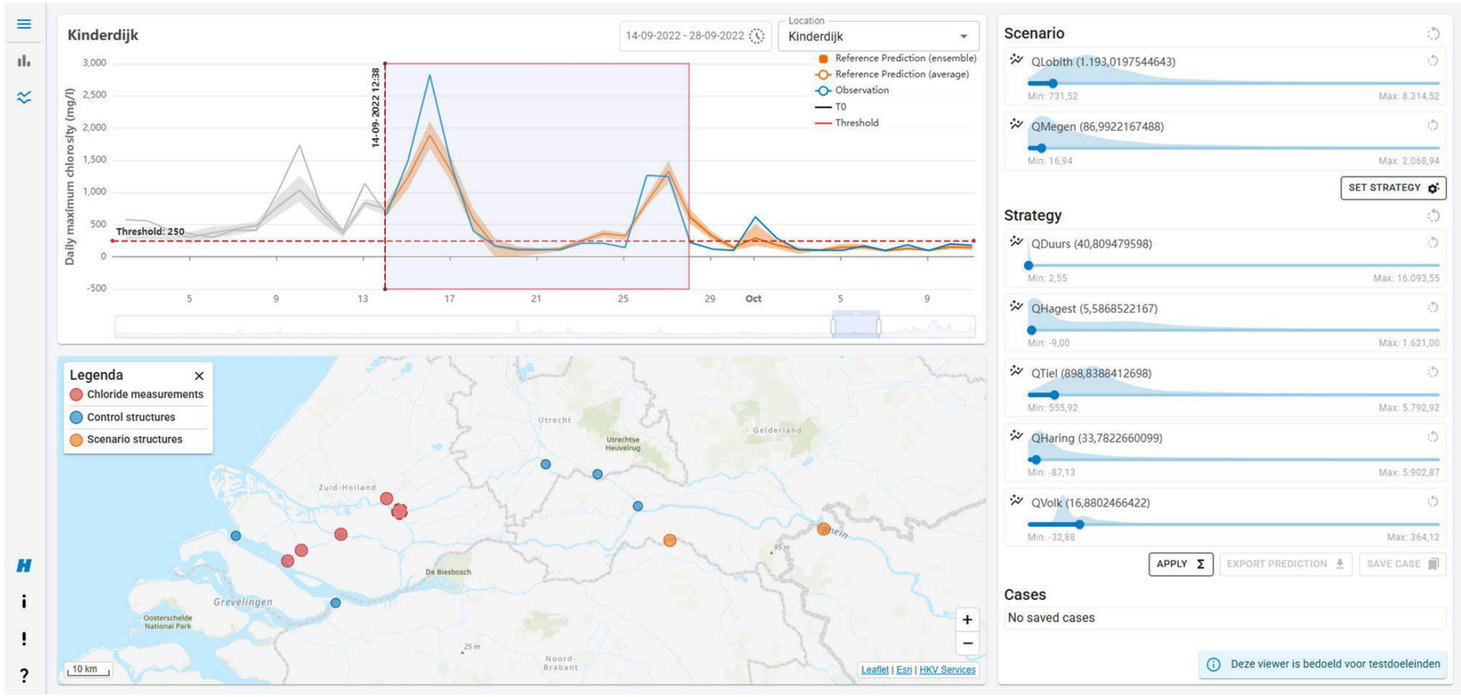
RWsOS-RMM Salti
(Delft-FEWS)

Decision-making →

DSS-RMM
(web-based tool)

The Virtual Delta (?)





Lessons learned

Digital Twins work best when they feel familiar, not like a brand-new tool.

- Start with what users already know and use.
- Involve users early so they can help shape the tool.
- Build trust step by step with real examples and small successes.

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