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MODELLING FOR GOLD

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ABSTRACT

Climate change is an important global issue, leading to sea level rise and extreme weather. The impact of climate change on local hydraulic and meteorological conditions such as wind, water levels and currents has to be taken into account when designing coastal and river protection structures worldwide, and in port development.

For optimal design of hydraulic structures, accurate and reliable knowledge of hydraulic conditions is essential, and application of numerical models is becoming more and more important. Simultaneously, the model requirements and standards become higher. Several alternative designs should be investigated under various conditions by model simulations in a short period of time. Flexible, fast and efficient deployment of hydraulic models in a multidisciplinary design process is necessary. This holds even more for developing countries, where in general knowledge is lagging and budgets are limited.

This paper discusses, by using a case study, how accurate and reliable site specific water level and current predictions can be obtained by means of the numerical flow model FINEL2D, in areas where no 'on the shelf' calibrated models are available yet, within a limited time frame and budget, and thus stimulating port development and other economic activities in developing countries The paper also shows how the triangular mesh provides flexibility to adapt the model to various alternative designs and the client’s whishes, also in a later stage of the project.

In recent years, the Dutch Olympic sailing team has started using numerical models to obtain accurate and reliable site specific current forecasts in important competitions such as the Olympic Games. Sailors use knowledge on the prevailing currents in the racing area to adjust their strategy in order to optimise their achievement in competition. The numerical flow model FINEL2D is used to provide specific current forecasts for the Dutch team during both training and races at the Olympics of 2008, 2012 and 2016. The Olympics of 2008 and 2016 were held in China and Brazil, which are both considered upcoming economies. The set up, calibration and use of the separate models for each of the venues are practical examples of how the FINEL2D model can be applied to obtain site specific conditions within limited time frame and budget, and may be considered as a guideline for the application of hydraulic models in port development in this paper.

1. INTRODUCTION

In order to develop hydraulic structures in the context of port development or coastal defence systems, a multidisciplinary approach is applied increasingly. In such a multidisciplinary team, model developers and users work closely together for a fast and efficient design process. The interaction between the results of numerical models and layout optimization in the design process is becoming more and more important. In developing countries, resources such as finance, knowledge, site specific data and numerical models itself not always readily available yet. Therefore there is a need for numerical flow models that can be deployed in a flexible way, within limited budget and time frame, at locations where no calibrated models are available yet.

The two-dimensional depth-averaged numerical flow model FINEL2D is a model that meets these requirements. The purpose of this paper is to show that this model possesses the properties listed above and to illustrate the application of this model in practice by means of a case study. Besides, the paper shows how the model output format can be easily adjusted to fully focus on the knowledge level, desires and goals of the client.

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The case study that is described in this paper focuses on the use of site specific current forecasts by the Dutch Olympic sailing team during the Olympic Games in Beijing (2008), London (2012) and this year (2016) in Rio de Janeiro. In this paper the focus is on the most recent application: the FINEL2D model of the Brazilian coast and Guanabara Bay.

Background information on the application of current information by sailors is given in Chapter 2. The FINEL2D model set up for the case study is explained in Chapter 3. Subsequently, Chapter 4 briefly discusses the current measurements that were done on site, followed by an explanation of the model calibration in Chapter 5. A description on how the current information of the models was brought to the sailors and their trainers in a practical and easy to interpret format is presented in Chapter 6. Finally, conclusions are drawn in Chapter 7.

2. BACKGROUND

Highly qualified sailors and high quality sailing equipment are key factors for success in international sailing competitions. Increasing innovation and professionalism in boat design and team training make it more complicated to make the difference on these key factors. Knowledge of other factors, such as the wind and currents conditions are becoming more and more important to stay one or more boat lengths ahead of the competition in decisive medal races.

Sailors use knowledge on the prevailing currents in the racing area to adjust their strategy in order to optimise their achievement in competition. Knowledge of current patterns is especially of importance in sailing competitions when there is little wind. With race duration of approximately one hour, distances sailed during the race are limited. In order to distinguish one in tactics, very accurate and reliable knowledge of the current can be essential.

In recent years, the Dutch Olympic sailing team has started using the numerical model FINEL2D to obtain accurate and reliable site specific current forecasts in important competitions such as the Olympic Games. For the Olympics of 2008, 2012 and 2016, separate models are set up and calibrated for each of the three venues, and used during both training and races. For the Games of 2012 and 2016, measurement campaigns have been carried out in the context of the model calibration, focusing on the specific racing areas.

In this paper the focus is on the FINEL2D model of the Brazilian coast and Guanabara Bay, used for the Olympics of 2016.

Guanabara Bay, the venue for the Olympic Sailing Games 2016, is a large bay adjacent to the city Rio de Janeiro. The bay has a length (north to south) of approximately 30 km and a maximum width (east to west) of approximately 28 km. The entrance of the bay and the connection with the ocean is only 1.6 km wide, which is relatively narrow (Kjerfve et.al, 2001). The mean tidal range in the area is approximately 0.7 m, with spring tidal range of about 1.1 m and a neap tidal range of about 0.3 m. In combination with the large surface area of the bay, the tidal prism is significant, leading to flow velocities which reach up to nearly 2 m/s in the narrow bay entrance.

The bay consists of deep and shallow areas, see Figure 1, and has alternately sandy beaches and rocky coasts. The bathymetry is complex, with characteristics like submerged rock outcrops and jagged rocky coasts. This results in complicated current patterns with impressive eddies and large velocity gradients. Experience has shown the importance of a number of (small scale) features in this sailing venue. This makes it a challenge for the sailors to make good progress, and also a challenge for the modellers to produce reliable current forecasts in this area.

3. NUMERICAL FLOW MODEL FINEL2D

General

The numerical flow model FINEL2D is a two-dimensional depth averaged and process-based model, developed by Svašek Hydraulics over a period of more the 25 years. This model is based on the shallow water equations and is numerically solved by means of the finite element method. The governing equations are described in Dam et.al. (2007).

The model uses an unstructured triangular grid, providing flexible mesh generation, ensuring that no nesting techniques are required for areas of specific interest where high resolution is required, while arbitrary coastlines and complex geometries can be resolved very well. Besides, the mesh is relatively easy to adjust, proving flexibility in the set up of the model and offering the opportunity of adapting the model grid several times during the design process to cope with changes in layout.

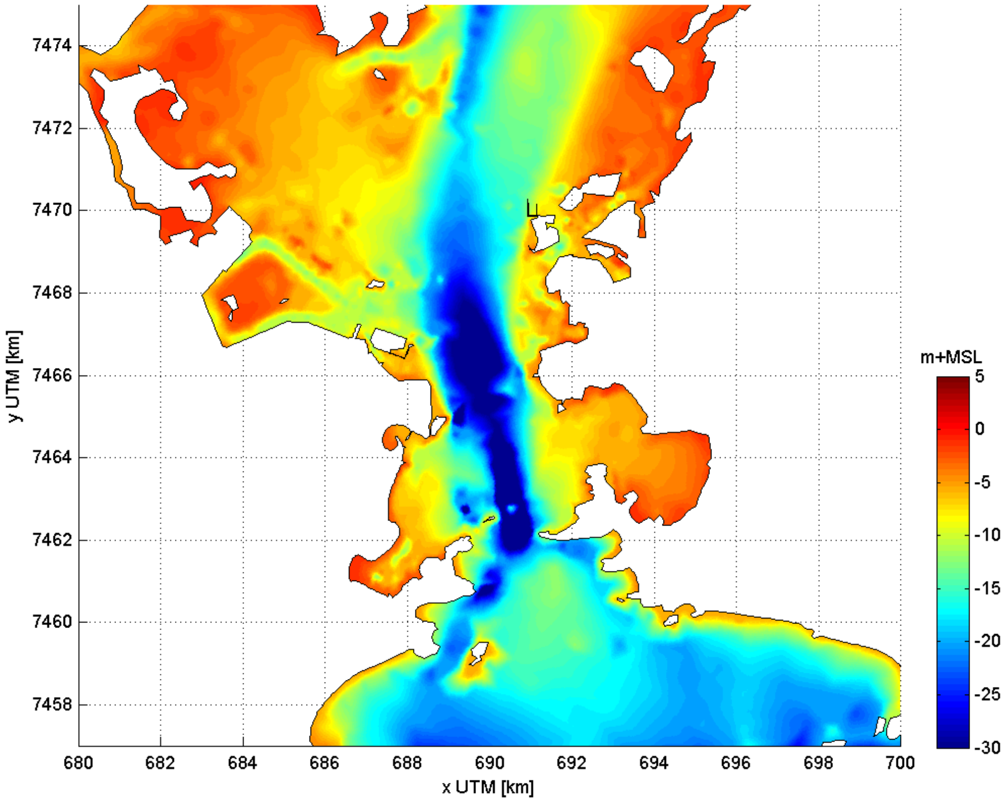

Figure 1: Bed level of the southern part of Guanabara Bay related to Mean Sea Level (MSL); based on Admiralty Charts.

Model set up

The model domain of the FINEL2D model of Guanabara Bay, the venue for the Olympic Sailing Games 2016, consists of a 400 km long part of the Brazilian coast, stretching from approximately Ubatuba to Macaé. The extent of the model domain is shown in Figure 2, together with the computational mesh. The size of the approximately 260.000 grid elements, in this case triangles, varies throughout the model domain and consists of large triangles with an element side length of 3500 m near the boundary and small triangles with a element side length of 40 m in Guanabara Bay, see Figure 3. By varying the grid size, an optimal mesh in terms of both computational speed (limited amount of elements) and accuracy (high resolution in area of interest) is created without using complex and time consuming nesting techniques. Besides, the use of triangular elements enables the model boundary to follow the coastline smoothly as illustrated in Figure 1, Figure 2 and Figure 3, without irregular jumps that are usually present at the coast in meshes consisting of rectangular elements.

The computational mesh is created by means of the public-domain software Triangle (Shewchuk, 1996). The input that is required to create a triangular mesh consists of little more than a set of polygons to define model boundaries, areas of specific element size, islands and local features. Mesh construction requires only limited time and effort, and is besides easy to adjust by simply changing the input polygons. Because of this, the mesh can be easily adjusted, for instance during the design process of ports or hydraulic structures and several designs can be investigated by model simulations in a short period of time.

The bathymetry of the Guanabara Bay model is based on the most recent Admiralty Charts of the area. The model bathymetry at the entrance of the bay is shown in Figure 1.

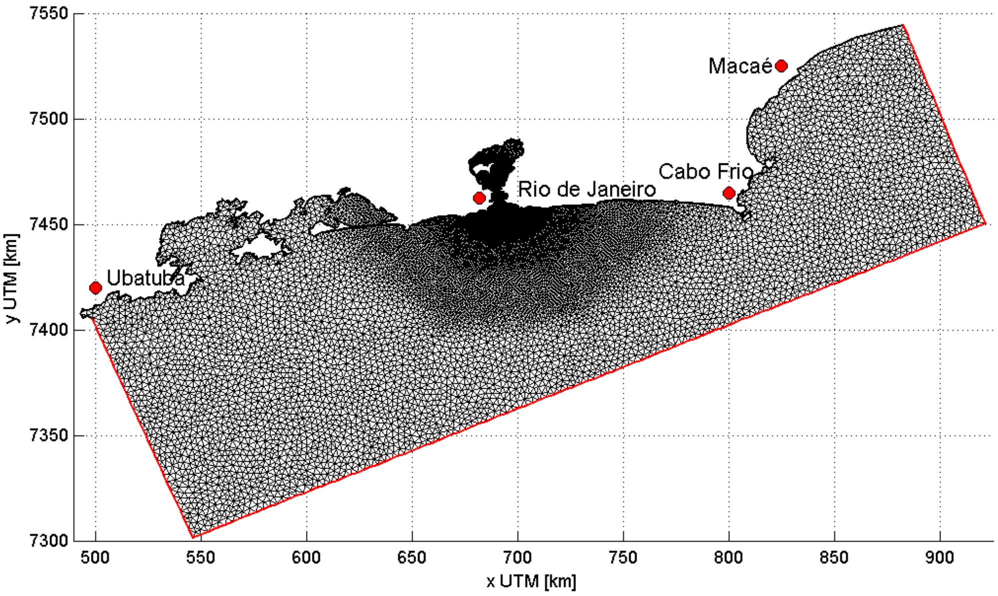

Figure 2: Computational mesh of the FINEL2D model of Guanabara Bay.

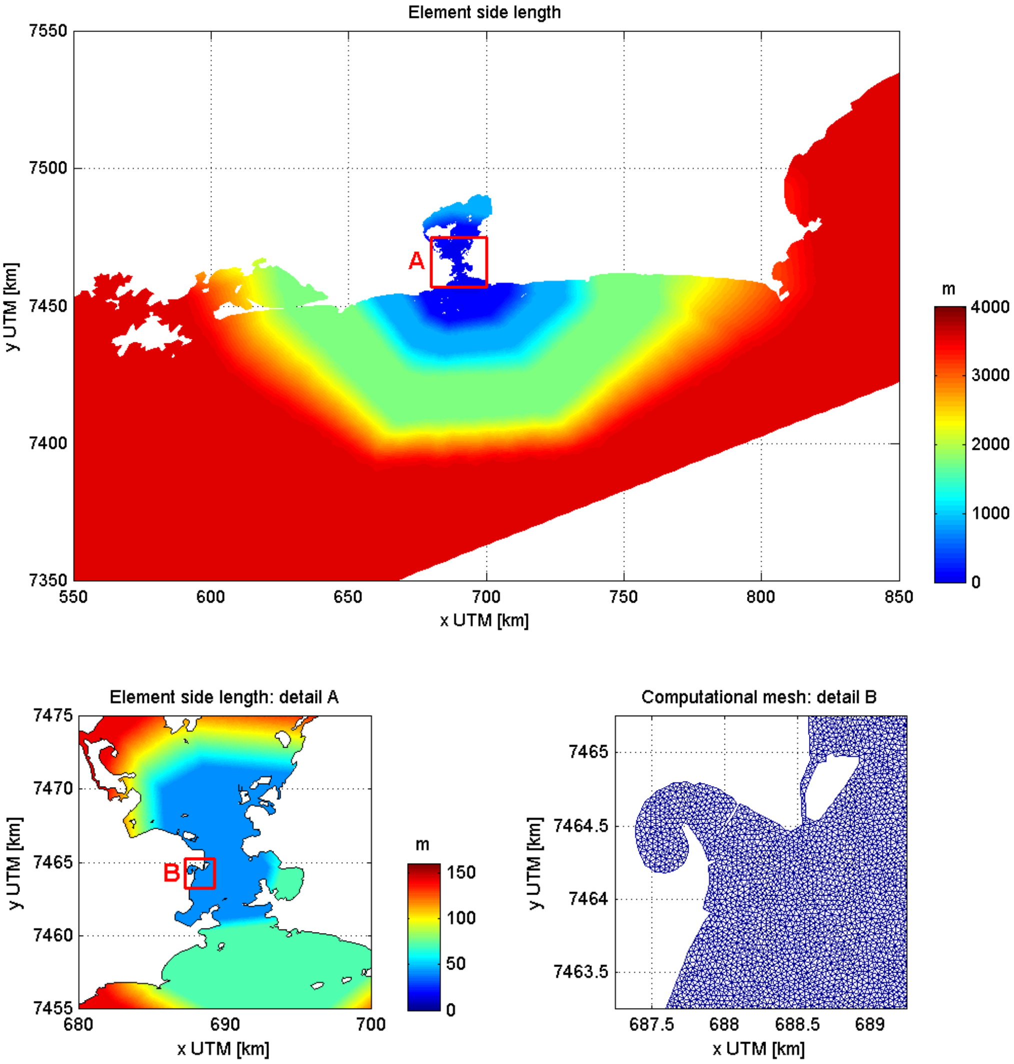

Figure 3: Horizontal grid size throughout the FINEL2D Guanabara Bay model domain, in Guanabara Bay (detailed view A) and around Marina da Gloria (detailed view B).

Harmonic tidal boundary conditions are imposed onto the seaward boundary of the model; see the red line in Figure 2. The boundary conditions are extracted from the TPXO model, which determines the amplitude and phase of several harmonic constituents based on TOPEX/POSEIDON and Jason satellite data. The methodology behind the TPXO model is described in Egbert et.al. (1994) and Egbert and Erofeeva (2002).

Inclusion of the effect of wind shear at the water surface by using wind fields that may vary in time and space is optional. The same applies for any outflow of rivers and/or the impact of wave induced currents.

A model option that has not been used in the application for the sailing event is to include the movement of sediments (sand and/or mud) in the model. Gradients in sediment transport can easily be transformed in bed level changes, which in turn have an impact on the currents. In this way the morphodynamic behaviour of the area of interest can be modelled over a period that can be as long as decades. An example of this application is shown in Dam et. al. (2013, 2016).

The FINEL2D model is capable of performing parallel computations, i.e. on several CPU's simultaneously, limiting the computation time of the model simulations. On a 16 Intel® Xeon® CPU E5-2640-v3 machine, the nature to computer time ratio is 25 to 1, simulating one day of hydrodynamics in circa one hour.

4. FIELD MEASUREMENTS

The application of numerical flow modelling as a support for sailing teams requires a high level of detail and precision in both space and time and sets even higher standards to the performance of the numerical model used than usually required in traditional model applications. Experience shows the importance of (small scale) features in the sailing venue. The complex bathymetry with characteristics such as islands, obstacles below the surface and a partly jagged rocky coast, results in complicated current patterns with impressive eddies and large velocity gradients, showing the importance of model calibration and the need of sufficient reliable water level and current measurements.

Developing countries can generally de characterized as data-poor environments, which complicates model calibration. Although Guanabara Bay cannot entirely be considered a data-poor environment, some of the data in this area is not publically accessible.

In the context of the model set up and calibration, a two-week measurement campaign has been carried out in cooperation with the Brazilian Navy and the Dutch Water Sport Association in March 2013, focussing on the specific racing areas in the bay.

The water level is measured during a complete spring-neap cycle using a Schlumberger Micro-Diver. A Baro-Diver is used to correct for air pressure variations. Necessary current data is gathered by means of five sessions of sailed current measurements, using a Nortek 1 MHz AWAC fixed to the vessel by a frame and connected to a GPS system to automatically correct for the vessel motion. Sailed current measurements offer the opportunity of mapping the current pattern in a significant part of the area of interest by sailing several transects in the bay, choosing the length of the transects such that it is long enough to cover a significant part of the area, but short enough to limit the time interval between two data points at each location. The measured transects are shown in Figure 4. Transect A has a triangular shape, transects B, C and D are straight lines. Transect A is measured twice, during both spring and neap tide. Each of the current measurements is performed over an entire tidal cycle, thus over 13 successive hours.

Although a measurement campaign is generally intensive and some experience is required, it also offers the opportunity to collaborate with and transfer knowledge to local engineering companies. Meanwhile, measurements do not necessarily have to be expensive, while the acquisition of existing data in relatively data-poor environments can be very time consuming, making a measurement campaign worth the effort in terms of both time and costs.

5. MODEL CALIBRATION

The obtained data is used to calibrate the FINEL2D model. The first step in the calibration process is on water levels at several tidal stations along the Brazilian coast, with focus on the tidal station in Guanabara Bay; see yellow dot near transect C in Figure 4. Several data sets have been used for water level calibration: predicted astronomical high and low water levels at several stations (Brazilian Navy), water level measurements at the Rio de Janeiro tide gauge (Figure 4) and water level measurements obtained with the Micro-Diver at Rio de Janeiro. Note that the tide gauge series and diver series are almost identical, and that the high and low water predictions are only order 10^{-1} m accurate. Differences up to 0.3 m are present between astronomical predictions and observed water levels; see Figure 5, showing the importance of air pressure and wind set-up or set-down effects.

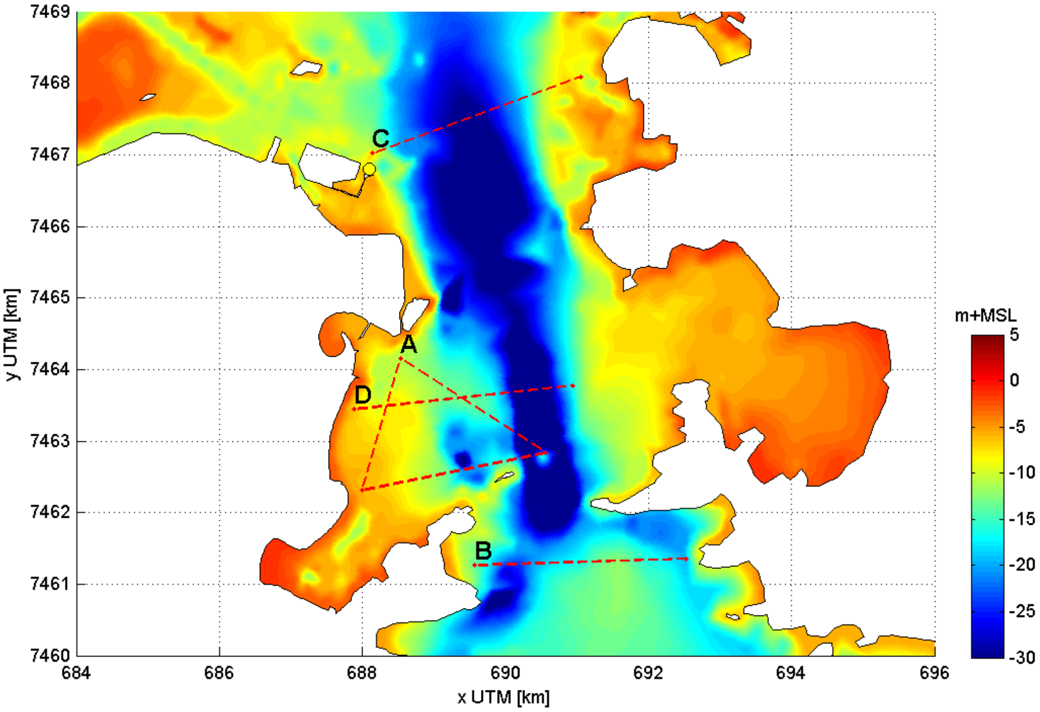

Figure 4: Transects for full-tidal cycle sailed current measurements. The yellow dot near transect C indicated the tide gauge of Rio de Janeiro.

During the water level calibration, the focus is on astronomical tidal conditions. Apart from Rio de Janeiro, not enough information on the air pressure and wind fields in the complete model domain is available to include metrological parameters in the FINEL2D model and reproduce the observed water levels correctly. Water level variations due to tidal motion are mainly influenced by the bottom roughness, which can be therefore used as a calibration parameter. Optimal results were obtained for a Nikuradse roughness height of 0.02 m over the full model domain; see Figure 5. The water level deviations are generally limited to several centimetres and are therefore within the accuracy limits of the astronomical predictions. Phase differences are generally not larger than 10 minutes.

Calibration on currents is the second step in the calibration process. For this purpose, the current data obtained by means of the measurements in March 2013 are compared to the FINEL2D model output. The focus has been entirely on Guanabara Bay, since this is the area of interest and no current measurements are available outside this area. Small variations in again the bottom roughness have been attempted for further improvement of the model results, confirming a Nikuradse roughness height of 0.02 m.

The FINEL2D solver causes some numerical diffusion. The impact of this numerical diffusion on the current is investigated by locally refining the computational grid, hence reducing the diffusion. Differences in model results were however not significant.

The modelled and observed current in Guanabara Bay on March 27th 2013 between circa 14.50 UTC and 15.30 UTC is shown in Figure 6. The observed current is indicated by means of black arrows; the modelled current is indicated by blue arrows. The observed and measured water levels are presented as well. The figure shows that the observed and modelled current patterns correspond very well. The calibration at other locations and time frames shows similar correspondence between measurements and model results (not included in this paper).

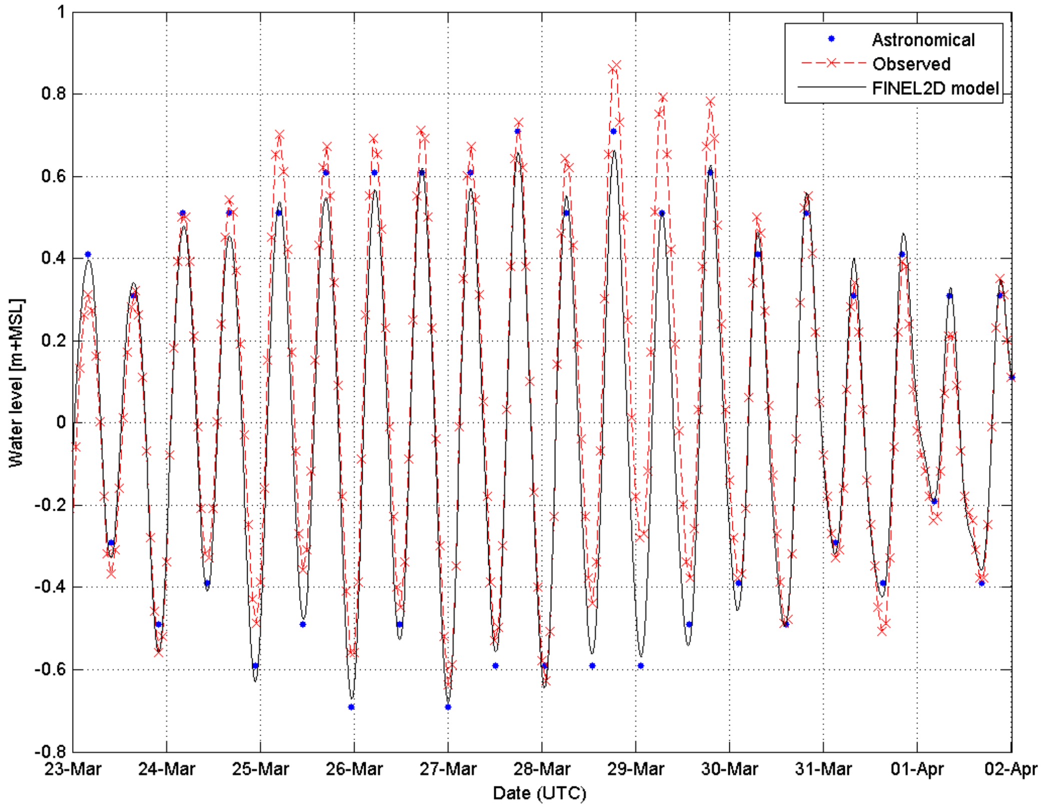

Figure 5: Observed, astronomical and modelled water level during a spring-neap cycle in March 2013, at Ilha do Fiscal, Rio de Janeiro.

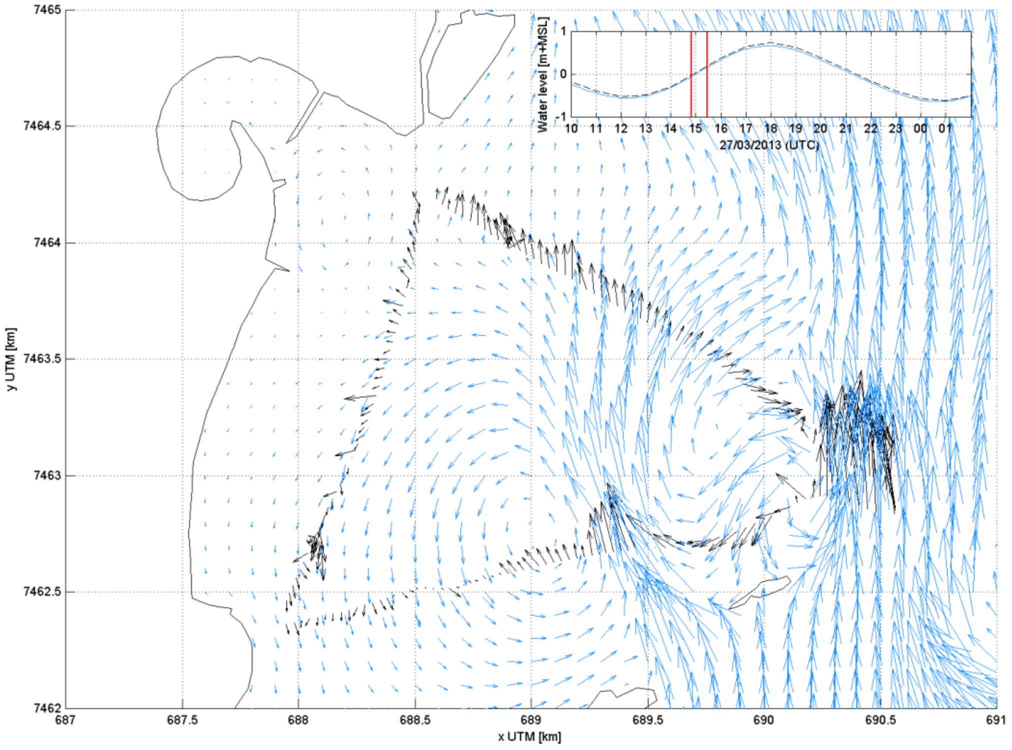

Figure 6: Measured (black) and modelled (blue) current and water level along transect A on March 27th, 2013, between approximately 14.50 and 15.30 (UTC).

The time series of the observed and modelled velocity at two points along transect A, near the northern and eastern corner, is shown in Figure 7. Both the variation in time and order of magnitude of the velocity are reproduced well by the FINEL2D model. Deviations are generally in the order of 10^{-1} m/s.

There are several reasons for the deviations, such as small errors in the model schematisation, the use of Admiralty Charts for the bathymetry (with focus on high spots) and inaccuracies in the measurements. Besides, in Figure 5 is shown that meteorological aspects, which have not been taken into account in the model calibration, have also an impact on the water levels in the bay, and consequently also on the currents in the bay. Considering the several aspects that can be responsible for deviations between observations and model results, it can be concluded that model output and current data correspond well and that the water motion in Guanabara Bay is adequately calibrated, allowing for application of the model for current forecasting for the sailing team.

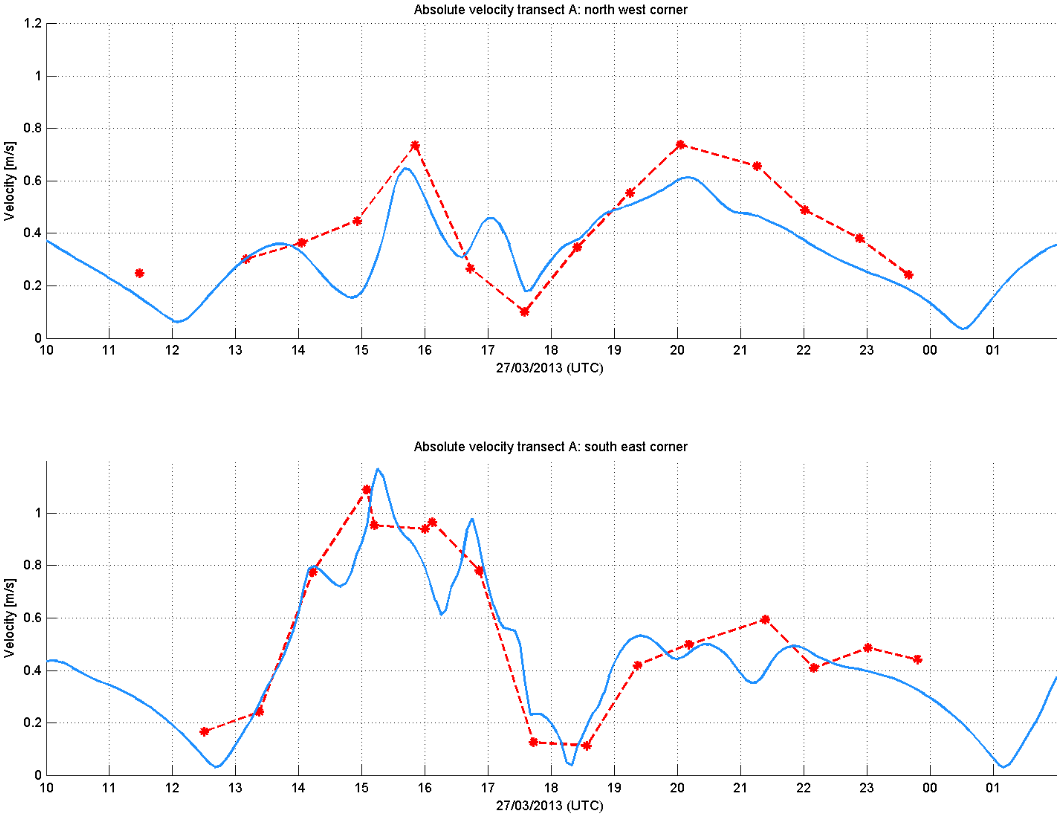

Figure 7: Observed (red) and modelled (blue) velocities at two locations along transect A on March 27th, 2013.

6. APPLICATION

The calibrated FINEL2D model of Guanabara Bay is used to provide accurate and reliable site specific current forecasts to the Dutch Olympic sailing team during both training and races at the Olympic Games of 2016. The current information of the models was brought to the sailors and their trainers in a practical and easy to interpret format, consisting of animations and charts of the currents of each of the racing areas, showing the current every 10 minutes. The currents is shown in m/min instead of m/s; a widely used unit in sailing. An example of such a chart is shown in Figure 8.

Taking meteorological forecasts into account in the FINEL2D model could improve the model results and subsequently the current forecasts, but also adds an uncertainty to the predictions. When the actual meteorological conditions deviate too much from the forecast, current forecasts could become suddenly less accurate then they would have been without inclusion of air pressure and wind, even when the FINEL2D model simulations are performed shortly in advance of the races. Therefore it is decided to deliver astronomical current forecasts to the sailors. These are completed with the results of an extensive sensitivity analysis on wind effects, showing coaches which deviations in the current pattern can be expected for specific wind conditions.

To improve the model performance, coaches carry out basic current measurements during training weeks in advance of the Games and report their experiences on the current pattern to the modelling team. Results are discussed between the modellers and the sailing team, this way validating the FINEL2D model. Feedback on the presentation of the forecasts is also given by the sailing team and if necessary, adjustments are made. This way, the validation and presentation of the model can be seen as a concerted action of sailing and modelling teams, while simultaneously achieving transferring knowledge on the physical processes concerned to the sailing team.

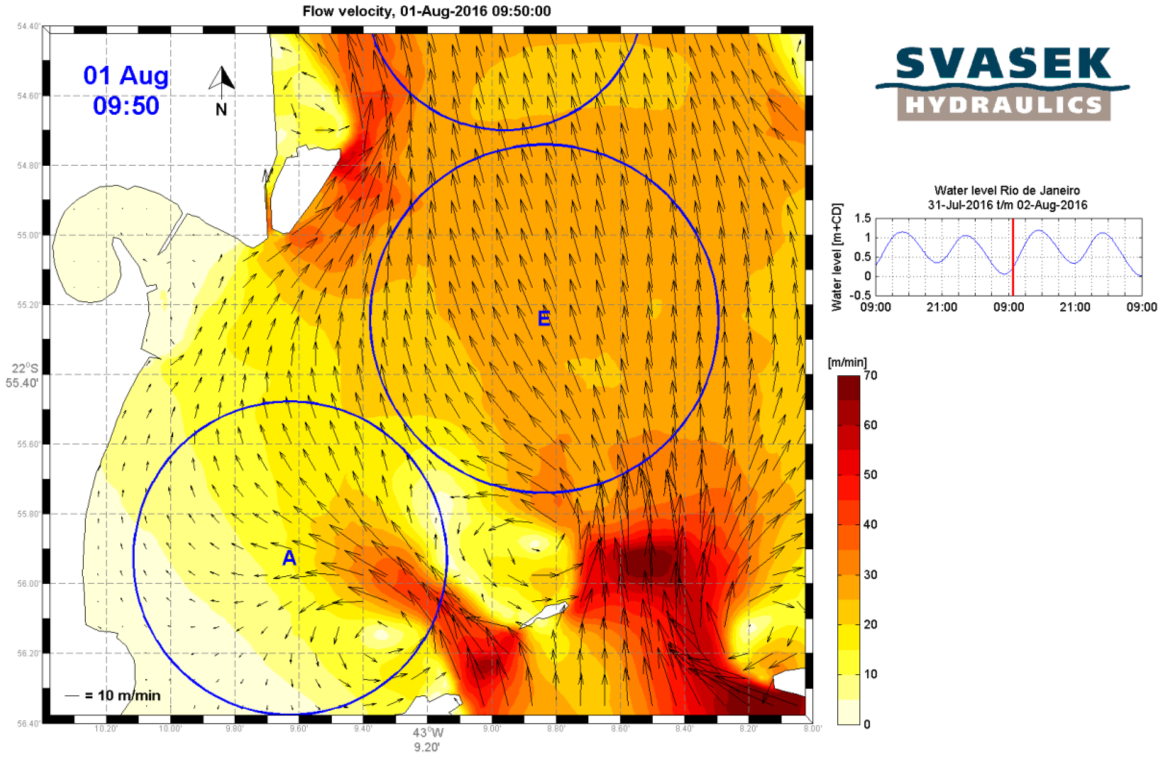

Figure 8: Example of a current chart provided to the Dutch Olympic sailing team for training in Guanabara Bay. Note that the velocity is indicated in m/min.

7. CONCLUSIONS

Optimal design of hydraulic structures and port development requires accurate and reliable knowledge of the hydraulic conditions. Several designs should be investigated in often a short period of time and within limited budgets, increasing the role of numerical models in the design process and demanding flexible, fast and efficient use of these models. This holds even more for developing countries, where in general knowledge is lagging, field data is poor and budgets are limited.

The two-dimensional depth averaged and process-based numerical flow model FINEL2D has proven to be a suitable tool to deal with these conditions. On the basis of the case study presented in this paper it is shown that by using a triangular mesh and grid generator TRIANGLE, a FINEL2D simulation is easy to set up, simultaneously offering flexibility for grid adaptations and computation speed, making it a very useful model in a design process.

The case study has also proven that the FINEL2D model accurately simulates water levels and currents even in very complex areas. The model is successfully calibrated for Guanabara Bay, where no ‘on the shelf’ model was available yet, within a limited time frame and budget.

By cooperating with local authorities during the field measurements, knowledge is transferred, to the client representatives. Involving the client already during the model calibration and validation, has resulted in a model that fully focused on the desires and goals of the client, bringing the current information of the models to the sailors and their trainers in a practical and easy to interpret format.

The model is not only suitable to repeatedly provide current forecasts to the Dutch sailing team, but also for port development and the design of hydraulic structures all over the world.

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