Ocean modelling and Early-Warning System for the Gulf of Thailand: An application of Delft-FEWS, Delft3D Flexible Mesh and SWAN

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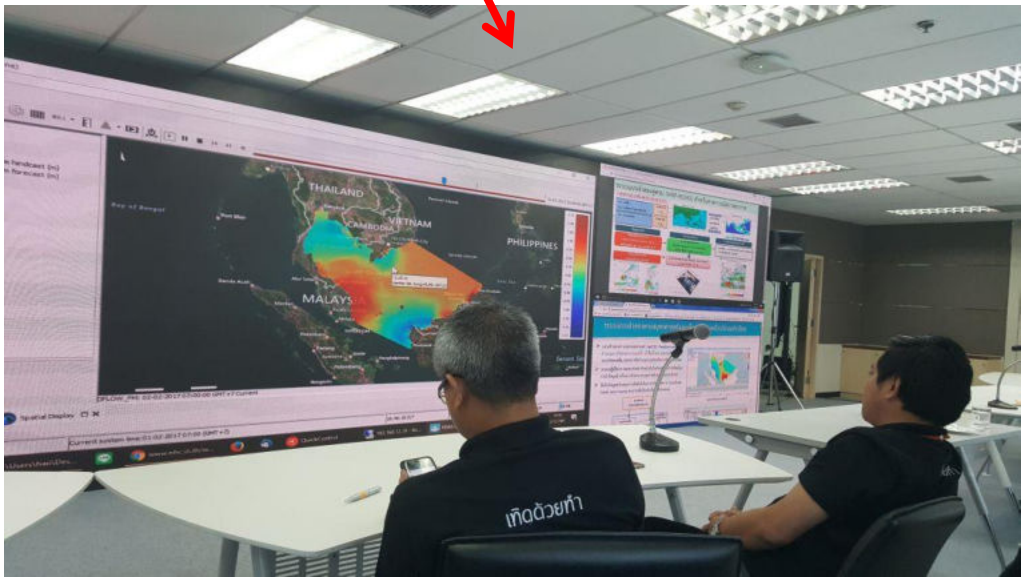
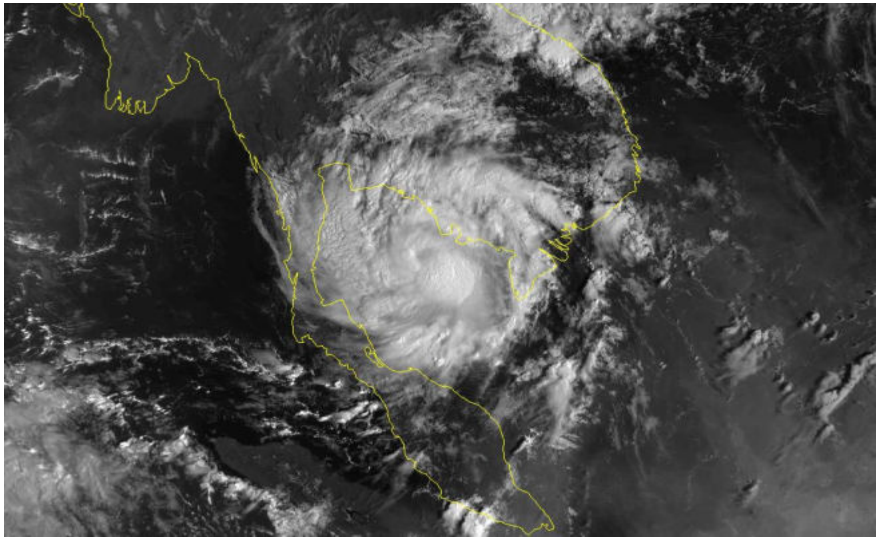
https://www.deltares.nl/en/webinars/ocean-modelling-and-early-warning-system-for-the-gulf-of-thailand/

WHAT we will show

… and why it's so interesting:

- Development and implementation of a new **E**arly-**W**arning **S**ystem to predict coastal flooding levels along entire (east) coast of Thailand.
- EWS providing three-day forecasts, generated daily, combine effects of tide, storm surge and wave setup.
- Based on Delft-FEWS and on open-source software Delft3D Flexible Mesh and SWAN.
- Now used by the **Hydro and Agro Informatics Institute (HAII)**, in Bangkok, to disseminate coastal predictions.





WHY an EWS for Gulf of Thailand?

The Gulf of Thailand (GoT) is periodically affected by typhoon-induced storm surges in the past (Harriet in 1962, Gay in 1989, Linda in 1997).

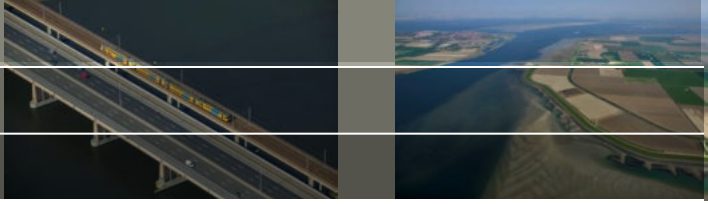
Due to increased development in the coastal zone, the combined risk of high water level and increased rainfall / river discharge has increased and is expected to increase in future due to climate change.

=> There was a clear need for a real-time operational storm surge, wave and wave setup forecasting system in the GoT.

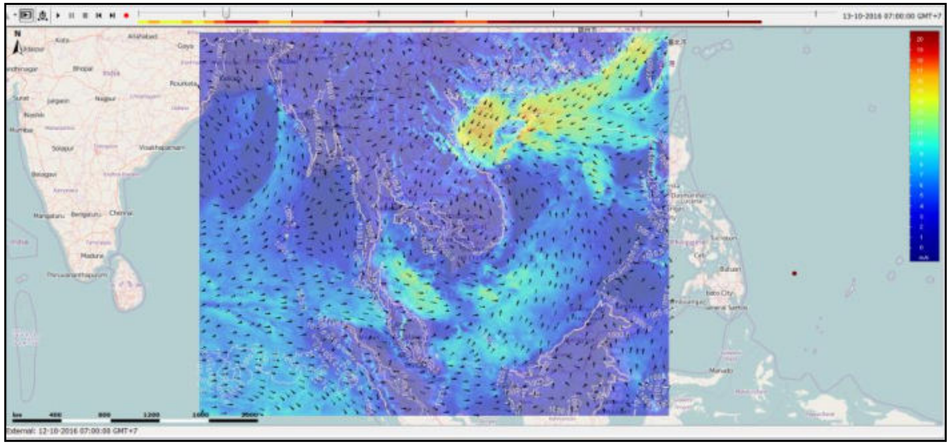
Main objectives:

- To provide automatically daily accurate tide, storm surge, wave and wave setup estimates.
- Every day, three-day coastal forecasts based on the latest regional meteorological predictions.
- Adding a coastal component to HAII's existing daily reports on fluvial flood forecasts for Thailand.

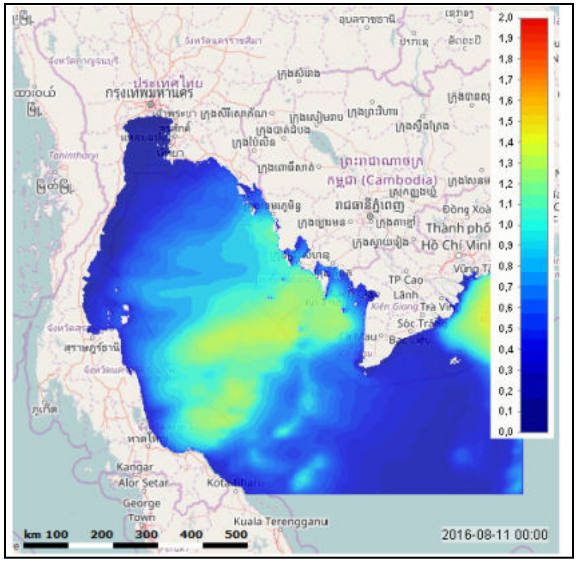
And HOW did we achieve it?

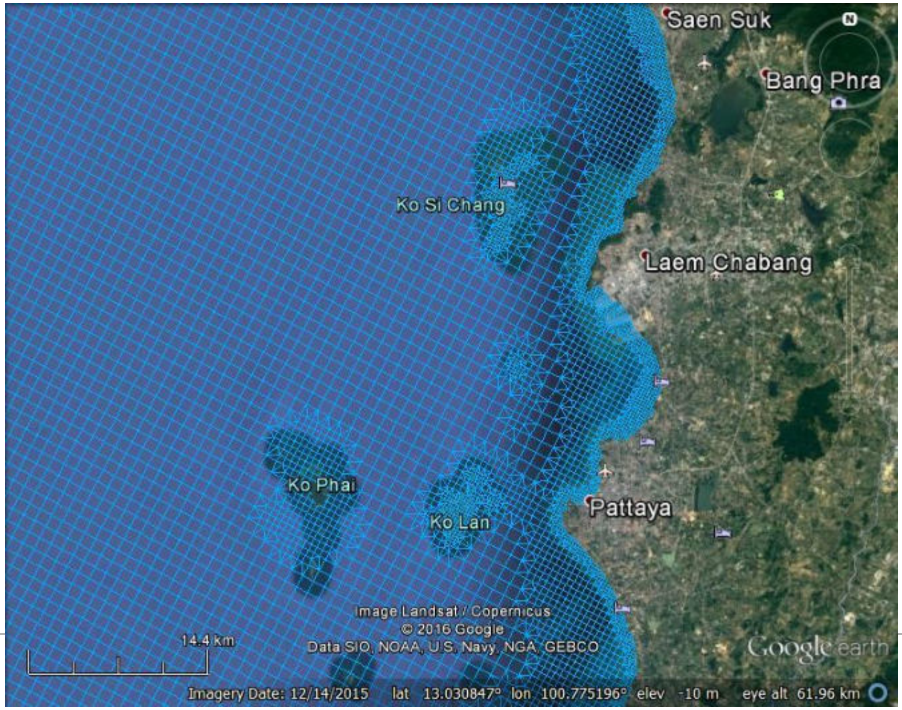


Meteo: High-resolution WRF forecasts (9x9 km^2)

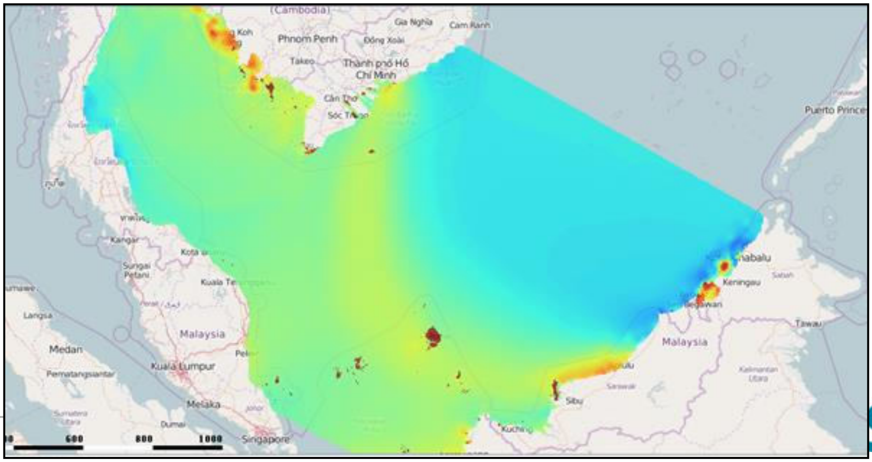


Waves: Regional and local SWAN forecasts (down to 300x300 m^2)

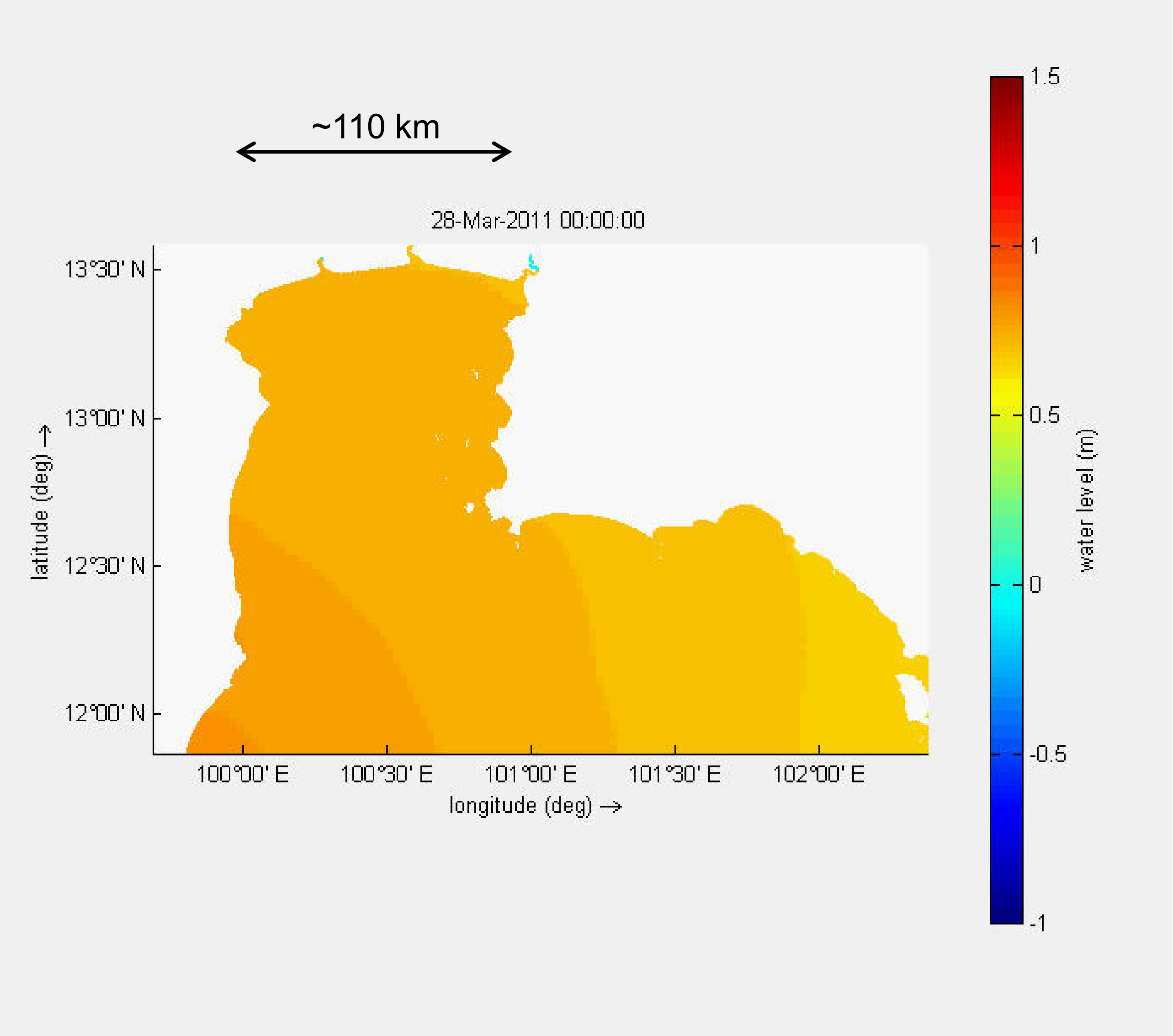




Hydrodynamics: Large domain, D-Flow FM forecasts (down to 250x250 m^2)



Teaser: Animation of water levels on Flexible Mesh



Tide & surge;
March 2011 event

Deltares

FEWS-GoT project: Joint development, Deltares & HAII

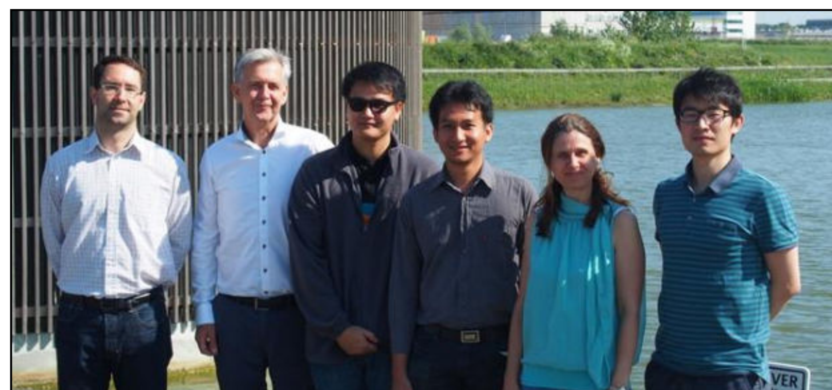
HAII: Hydro and Agro Informatics Institute, in Bangkok

https://www.haii.or.th/

#1. Development & implementation (2016)

- Deltares leading D-Flow FM modelling;
- Deltares leading operational FEWS component;
- HAII leading SWAN modelling.

Several visits:
- to Bangkok (Deltares team),
- to Delft (HAII team).

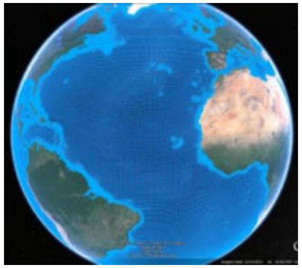


#2. Fully operational stage (since Jan. 2017)

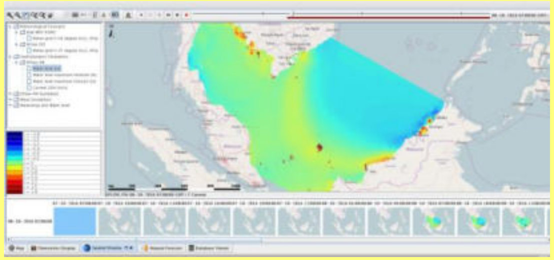
- HAII responsible & independent using operational system.

Intro: Similar recent projects using Delft3D FM

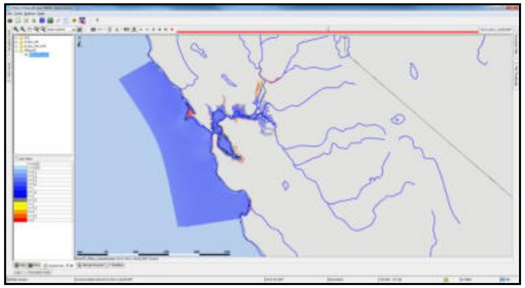
Global Surge Model, “GLOSSIS”
2014-present



Surge+Wave EWS, <u>G</u>ulf <u>o</u>f <u>T</u>hailand
March-December 2016



Surge and waves in FEWS, USGS in San Francisco
2017

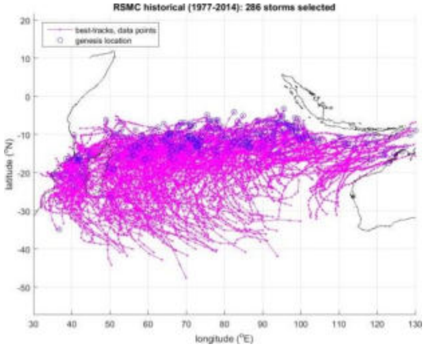


Operational ↗

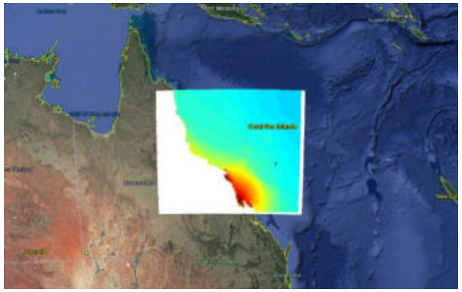
…time…

Non-FEWS ↘

Various training projects
(eg AON Benfield Vietnam, WMO BMKG Indonesia)
2014-2016



Coastal flooding estimates in Mozambique & Cabo Verde
2016-2017



Cyclonic surges, North Queensland (AUS)
2017

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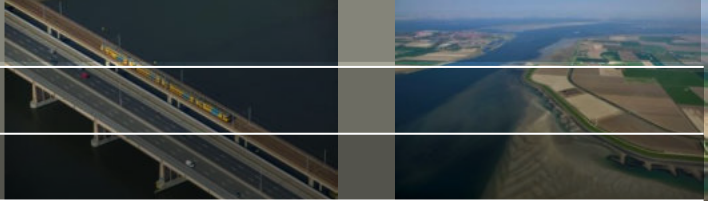
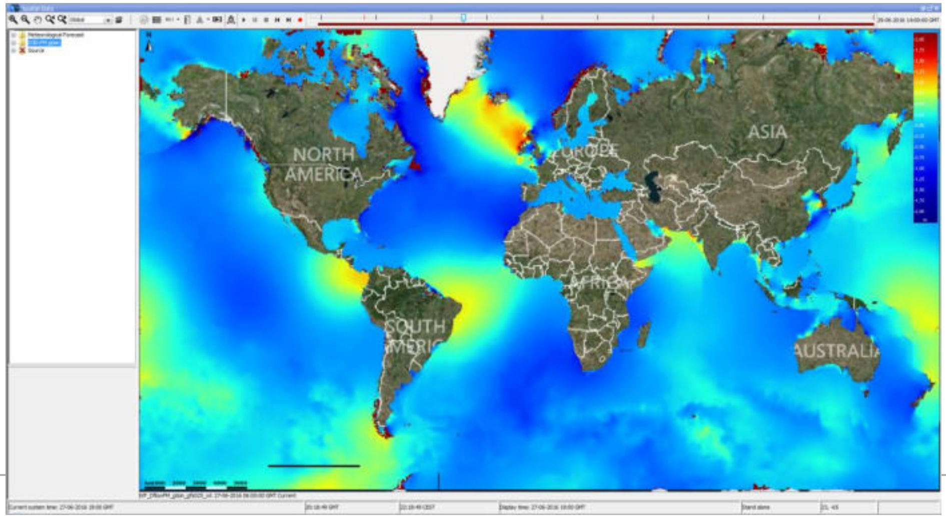


Delft-FEWS

Deltares' world leading software to develop flood forecasting and warning systems

- Open approach to integrating models and data (supports Deltares and non-Deltares models)
- Configurable and scalable to requirements by users and organizations
- Fully automated process and data management
- Robustness required for 24/7 operational services
- License fee free, and central role for user community

See *http://oss.deltares.nl/web/delft-fews*



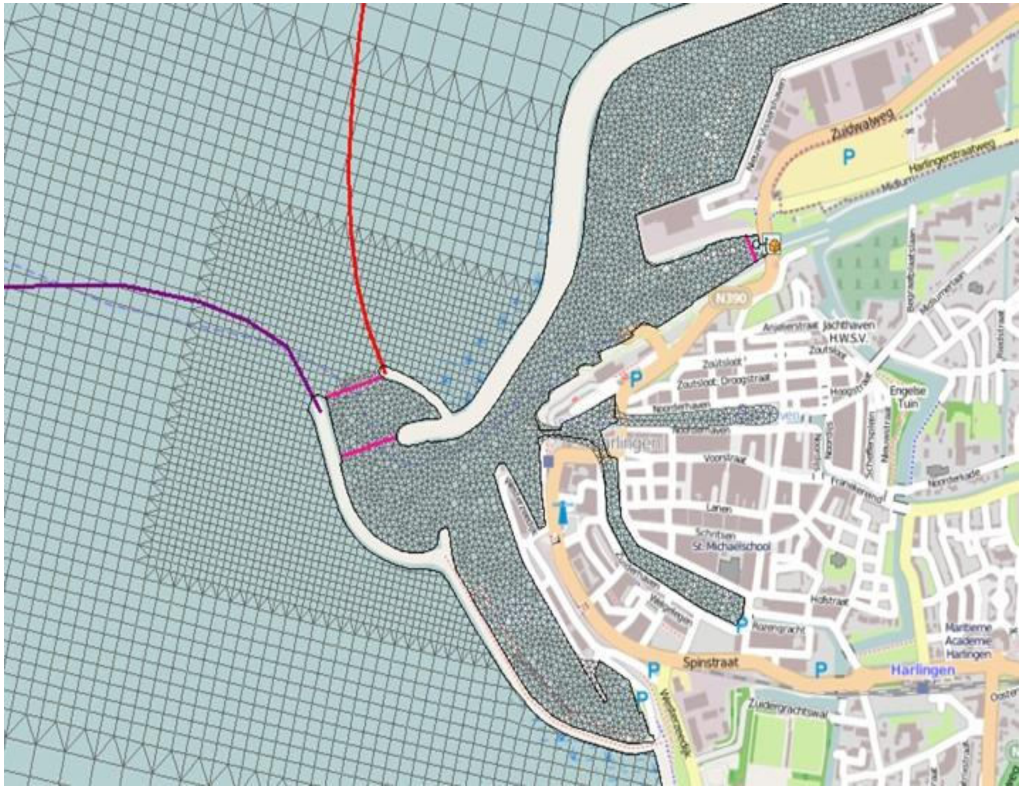
Software: Hydrodynamics, D-Flow Flexible Mesh

We used the Delft3D Flexible Mesh model suite, which is the successor the Delft3D 4 model suite that uses structured grids. These are world leading model suites for simulating hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments with 2D and 3D models.

The hydrodynamic module of the Delft3D Flexible Mesh suite is D-Flow Flexible Mesh (D-Flow FM), which is used for hydrodynamic simulations on unstructured or structured grids, with 1D, 2D or 3D models.

The D-Flow FM module allows for spatially-varying (un)structured grids cells, thereby producing very flexible grids with a high-resolution in the areas of interest only, yielding a high computational efficiency.

See http://oss.deltares.nl/web/delft3dfm.



Software: SWAN to simulate short-crested waves

SWAN is a third-generation wave model, of the Delft University of Technology, that computes random, short-crested wind-generated waves in coastal regions and inland waters.

SWAN accounts for:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth.
- Wave generation by wind.
- Three- and four-wave interactions.
- *Whitecapping*, bottom friction and depth-induced breaking; Dissipation due to vegetation.
- Transmission through and reflection (specular and diffuse) against obstacles.
- Diffraction (in an approximate, parameterized way).
- Wave-induced set-up.

In short, the model solves the action balance equation, in Cartesian or spherical coordinates, without any *ad hoc* assumption on the shape of the wave spectrum.

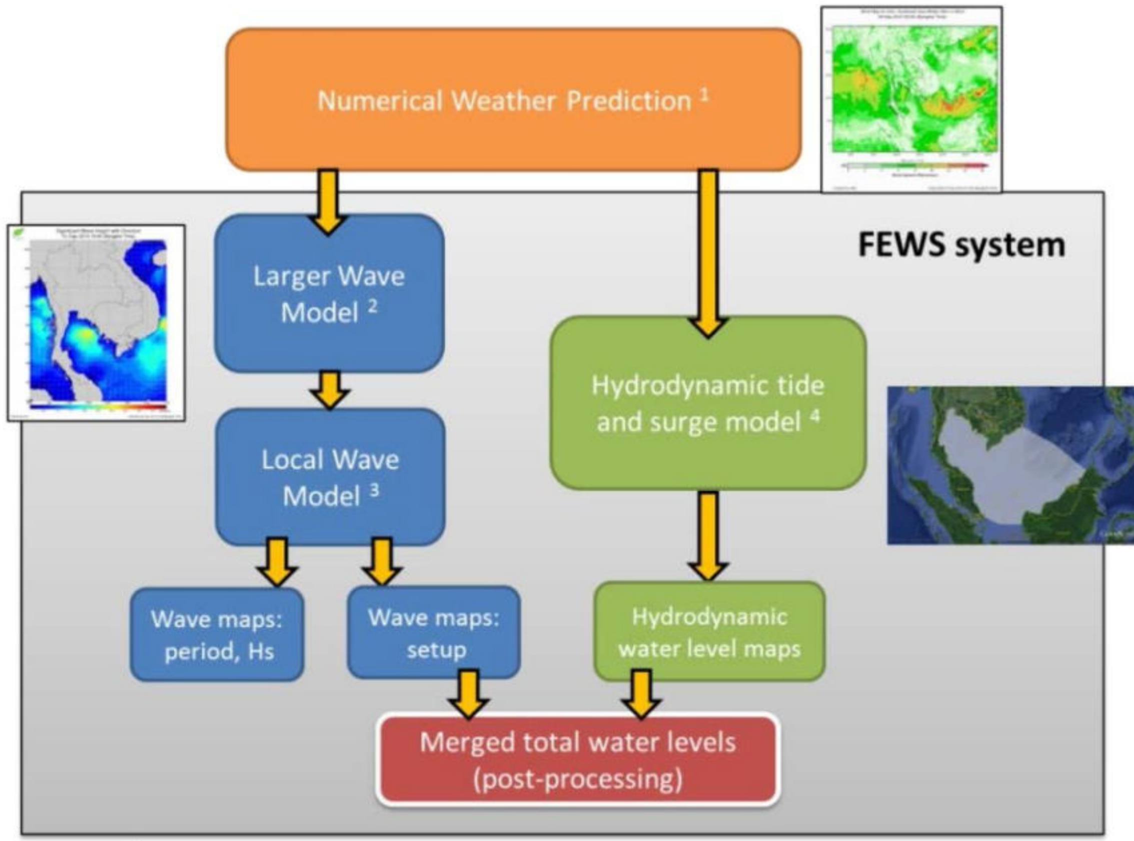
Nested runs, using 2D wave spectra, from other (larger scale) models can be made with SWAN.

For more info or downloading the SWAN code & documentation, see http://swanmodel.sourceforge.net/

Keep in mind, today's focus will be on FM modelling and on FEWS work.

Overview: Thailand coastal ocean modelling system

Waves / SWAN: HAII's regional model forcing a new detailed model



Hydrodynamics / Delft3D: Deltares developing a new regional-to-local flexible mesh model

Delft-FEWS combines all "work flows" (including all models, plus external data and external forecasts) and processes all output.

Deltares

Hydrodynamic model development: Purpose

Main objective: “to simulate coastal water levels accurately”.

The D-Flow FM model is in 2DH mode (two-dimensional in the horizontal, depth-integrated), which is sufficient for this application. Along the coast a high resolution of approximately 250 by 250 m is applied.

Given the desired purpose, we needed to simulate the following processes:

1. **Tidal propagation** (tide coming into model from open boundaries);
2. **Tidal generation** (tidal-generating forces, inside our domain);
3. **Surge propagation** (external surge entering through boundaries);
4. **Surge generation** (storm surge generated inside domain);
5. **Complex meteorologic fields** (time- and spatially-varying wind and pressure);
6. **Large-scale** (parts of South China Sea, incl. Borneo, Vietnam, Singapore…);
7. **Fine-scale** (highest detail along Thai coast, incl. estuaries & many small islands);
8. **Wetting and drying** (intertidal areas included in domain).

Modelling work: Overview of Required Data

Hydrodynamics

Model setup:
- Shoreline / land boundary
- Bathymetry fields (i.e. depths)

Forcing:
- Tidal constituents at boundaries
- Meteorological fields (i.e. wind and air pressure)

Calibration / Validation:
- Water level time series at stations
- Co-tidal charts (literature)

Waves

Model setup:
- Shoreline / land boundary
- Bathymetry fields (i.e. depths)

Forcing:
- Wave info (spectra) at boundaries
- Meteorological fields (i.e. wind and air pressure)

Calibration / Validation:
- Wave measurements at stations
- Other wave info (literature)

(like “your typical” hydrodynamic & wave coastal ocean modelling project)

Shoreline(s)

Several datasets with shoreline information were obtained:

(i) the NOAA-GSHHG batch covering the entire world but with less accuracy,

(ii) A local one with higher accuracy covering mainland Thailand, and

(iii) A local one including all the Thai islands.

After comparison against Google Earth satellite images, decisions were made on which data to use where, and datasets merged such that entire model domain is covered, optimally.

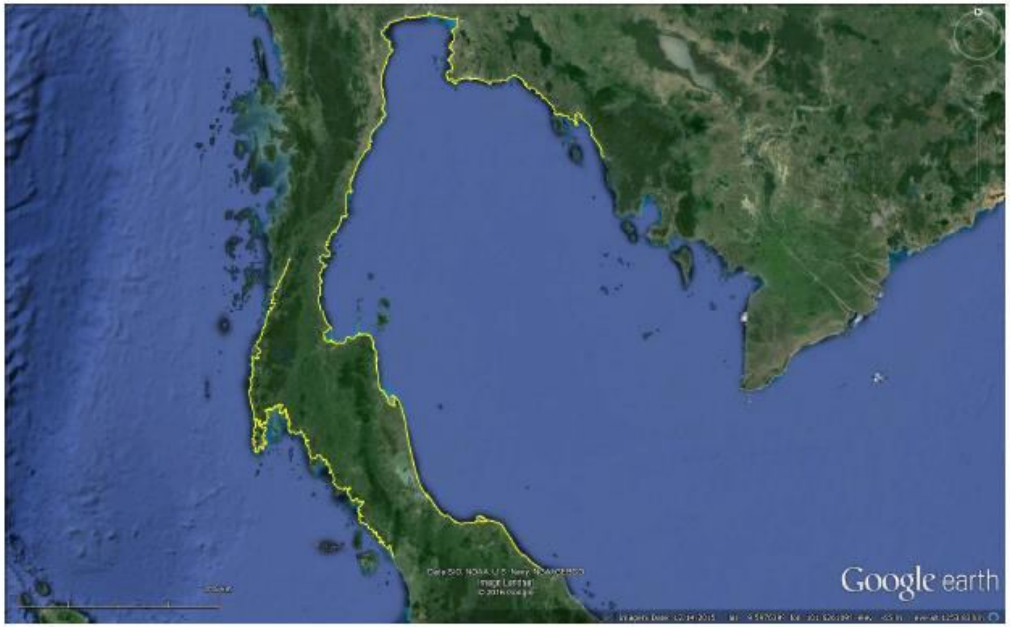


Figure 2.2   GISTDA shoreline used in this project.

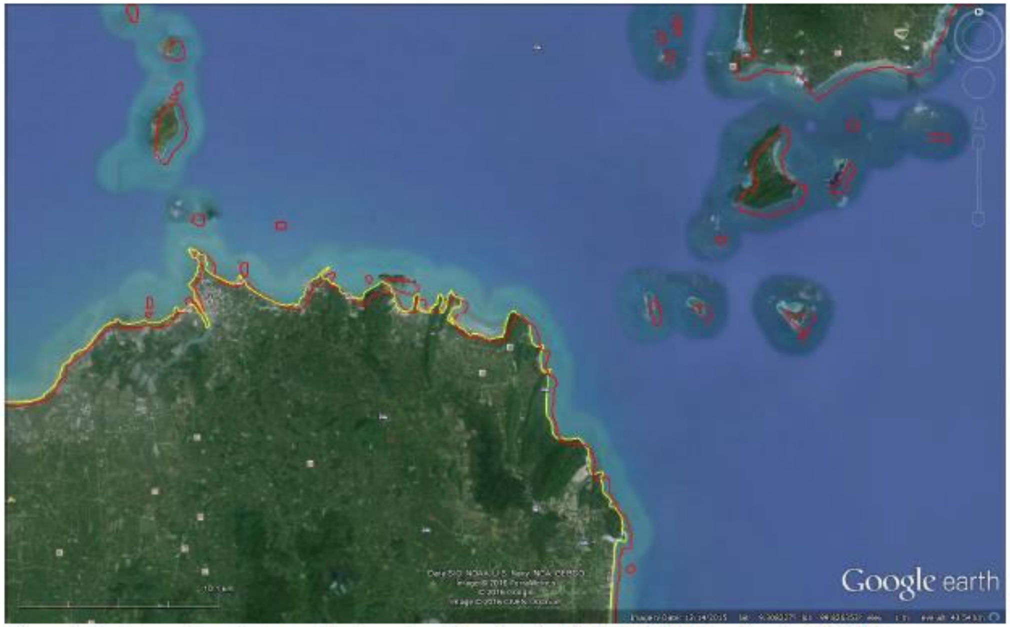
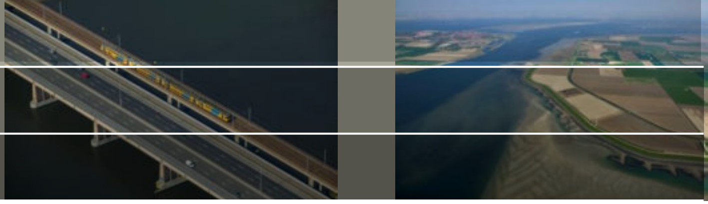


Figure 2.3   Comparison between the two shorelines (red is NOAA-GSHHG, yellow is GISTDA).



Bathymetry

Tree datasets were used:

1. Digitized nautical charts, based on charts of the Thai Royal Navy;
2. Very fine, recent survey around upper Gulf of Thailand;
3. GEBCO 0.5-min global datasets, publicly available.

All data sets <u>converted to Mean Sea Level </u>(the model's reference level). All in all, very good "data density".

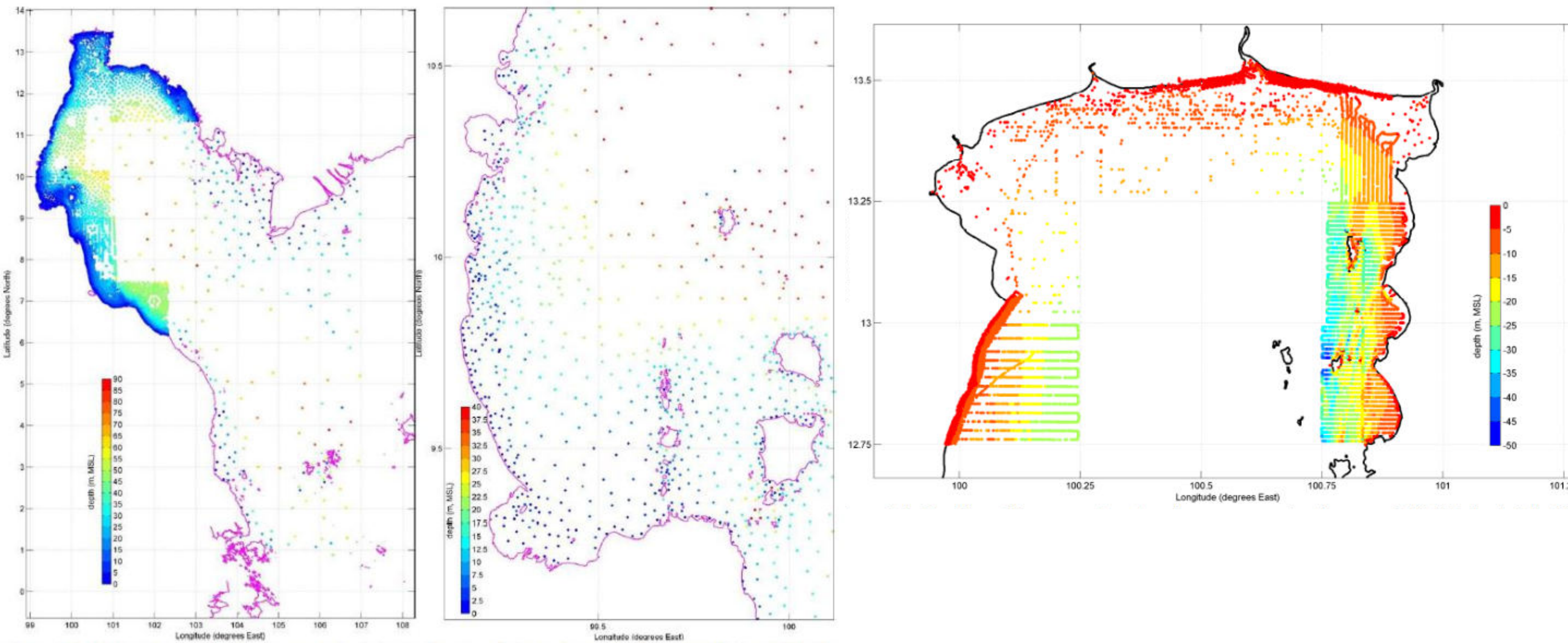


Figure 2.5 Digitized content of the seven nautical charts. Overview (left panel), and detail around Ko Samui (right).

Observed water level data

Figure 2.7 Same as Figure 2.6, but zooming-in on the Upper Gulf of Thailand.

17 timeseries obtained in local time zone (UTC+7h) were converted to UTC

The model is run in UTC and has UTC open boundary forcing.

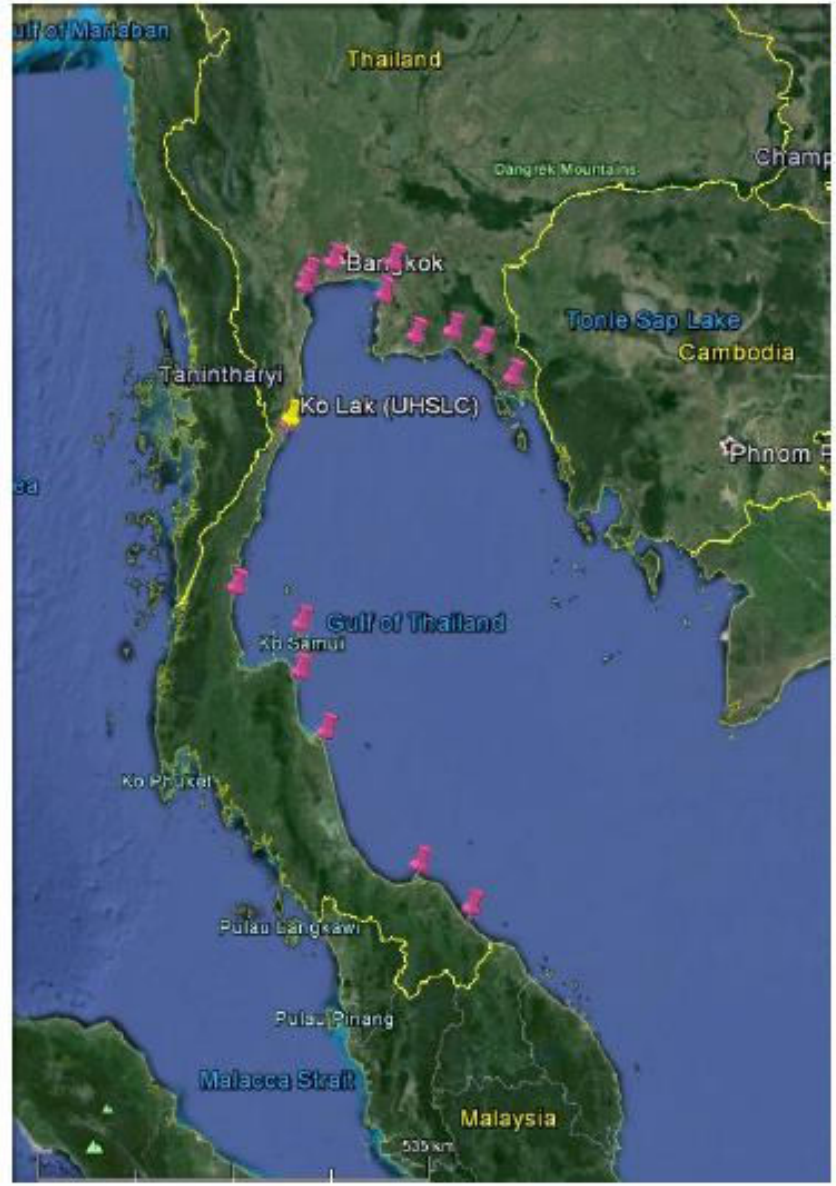


Figure 2.6 Map overview of the 17 tidal stations from whic

Measured water levels

Hourly water level data were used in validation of the hydrodynamic model, spanning more than 1 year, allowing for model verification both for long periods and storm surge events.

An event at the end of March 2011 presented the most interesting conditions, with consistent high surges among several stations.

Blue: total water level
Black: tide-only

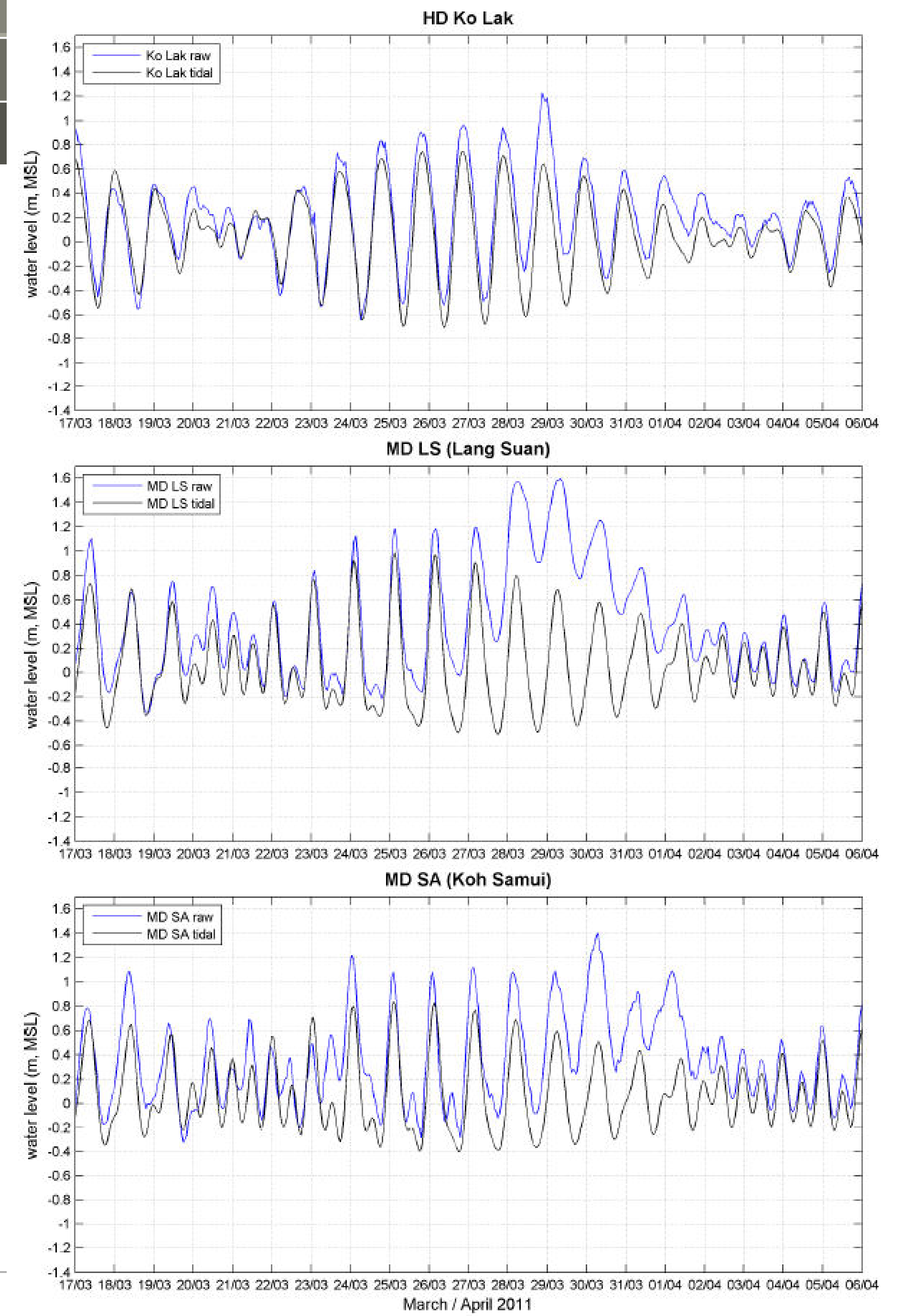


Figure 2.8 Water level timeseries at three of the central tidal stations Ko Lak, LS, SA. Black curve shows tide-only

Meteorological forcing

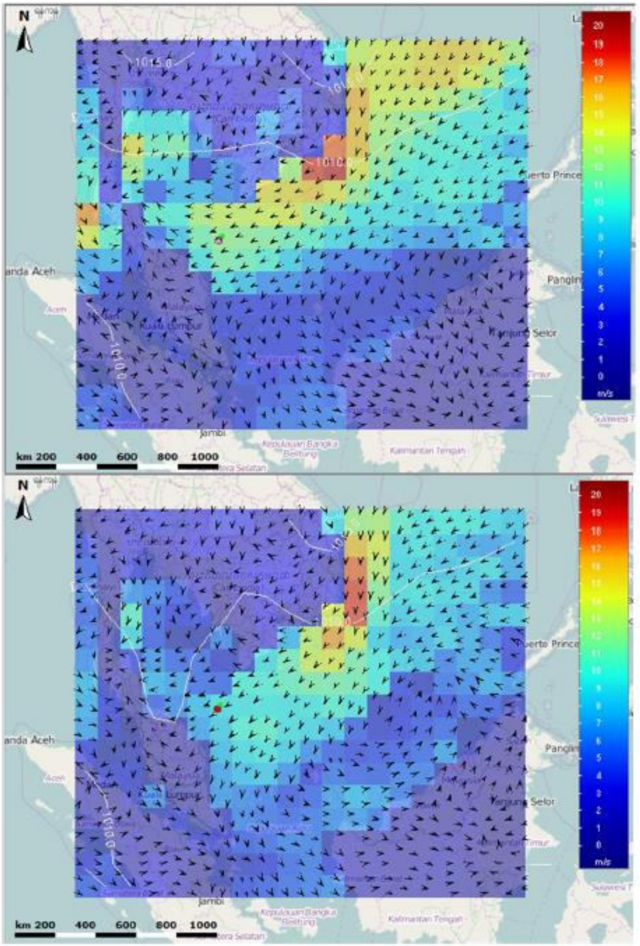


Figure 2.10 Surface air pressure and surface wind fields: Top panel, 29-mar-2011 19h and 30-mar-2011 19h (local).

The best option available was NOAA-GFS 1°x1° product, every 6h.

Three are needed to force the hydrodynamic model at the surface: (i) eastward wind component (u, in m/s) at 10m from the surface, (ii) northward wind component (v, in m/s) at 10m from the surface, and (iii) air pressure (in Pa).

Although this product generally has few gaps, it had several gaps in March-April 2011 (the main surge event!)

The NOAA-GFS product was used in model development, though a finer regional model is now used operationally (produced by HAII).

[3] *Online at http://nomads.ncdc.noaa.gov/dods/NCEP_GFS_ANALYSIS/analysis_complete*

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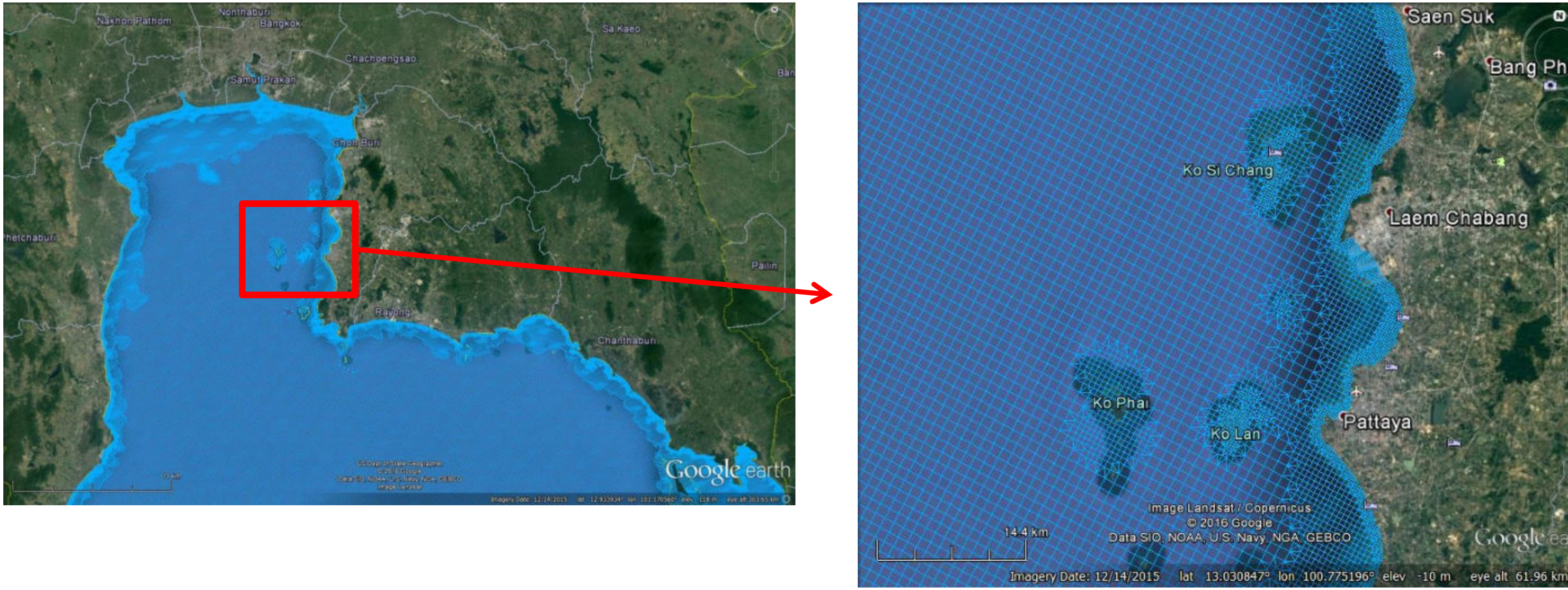
D-Flow FM grid generation



A **courant grid** is generated automatically, based on the depths.

This allows for optimal, automatically-generated grid which avoids time-step limitation, i.e.
- coarse grid over the deepest waters (4x4 and 8x8km^2 cells, in our case);
- fine grid over shallower waters (250x250 and 500x500 m^2, in our case).

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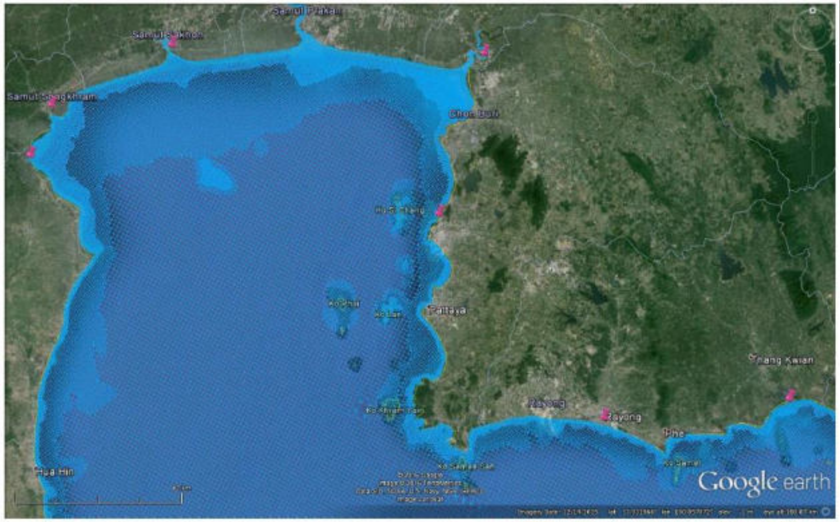


Figure 3.3 Same as Figure 3.2, but showing the upper Gulf of Thailand in greater detail. Horizontal resolutions of 1000m, 500m and 250m are noticeable.

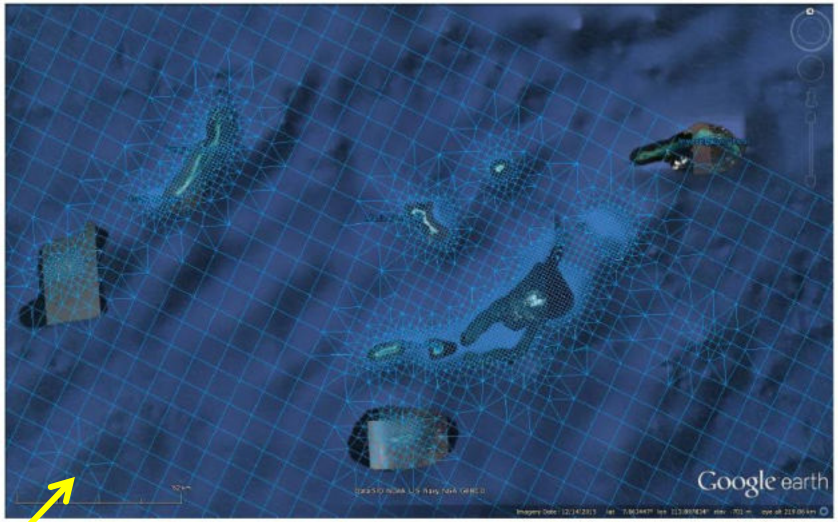
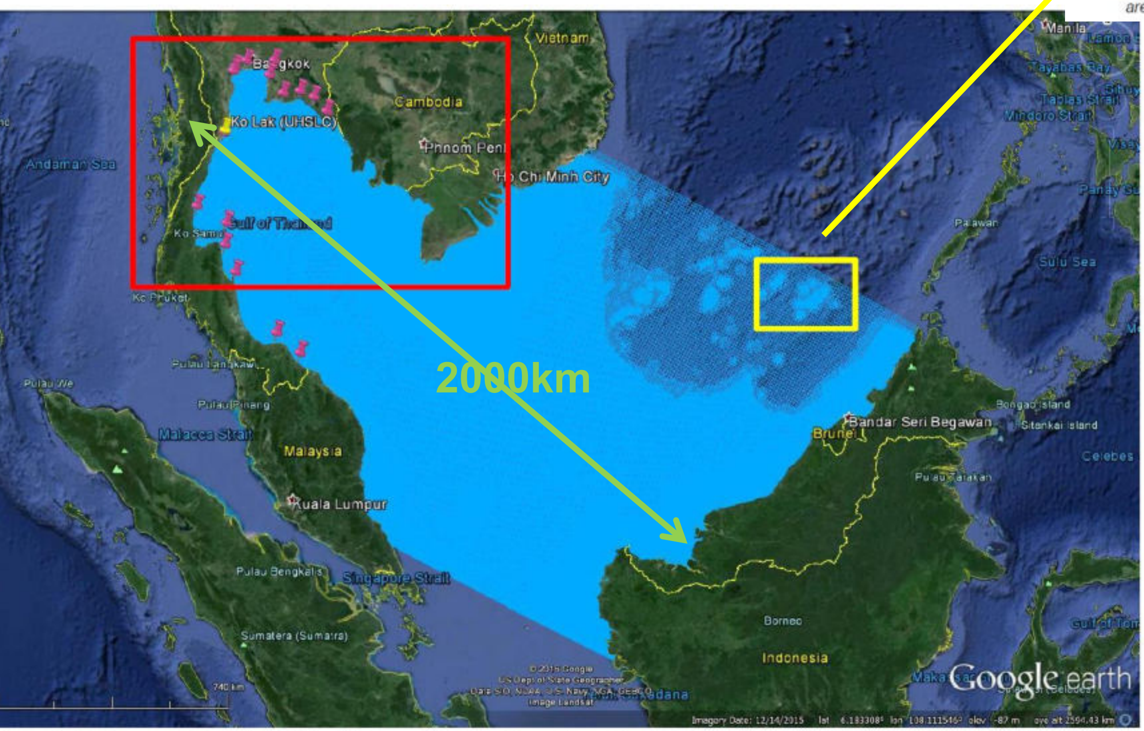


Figure 3.4 Same as Figure 3.3, but showing region near the northern open boundary in greater detail. Horizontal resolutions of 8000m, 4000m, 2000m and 1000m are noticeable. Transition areas where triangles are used are clearly visible.



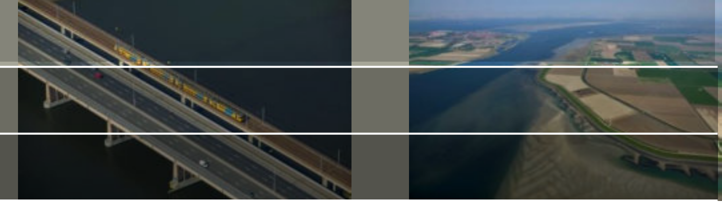
"Large grid", with ~ 815,000 nodes.

Horizontal resolution

- **250m along Thai coast,**
- 1,000m along other coasts,
- 8,000m at deep water.

igure 3.1 Computational grid (flexible mesh) overview. Pins show the locations of all tidal stations. Horizontal resolutions of 8000m, 4000m and 2000m are noticeable. The red rectangle indicates the zoom level shown

Model setup: Bathymetry



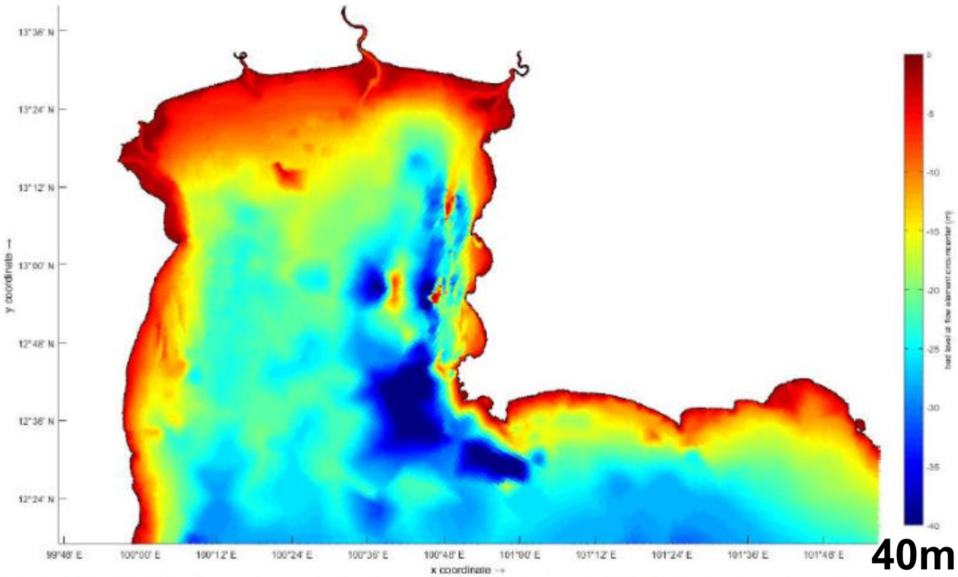


Figure 3.7 Model bathymetry; zoom-in on upper Gulf of Thailand (notice different colour-scale to previous figures). Shoreline shown is the more accurate GITSDA line, which does not include islands.

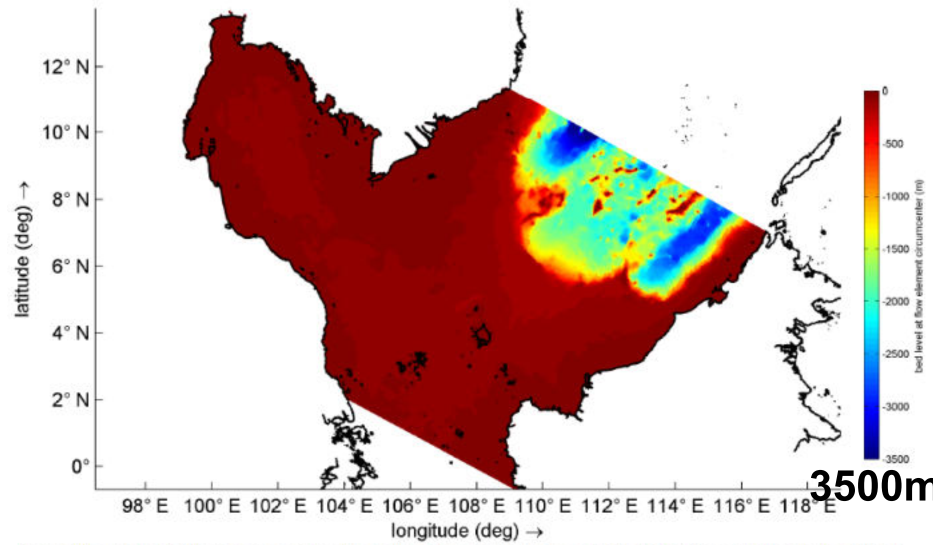


Figure 3.5 Model bathymetry; overview. Shoreline shown is the less accurate NOAA line, which includes islands.

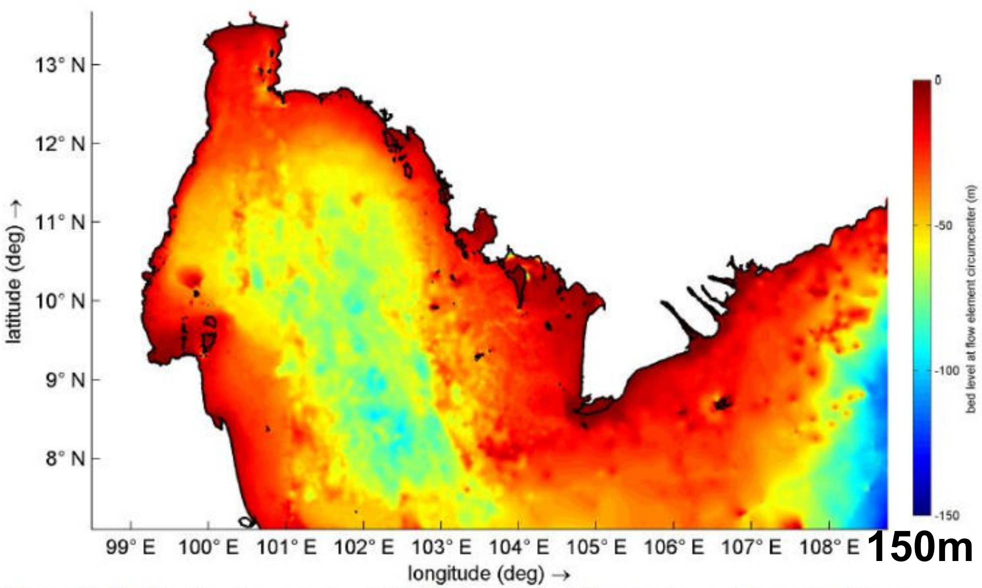


Figure 3.6 Model bathymetry; zoom-in on Gulf of Thailand (notice different colour-scale to previous figure). Shoreline shown is the less accurate NOAA line, which includes islands.

Used all available data in XYZ files (converted from LLW to MSL).

Model setup: Open Boundaries

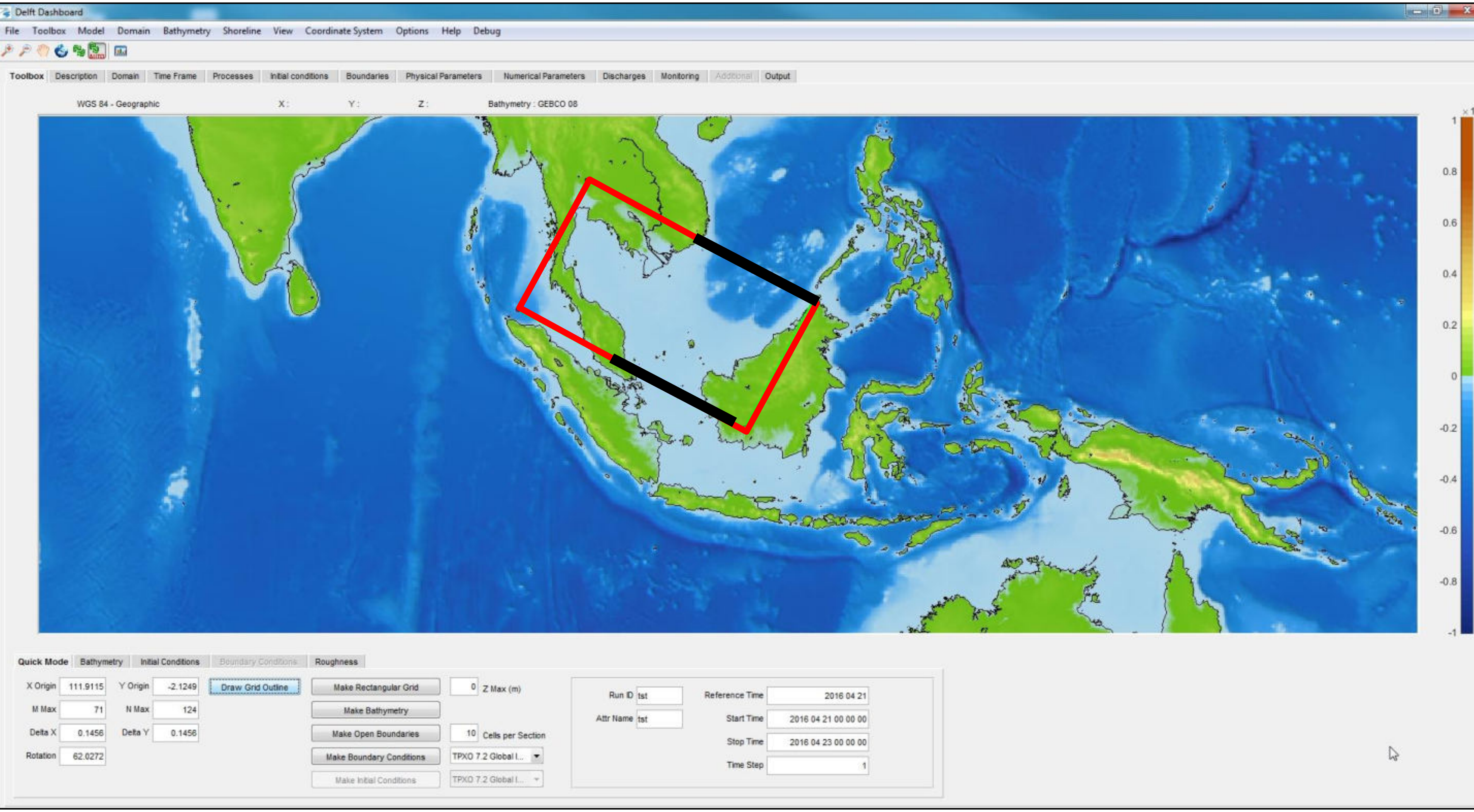
Tidal constituents (spatially-varying amplitudes and phases) were obtained from the Delft Dashboard, which uses the *TPXO 7.2 Global Inverse Tide model* database.

Since the Gulf of Thailand and the South China Sea are complex regions to model tide, including several amphidromic points and large variations in tidal amplitude, it is very important to force the boundaries with such a complete and tested dataset.

A further improvement (iterative process) was made in order to also capture low-frequency constituent Sa (solar annual), representing the yearly seasonal cycle.

The 13 constituents applied are:
SA, MM, MF, K1, O1, P1, Q1, M2, S2, N2, K2, M4, MS4, MN4

Tidal constituents using Delft Dashboard



D-Flow FM performance

During model development, the D-Flow FM model was run:
- on the Deltares Linux cluster;
- in parallel (on 12 cores).

We're using a "large grid", with 815,000 nodes and horizontal resolutions between 8km and 250m.

In the calibration runs (entire year of 2011), the average time-step was 101 seconds.

With this setup, it takes
- 16 hours to simulate 1 year, or
- **About 9 minutes to simulate 3 days.**

Runtimes can be a little slower when run in other machines.
There was no special reason not to use more cores (e.g. 16, 32, 64 is possible)

Model validation: Time series (year long)

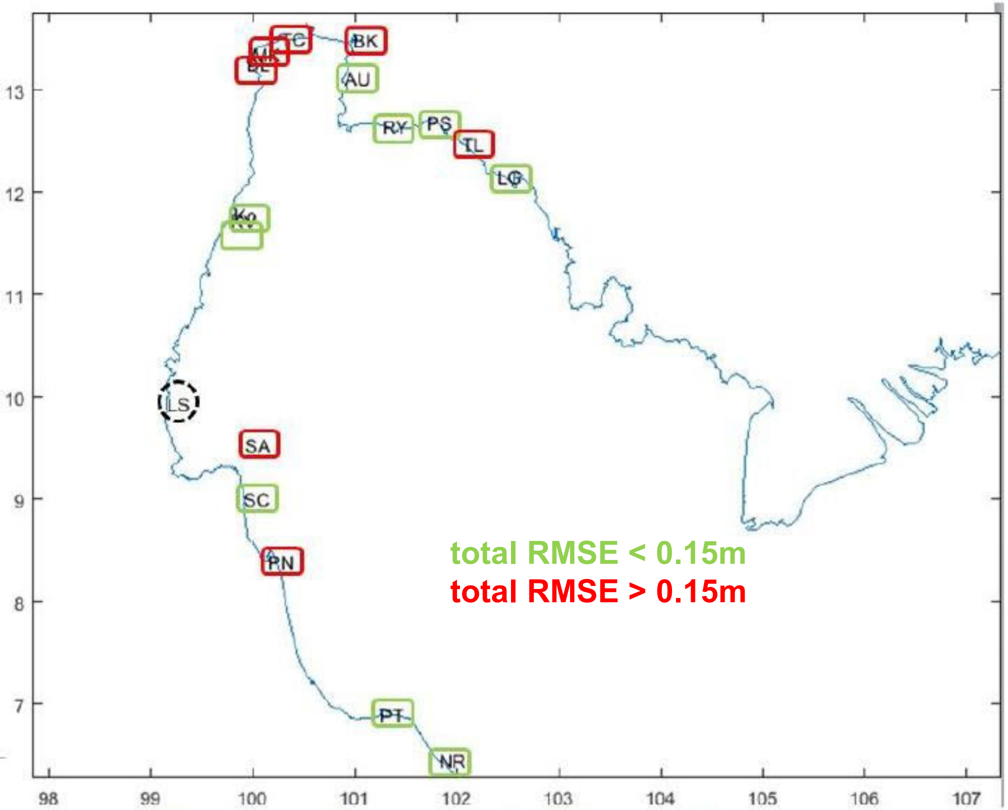


Figure 4.3 Spatial distribution of total water level RMSE (based on Table 4.4). Green is below 0.16m. Timeseries at station LS was not long enough, in 2011.

Table 4.4 Goodness-of-fit parameters (entire year analysed).

Station ID	R^2 (total)	R^2 (tide)	R^2 (surge)	rmse, m (total)	rmse, m (tide)	rmse, m (surge)
AU	0.958	0.973	0.397	0.152	0.119	0.095
BL	0.943	0.964	0.333	0.183	0.145	0.112
KV	0.950	0.977	0.538	0.113	0.074	0.087
LG	0.948	0.969	0.547	0.104	0.077	0.070
NR	0.841	0.887	0.626	0.124	0.094	0.080
PS	0.939	0.963	0.504	0.119	0.091	0.079
PT	0.745	0.767	0.645	0.135	0.117	0.069
SC	0.901	0.956	0.622	0.116	0.071	0.092
TC	0.953	0.967	0.421	0.164	0.134	0.094
TL	0.848	0.864	0.550	0.174	0.160	0.069
BK	0.933	0.954	0.285	0.191	0.157	0.110
MK	0.920	0.942	0.229	0.209	0.178	0.110
PN	0.743	0.804	0.432	0.190	0.149	0.125
RY	0.955	0.972	0.584	0.108	0.083	0.071
SA	0.826	0.904	0.261	0.208	0.146	0.147
Ko Lak	0.930	0.969	0.403	0.131	0.083	0.107
Means	**0.896**	**0.927**	**0.461**	**0.151**	**0.117**	**0.095**

Stations that "need attention" already have high goodness-of-fit ($R^2 > 90\%$) and the <u>local bathymetry</u> was identified as the major culprit.

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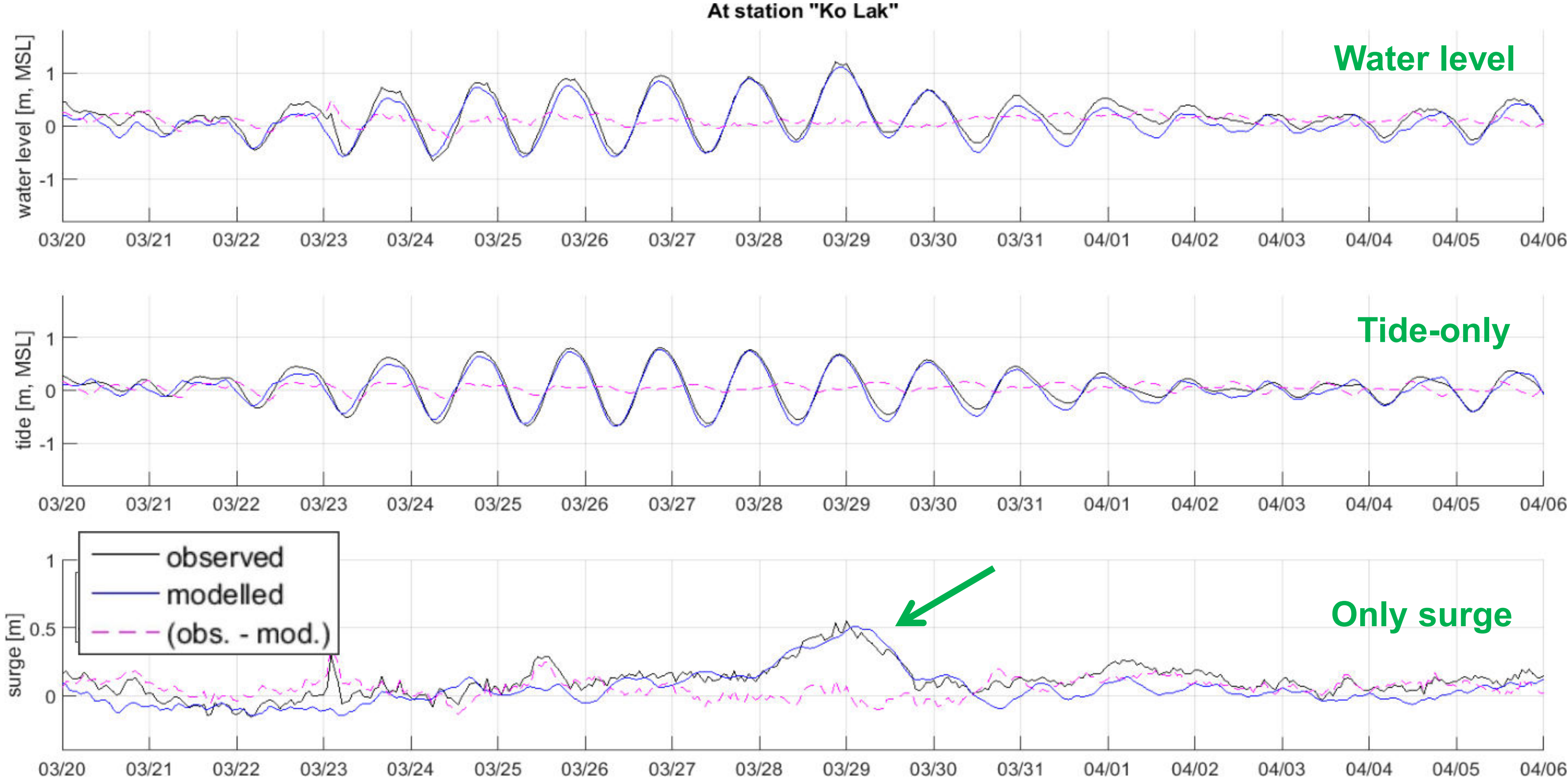
Model validation: March 2011 event



- Peak surge caused higher high-waters.
- Very good match between observed and modelled total water level time series, especially during the peak hours / days.

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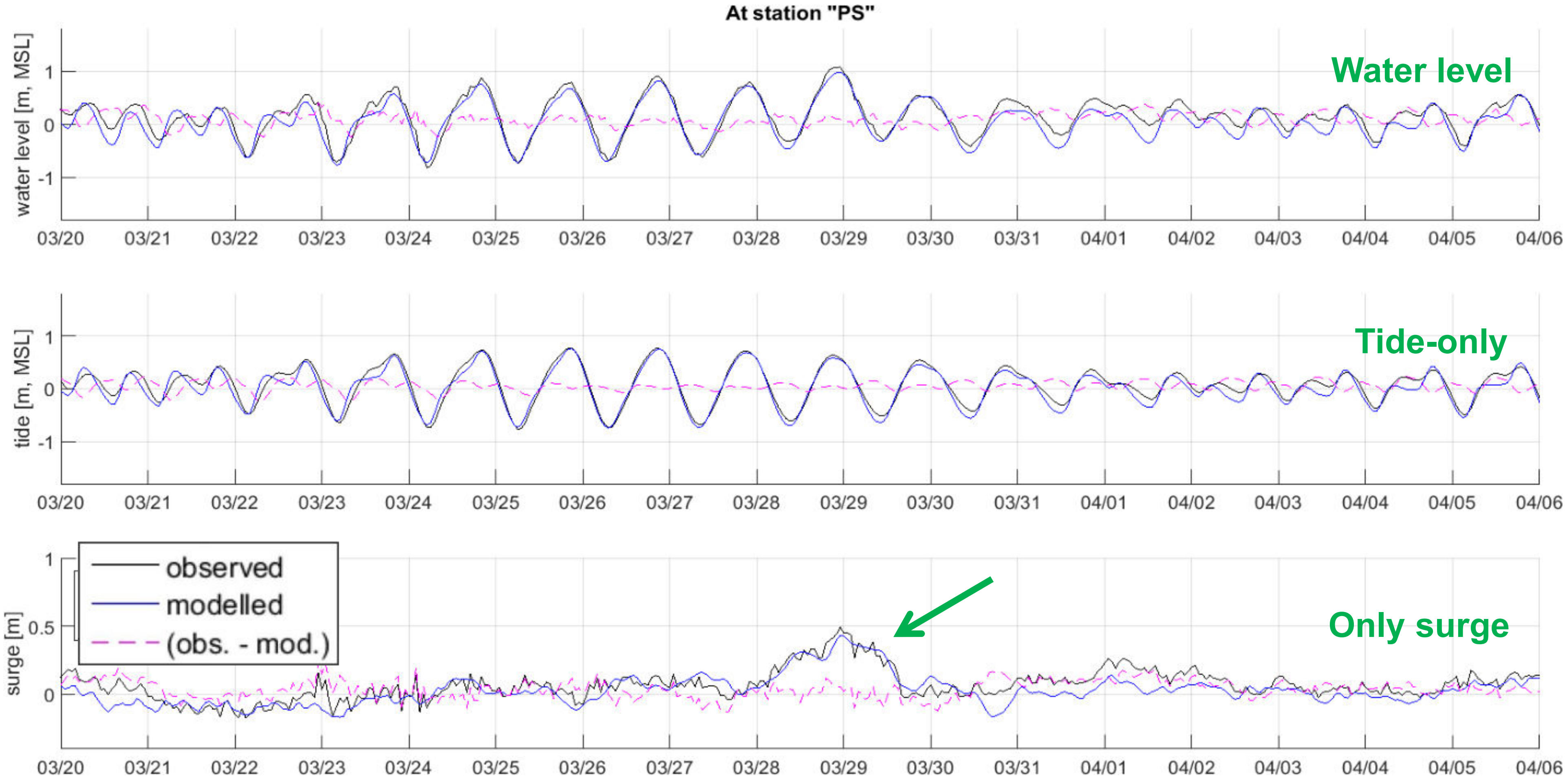
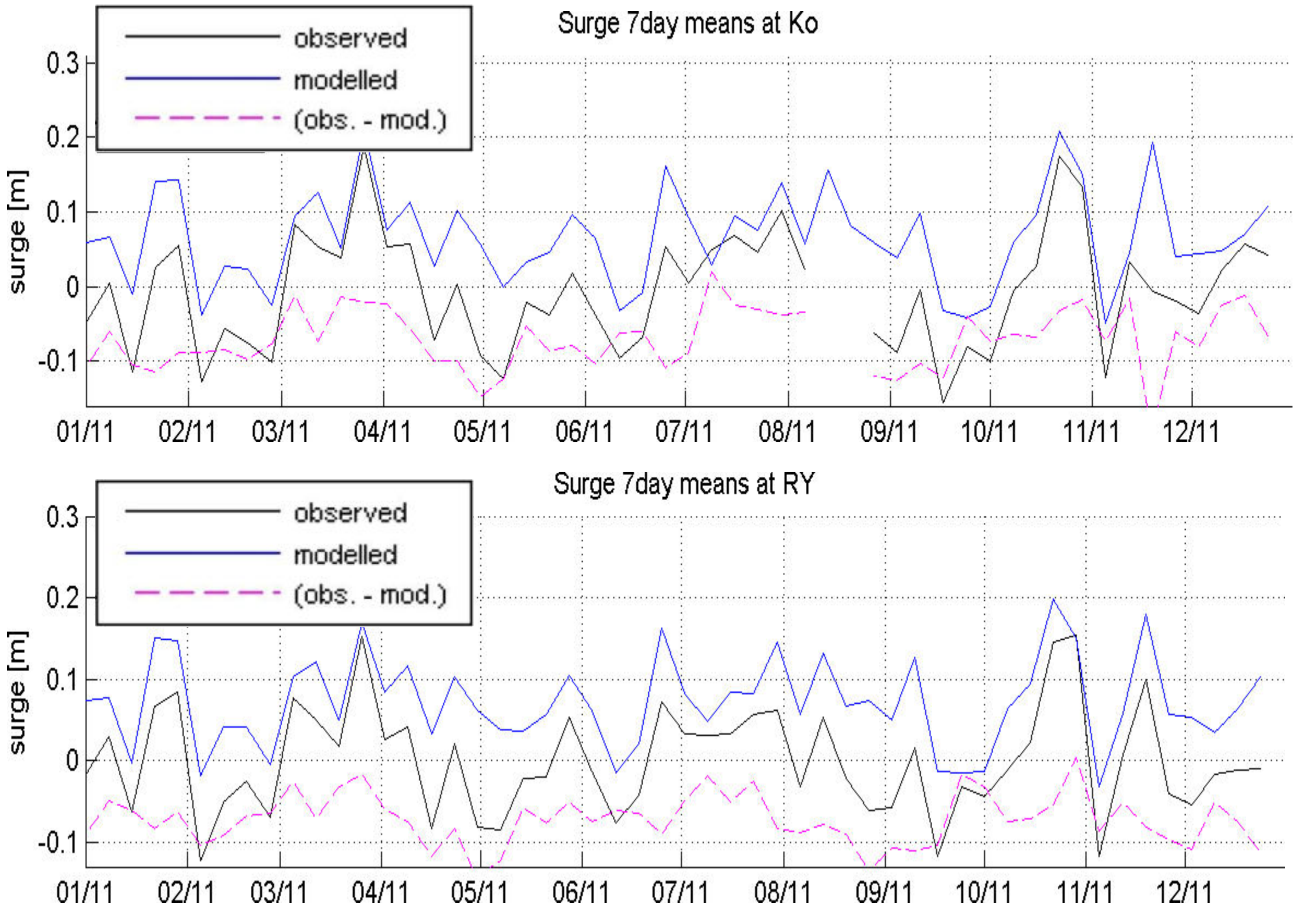
Model validation: Time series and March 2011 event



- Typical stations show the high quality of station *Ko Lak* (when no issues with local bathymetry nor with measuring sensor).
- In most cases, even if the shape of the surge is not exactly reproduced, at least the peak amplitude is captured with minimal phase error.

Deltares

Model validation: Time series (year long)



- How about the seasonal surge patterns? Plotting the 7-day means throughout the year 2011.
- Averaged over the entire year of 2011, the modelled surge is overestimated by about 0.10m. This tends to zero during the March event described above.

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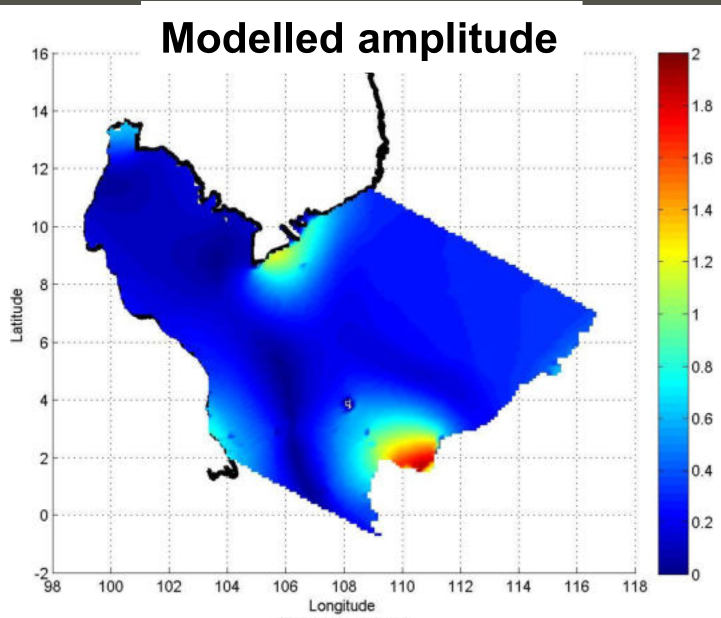
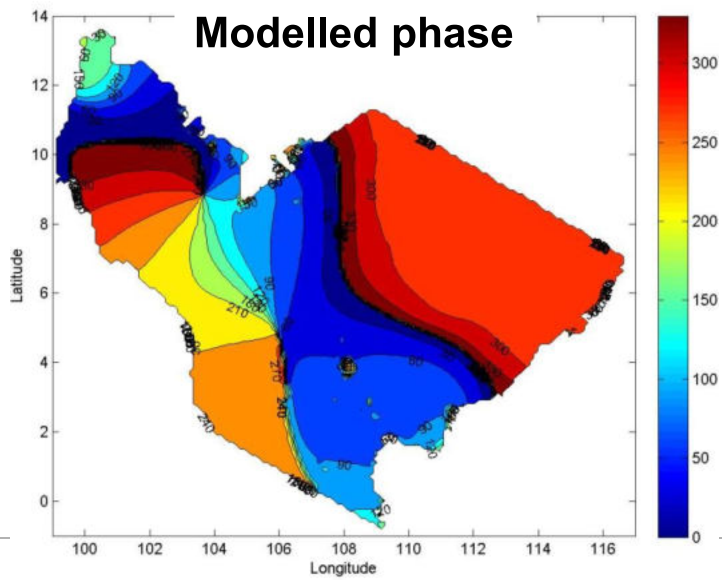
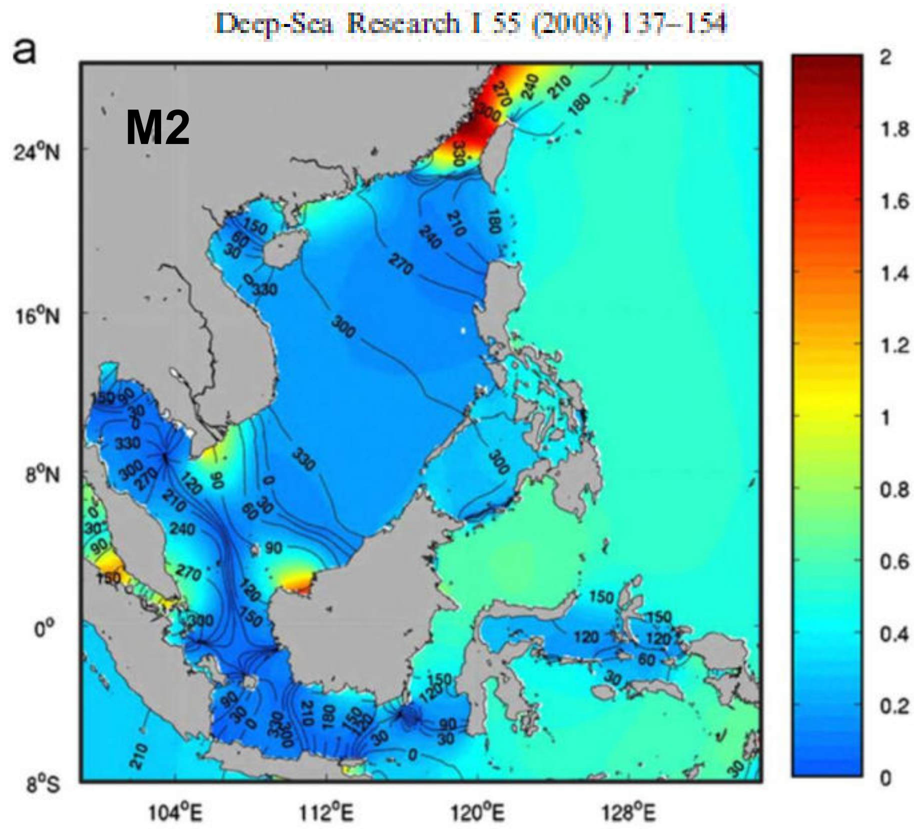
Co-tidal charts: published versus modelled







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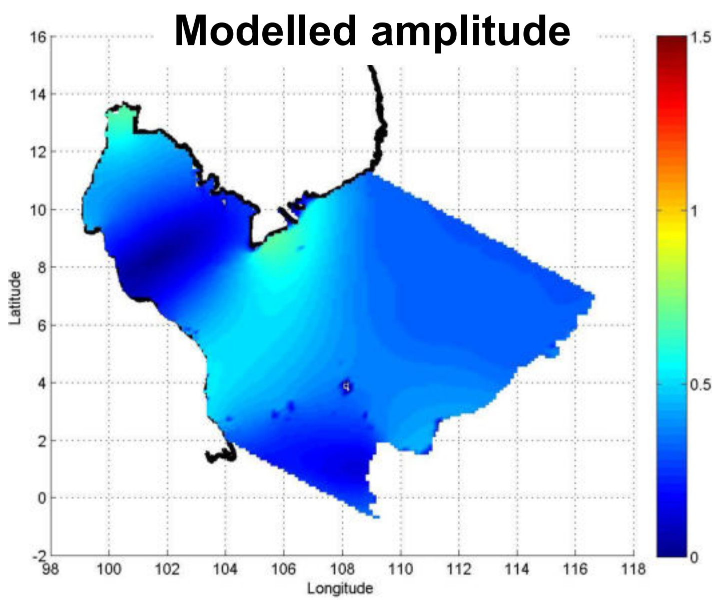
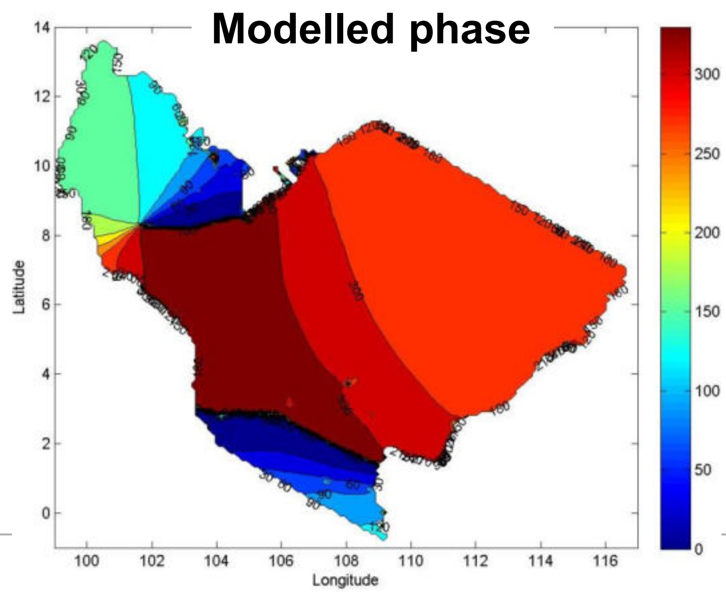
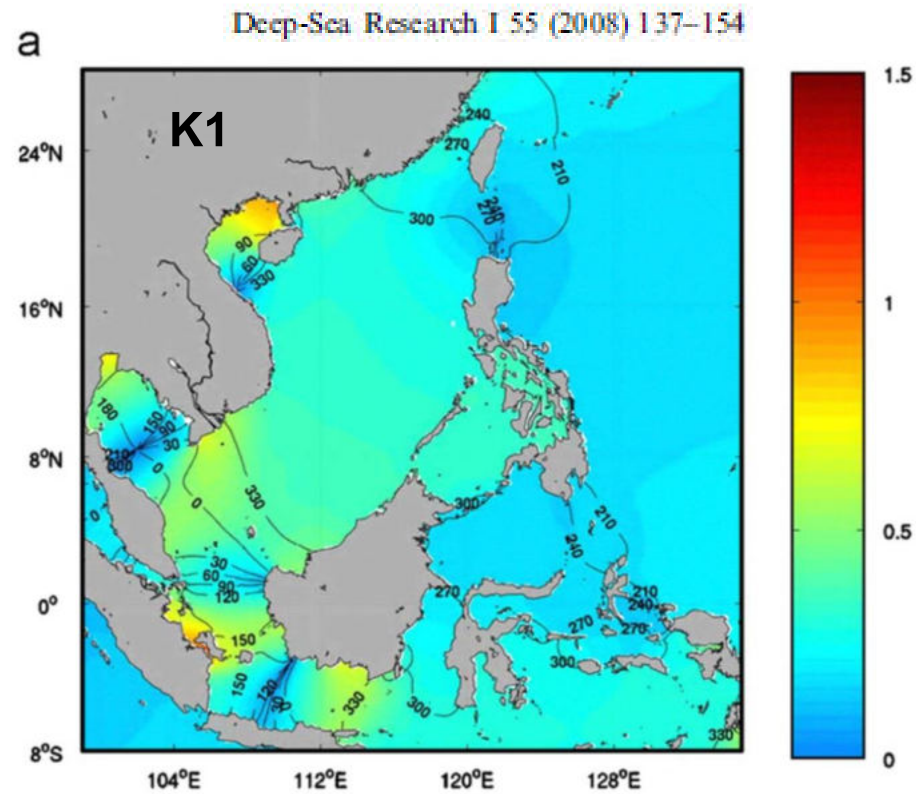
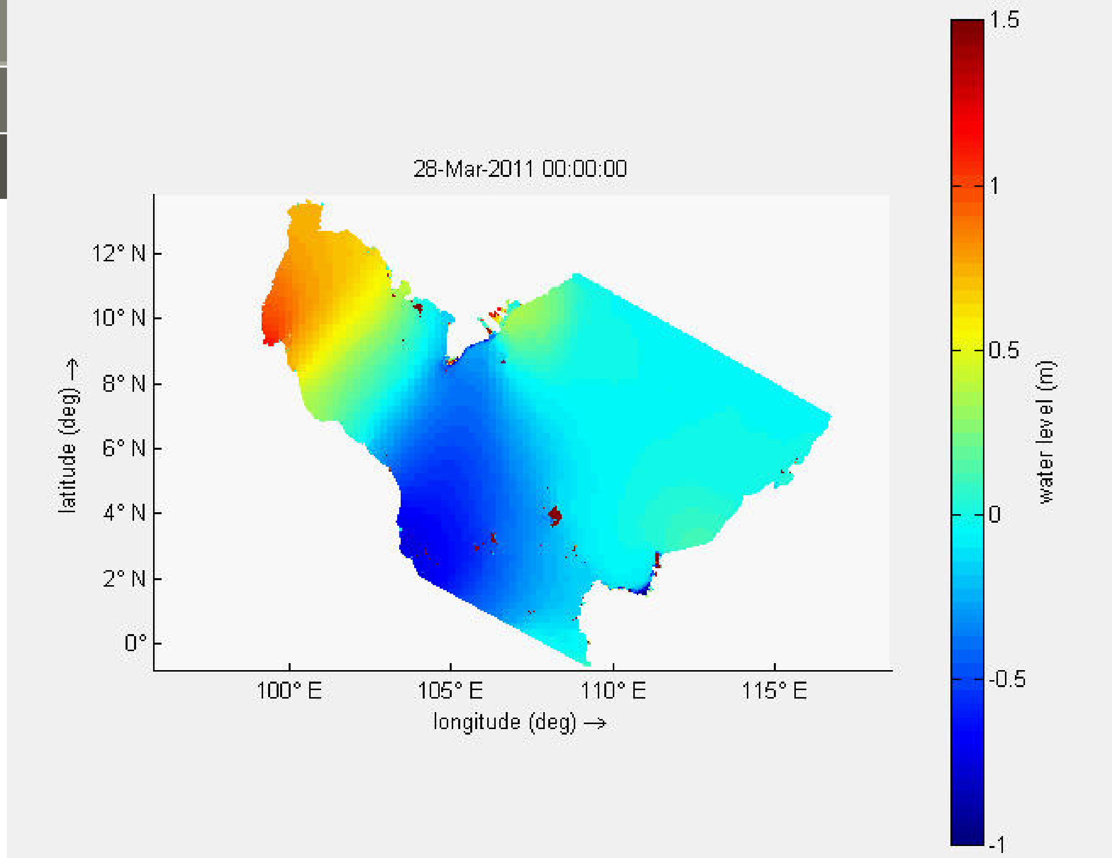
Co-tidal charts: published versus modelled





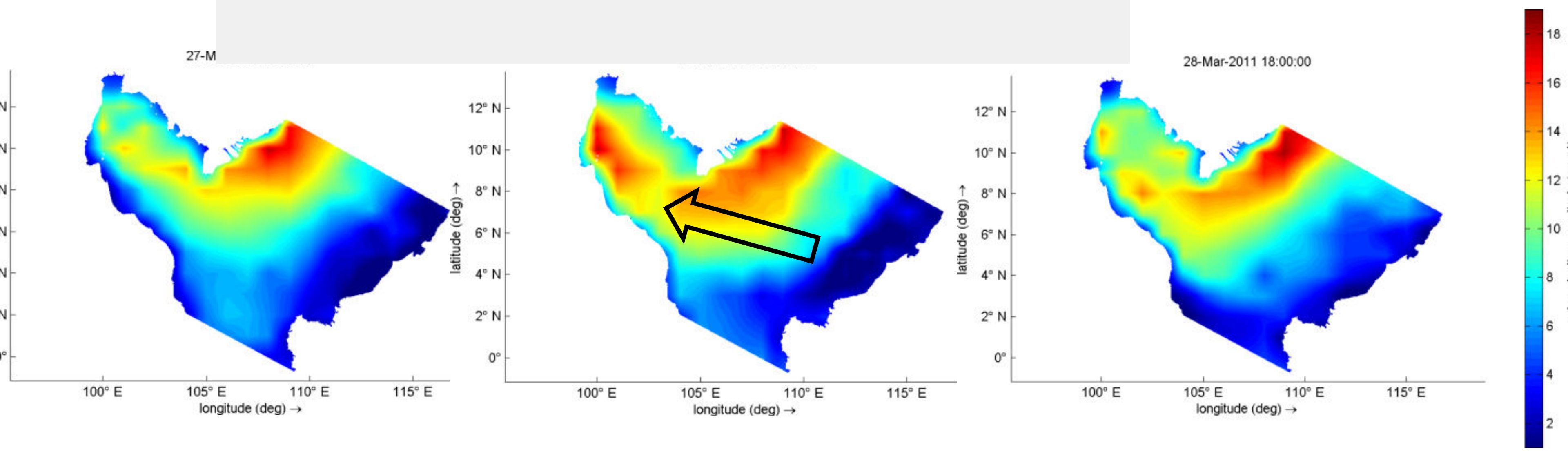


Deltares

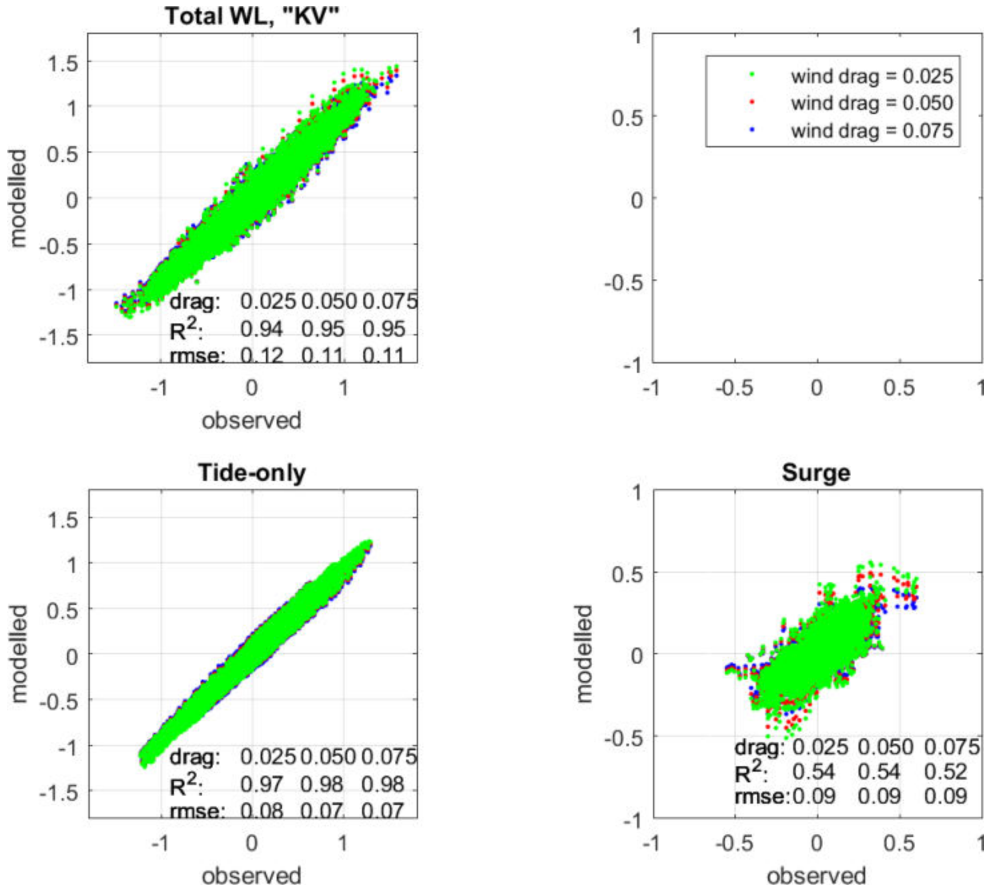


Animation:
Total water levels (m)

Stills:
Wind speeds (m/s)



Surge sensitivity to the wind drag coefficient



Tests performed by varying the Charnock parameter, defining how responsive water levels will be to the wind.

Runs performed with Charnock parameter values of 0.025, <u>0.05</u> and 0.10.

Conclusions:
Relatively small impact on the overall goodness-of-fit values, and a relatively small difference in the scatter plot slopes.

While the impact in the surge throughout the year is limited, the impact is larger during storm surge events (surge > 0.3m).

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Conclusions on hydrodynamics

The hydrodynamic model is based on Delft3D Flexible Mesh, a new-generation numerical modelling framework. The development of the new hydrodynamic model to simulate tide and storm surge was described, along with first results.

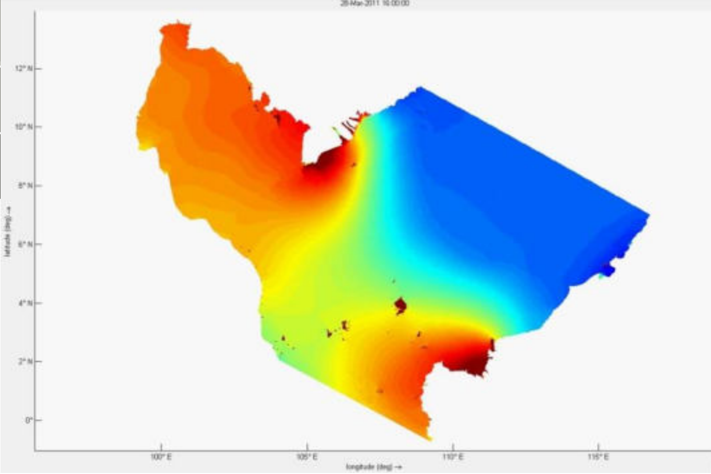
The major objectives were to

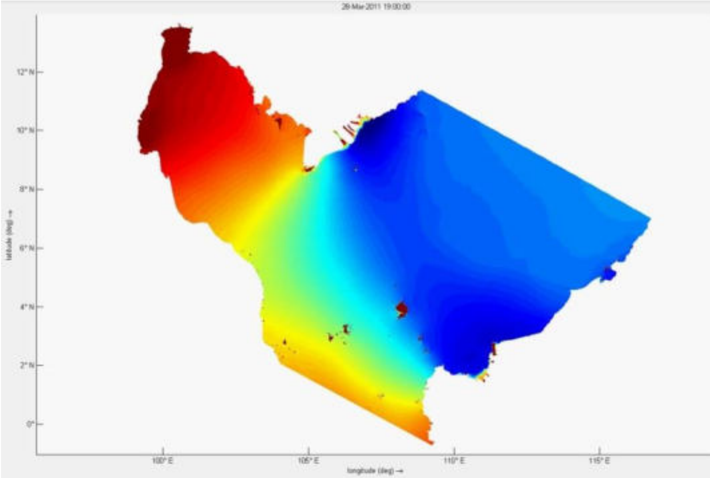
- build an unstructured-grid hydrodynamic model capable of representing tide and storm surge at a sufficient spatial resolution,
- with manageable runtimes to provide a first operational model in HAII's EWS.

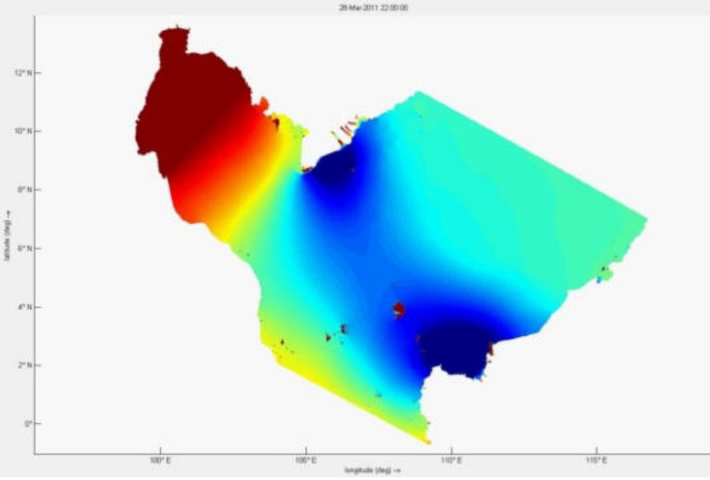
The models in the EWS need to be of sufficient quality, otherwise warnings are too often unreliable.

The model characteristics achieved are very adequate for the envisaged coastal ocean operational system,

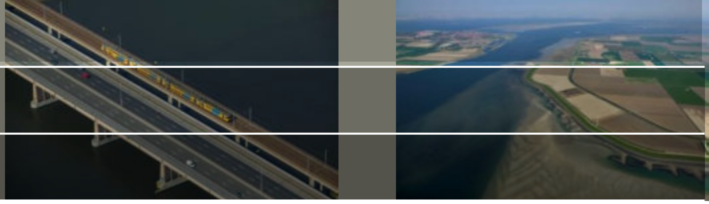
- The fine horizontal resolution and the low run-times,and
- The overall high quality of this first Gulf of Thailand tide-surge model.







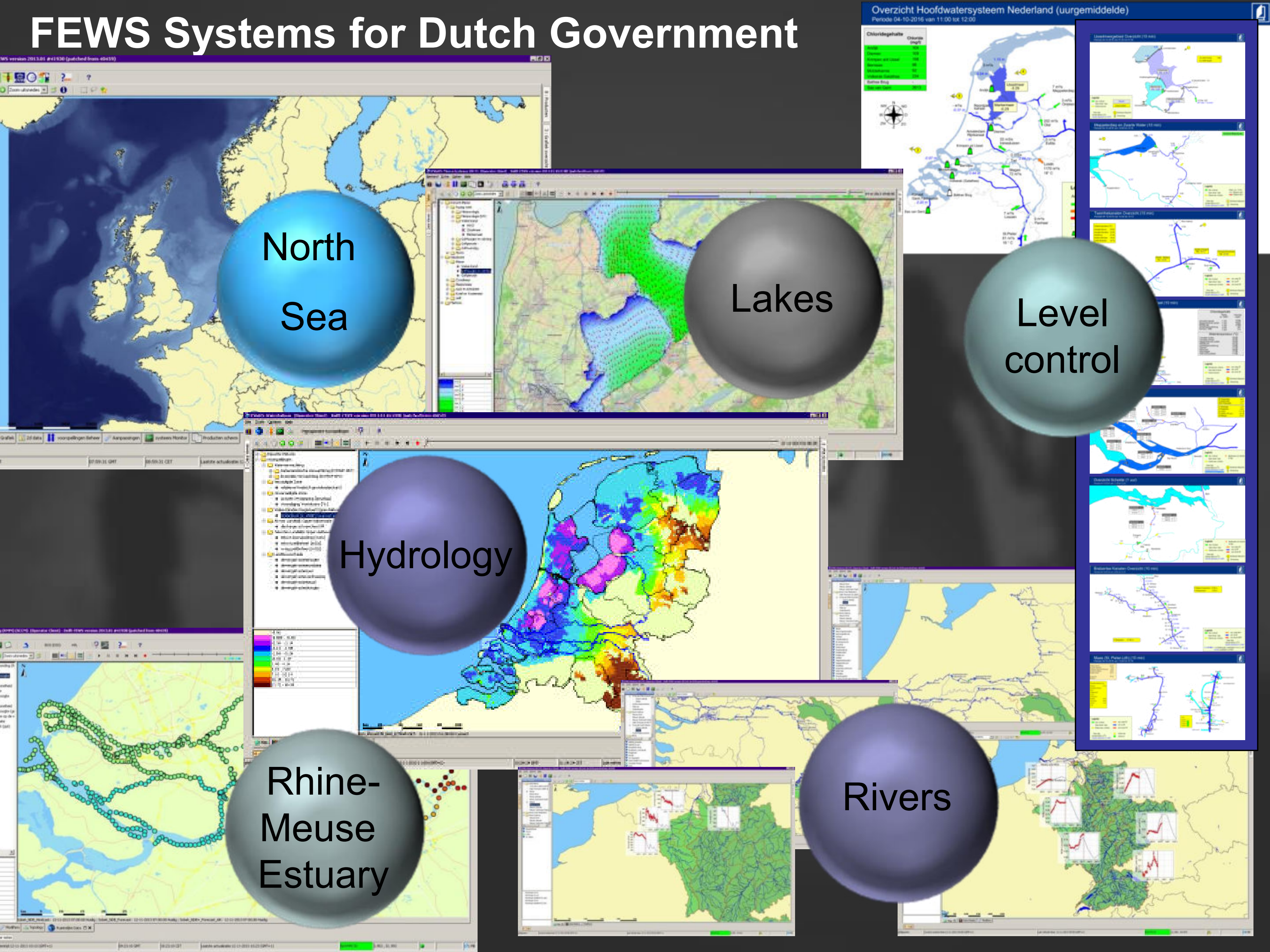
Delft-FEWS



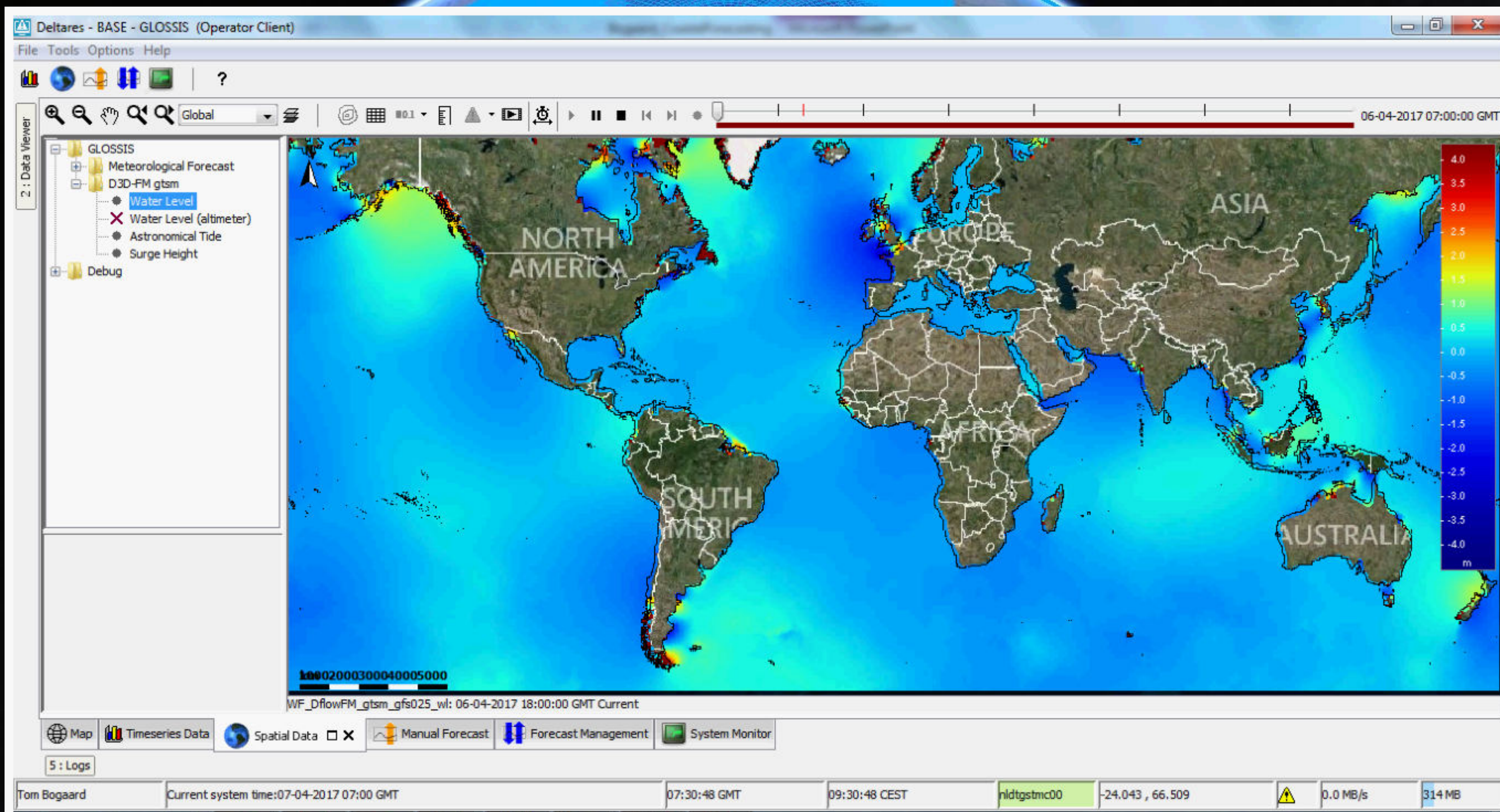
Community development approach:

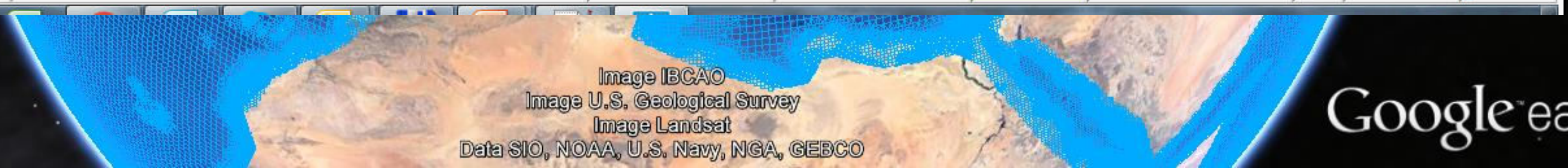
- Free software with contributions from all users

FEWS Systems for Dutch Government



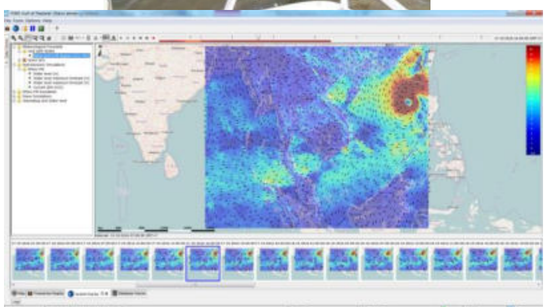
Global Storm Surge Information System (GLOSSIS)





Forecasting systems: Gulf of Thailand

Data → ***Models*** → ***Forecasts & warnings***



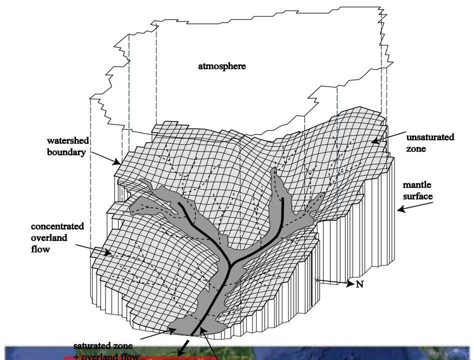
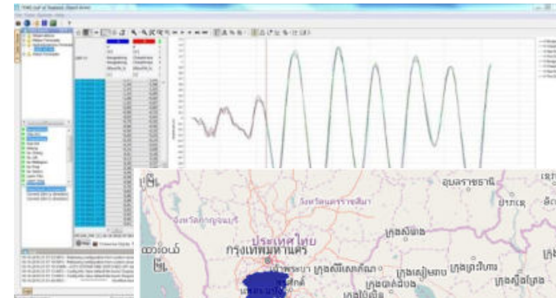
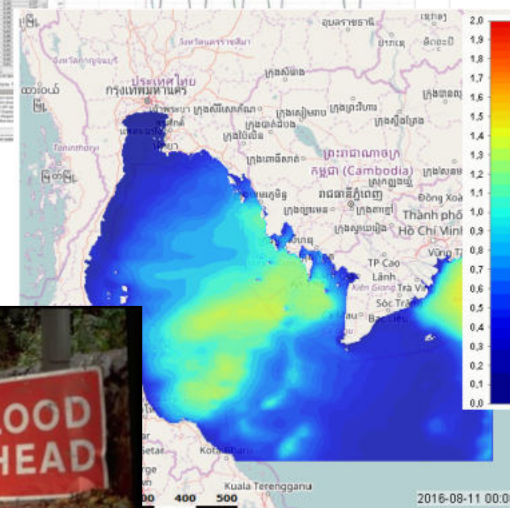


Figure 3.1 Computational grid (flexible mesh) overview. Pins show the locations of all tidal stations. Horizontal resolutions of 8000m, 4000m and 2000m are noticeable. The red rectangle indicates the zoom level shown





Complexity in functionality

- **Data retrieval** system (measurement, forecast)
- Data **processing**

- Forecasting **models**
- Data and forecast **management**

- Visualization
- Reports / Export **Online dissemination**

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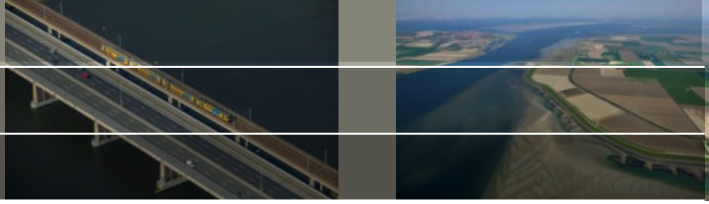
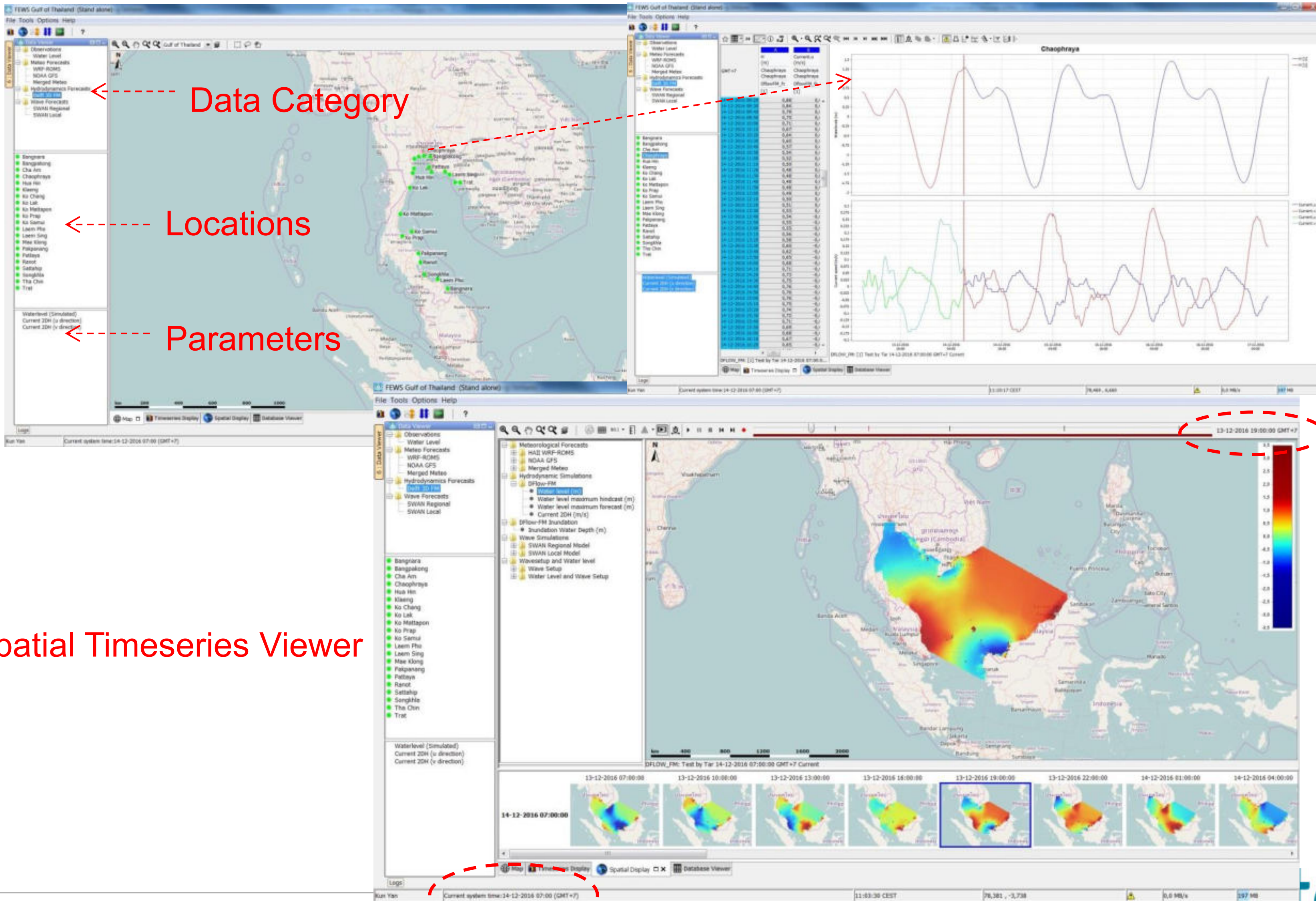
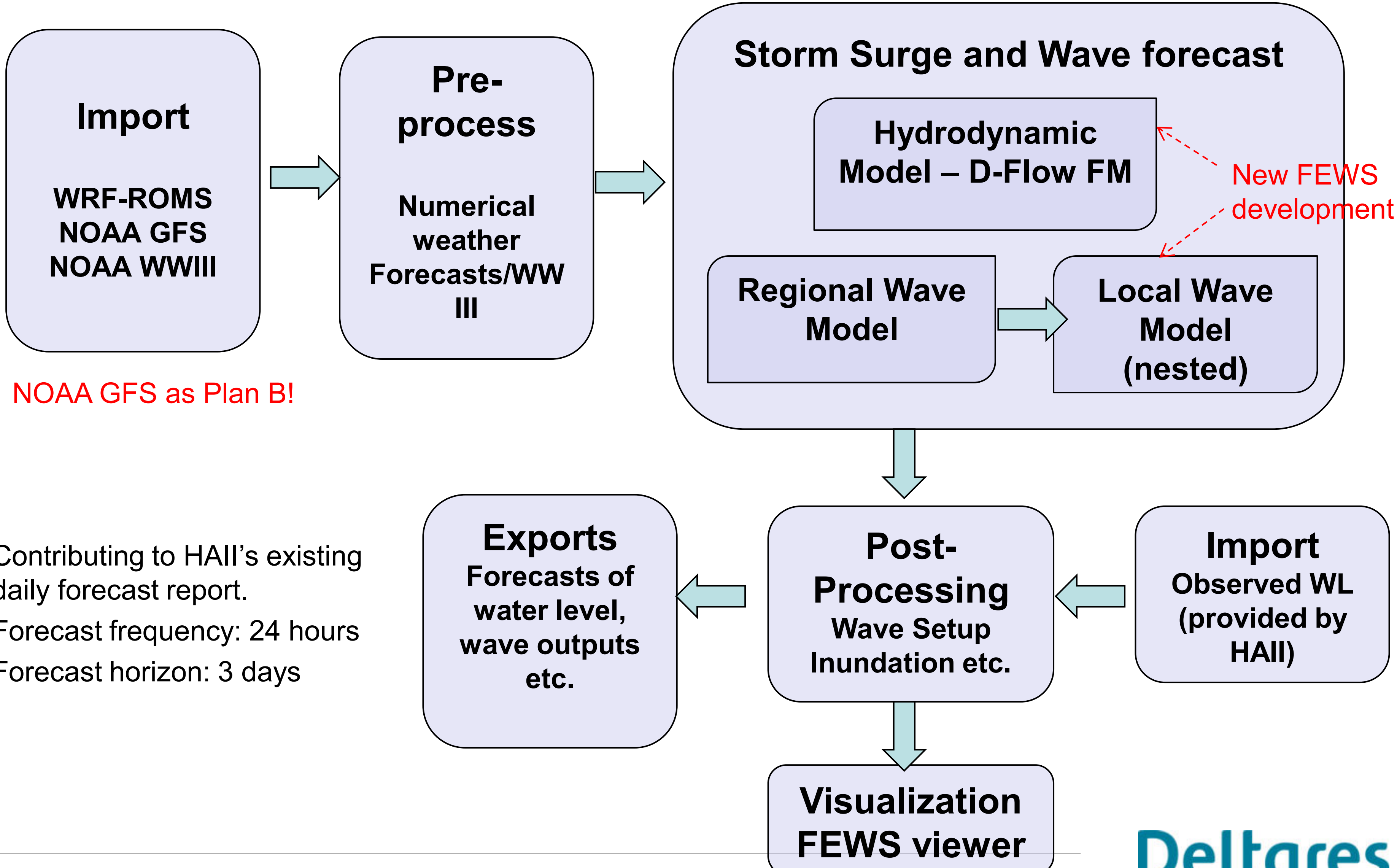
FEWS-GoT Viewer





Operational System Setup – FEWS-GoT



Contributing to HAII's existing daily forecast report.

Forecast frequency: 24 hours

Forecast horizon: 3 days

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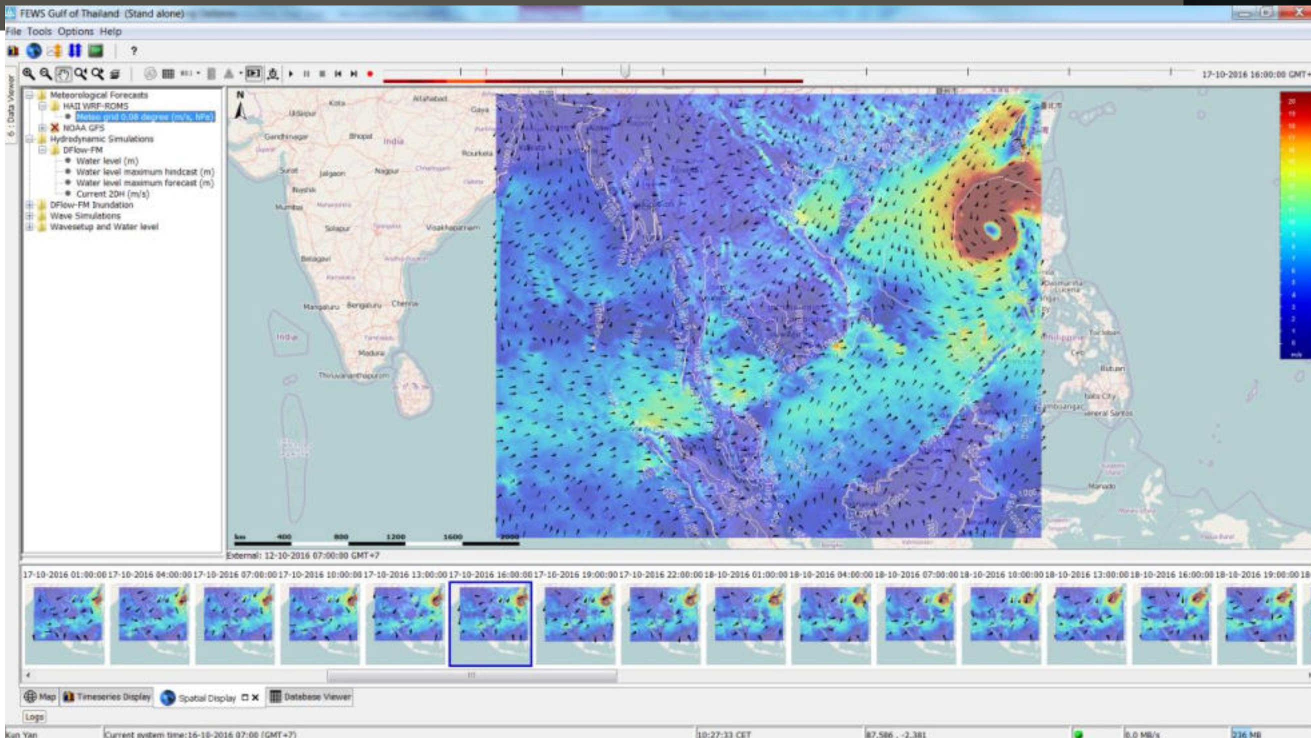
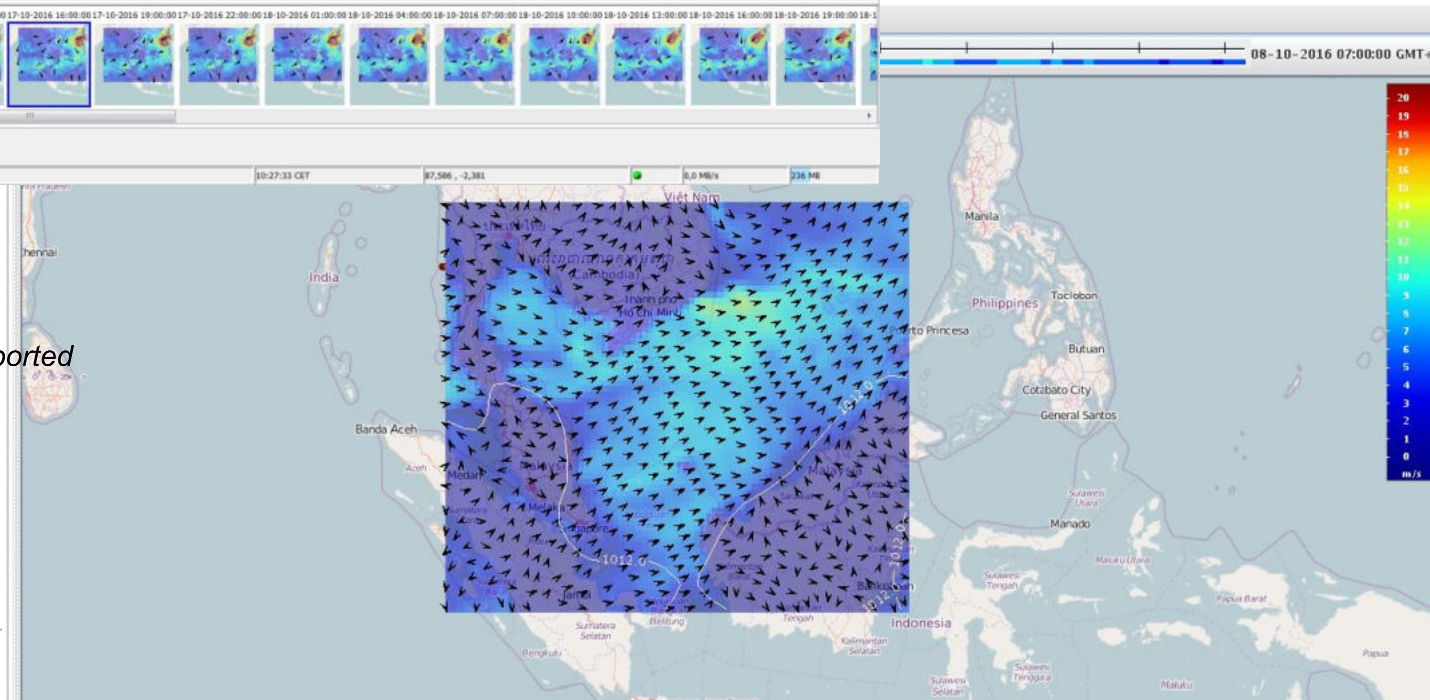
Numerical Weather Forecast in FEWS Viewer



WRF-ROMS meteo forecasts (9 km, ~0.08 degree) imported and displayed in FEWS-GoT.

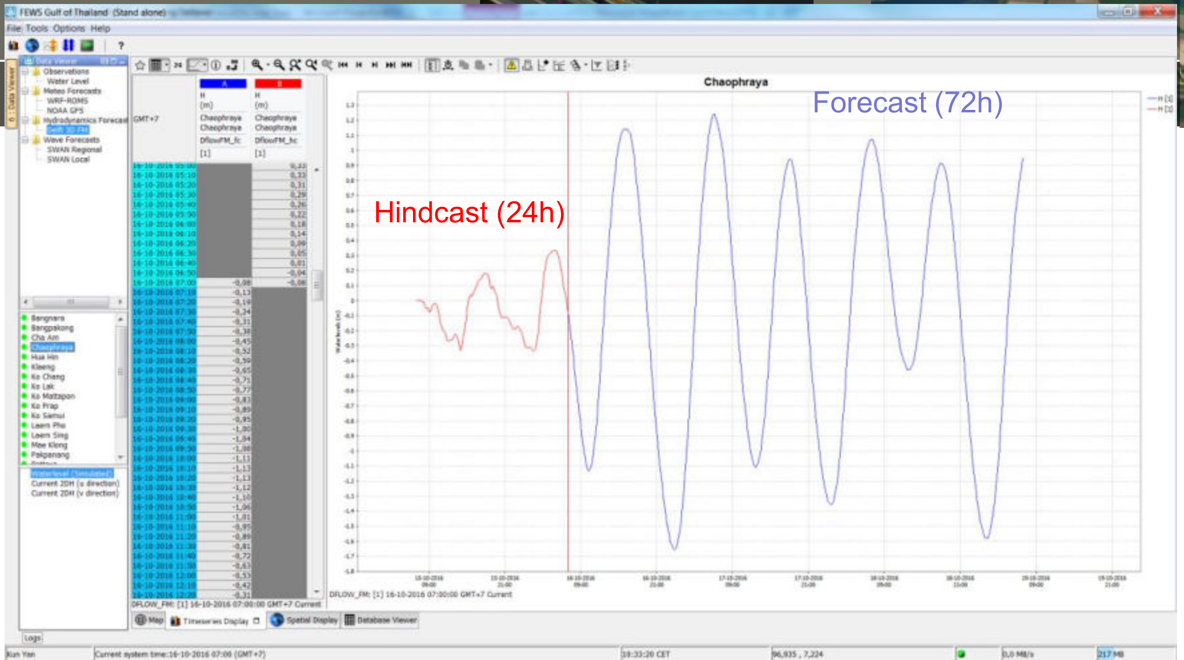


NOAA's GFS (0.25 degree) meteo forecast imported and displayed in FEWS-GoT

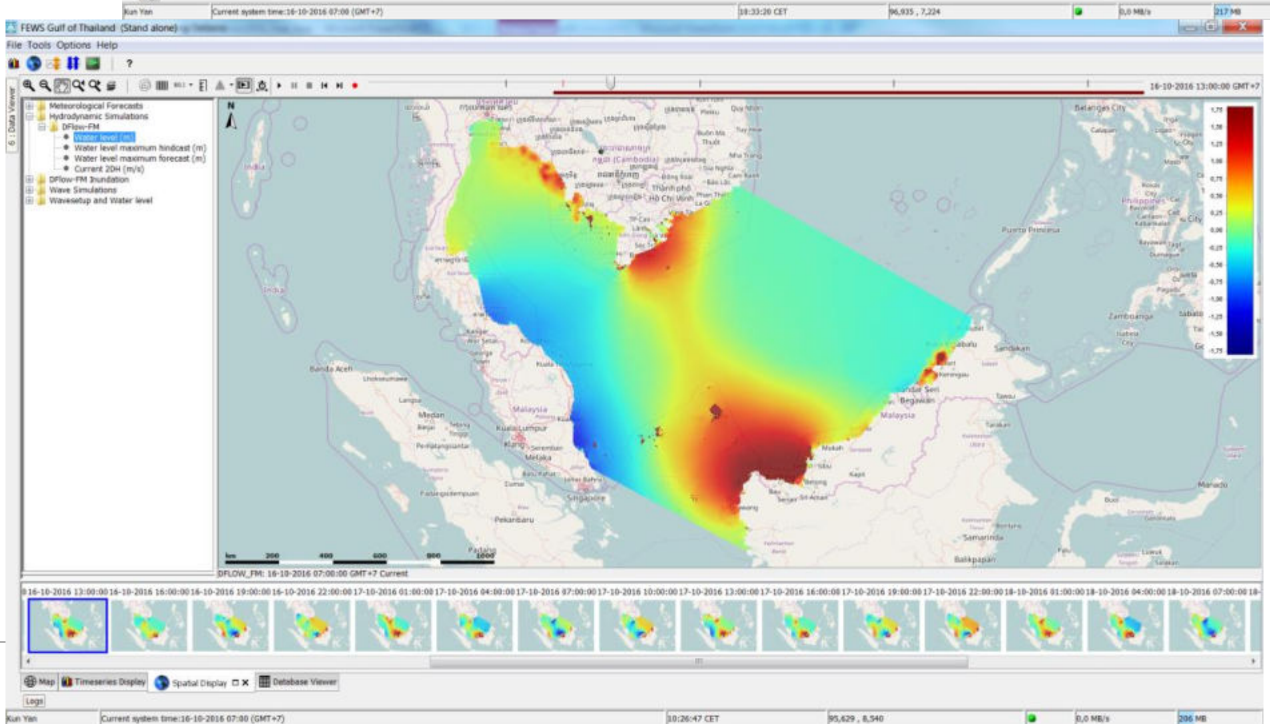
Serve as back-up Meteo forcing

Operational aspects

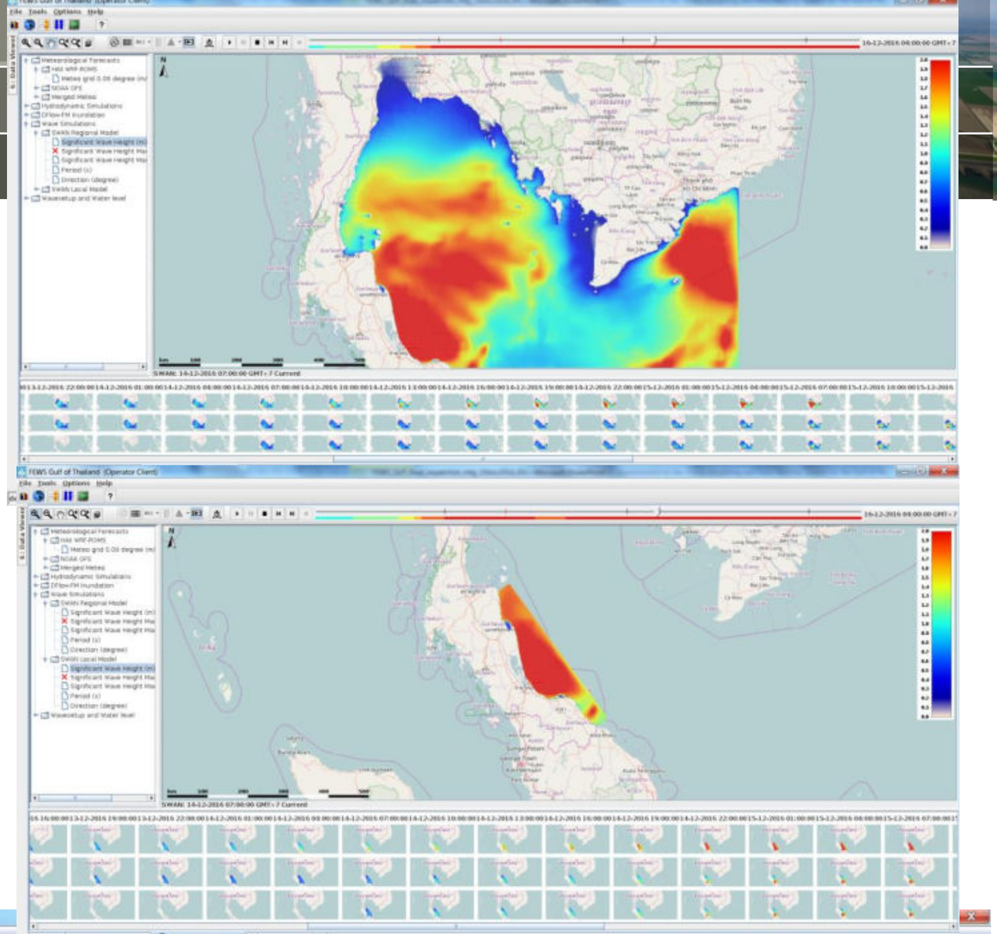
Water level forecast in Chao Phraya: Cold start of hindcast, Warm start of forecast



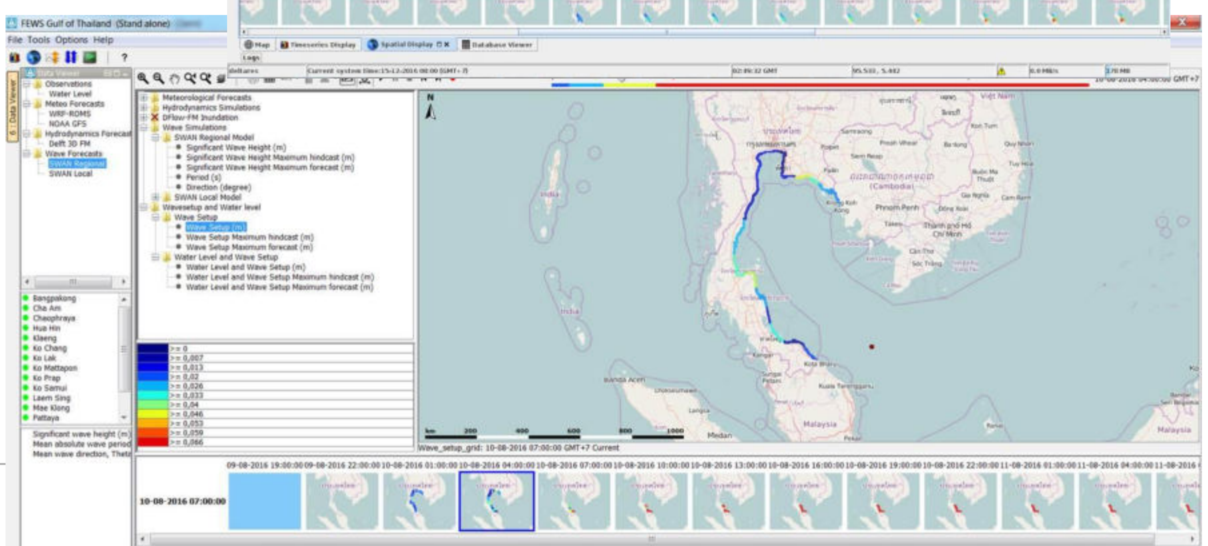
Water level simulated by D-Flow FM displayed in FEWS-GoT Spatial Display.



Wave forecasts

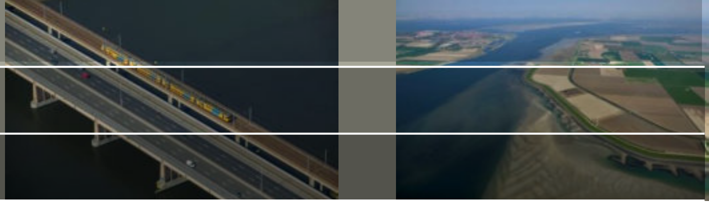


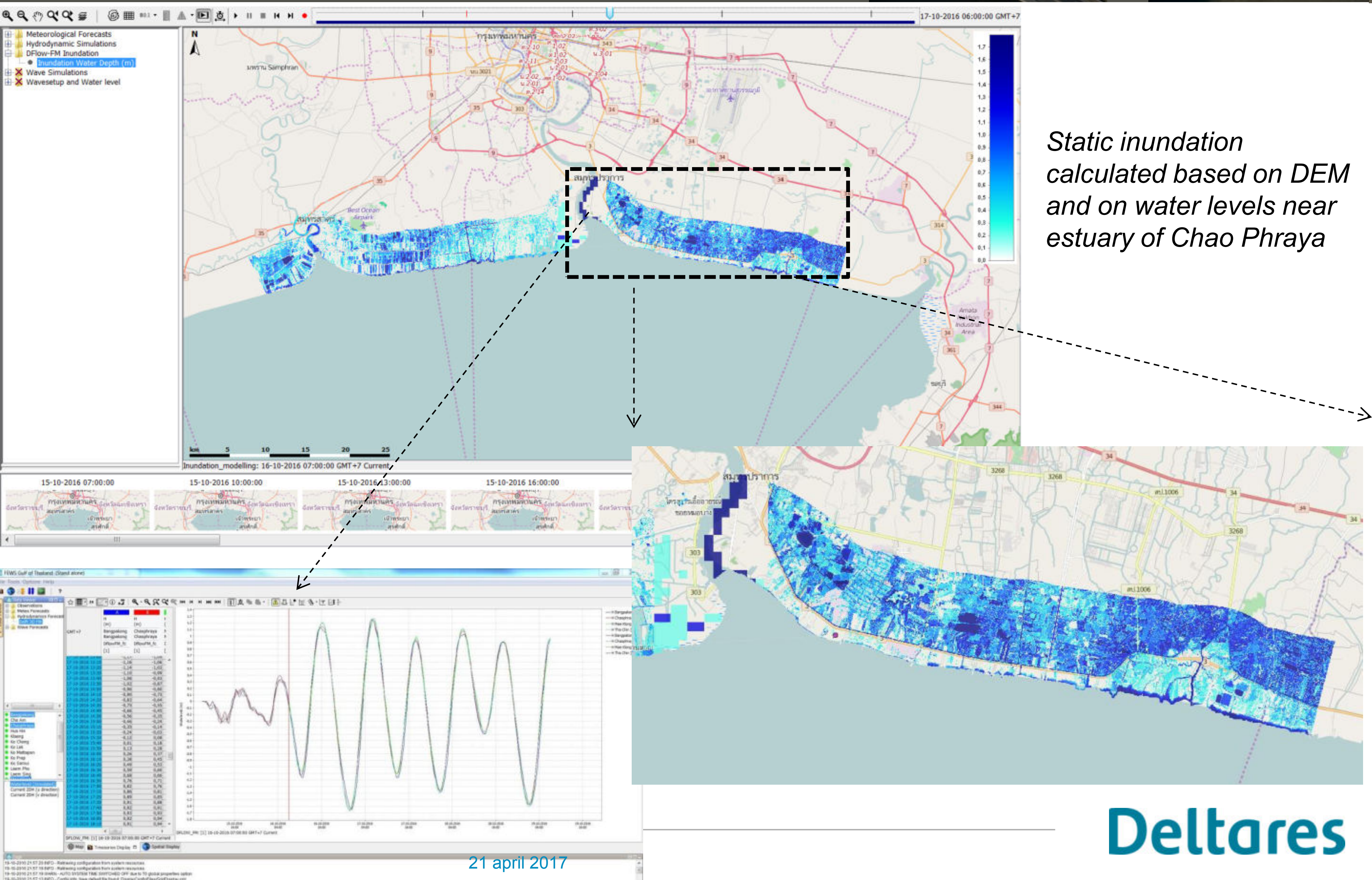
- *SWAN regional model forced by global WaveWatch III*
- *Nested SWAN local model*
- *Hs, Tmm10, Theta0 visualized separately*



Wave setup calculated and displayed in FEWS-GoT Spatial Display.

Static inundation (GIS-based)





Static inundation calculated based on DEM and on water levels near estuary of Chao Phraya

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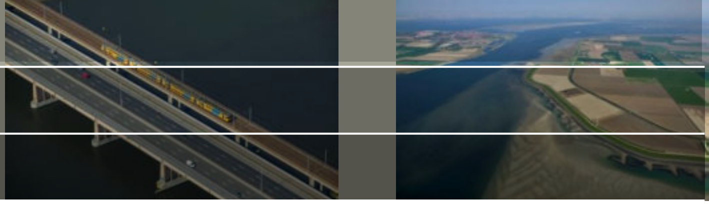
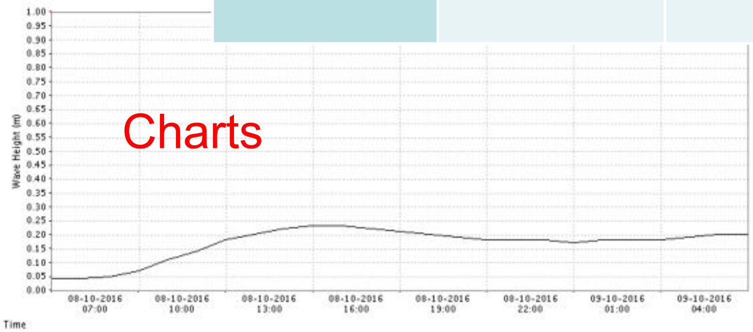
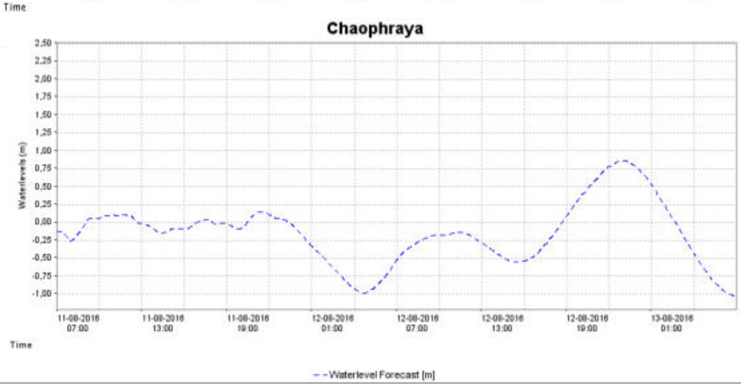
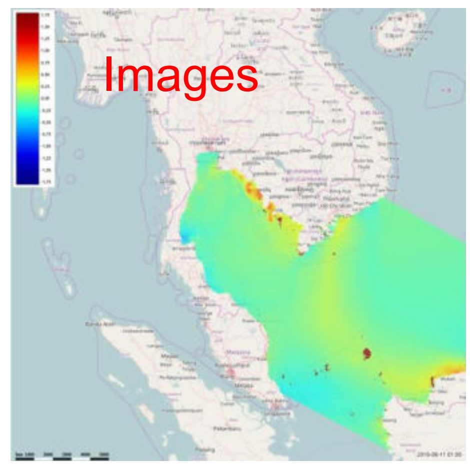
Export & Report

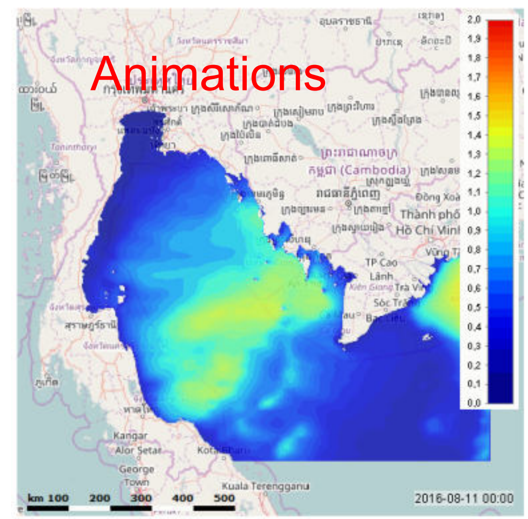


Variable / file	Time series charts (PNG)	Map images, hourly (PNG)	Map images, max (PNG)	Map animations (GIF)	Data export (NetCDF)
Water level	1. At each station (for 3 days)	2. Inner GoT plots (hourly, for 3 days)	3. Inner GoT plots (max. of 3 days)	4. Inner GoT film (for 3 days)	1, 5, 9 in one NetCDF file
Water level + Wave setup	5. At each station (for 3 days)	6. Inner GoT plots (hourly, for 3 days)	7. Inner GoT plots (max. of 3 days)	8. Inner GoT film (for 3 days)	2, 3, 6, 7 in one NetCDF file
Significant Wave Height	9. At each station (for 3 days)	10. Inner GoT plots (hourly, for 3 days, regional and local)	11. Inner GoT plots (max. of 3 days, regional and local)	12. Inner GoT film (for 3 days, regional and local)	10, 11 (regional) in one NetCDF file 10, 11 (local) in one NetCDF file









In total 288 images per forecast

and NetCDFs…

21 images for each parameter, in total: 63 charts per forecasts

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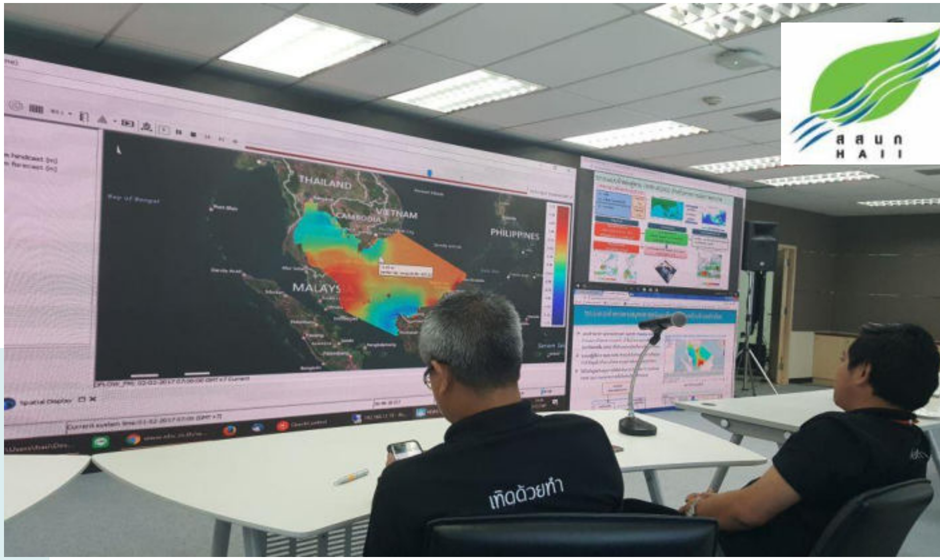
Concluding remarks

We've shown

- The new Early-Warning System to predict coastal flooding levels along the Thai coast.
- This system, now used by the Hydro and Agro Informatics Institute (HAII), provides three-day forecasts, generated daily, combining effects of tide, storm surge and wave setup.

Now what?

- HAII is operating this operational system independently.
- Given easy "plug-in" options with Delft-FEWS, HAII may include other new nested models to represent smaller estuaries, or water quality.



Why was this a success?

In one word… "flexibility"!

- The researchers at HAII were very motivated & capable during on-the-job training.
- Delft3D Flexible Mesh allows for optimal configuration, resolution and run-times.
- Delft-FEWS modular nature allows for tailor-made solutions and for all kinds of data exports.

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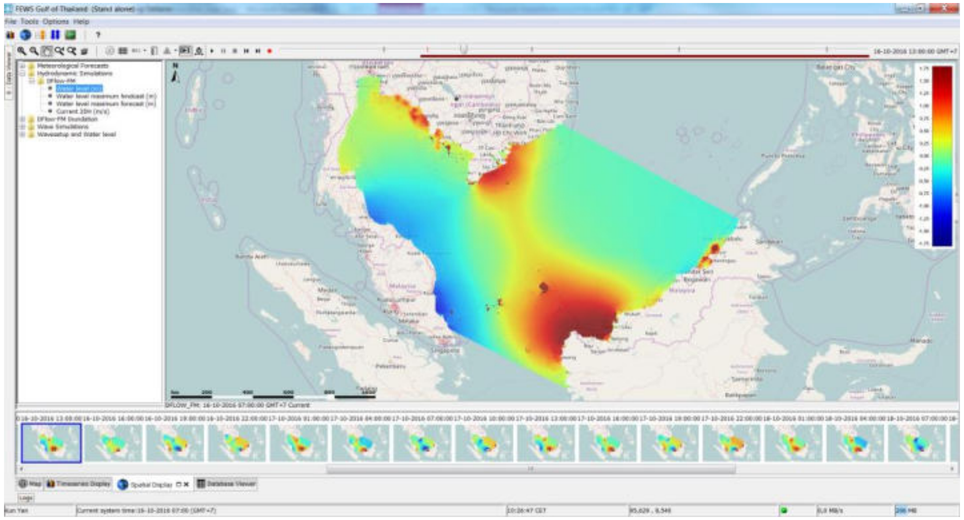
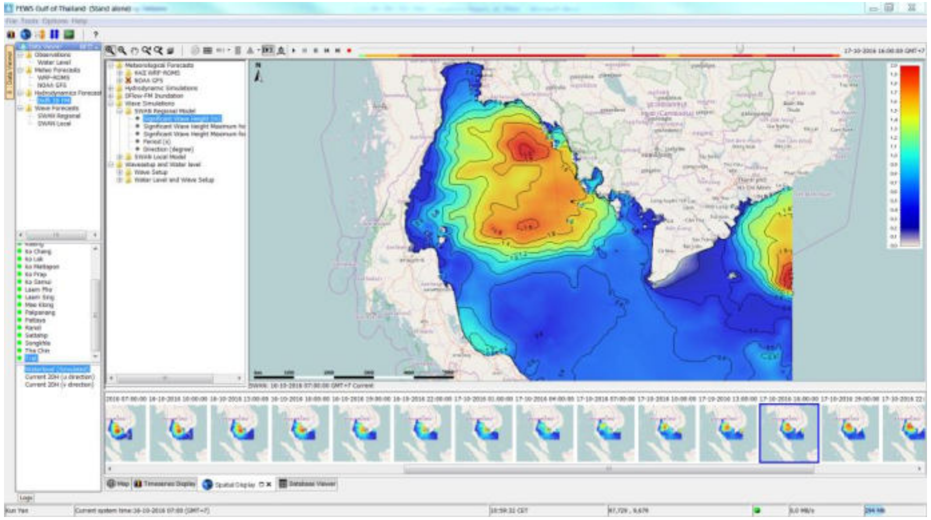
Thanks for your attention – We welcome any questions

“Ocean modelling and Early-Warning System for the Gulf of Thailand: An application of Delft-FEWS, Delft3D Flexible Mesh and SWAN”





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Dr. Kun Yan (kun.yan@deltares.nl)

https://www.deltares.nl/en/webinars/ocean-modelling-and-early-warning-system-for-the-gulf-of-thailand/