Towards Better Prediction of Dredging Plumes:

Numerical and Physical Modelling of Near-field Dispersion

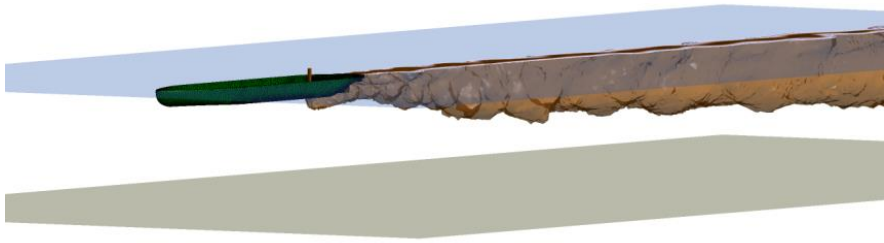
Boudewijn Decrop

PIANC AGA 2017, June 19, Cairns, Australia

IMDC
International Marine & Dredging Consultants

UNIVERSITEIT GENT

KU LEUVEN



Overview

Introduction

Different types of sediment spills

Objectives of the developments

Requirements for (operational) plume dispersion simulations

3D Near-field models: Physical and CFD

Development of parameterised near-field models

Implementation in 3D tidal flow models

Operational turbidity forecasting

IMDC EXPERTISE IN WATER

The project

- Baekeland mandate with funding from
  - IWT (currently called VLAIO)
  - International Marine & Dredging Consultants
- PhD, with scientific support by:
  - Prof. T. De Mulder (Ghent University)
  - Prof. E. Toorman (KULeuven)

Introduction

WHY ARE WE DREDGING ?

- Building new land
- Navigation channels
- Canals
- Port Construction
- Offshore construction
- … many more

Introduction

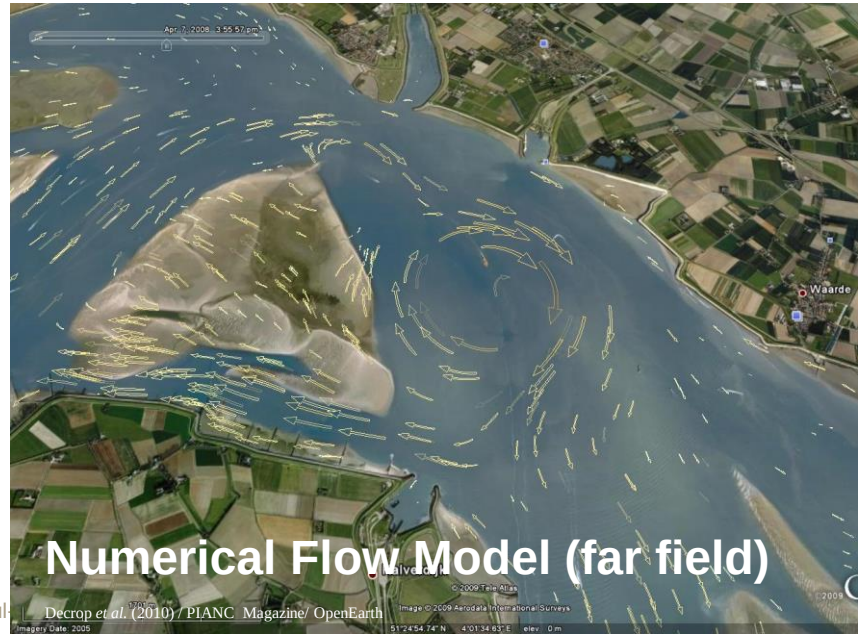
- Sediment spills: Environmental management
- Fate of turbidity plumes
- Large-scale dispersion simulations
- Source terms needed

→ Near-field behaviour?

Introduction

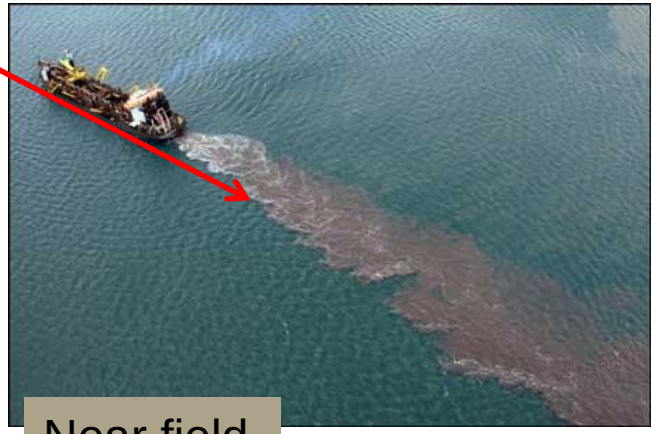
PLUME MODELLING:

- ➢ Simulations of plume dispersion through marine environment
- → Predict whether plumes move to environmentally sensitive areas (e.g. coral reefs, …)
- → Large-scale numerical models of tides and current
- → Source terms needed (how much sediment goes in?)



Numerical Flow Model (far field)

Decrop *et al.* (2010) / PIANC Magazine/ OpenEarth



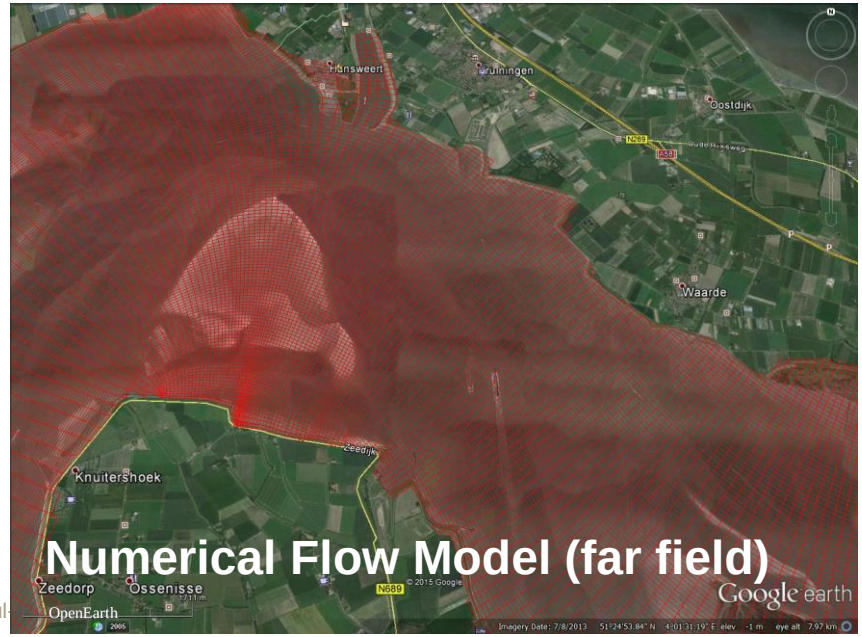
Near field

IMDC EXPERTISE IN WATER

Introduction

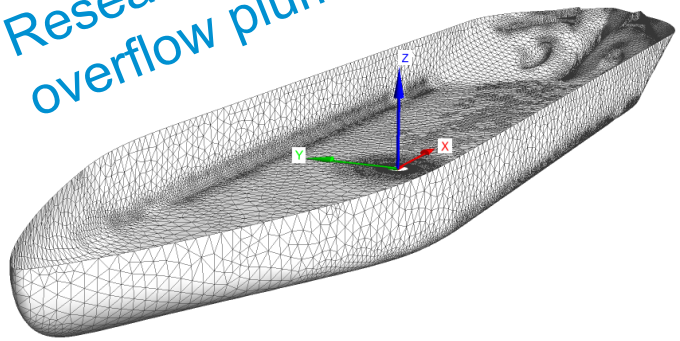
PLUME MODELLING: How?

- Far-field model: coarse grid, extent = 10's-100's of kilometers
- Near-field processes: scale difference prohibitive in far-field model
- Near-field model: fine grid, extent = 100's of meters



Numerical Flow Model (far field)

Research topic = overflow plume models



3D CFD Model (Computational Fluid Dynamics)

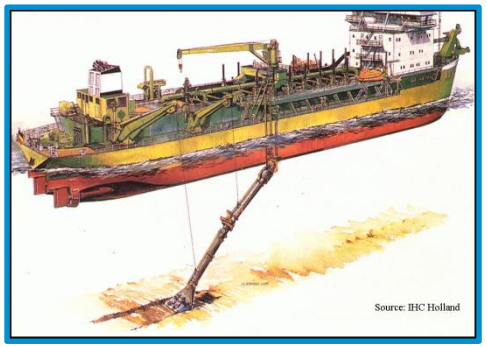
IMDC EXPERTISE IN WATER

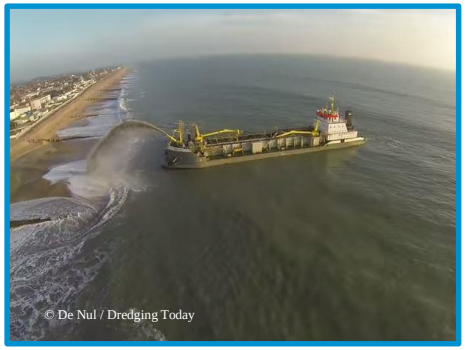
Introduction

THE OVERFLOW:

- Trailing Suction Hopper Dredger (TSHD)
- Cost efficiency:
  - ✓ Transport from dredging site to disposal site
  - ✓ Reduce number of trips
  - ✓ Minimise transport of water

Load → **Transport** → **Dispose**





Introduction

THE OVERFLOW

- Loading: sea bed material <u>+ water</u>
- Water ends up in hopper
- Return back to sea: <u>water + fine sediment + air bubbles</u>

Introduction

THE OVERFLOW PLUME

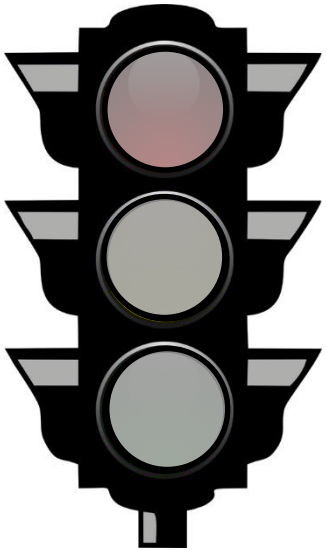
- Released water contains mud particles
- A plume can be formed behind the ship (at surface and/or below)
- Environment: avoid negative effects of turbidity

Environmental Scope of Dredging Projects

- Env. Quality Objectives (EQO) are translated to Trigger levels for measurable parameters (eg. turbidity), with stepwise management actions if breached:

Environmental STRESS

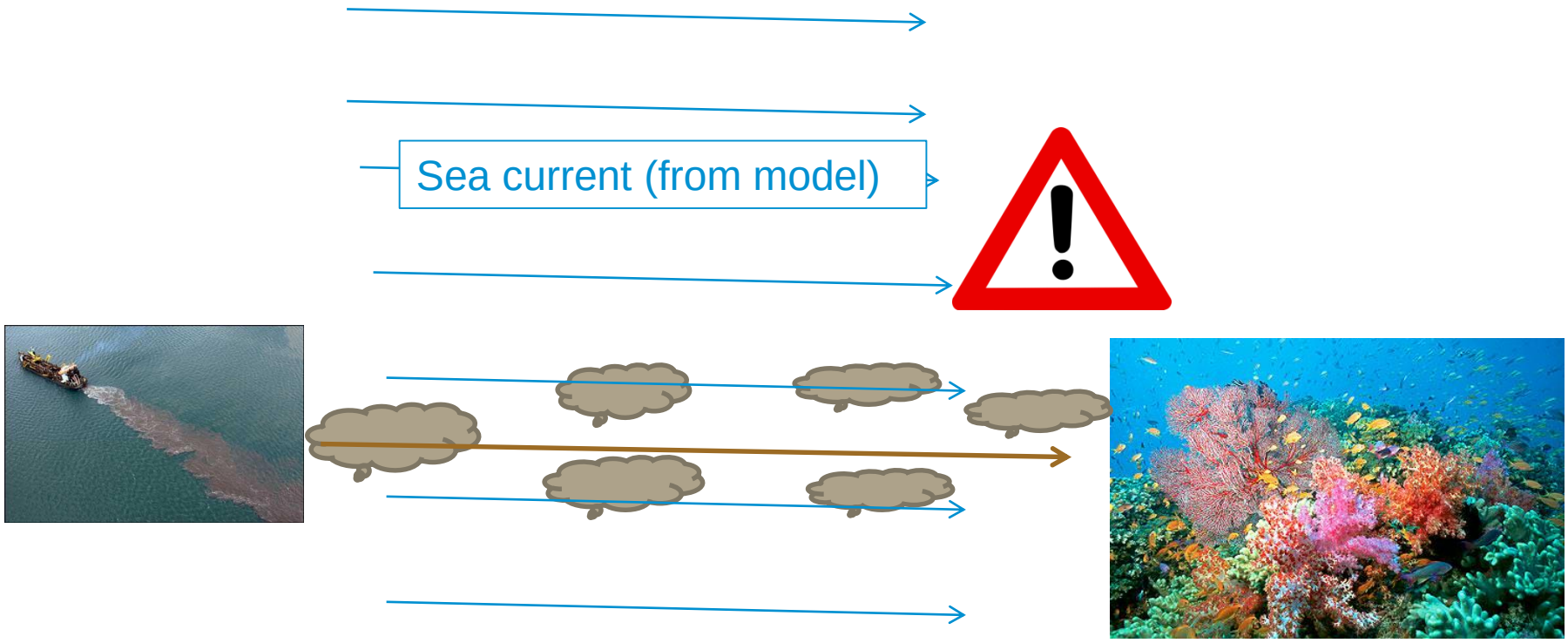
- Trigger level 3: STOP dredging
- Trigger level 2: Operational actions (reduced overflow, move dredging equipm.,…)
- Trigger level 1: Investigate and increased monitoring



IMDC EXPERTISE IN WATER

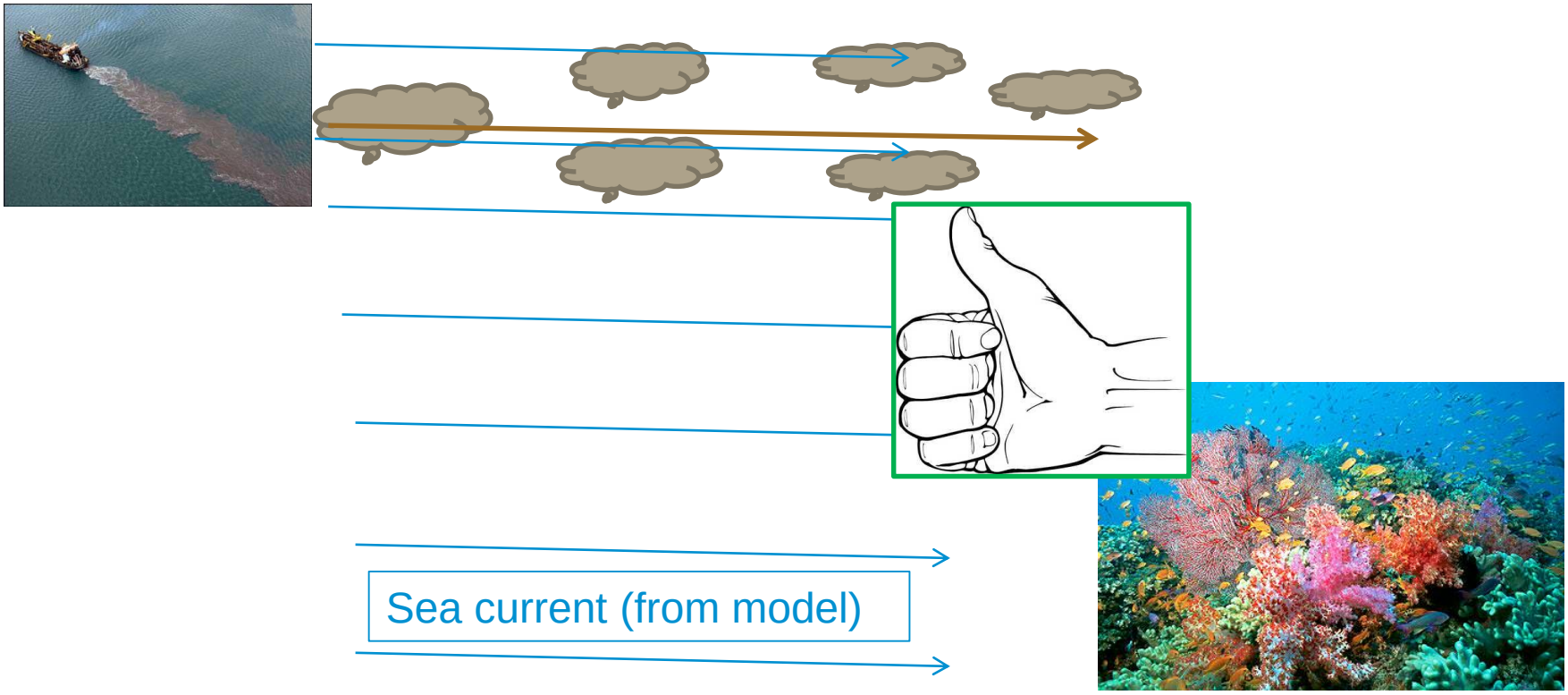
Introduction

Plume predictions ⟷ Environmental management



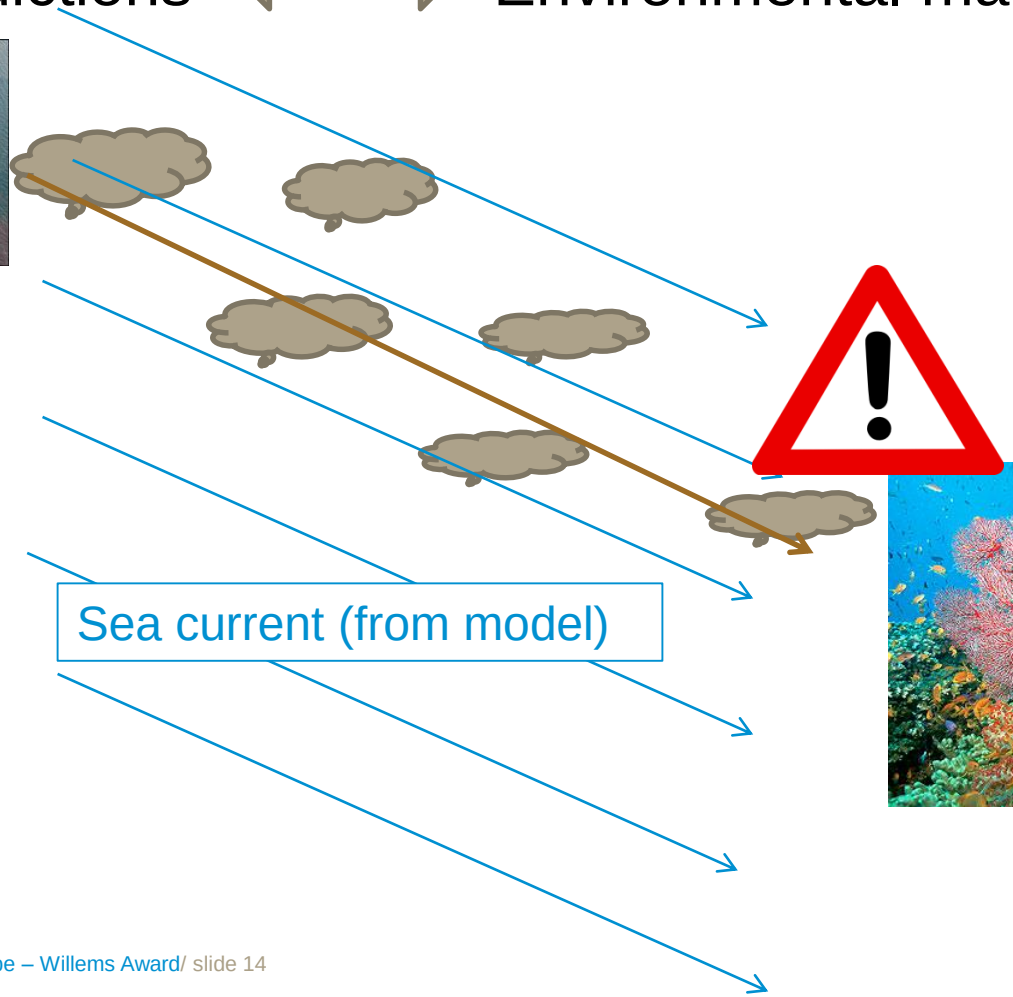
Introduction

Plume predictions ⟷ Environmental management



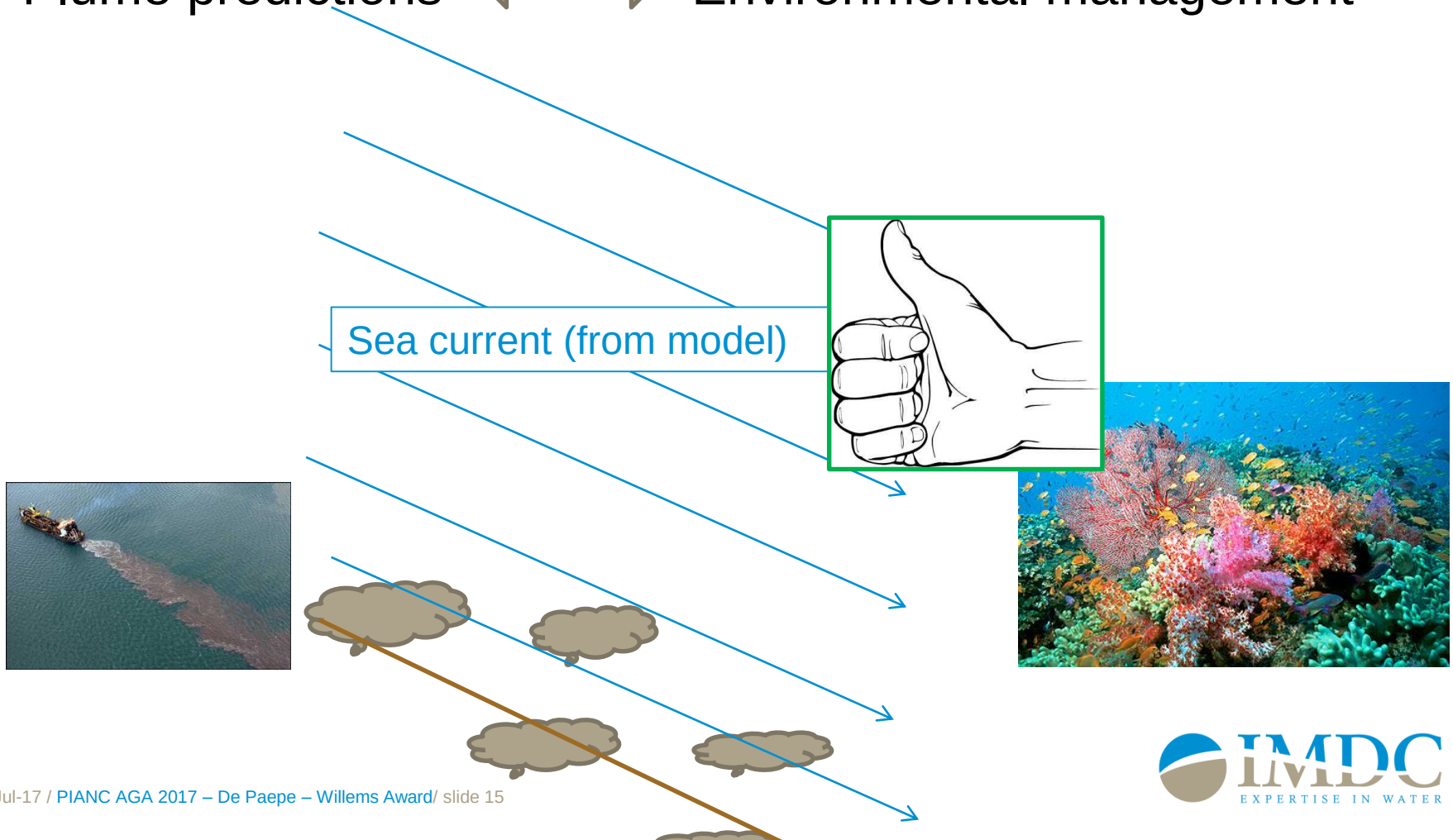
Introduction

Plume predictions ⟷ Environmental management



Introduction

Plume predictions ⟷ Environmental management

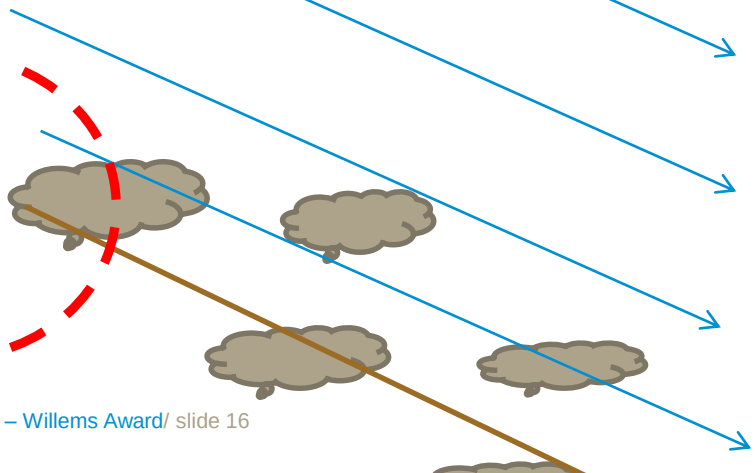


Introduction

Plume predictions ⟷ Environmental management

MAIN RESEARCH QUESTION:

How much sediment to introduce in the far-field model and how is it distributed??



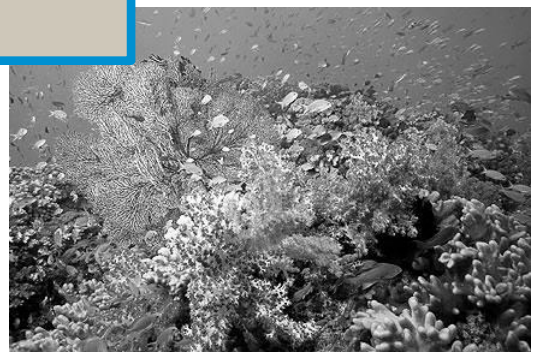
Introduction

Plume predictions ⟷ Environmental management

TODAY:

*** Assumptions with weak justification**

*** 'Best guess' sediment distribution**

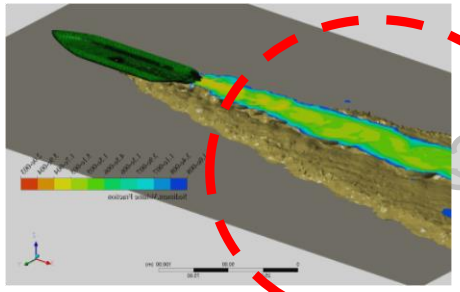


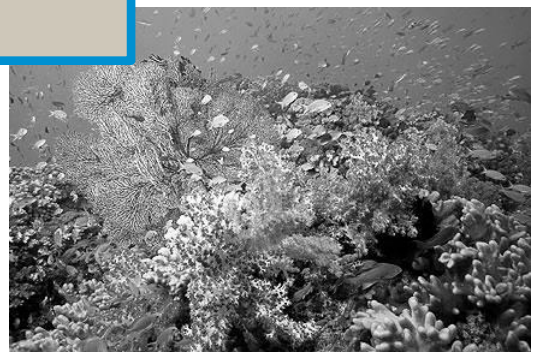
Introduction

Plume predictions ⟷ Environmental management

SOLUTION:

Develop a new near-field model to simulate detailed flow near ship!





Different types of sediment spills

Types of sediment spills taken into account

- Draghead (TSHD)
- Propeller wash (TSHD, self-propelled barges with DP)
- Cutterhead (CSD)
- Bucket loss (Backhoe, Grab dredge)
- Reclamation area runoff
- Open-water placement
- Placement using spreader pontoon

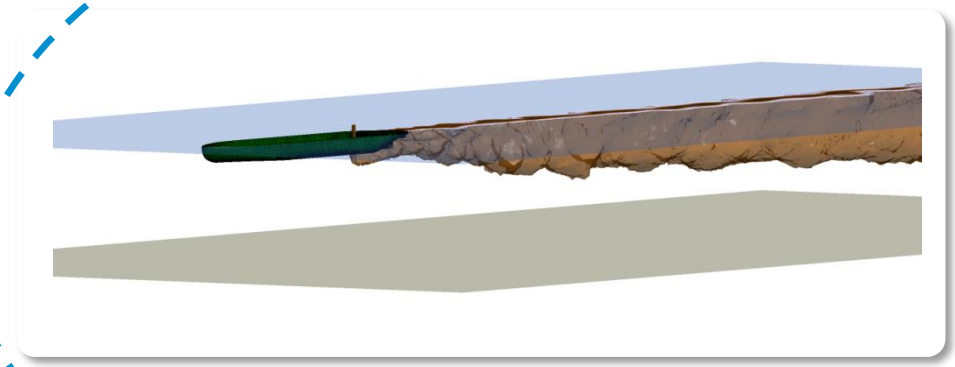
IMDC EXPERTISE IN WATER

Different types of sediment spills

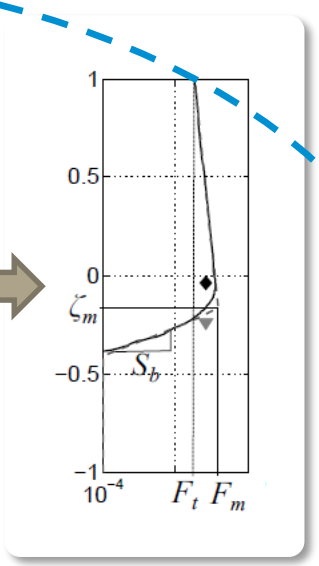
For each active spill type, determine:

- Spill rate (kg/s)
- Vertical distribution in the water column

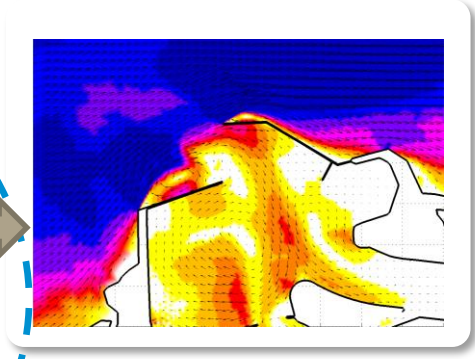
✓ Optimal methodology:



Near-field models



Parameterisations



Far-field model

Objectives - long-term vision at IMDC

General

- Increase accuracy of scenario predictions (tender phase + operational)
- Decrease probability of project shutdown due to turbidity threshold violations

Specific

1. Improve near-field models for overflow plumes (CFD)
2. Develop fast but accurate parameterisations for overflow plumes
3. Flexible framework for Pro-Active Adaptive Management of spills
4. Develop simulation tools for other types of spills

IMDC EXPERTISE IN WATER

Objectives (PhD)

General

- Increase accuracy of scenario predictions (tender phase + operational)
- Decrease probability of project shutdown due to turbidity threshold violations

Specific

1. Improve near-field models for overflow plumes (CFD)
2. Develop fast but accurate parameterisations for overflow spills
3. Flexible framework for Pro-Active Adaptive Management of spills
4. Develop simulation tools for other types of spills

IMDC EXPERTISE IN WATER

Overview

Introduction

Different types of sediment spills

Objectives of the developments

Requirements for (operational) plume dispersion simulations

3D Near-field models: Physical and CFD

Development of parameterised near-field models

Implementation in 3D tidal flow models

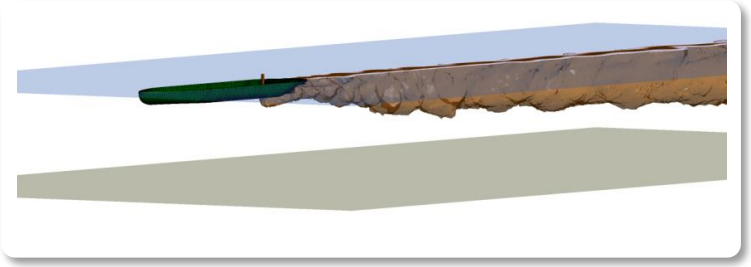
Operational turbidity forecasting

IMDC EXPERTISE IN WATER

Requirements for plume dispersion simulations

- **Far-field model**:
  1. Regional model
  2. Local flow model

- **Near-field models**
  - for dispersion of specific type of spills:

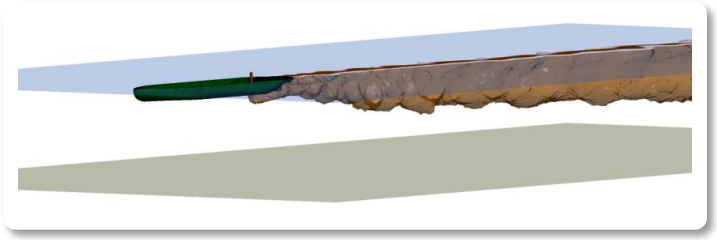


- **Spill parameterisations** (based on near-field models)
- **Soil model project site**
- **Dredge equipment characteristics**
- **Planning of foreseen dredging activities**

Requirements for plume dispersion simulations

- **Far-field model**:
  1. Regional model
  2. Local flow model

- **Near-field models** for dispersion of specific type of spills:
  - Overflow (with/without green valve)
  - Sidecasting
  - Containment bund runoff
  - Propeller wash



- **Spill parameterisations** (near-field models)
- **Soil model project site**
- **Equipment characteristics**
- **Planning of foreseen dredging activities**

IMDC EXPERTISE IN WATER

Requirements for plume dispersion simulations

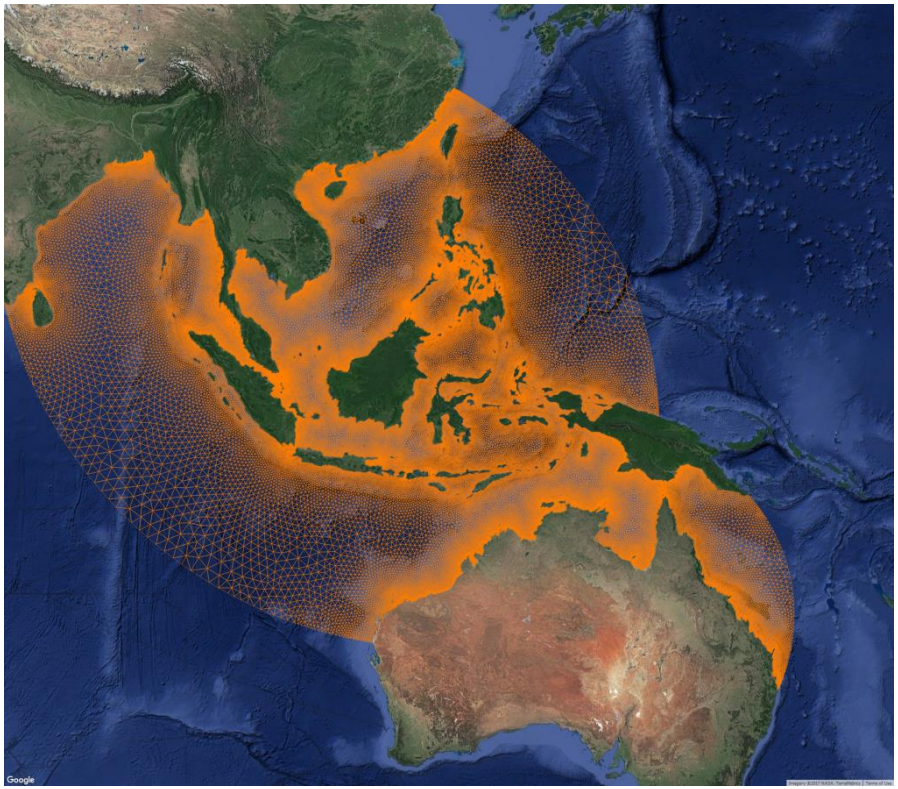
1. Regional models at continental shelf scale:

- Large-scale tidal propagation models (in-house IMDC, 1000's of km, in 2D)
- Very efficient (1 month tidal flow simulation in ~ 1h on 16 CPU's)

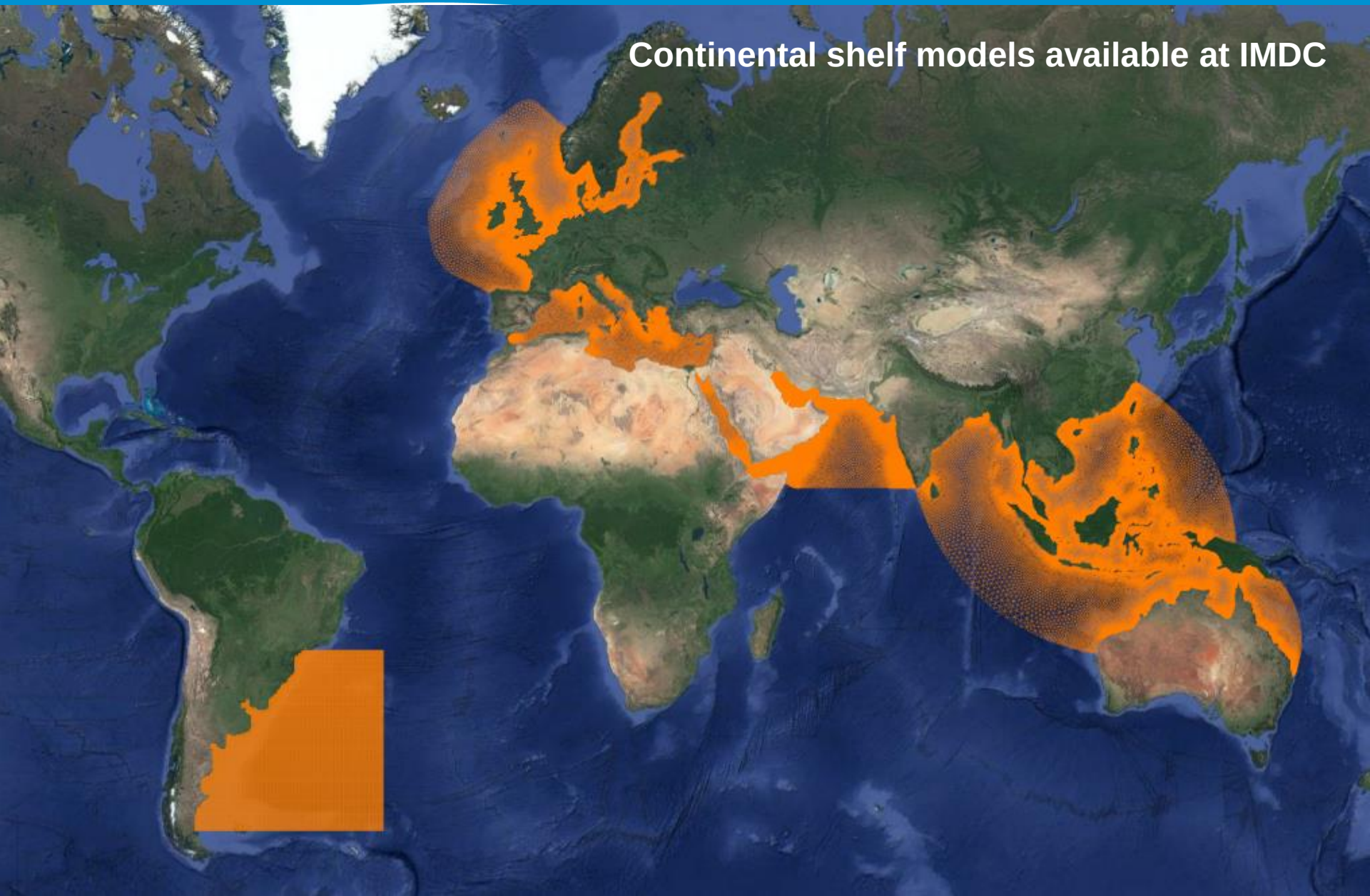
iCSM

Tethys model

iSAM model



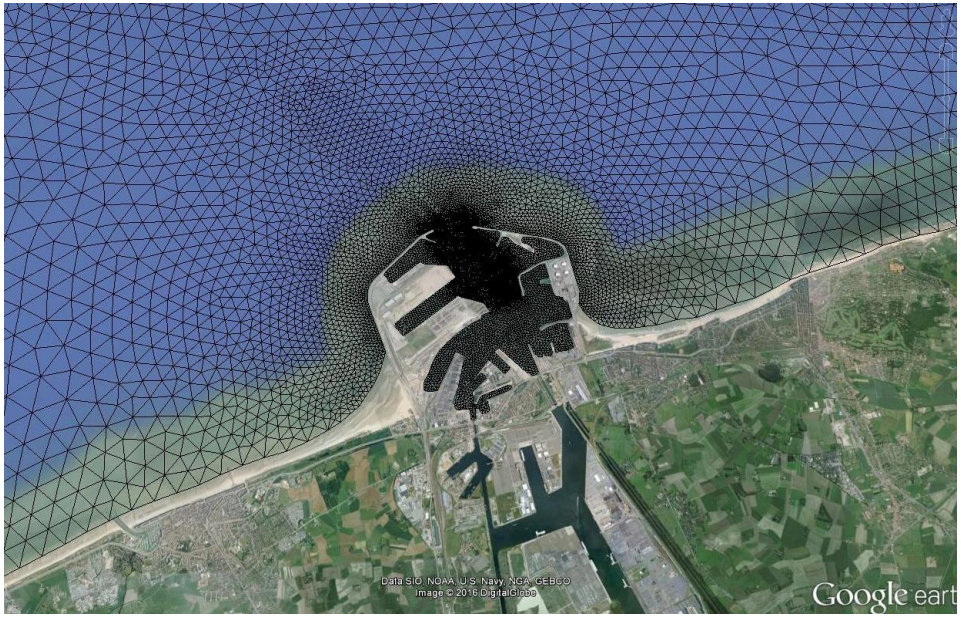
Requirements for plume dispersion simulations

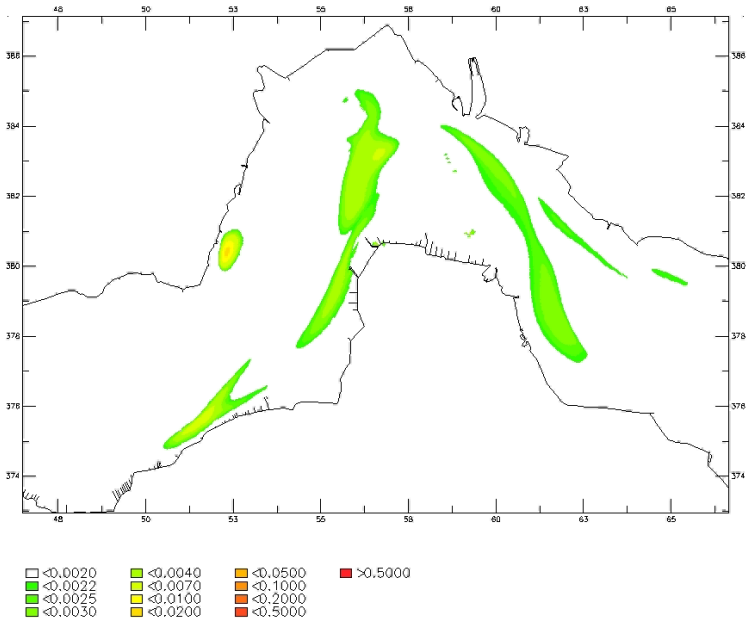


Requirements for plume dispersion simulations

2. Local models at estuary/coast/port scale:

- Local flow models (10-100 km, usually in 3D)
- At present: usually unstructured grids, focussed on area of interest
- Detailed calibration of tides and flow velocity





Overview

Introduction

Different types of sediment spills

Objectives of the developments

Requirements for (operational) plume dispersion simulations

3D Near-field models: Physical and CFD

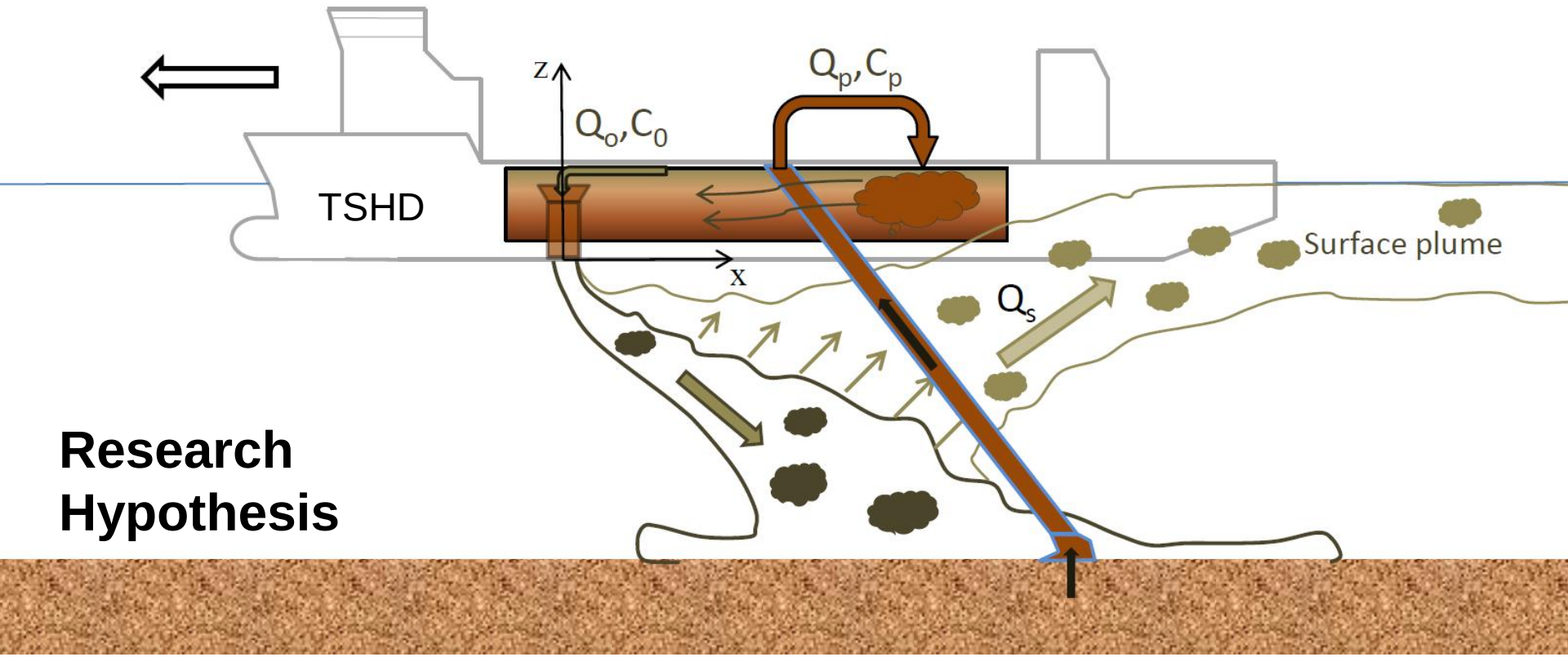
Development of parameterised near-field models

Implementation in 3D tidal flow models

Operational turbidity forecasting

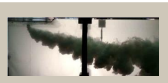
IMDC EXPERTISE IN WATER

Near-field model overflow plumes



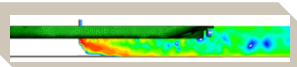
Research Hypothesis

Overview Model development



Lab
EXPERIMENTS

Lab-scale
MODEL



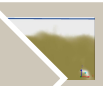
Real-scale
MODEL

Real-scale
MEASUREMENT

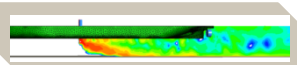
IMDC
EXPERTISE IN WATER

Overview Model development

Lab
EXPERIMENTS



scale
ODEL

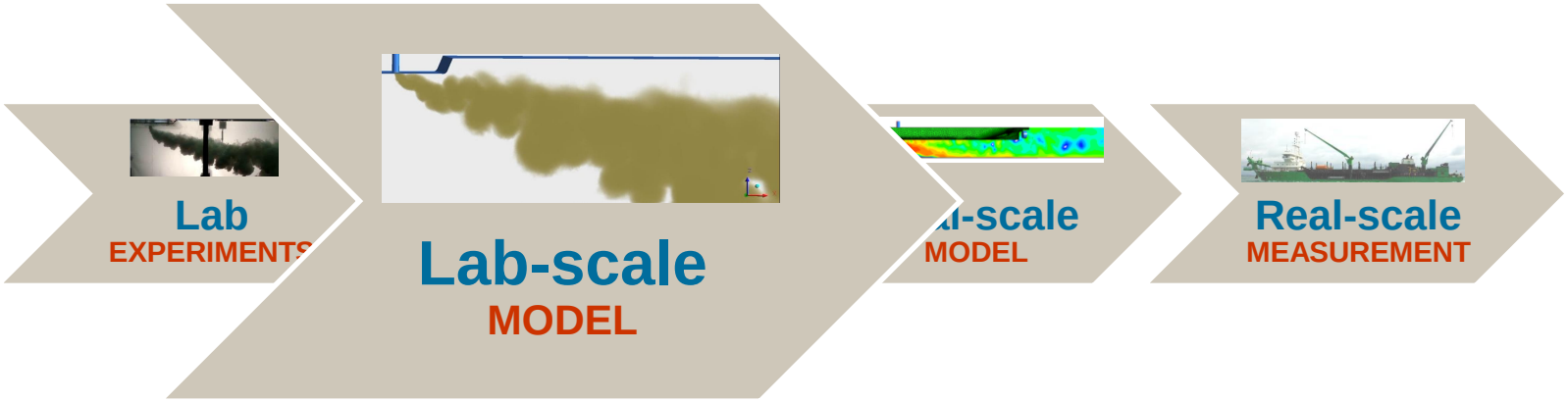


Real-scale
MODEL

Real-scale
MEASUREMENT

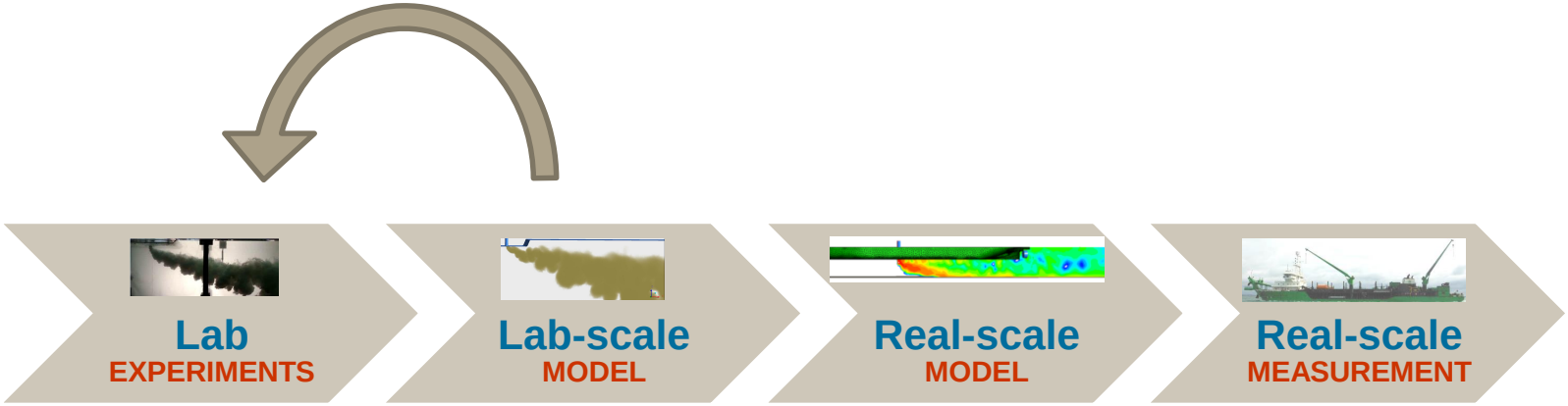
IMDC
EXPERTISE IN WATER

Overview Model development



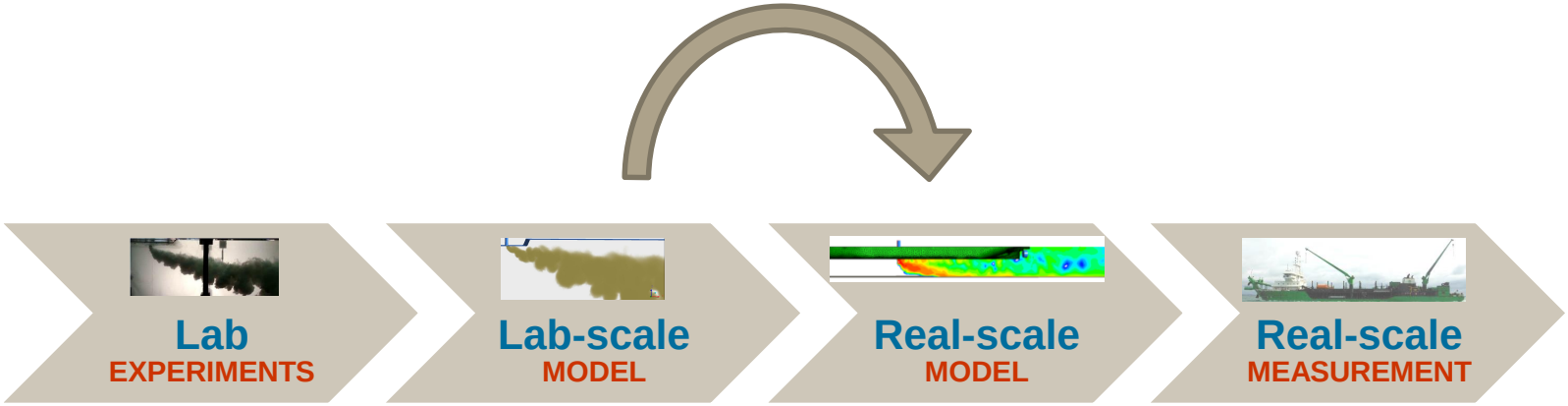
Overview Model development

Model matches Experiment ?

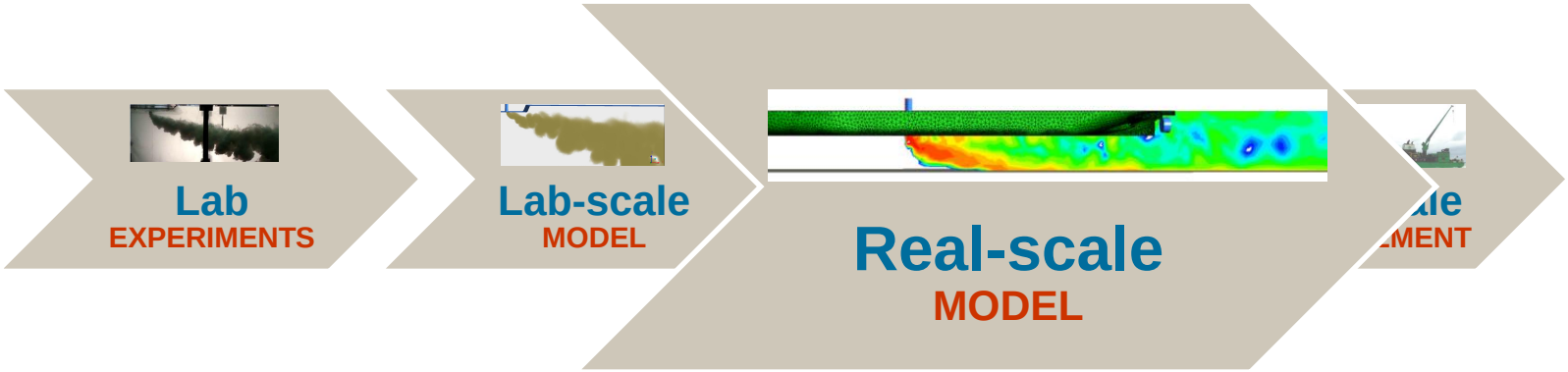


Overview Model development

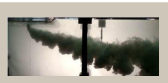
Next step: validate upscaling to real-life scale



Overview Model development

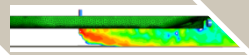


Overview Model development



Lab
EXPERIMENTS

Lab-scale
MODEL



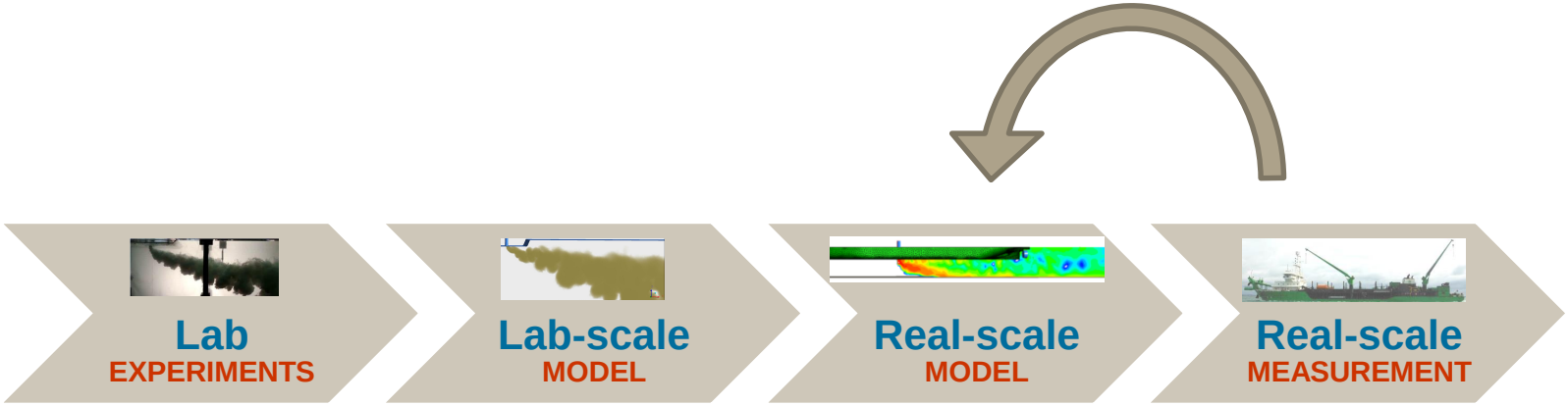
Real-scale
MODEL

Real-scale
MEASUREMENT

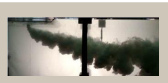
IMDC
EXPERTISE IN WATER

Overview Model development

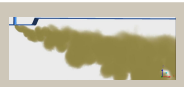
Model matches Field Measurements ?



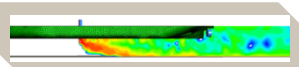
Overview Model development



Lab
EXPERIMENTS



Lab-scale
MODEL



Real-scale
MODEL

Real-scale
MEASUREMENT

Applications:

*Simplified Model

*Influence factors

* Ship Design

IMDC
EXPERTISE IN WATER

Experiments

Lab
EXPERIMENTS

Lab-scale
MODEL

Real-scale
MODEL

Real-scale
MEASUREMENT

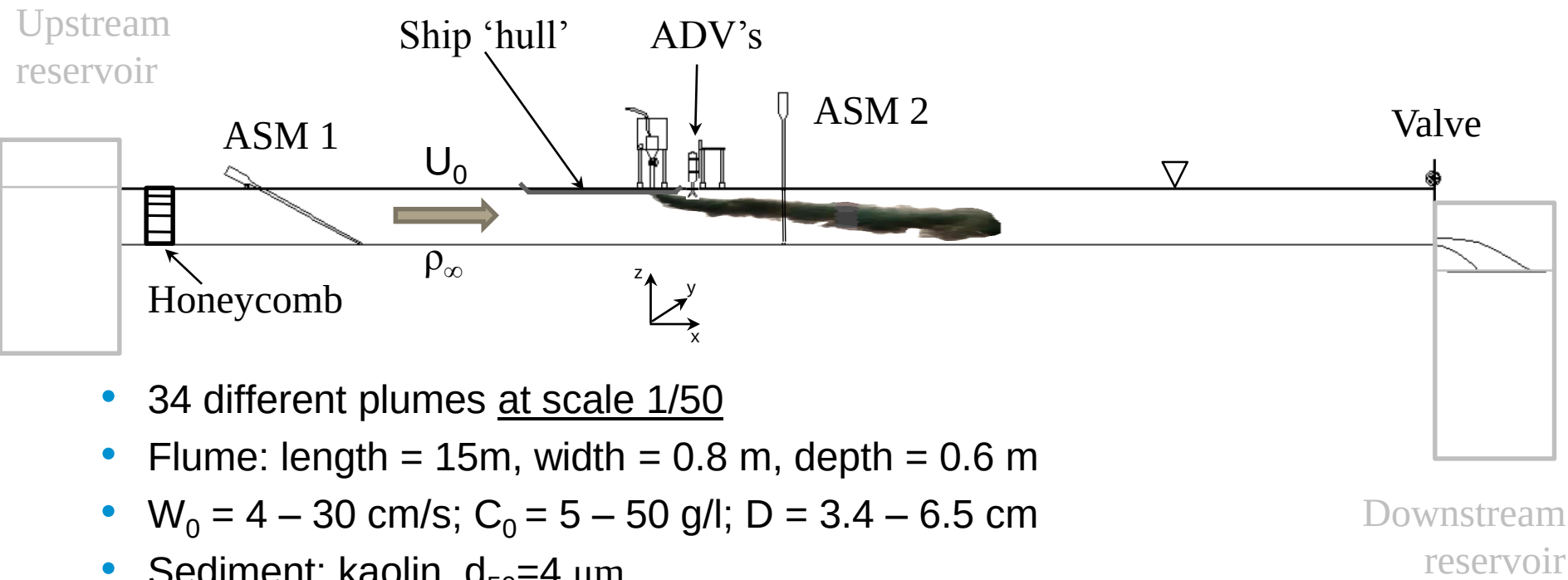
Experiments

Goal of the experiments:

- Insights in sediment plume behaviour
- Produce data set to compare with model results
- Preliminary estimate of influence factors:
  - Air bubbles
  - Ship hull

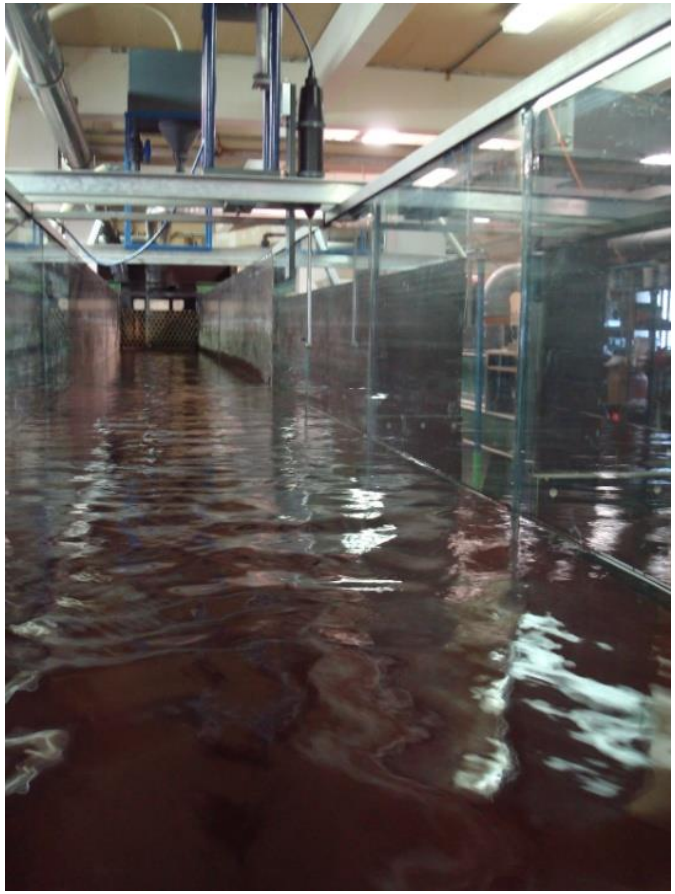
IMDC EXPERTISE IN WATER

Experiments



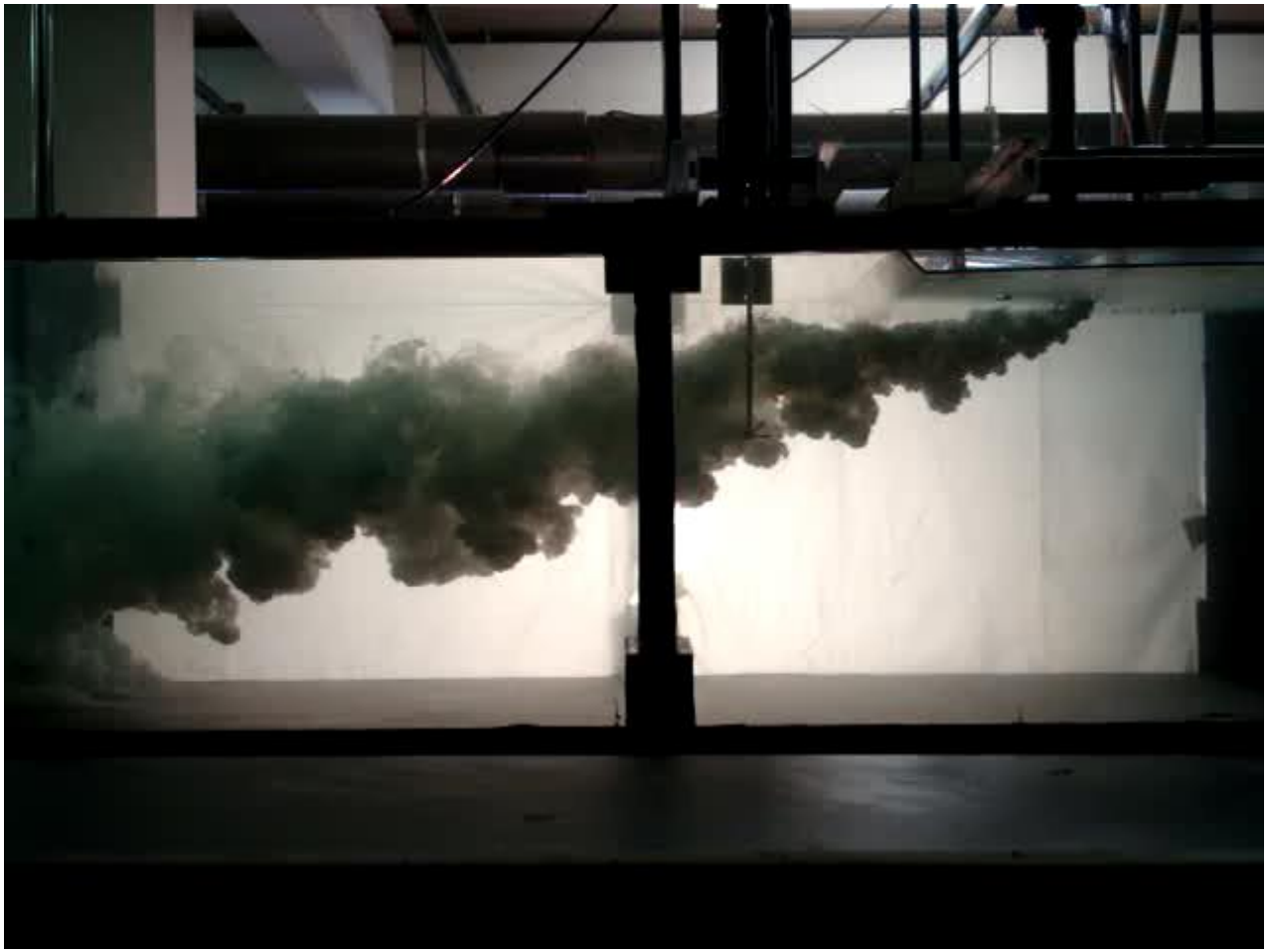
- 34 different plumes <u>at scale 1/50</u>
- Flume: length = 15m, width = 0.8 m, depth = 0.6 m
- W_0 = 4 – 30 cm/s; C_0 = 5 – 50 g/l; D = 3.4 – 6.5 cm
- Sediment: kaolin, d_{50}=4 μm
- Dynamically scaled:
  - Densimetric Froude number F_Δ
  - velocity ratio λ

Experiments



IMDC
EXPERTISE IN WATER

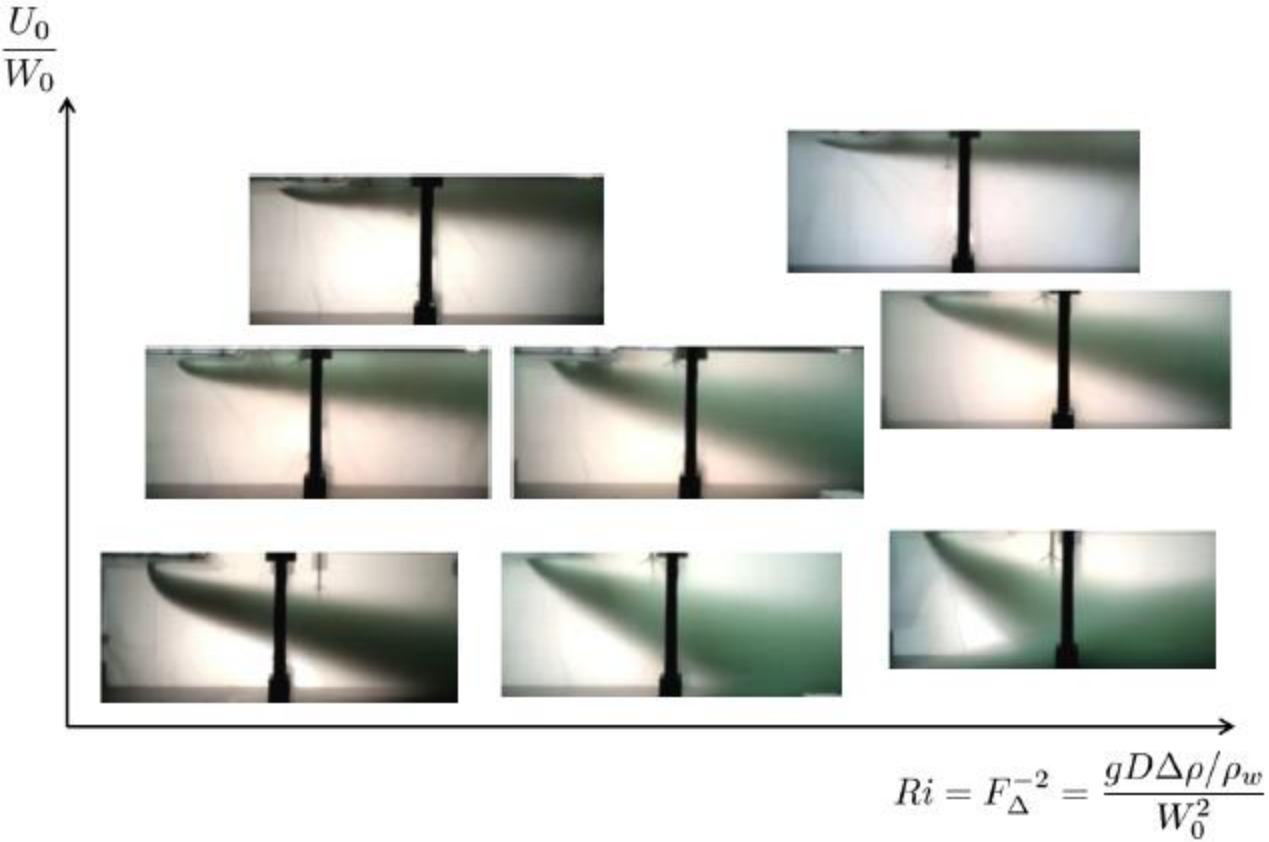
Results



IMDC
EXPERTISE IN WATER

Results

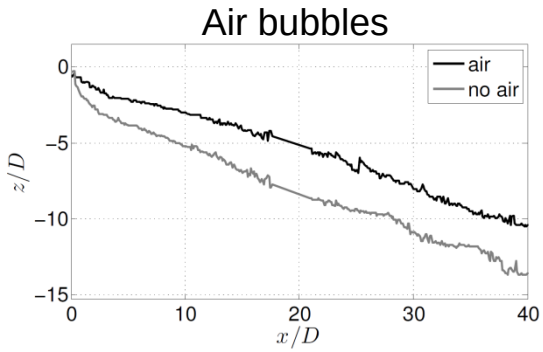
1. Plume trajectory

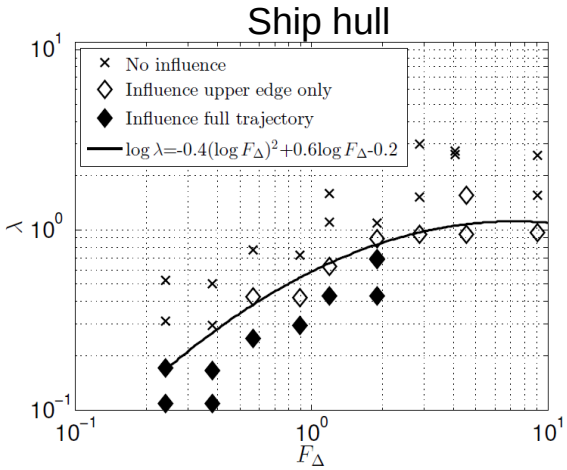


2. Profiles of:

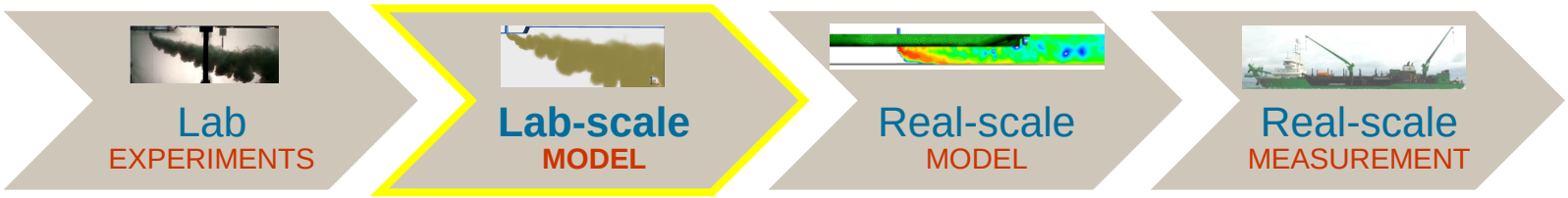
- Sed. concentration

3. Influence factors



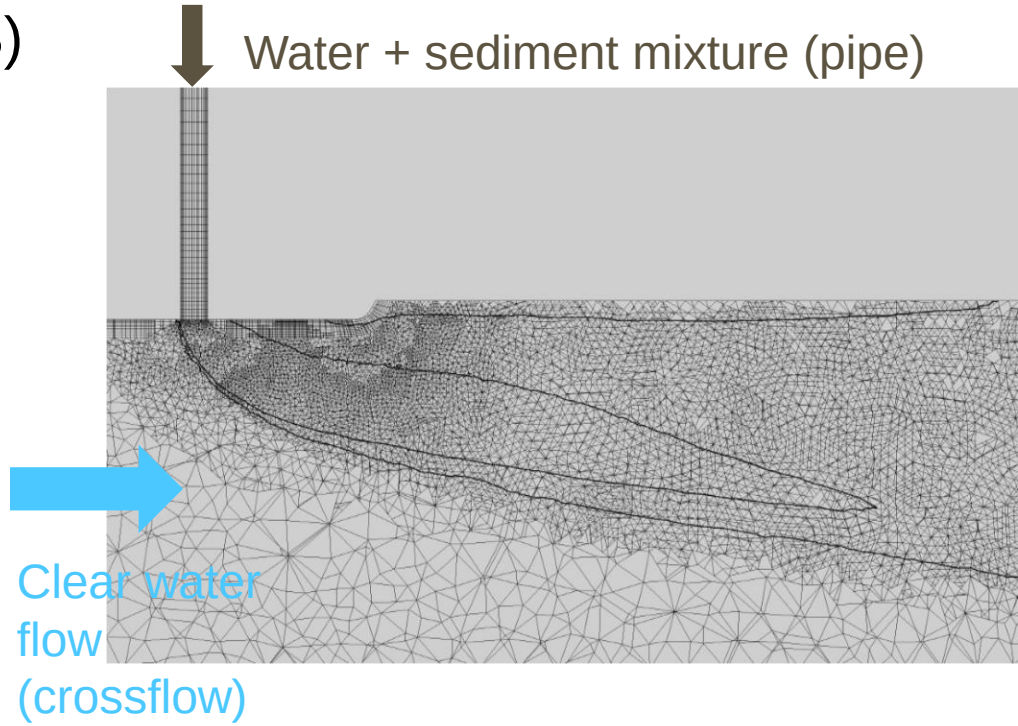


Overview Model development



Lab-scale Model

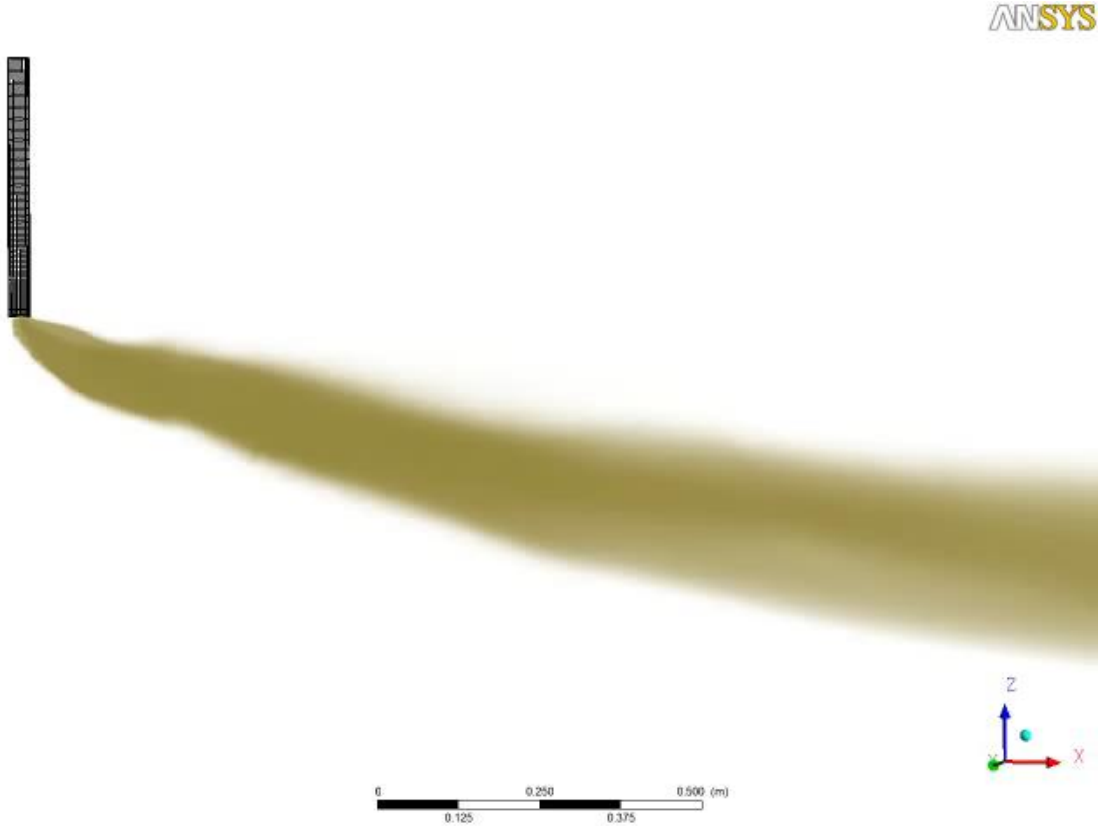
- Navier-Stokes eq's for the water-sediment mixture
- Large-Eddy Simulation (LES)
- Open boundaries:
  - water+sediment in pipe
  - clear water crossflow
- Numerical
  - Finite Volumes
  - grid of ~2M cells
  - dt= 0.02 s
- Variables:
  - pressure
  - velocity components
  - sediment fraction
  - sub-grid scale turbulence variables



IMDC EXPERTISE IN WATER

Results

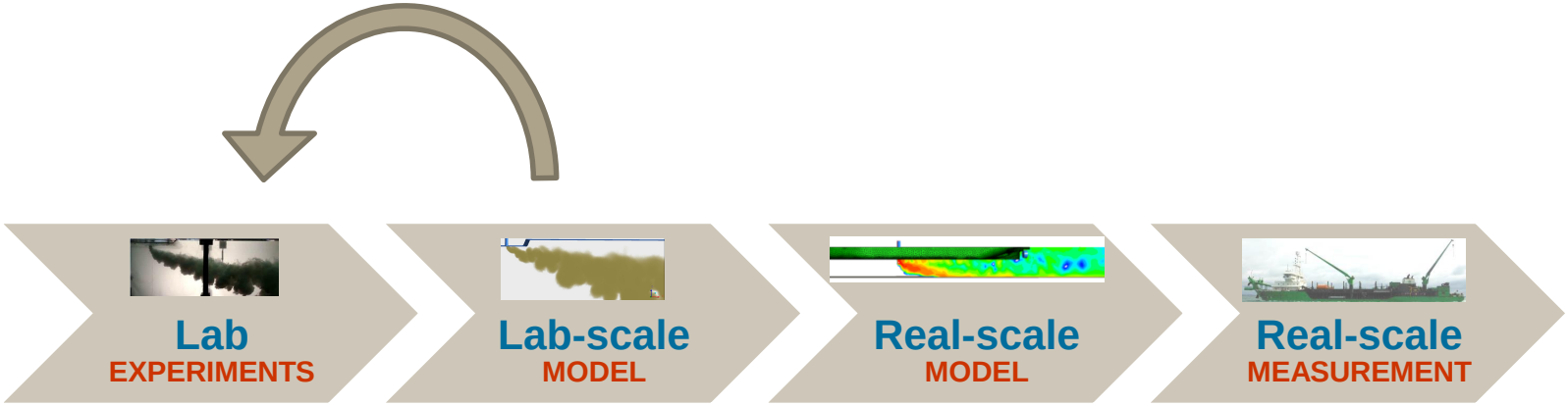
- Impression of the sediment plume



IMDC
EXPERTISE IN WATER

Overview Model development

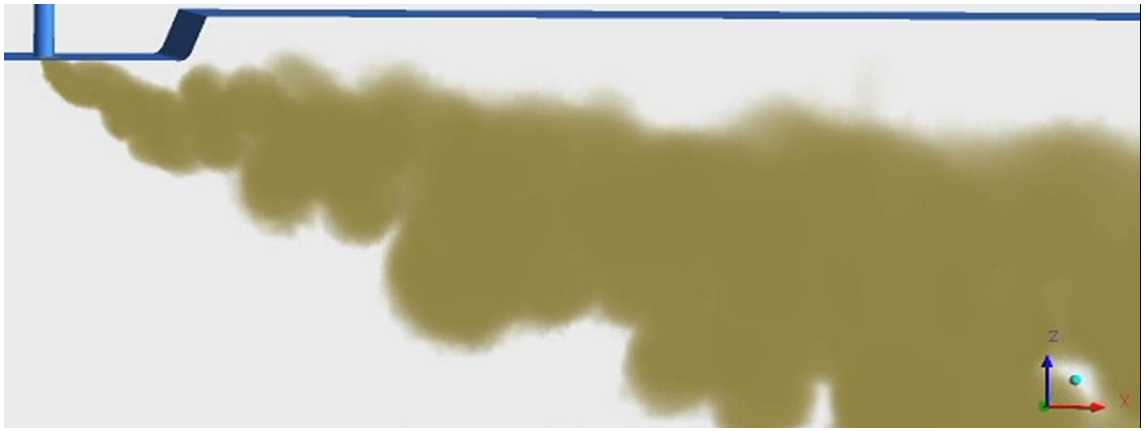
Model matches Experiment ?



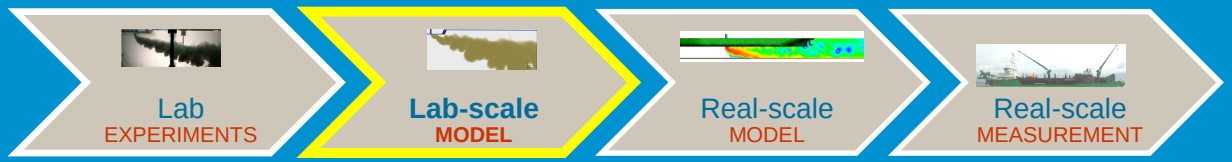
Results

- Qualitatively:

Visually : Lab vs CFD

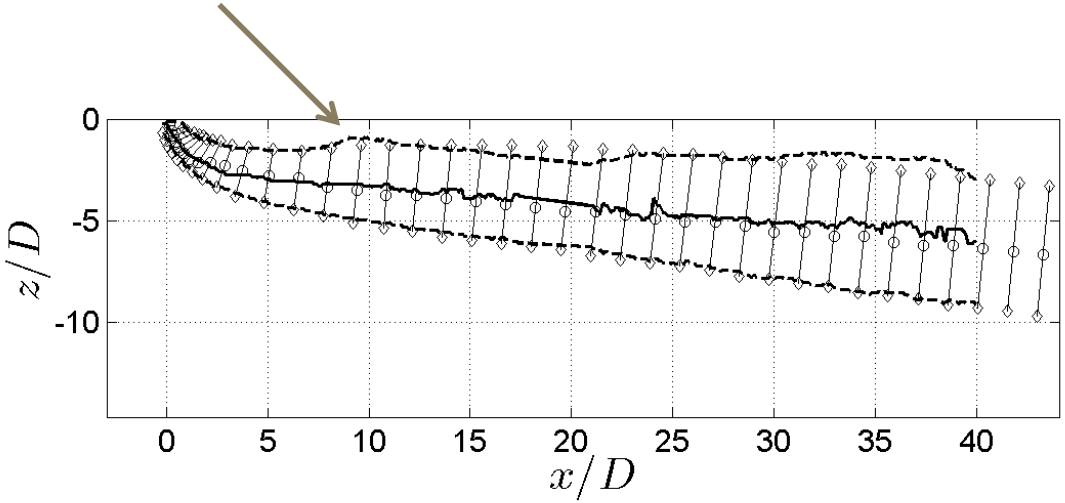


Results



Quantitatively:

1. Trajectory : Laboratory vs CFD
   - Centerline
   - Upper/lower edge
   - Plume entrainment due to vessel hull



Decrop, B. *et al.* (2015). Large-Eddy Simulations of turbidity plumes in crossflow. *European Journal of Mechanics - B/Fluids* (53), p68-84,

IMDC EXPERTISE IN WATER

Results

Lab EXPERIMENTS | **Lab-scale MODEL** | Real-scale MODEL | Real-scale MEASUREMENT

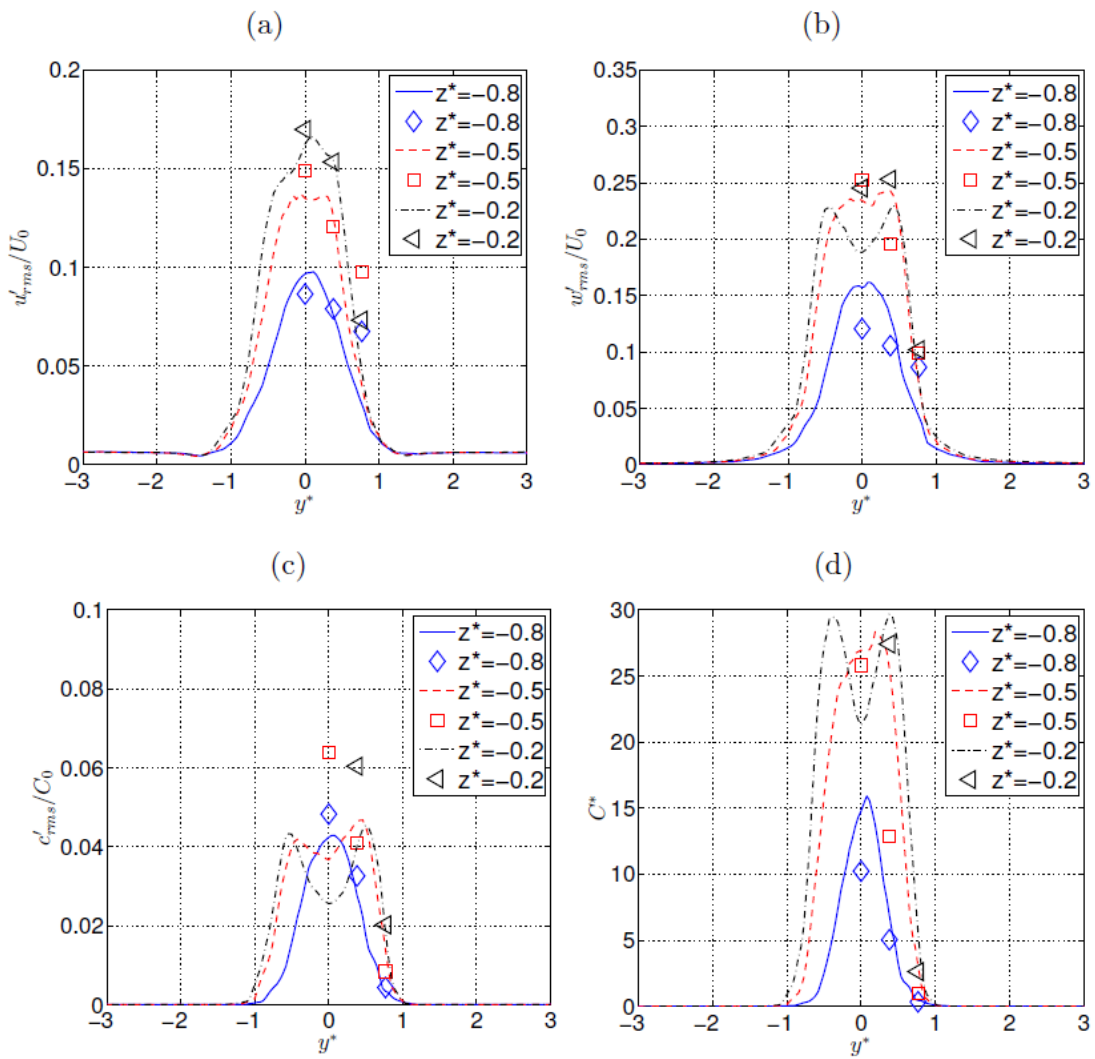
Quantitatively:

2. SSC & Turbulence

- RMS u_i'
- RMS c'

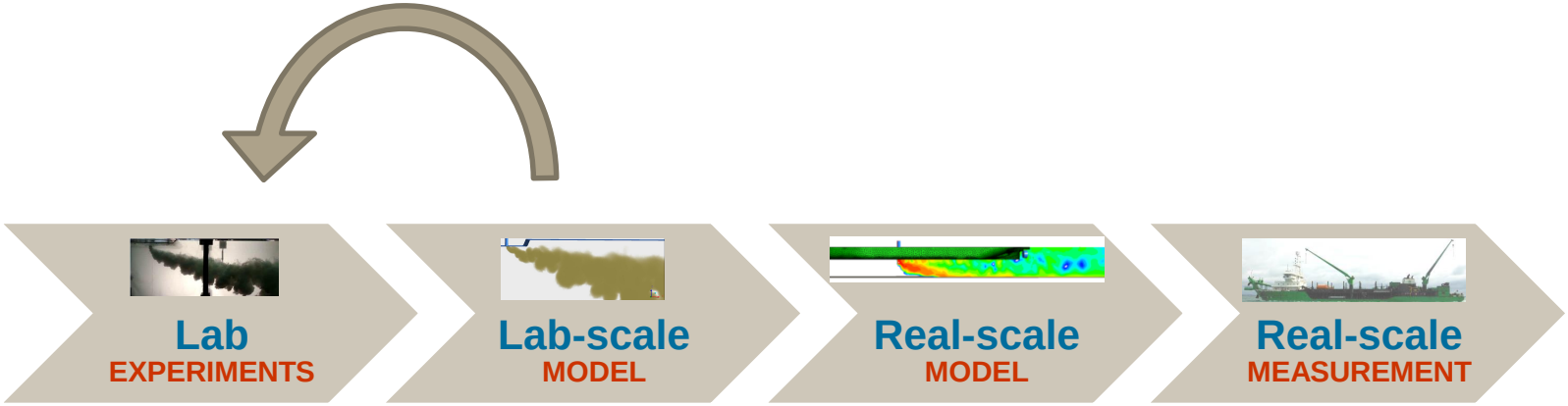
$$y* = y/|\bar{z}|$$

$$z* = (z - \bar{z})/|\bar{z}|$$



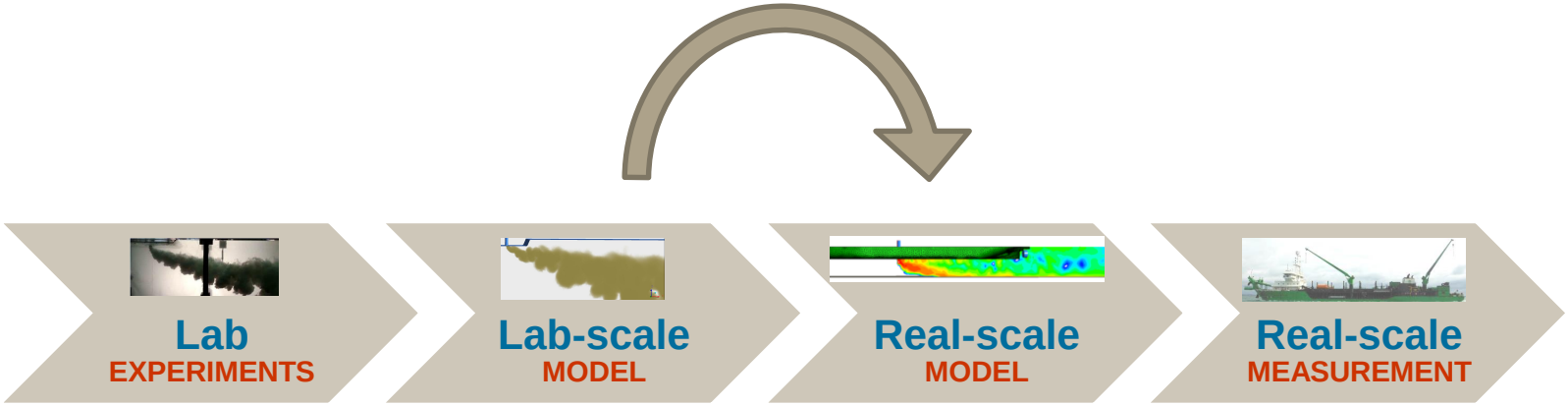
Overview Model development

Model matches Experiment ? YES!



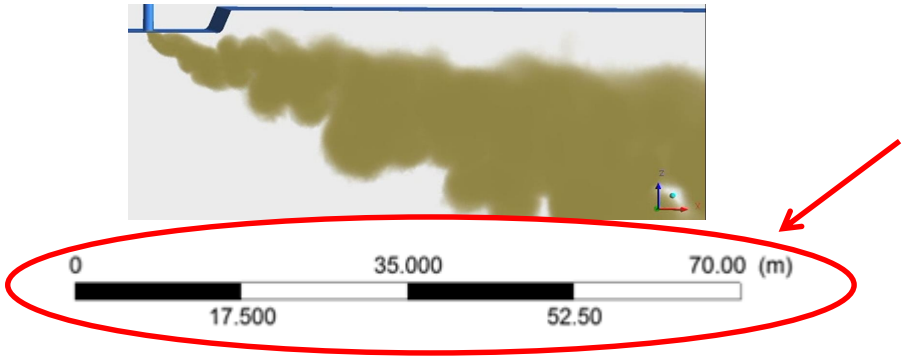
Overview Model development

Next step: validate upscaling to real-life size



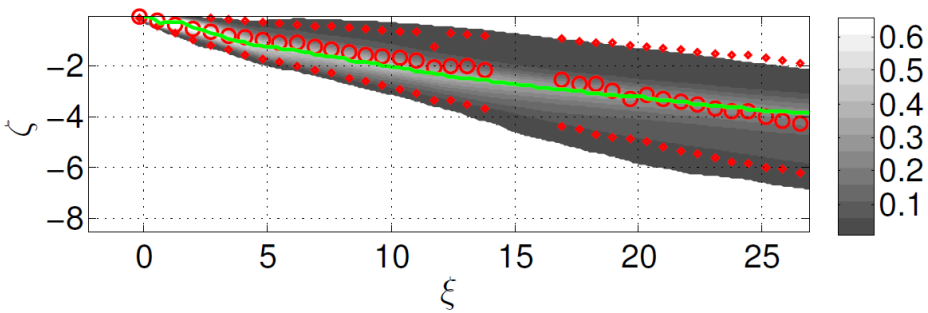
Upscaling to realistic scale:

CFD model with lab geometry



Upscaling LES model to prototype scale

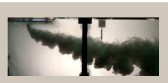
1. Take CFD model lab scale
2. Scale grid to large scale (similarity laws buoyant jets)
3. CFD simulation
4. Validation, based on:
   - Trajectories in similarity coordinates must coincide with lab scale
   - TKE resolved > 80%, for LES completeness (Pope, 2004)



CFD (large scale, Re=1.9 10^6)

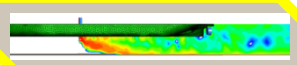
Physical model (small scale, Re=1.2 10^4)

Overview Model development



Lab
EXPERIMENTS

Lab-scale
MODEL



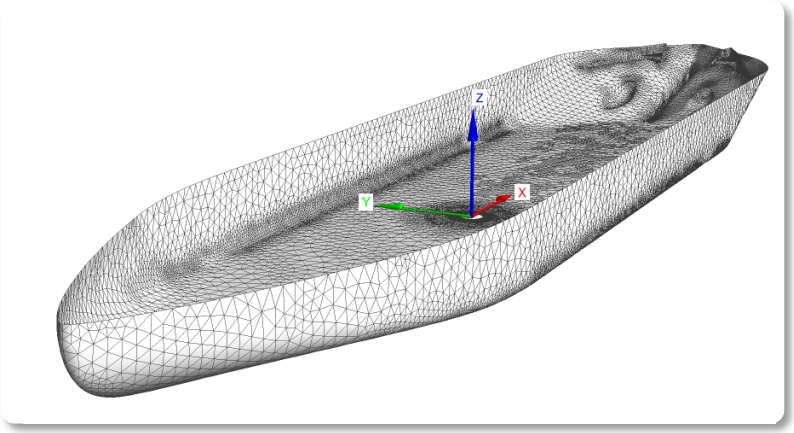
Real-scale
MODEL

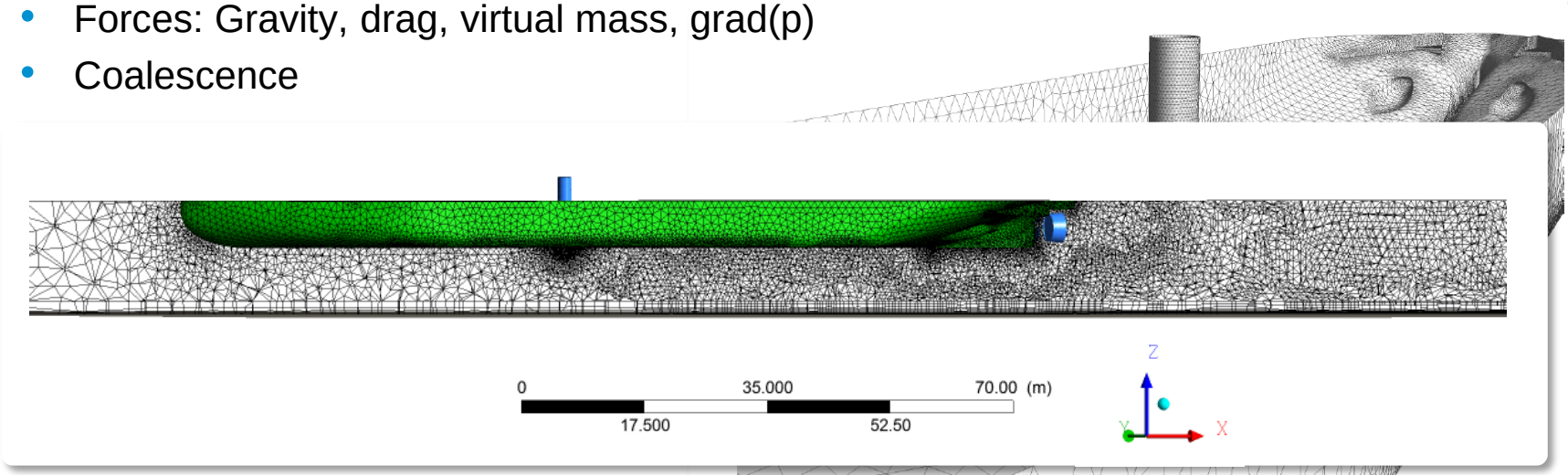
Real-scale
MEASUREMENT

IMDC
EXPERTISE IN WATER

Real-scale model

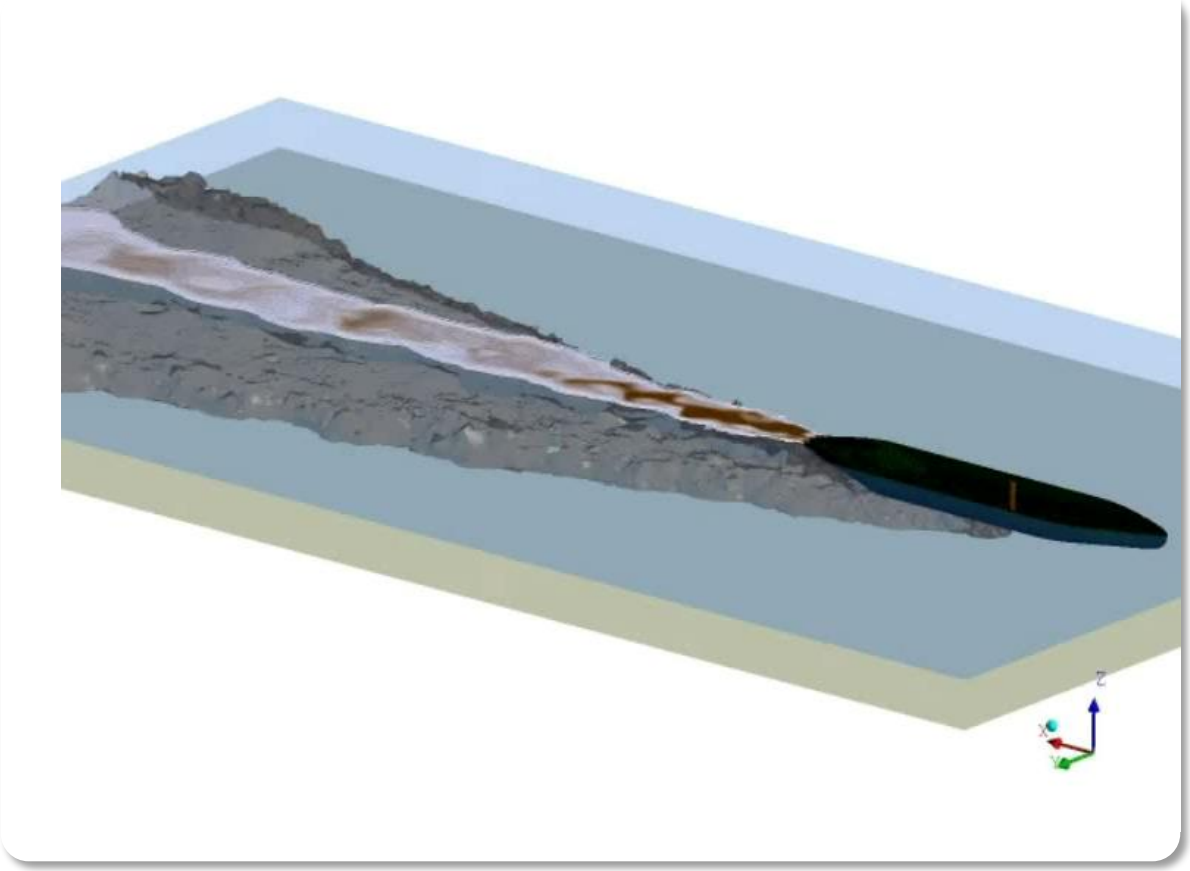
- 3D CFD
- 3 phases: water, sediment, air bubbles
- Resolves large turbulent motions (LES)
- Full-size TSHD
- Propellers included (actuator disk)
- Dynamic air bubble transport model:
  - Lagrangian,
  - Forces: Gravity, drag, virtual mass, grad(p)
  - Coalescence





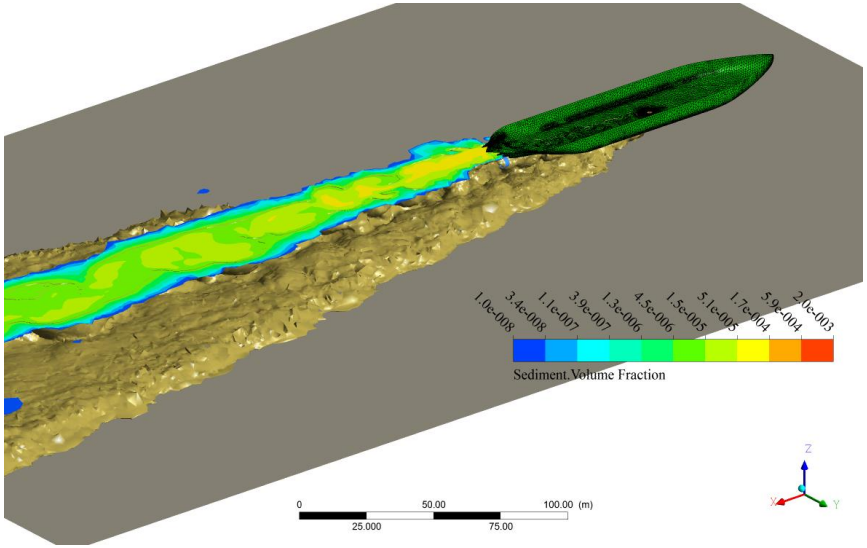
Real-scale model

- CFD simulation result

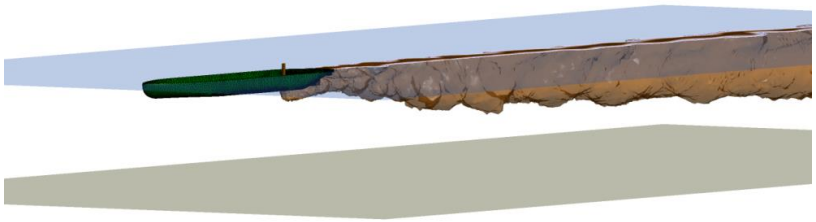


Real-scale model

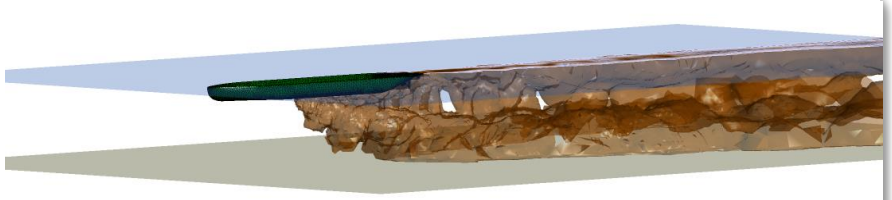
- CFD simulation result



Real-scale model

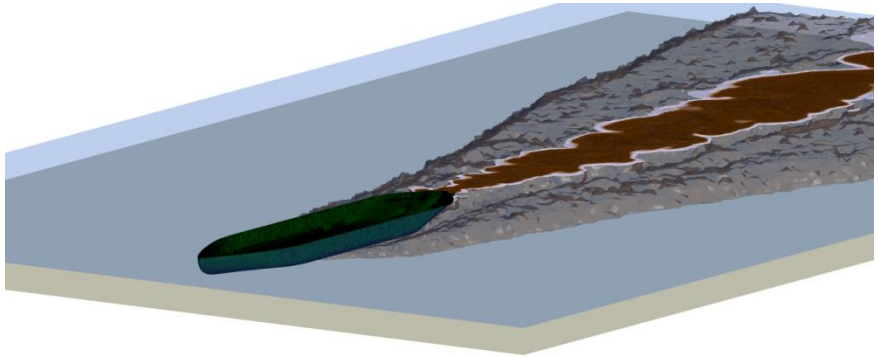


Deep water, light mixture



Deep water, heavy mixture

Shallow water

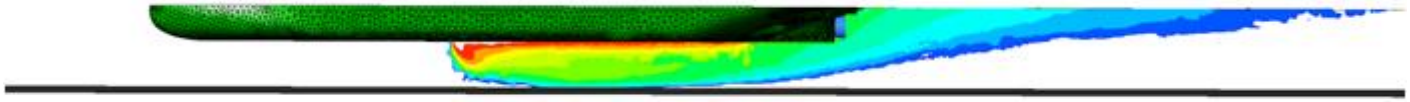


! Validation needed

↓

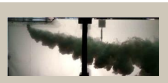
Monitoring campaigns

Air bubble concentration



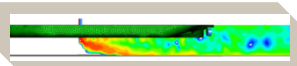
IMDC EXPERTISE IN WATER

Overview Model development



Lab
EXPERIMENTS

Lab-scale
MODEL

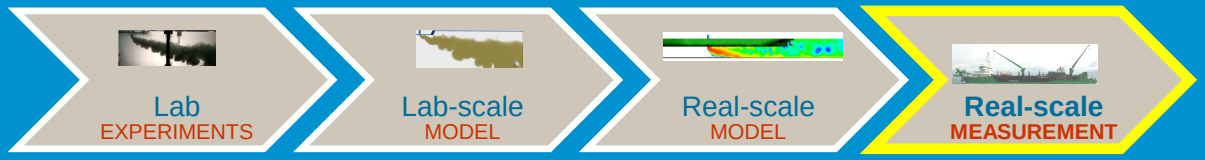


Real-scale
MODEL

Real-scale
MEASUREMENT

IMDC
EXPERTISE IN WATER

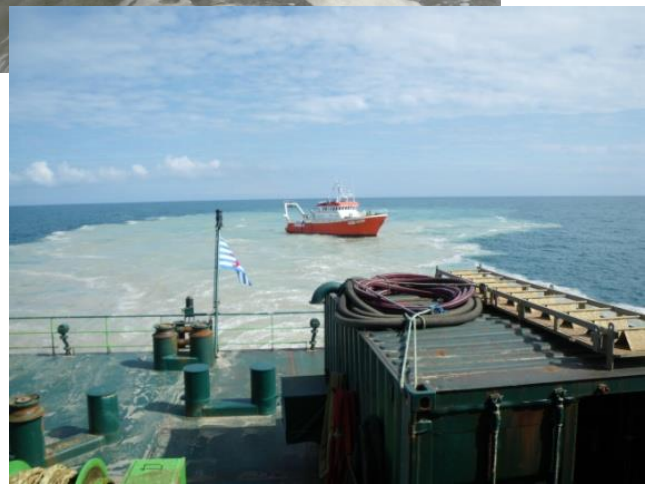
Measurements



Determination of sediment concentration:

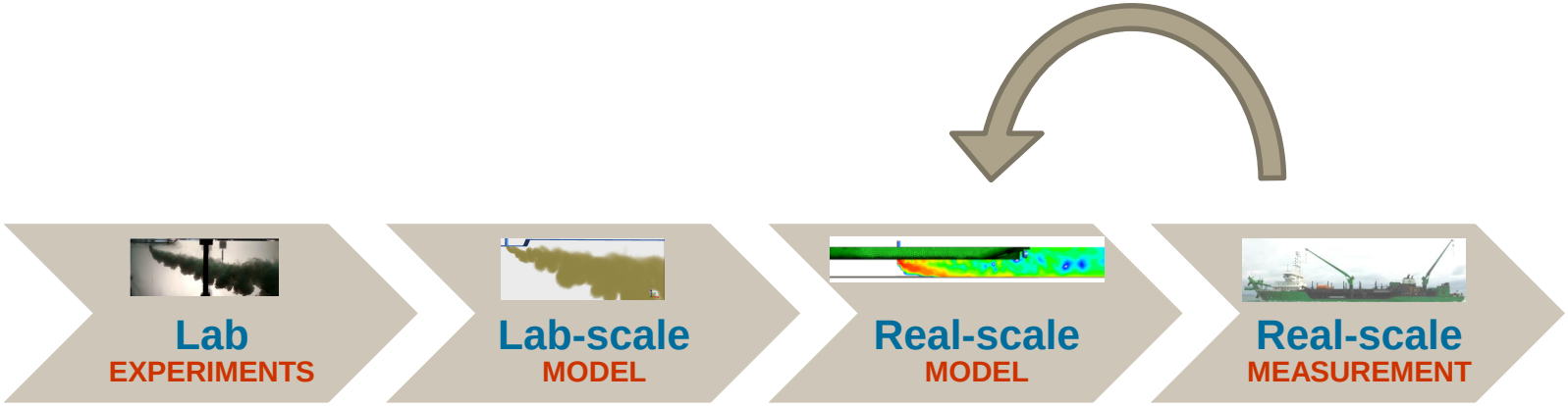
- Sampling inside the overflow (to impose in model runs)

- Measurements and samples in the dredging plume



Overview Model development

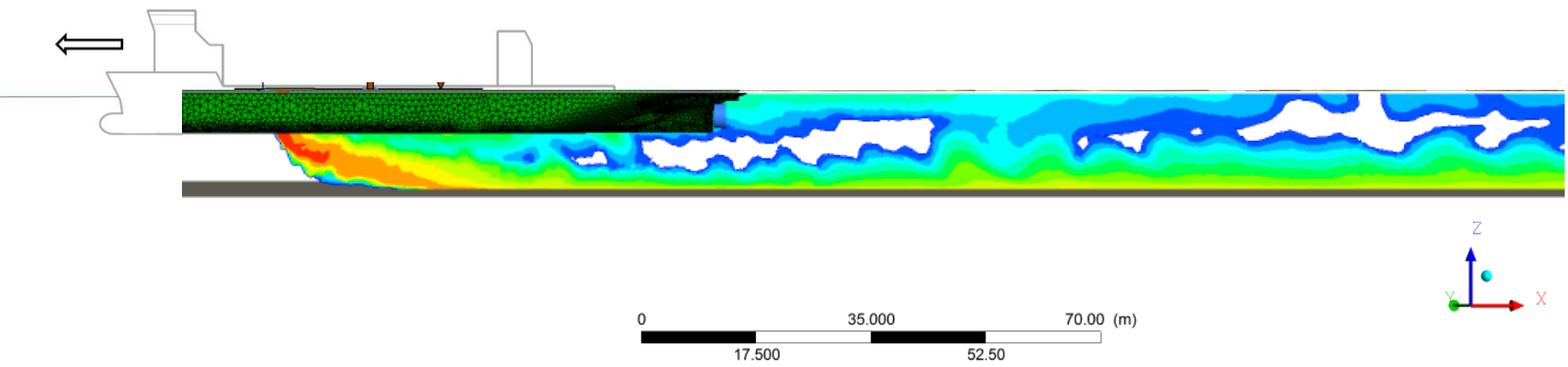
Model matches Field Measurements ?



Results Validation CFD

Validation Case 1:

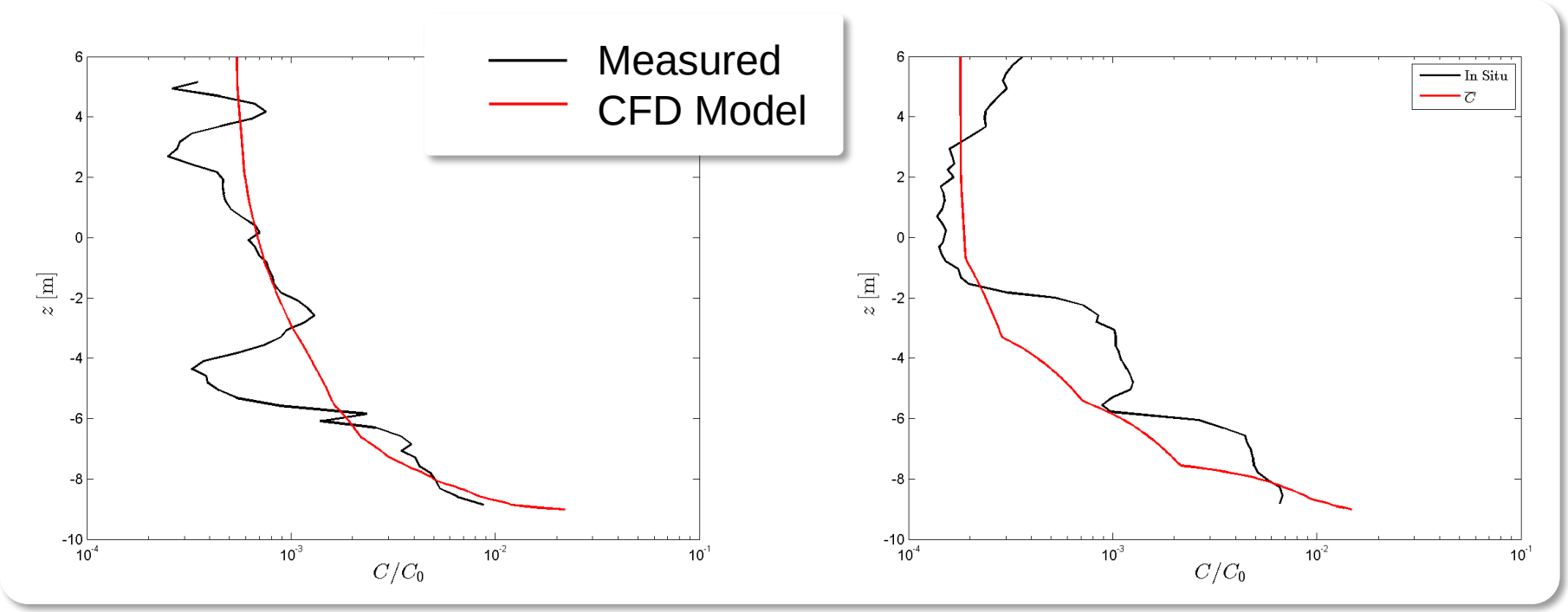
- H=16m ; D=2m; W_0=1.9 m/s; U_∞=1.5 m/s, C_0=55 g/l
- Field measurements: Vertical profiles of SSC
- CFD model: CPU time = 25 hours at 32 CPU's



Results Validation CFD

Validation Case1: Vertical profiles

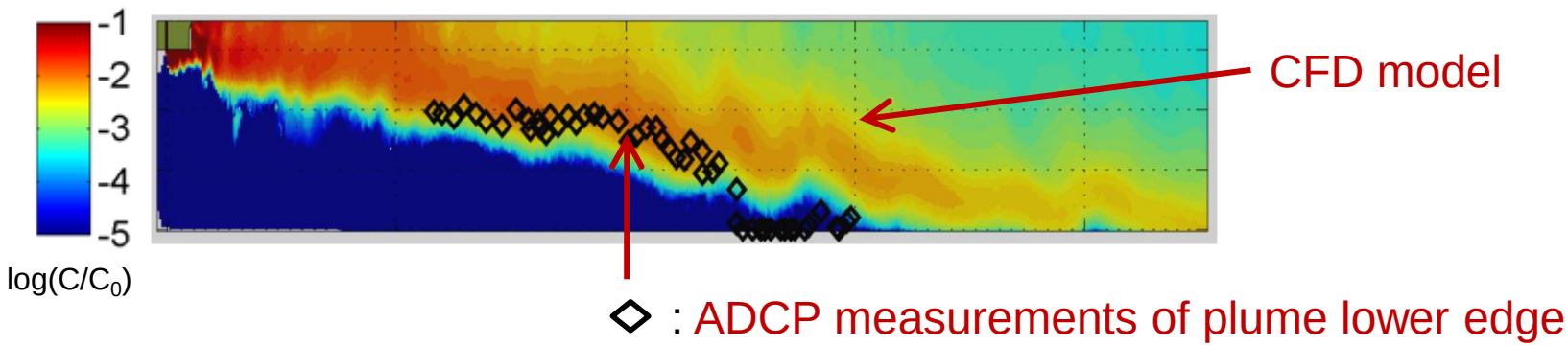
- Measurement carried out at < 200 m for near-field validation
- Compared with time-averaged model results



Results Validation CFD (Site 2)

Validation <u>Case 2</u>:

- Data from second campaign
- <u>H=39m</u> ; <u>D=1.1m</u> ; W_0=3.2 m/s; U_∞=1.5 m/s, C_0=10 g/l

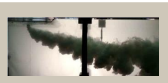


→ In some cases: majority of sediments released to far-field plume

Overview Model development

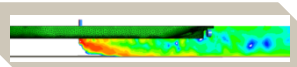
Model matches Field Measurements ?

YES!



Lab
EXPERIMENTS

Lab-scale
MODEL

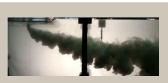


Real-scale
MODEL

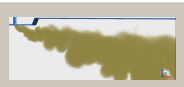
Real-scale
MEASUREMENT

IMDC
EXPERTISE IN WATER

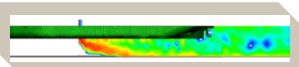
Overview Model development



Lab
EXPERIMENTS



Lab-scale
MODEL



Real-scale
MODEL

Real-scale
MEASUREMENT

Applications:

*Influence factors

* Ship Design

*Simplified Model

IMDC
EXPERTISE IN WATER

Influence factors on plume dispersion

Applications:

*Influence factors

* Ship Design

*Simplified Model

- Influence factors on near-field dispersion
- Influence factors on green valve efficiency

(Decrop *et al*, 2015, *J. Environ. Eng. 141 (12)*)

Examples shown today

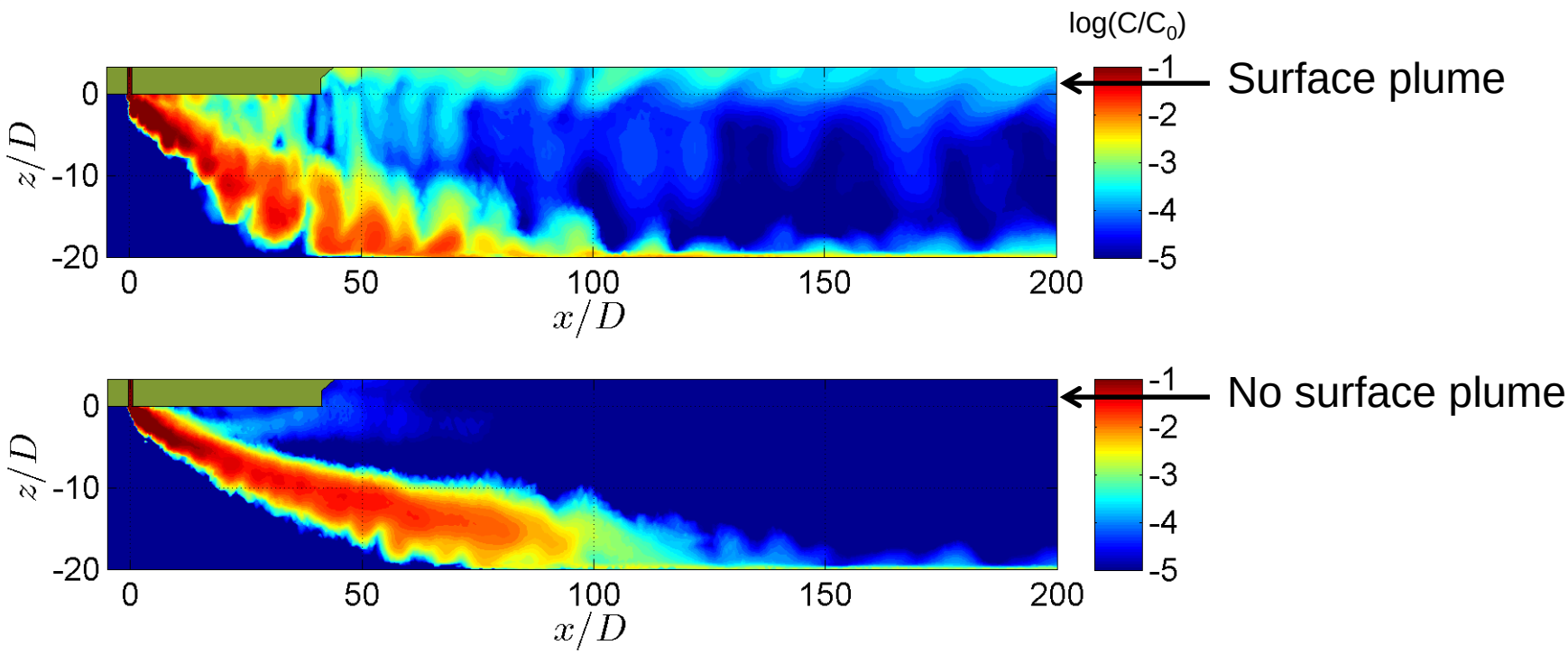
- Air bubbles
- Speed-through-water
- Overflow position
- Overflow extention
- Shape of the overflow shaft

IMDC EXPERTISE IN WATER

Influence of air bubbles

Applications:
Influence factors
Ship Design
Simplified Model

- Environmental valve: air bubbles -90% (Saremi, 2014)
- Perform simulations with/without air flow rate reduction
- But: efficiency of the valve is function of ambient conditions! (Decrop *et al.*, 2015, J. Environ. Eng 141 (12))



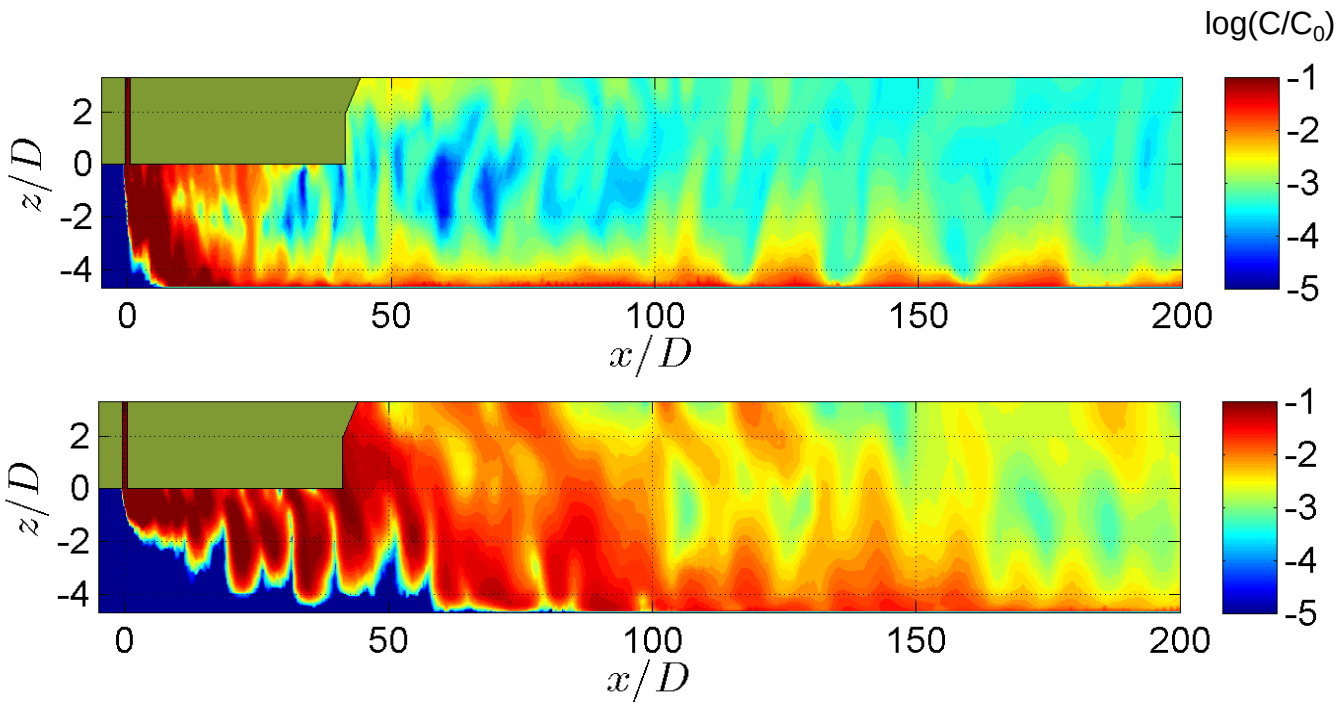
Influence of sailing velocity

Applications:
Influence factors
Ship Design
Simplified Model

Relative velocity sea water - ship

2 knots

6 knots

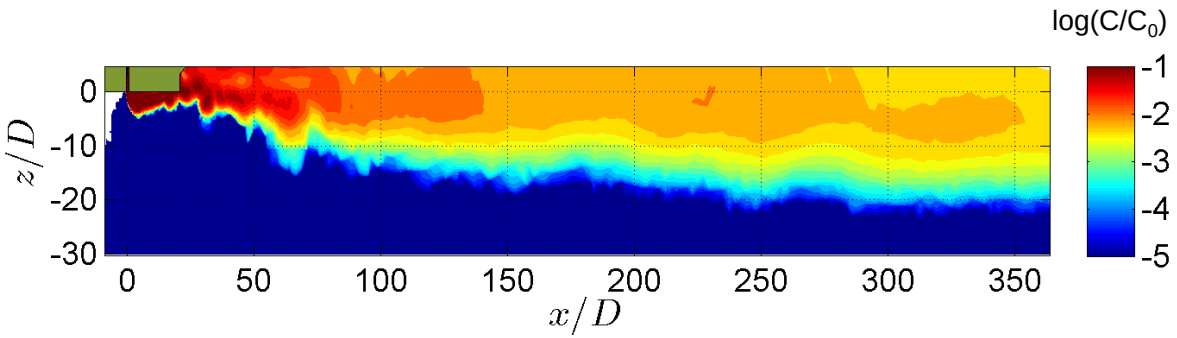


→ **sediment in surface plume x 10**

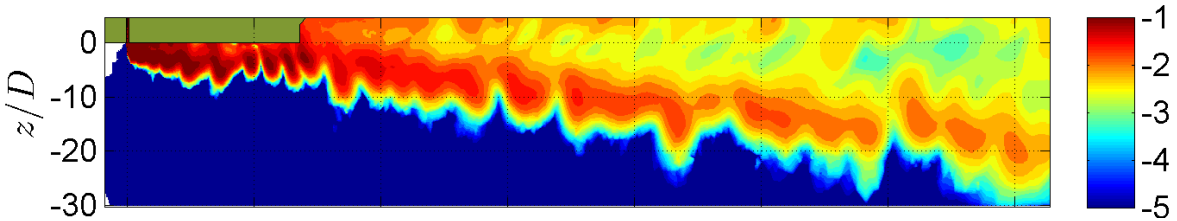
Overflow position

Applications:
Influence factors
Ship Design
Simplified Model

- Overflow at stern: plume mixed by propellers



- Overflow at aft: plume has more time to descend

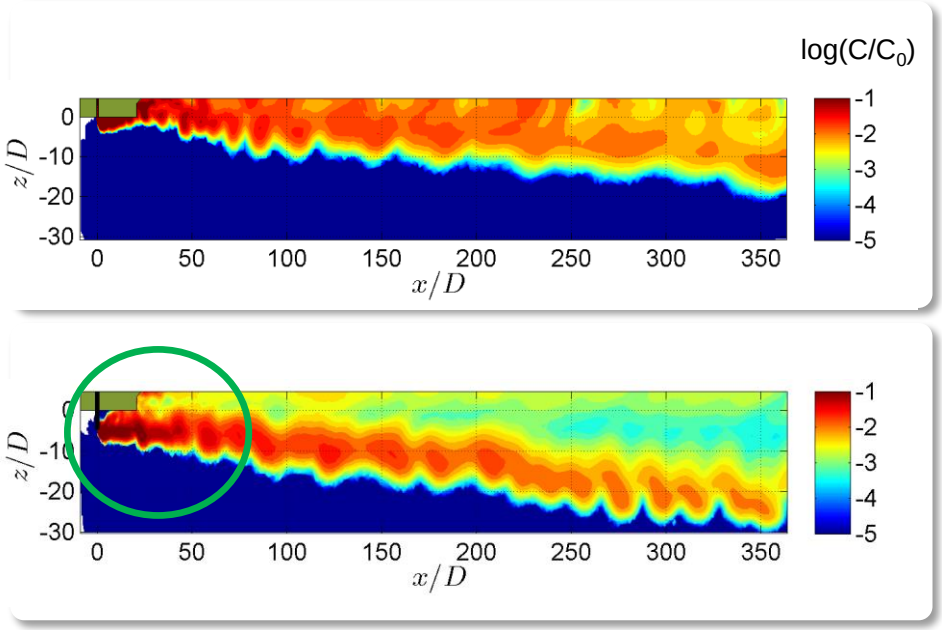


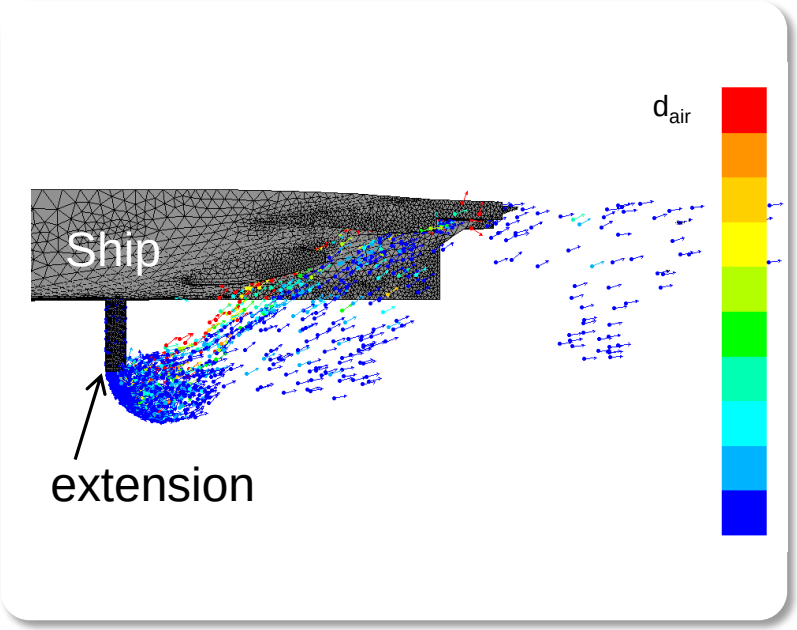
Ship design: Overflow shaft extension

Applications:
Influence factors
Ship Design
Simplified Model

- Studied earlier by de Wit et al. (2015)
- C at surface reduced with factor up to 10
- Open question: feasibility

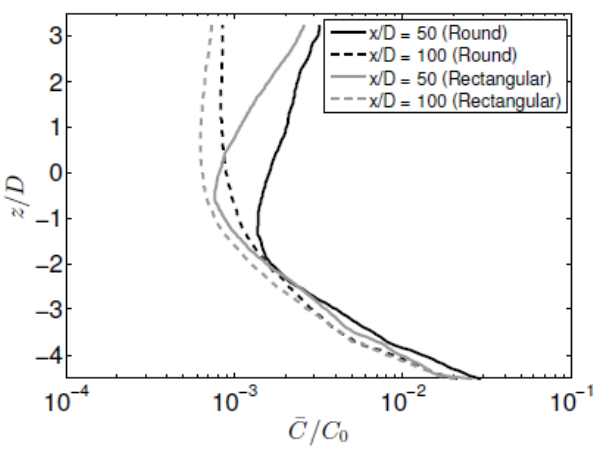
- Surface plume partially remains because of rising air bubbles



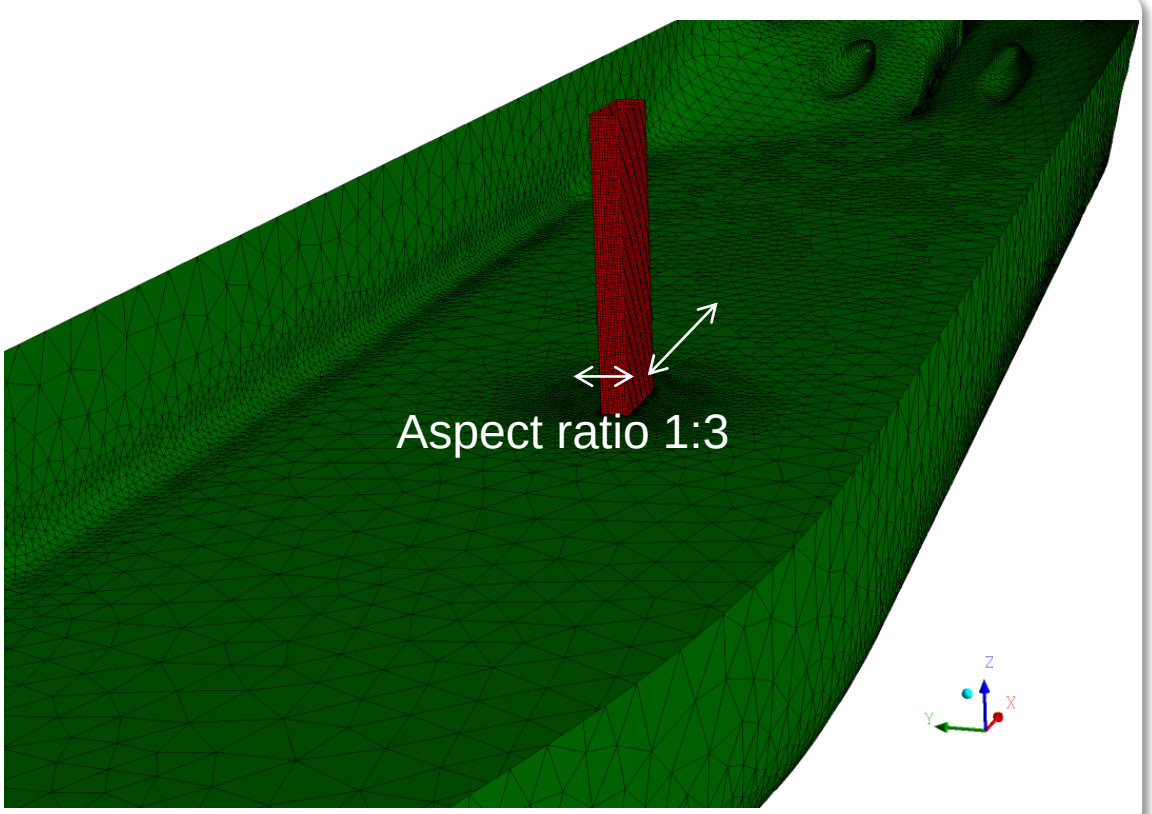


Ship design: rectangular overflow shaft

Applications:
Influence factors
Ship Design
Simplified Model



→ **Potentially 50% reduction of surface plume sediment concentration**



IMDC EXPERTISE IN WATER

Overview

Introduction

Different types of sediment spills

Objectives of the developments

Requirements for (operational) plume dispersion simulations

3D Near-field models: Physical and CFD

Development of parameterised near-field models

Implementation in 3D tidal flow models

Operational turbidity forecasting

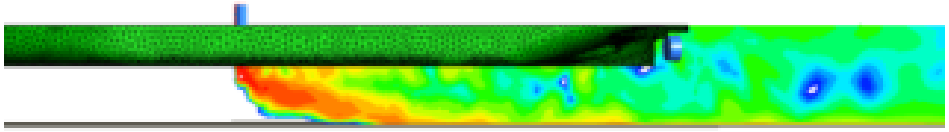
IMDC EXPERTISE IN WATER

Parameter model overflow plumes

Applications:
Influence factors
Ship Design
Simplified Model

Motivation

CFD model has **high CPU cost**, **not practical in some cases**



Find a simple model that is:

- Much faster
- Almost as accurate

A model with output:

- In suitable form for input to far-field models

→ Vertical profile of sediment flux behind ship

Parameter model

= combination of

- Analytical plume solutions
- Parameter fits on data of +/- 100 CFD model runs

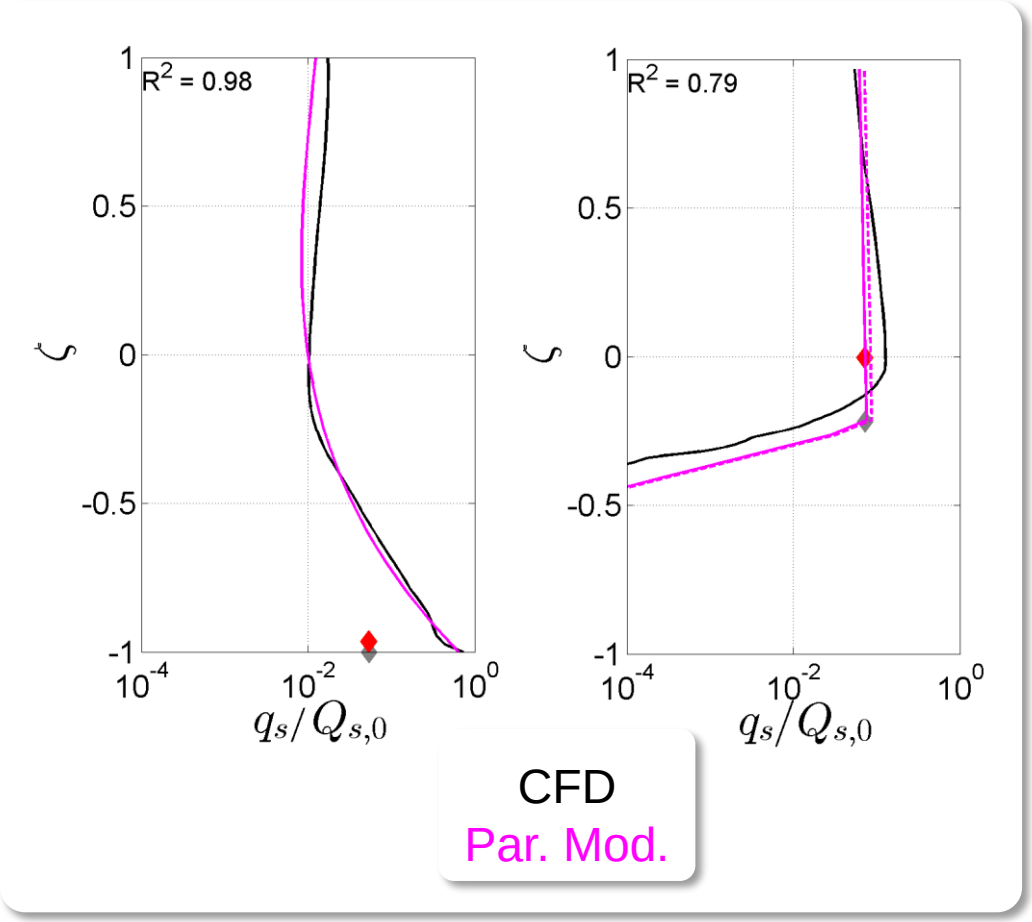
IMDC EXPERTISE IN WATER

Parameter model overflow plumes

Applications:
Influence factors
Ship Design
Simplified Model

- >100 CFD runs, with variation of:
  - Current velocity
  - Sailing speed
  - Sediment concentration
  - Overflow diameter, position
  - Air bubble concentration

  → For 'Model Training'
- Model Validation: against extra dataset CFD results
- 90% has R^2>0.5
- Valid for standard cases, for specific cases still CFD needed



More info: *Decrop et al. (2017). Ocean Dynamics 67:137–146*

Overview

Introduction

Different types of sediment spills

Objectives of the developments

Requirements for (operational) plume dispersion simulations

3D Near-field models: Physical and CFD

Development of parameterised near-field models

Implementation in 3D tidal flow models

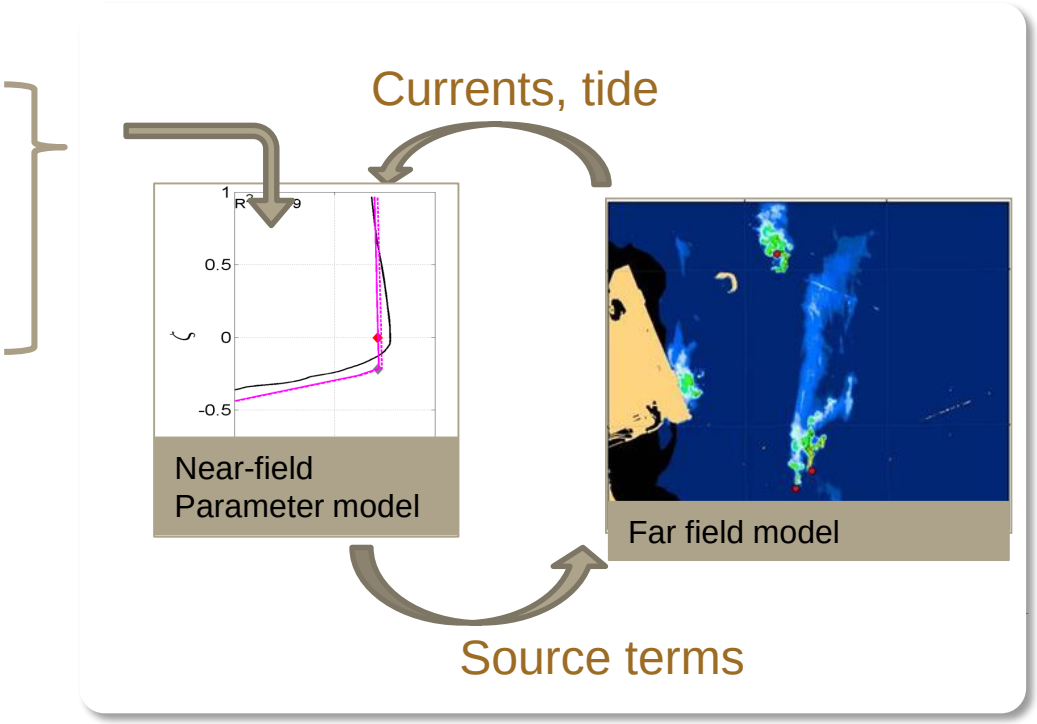
Operational turbidity forecasting

IMDC EXPERTISE IN WATER

Implementation in far-field models

For overflow:

- Hopper model for sediment content in overflow discharge (Hjelmager et al., 2014)
- Fast parameter model for near-field overflow plume dispersion (< 1 sec.)
  - Programmed inside far-field modelling software → real-time evolution of overflow flux
  - Distribution of sediment sources depends on:
    - Current velocity and direction
    - Sailing speed
    - Sediment Concentration, % fines
    - Overflow diameter and position



Implementation in far-field models

In tender/planning phase:

- Include all other expected sediment spills on the site:
  - Reclamation runoff
  - Bucket loss
  - Draghead
  - …
- Define evolution in time of equipment position, spill rate (kg/s), near-field distribution

- Implement time series of sediment sources in 3D far-field model
- Simulate different dredging works scenario cases
- Select work strategy with minimum turbidity impact at receptors

Overview

Introduction

Different types of sediment spills

Objectives of the developments

Requirements for (operational) plume dispersion simulations

3D Near-field models: Physical and CFD

Development of parameterised near-field models

Implementation in 3D tidal flow models

Operational turbidity forecasting

IMDC EXPERTISE IN WATER

Implementation in far-field models

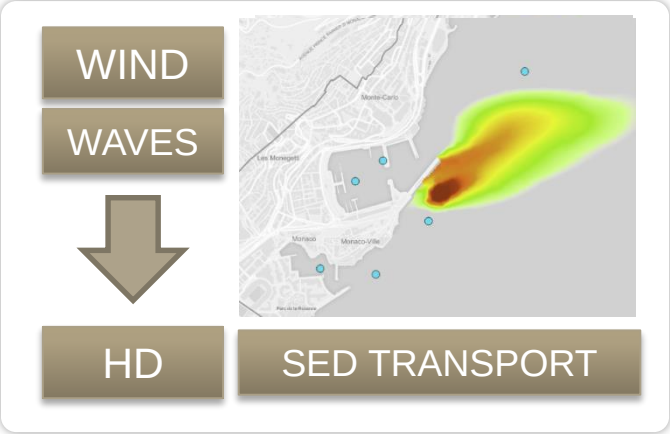
Real-time plume forecasting

- In operational phase
- Simulate, Evaluate, Adapt

→ **Pro-active Adaptive Management**

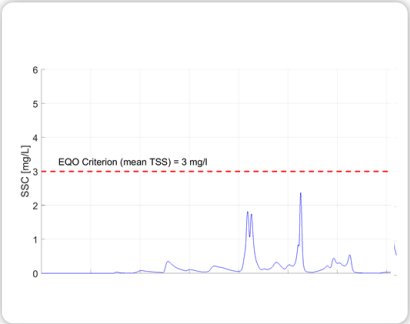
IMDC EXPERTISE IN WATER

Pro-active Adaptive Management (EcoPAM)



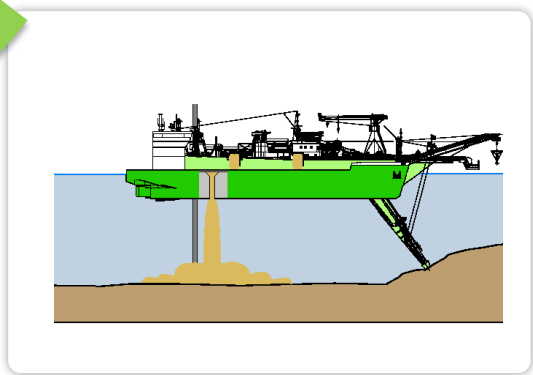
SEDIMENT PLUME MODEL

EVALUATE vs ENV. CRITERIA



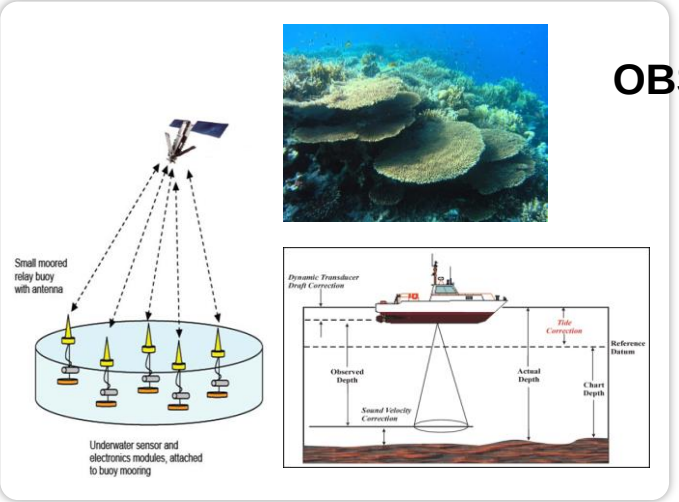
ADAPT

DREDGING SCENARIO



DREDGE & MONITOR

FIELD OBSERVATIONS



Pro-active Adaptive Management (EcoPAM)

- Platform = Synapps (web-based, developed by IMDC)
- The system:
  - Runs on daily basis (forecast mode)
  - Can be used to assess environmental impact of modified dredging strategy (scenario mode)

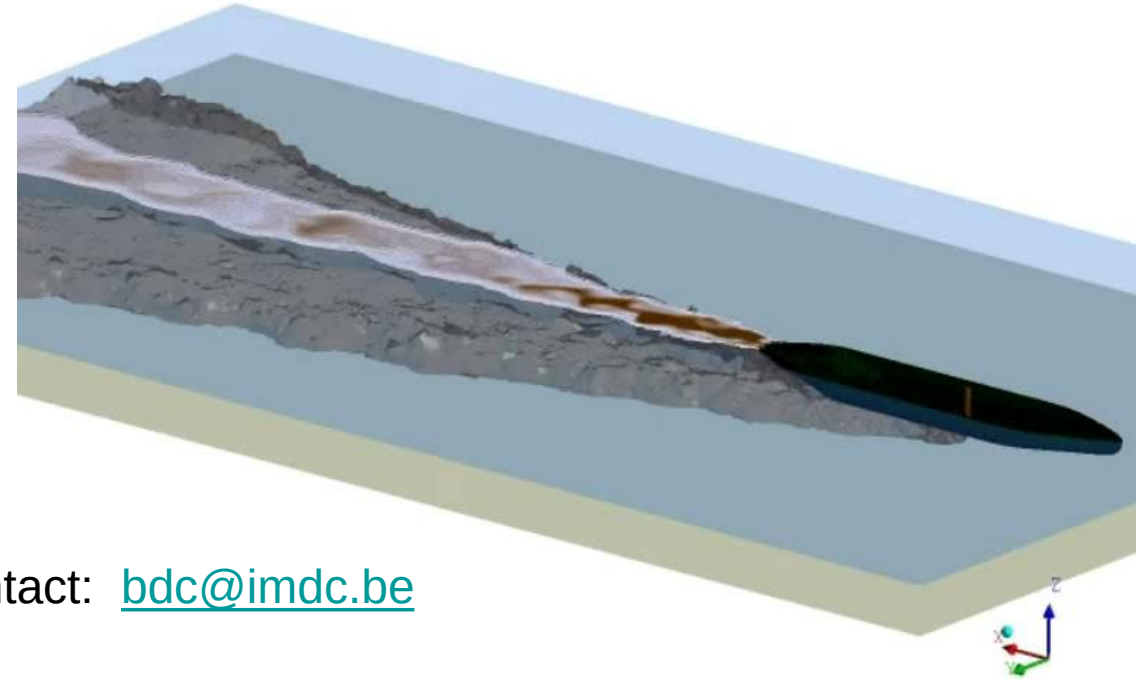
IMDC EXPERTISE IN WATER

Conclusions

- New generation of efficient far-field models
- Recent developments in CFD for near-field models
- More accurate plume dispersion simulations:
  - Reduces risk of inaccurate assessment in tender phase
  - Enhances real-time plume dispersion forecasting in operational phase
- Overall:
  - Reduced risk of turbidity threshold violations during operations
  - Impact of alternative dredging strategies can be predicted

IMDC EXPERTISE IN WATER

Questions?



Contact: bdc@imdc.be