PAPER 7

MODELLING AND FORECASTING DURBAN'S OCEAN AND NEARSHORE WATERS

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ABSTRACT

Climate change has increased the need for reliable modelling and forecasting across the globe. eThekwini Municipality in conjunction with Deltares, for more than 10 years now, has established and continuously developed their Forecast Early Warning System (FEWS) to predict inland flooding. The Municipality is now extending this system to operationally model and forecast scenarios at the coast.

Durban's shore faces several challenges and threats from the coast. These include incidental flooding of the promenade, rip currents, and poor water quality due to spills and floating debris. This supports the need for an integrated coastal modelling system, linking the offshore currents and waves with detailed nearshore models. Data inventory, data collection and process understanding relevant to the location of interest, are extremely important for model validation and calibration. Fortunately, eThekwini already has extensive monitoring in place that can be used to validate these models. These include tide gauges, ADCP's, wave buoys, radar, and beach cameras, which are all already incorporated within eThekwini's FEWS.

The coast of Durban experiences many contributing factors which requires the integration of ocean and nearshore modelling to accurately depict its complex dynamics. Therefore, several models need to be developed and calibrated to incorporate ocean and nearshore currents, waves and inundation. These were Delft3D Flexible Mesh, SWAN, Xbeach, and SFINCS respectively. Water levels affect Durban's coastline from tide, storm surge, waves, sea level rise and potentially tsunamis. Durban's tidal range reaches up to 2m with storm surge only reaching 0.4m. Durban has two dominant wind directions: South to Southeast between March and November; and a dominantly North Easterly from December to February. Ocean swell waves and local wind-induced waves are propagated to the shore and affected by refraction, shoaling, and breaking. The Agulhas Ocean current creates spin-off features such as eddies which together with tide- and wind-induced currents impact the Durban nearshore region.

All these driving forces need to be considered when developing a well-calibrated coastal modelling system for operational use. This article will present the integrated coastal modelling presently being developed and calibrated at eThekwini Municipality.

INTRODUCTION

Coastal cities are continuously being affected by changing sea levels. Rising sea levels promote inundation of low-lying areas, erodes shorelines and contributes to coastal flooding. This in turn makes coastal infrastructure more vulnerable to damage from coastal storms. Coastal storms can be devastating to coastal communities and can result in loss of life, displacement of residents and damage from coastal flooding. Coastal flooding can be driven by different forcing mechanisms occurring at the same time. Compound flooding in coastal areas can be caused by the interaction of high sea levels, large river discharges and local precipitation (Wahl et al., 2015). To reliably assess the flood risk caused by compound flooding events in specific regions, uncertainties regarding these different flooding mechanisms need to be considered for the area of interest.

Durban is located on the east coast of South Africa in the KwaZulu-Natal Province. It is one of the country's biggest cities and has one of the busiest ports in Africa (Guastella, 1994). Durban experiences a semi-diurnal tide with a meso-tidal range of 1-2m (Bosboom and Stive, 2013). The associated Tidal currents are small compared to other hydrodynamic processes along the coast and the water column is considered to be generally well mixed, with mixed layer depths reaching more than 20m deep (Malange, 2018). Durban has a maximum tidal range of 2m, and storm surges can increase the water level up to 0.4m (Rautenbach, Barnes and de Vos, 2019).

The wind along the Durban coastline originates from two pre-dominant wind directions: South to southeast from March to November and Northeast from December to February (Lamont et al, 2016). Storm winds, extreme swell and heavy rainfall are mostly related to cut off lows. These cut off lows can become isolated and persist for several days southeast of Durban. Wind induced currents only reach up to 0.2m/s on the adjacent shelf off Durban (DNV-RP-C205, 2010). The annual wave climate consists of south to south-eastern swell (Corbella and Stretch, 2012), with the significant wave height reaching up to 8m during storm events. Tidal currents are less than 0.1m/s, and wave induced currents occur only at the breaker zone (Naidoo, 2021).

A predominantly north-eastward flow (as evident from the longshore drift of sediment) persists off Durban, with the occurrence of regular current reversals (Schumann EH, 1988). Local wind patterns can occasionally cause flow reversals of near-surface water, but the consistent nature of the flow suggests the recirculation of inshore water off a stronger current, the Agulhas Ocean Current (Naidoo, 2021). Consideration of the effects of this ocean current

FIGURE 1: *Delft-FEWS Coastal Framework*

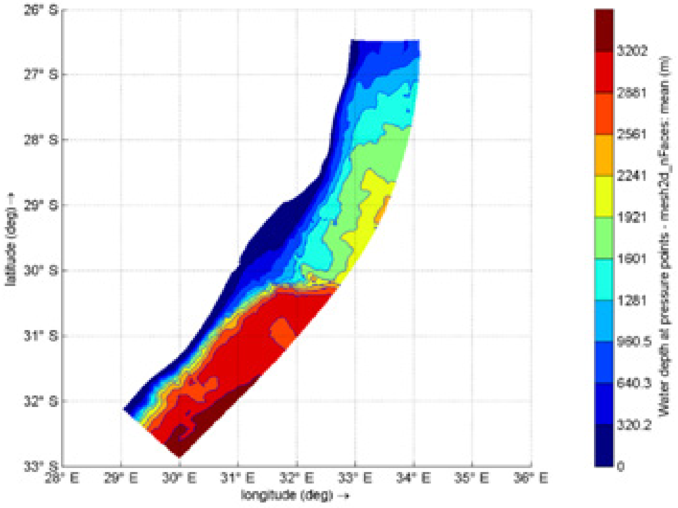

FIGURE 2: *Location of the model in spherical co-ordinates.*

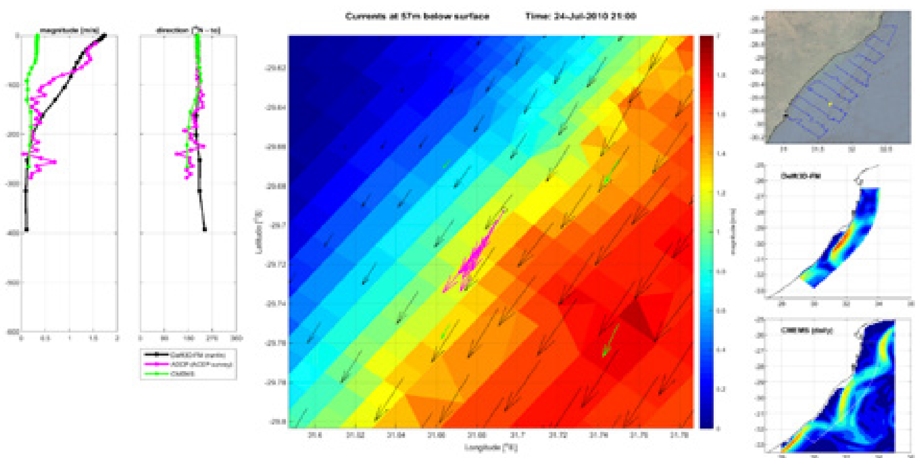

FIGURE 3: *Left: Vertical Profiles for Velocity Magnitude and Direction for Delft3D FM, ADCP and CMEMS. Middle: Surface map showing velocity vectors indicating current magnitude at 57m below surface of water. Right: Top image shows location of ADCP within ACEP survey, Middle image shows velocity magnitude surface map for Delft3D FM model and bottom right shows CMEMS surface map for velocity magnitude. Taken from Naidoo, 2021.*

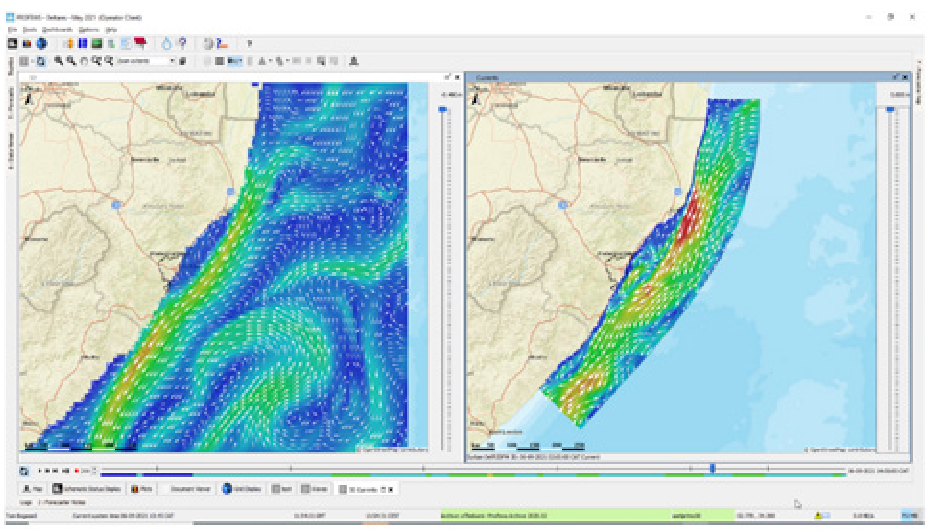

FIGURE 4: *Screenshot taken from eThekwini Municipalities FEWS, showing CMEMS model (left) and Delft3D Flexible Mesh model (right).*

is crucial in the first step of modelling and forecasting Durban's Ocean and nearshore waters. Responsible coastal engineering designs require predicting the impacts that these currents have on eThekwini's coast and to quantify coastal processes. The configuration and combinations of eThekwini's Coastal FEWS (Forecast Early Warning System) will be discussed in this paper.

MODELLING AND FORECASTING

eThekwini Municipality has developed a Forecast Early Warning System (FEWS) that focuses mainly on predicting stormwater related floods. The next phase of the early warning system for the Municipality is to couple inland and coastal forecasting and modelling. As shown in Figure 1, the three key areas within the modelling framework include a hydrodynamic model (Delft3D Flexible Mesh), a wave model (SWAN) and inundation models (X-beach and SFINCS). These will be used to model currents, waves and coastal flooding respectively.

Currents

In order to include the dynamics of nearshore processes along the eThekwini coastline, a regional-scale ocean model needed to be developed to incorporate tide, wind and ocean currents. The Agulhas current is a strong western boundary current that flows along the east coast of South Africa. This current could significantly influence the coastal dynamics of Durban and will therefore be critically analysed in this research.

Currently, large scale global ocean models are useful in predicting mesoscale (10 – 100km) hydrodynamics associated with ocean currents. However, models with higher grid resolution are required to better predict regional-scaled features and is more beneficial for near shore analytical purposes for role players of coastal cities (Naidoo, 2021). Therefore, the need for an ocean model for the KZN coastline stems from the increase in interest of wave and current activity.

A Delft3D Flexible Mesh model was configured for eThekwini's coastline. Figure 2 shows the extent of the model and the associated water depth. Model Forcing included ECMWF ERA5 wind and air pressure fields, FES-2012 astronomical tide constituents (excluding seasonals), Copernicus Marine Environment Monitoring Service (CMEMS) boundary conditions for sea surface height, currents (u,v), salinity and temperature and CMEMS data fields (as initial conditions) for temperature and salinity.

Details of Model:

- Flexible Mesh Grid
- Model Extent: 150km cross-shore, 850km long-shore
- 3 open boundaries (north, east and south)
- Coarse resolution (5km) in deep water, high resolution (200m) along the coast and relatively high resolution at upper shelf slope
- Interpolation of bathymetry: detailed survey near Durban port (eThekwini internal data), digitised depths from a nautical chart (from Navy) and GEBCO in the deeper ocean

The initial results of the Delft3D FM model with ocean forcing at the open boundaries look very promsing when compared to Accoustic Doppler Current Profilers (ADCP) data from the African Coelacanth Ecosystem Programme (ACEP) survey and CMEMS. At times the model compares very well with measurements, but sometimes the model can be off. This however is not surprsing given the stochastic and 3-dimensional behaviour of this complex flow regime. One relevant aspect is to get more accurate and detailed data on the depths at the upper shelf slope.

oth the Delft3D FM model and CMEMS currently run operationally in eThekwini's FEWS. From Figure 4 above, the Delft3D FM model depicts more refined results for velocity magnitude and direction closer to the coastline compared to CMEMS. Similarly, within FEWS, the same can be compared for temperature and salinity. In this instance, the formation of a Durban Eddy can also be noticed in the Delft3D FM model.

Accurate water level and current forecasts are currently being produced by the Delft3D FM model which is running live in FEWS. These forecasts can then be used as input conditions for a wave model.

Waves

Simulating Waves Nearshore (SWAN) was used to develop a wave model for eThekwini's offshore waves. SWAN is a third-generation wave model that computes random, short-crested, wind-generated waves in coastal regions and inland waters. Model forcing includes GFS surface winds, WW3 Ocean Waves as open boundary conditions and water level fields from the D-Flow FM model. This model will be used to forecast waves (combined sea and swell) along the coast and produce wave parameters (significant wave height and wave period) as input for the inundation models.

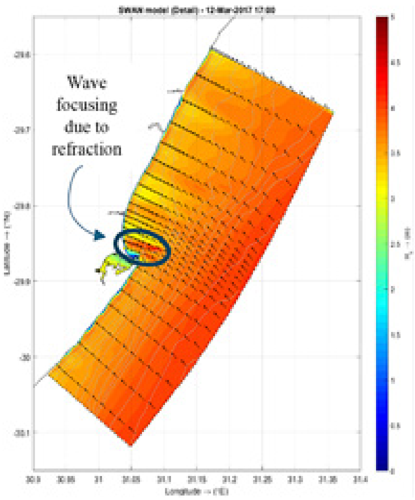

FIGURE 5: *eThekwini's unstructured SWAN Model showing significant wave height (Hs) for the 12th of March 2017*

Details of Model: Unstructured SWAN Grid

- Extent: 150km longshore and 60km cross-shore
- Resolution: Deep waters is 2km grid cells, with 20m resolution along the coast
- 3 open boundaries (north, east and south)

In Figure 6, one of eThekwini's datawell buoys was used to compare the results from the SWAN model. The model performs well when compared to the measured data and was therefore configured in FEWS to run operationally.

Figure 7 below shows a typical illustration of the SWAN models outputs in the FEWS Operating Client. Wave roses showing directional spread can be seen as well as the hindcast model data in comparison to observed measurements, with a continuation of this model predicting a wave forecast.

INUNDATION

In March 2017, Durban experienced overtopping of its promenade along its main beachfront area (see Figure 8). Although coastal flooding is not common in this area, mini "tsunami-like" waves were seen approaching New Beach in Durban's central beachfront. It was speculated that the cause of this coastal flooding could have been from the aftereffects of cyclone Enawo which

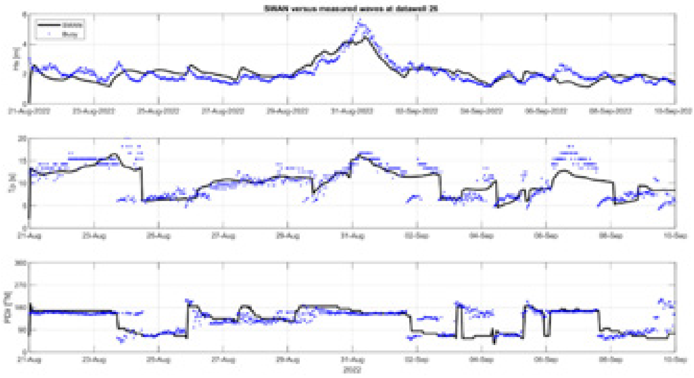

FIGURE 6: *Results of SWAN model compared to a Datawell buoy off Bluff. Top: Significant Wave Height (Hs) in metres. Middle: Wave Period (Tp) in seconds. Bottom: Wave Direction (PDir) in degrees north.*

landed over Madagascar on the 8th of March 2017, or that it was just a result of strong winds that provoked a tropical cyclone storm surge.

Unfortunately, the only available evidence of this coastal event, besides the damage to infrastructure, is video footage that can be found on YouTube. From inspecting and collating these videos, the extent of the flooding was demarcated in Figure 9 (between North and South Beach). In particular, the pools seen in Figure 9 were completely covered with sea water from the coastal flood. This was an unusual event as this stretch of beach is generally well protected by the shape of the coastline and the harbour breakwaters. Therefore, it was difficult to determine the cause of the flood. High tide, storm surge and swell waves were all investigated for this case study.

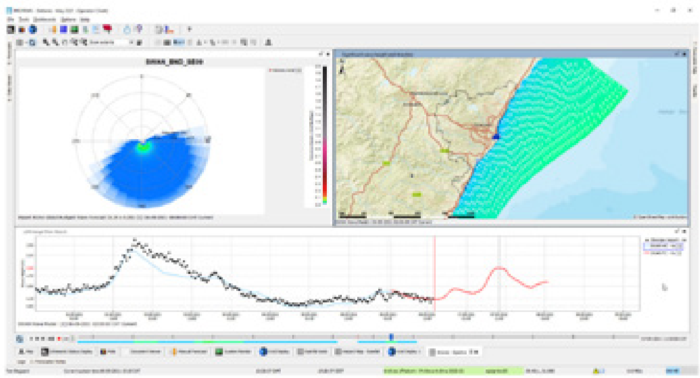

FIGURE 7: *Typical SWAN output from FEWS, including wave composition (top left), SWAN model grid (top right) and hindcast and forecast data (bottom).*

FIGURE 8: *Overtopping of Durban's Beachfront on 12 March 2017, taken from an article in Times Live (Patrick, 2017)*

Although limited real-time data was available during the event, that by collecting and studying data from various public sources and by using our models, a very realistic representation of the promenade flooding could be made.

In Figure 5, it is important to note the wave focusing that is being modelled for the same date as the coastal flood in Figure 8. This is due to refraction primarily caused by the angle (from 132°N or SE) in which the waves approached the coast. In order to accurately depict this coastal flood, the SWAN models' outputs were translated to provide the water levels and waves near the beach. A 1D X-Beach non-hydrostatic model that resolves individual surface gravity waves was developed to interpolate and model the wave inputs.

Details of Model: 1D X-Beach non-hydrostatic
Forced offshore with a Jonswap spectrum
(wave parameters from SWAN model)

- Extent: 1D transect out to 40m water depth
- H_{m0} = 3.9 (Significant wave height offshore)
- T_p = 15.3 (Peak period)
- z_s = 1.25m above MSL (tidal water level)

Figure 11 shows the results for the X-beach run for the coastal flooding event. Individual incoming waves can be seen as relatively high, with individual waves overtopping the promenade level. Although the slope of the nearshore zone dissipates the incoming waves, it is evident that some part of the wave overflows onto the level of the promenade. These results were then used for the boundary conditions of the overland model to replicate the coastal inundation experienced for this event.

The Super-Fast INundation of CoastS (SFINCS) model will be used for overland inundation in FEWS. SFINCS is the first reduced-physics model to include all relevant processes for the computation of coastal compound flooding, i.e. fluvial, pluvial, tidal, wind-driven surge and waves (Leijnse et al., 2021). This application was chosen over the 2D X-Beach model as it efficiently simulates compound flooding events with limited computational cost and good accuracy. Operationally, computational power is crucial when predicting upcoming forecasts and SFINCS allows the optimisation of computational ability as its processing potential is much faster than other inundation models. SFINCS was used as a pilot study for the Durban's main beachfront area to replicate the coastal flooding experienced on the 12th of March 2017.

Details of Model: SFINCS
Split water level into in- and outgoing wave components at 2m water depth - only incoming waves contribute to inundation

- Extent: 1D transect out to 40m water depth
- Boundary conditions = Incoming waves + tide (1.25m above MSL) + wave setup
- Promenade topography where topo > 1.5m above MSL was taken from eThekwini Lidar
- eThekwini bathy survey was merged with topography

The SFINCS model results in Figure 13, directly correlates to estimated coastal flooding in Figure 9. This map output clearly shows the overtopping of the promenade at New Beach as well as the pools completely being covered by sea water (as identified by the numerous YouTube videos).

This concludes that the SFINCS model was successful in replicating the March 2017 coastal flood event for the main beachfront area in Durban.

The model is now running operationally in eThekwini's FEWS as shown in Figure 14. However, this model does not cover the entire coast of eThekwini, but only the area indicated for the pilot study.

Critical points or points of interest for eThekwini Municipality have been included in this model to trigger notifications whenever the relevant threshold levels for these points are crossed by the forecasted water depths.

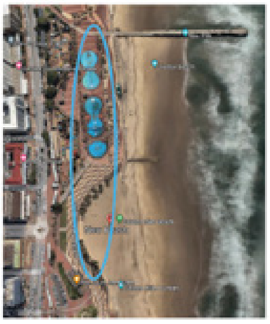

FIGURE 9: *Location of coastal flooding for Durban derived from YouTube videos in relation to Figure 8, adapted and taken from Google Earth.*

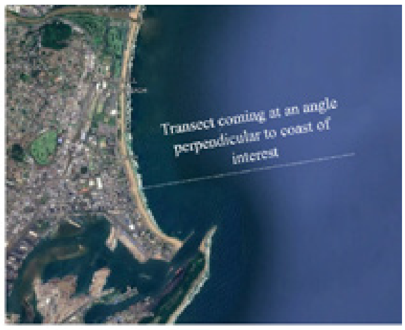

FIGURE 10: *Location of Transect used for 1D X-Beach model run for cross section at New Beach on Durban's main beachfront region for the 12th of March 2017.*

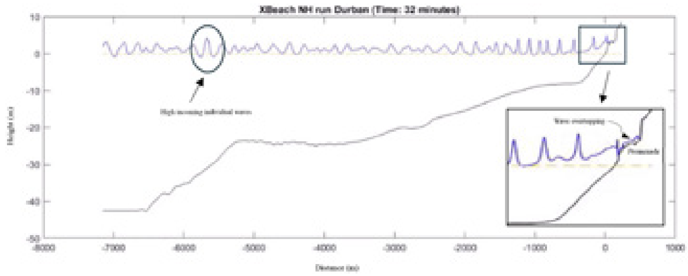

FIGURE 11: *1D X-Beach model run for cross section at New Beach on Durban's main beachfront region showing individual wave translation for the 12th of March 2017.*

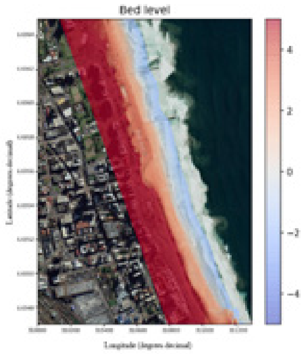

FIGURE 12: *Bed levels used for SFINCS model for Durban's main beachfront area*

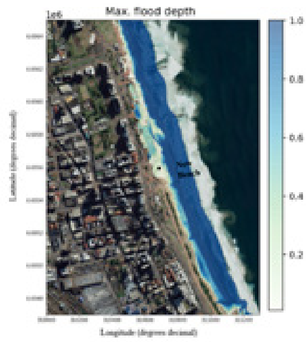

FIGURE 13: *SFINCS model results for maximum flood depth for the 12th of March 2017 for Durban*

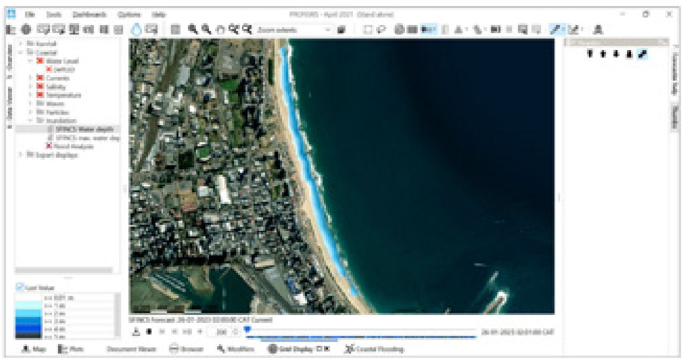

FIGURE 14: *Snapshot of SFINCS model running operationally in eThekwini's FEWS for the main beachfront area of Durban.*

These points include piers, sand pumping stations, outfall locations and promenade levels.

An interactive display was also created in FEWS to allow for typical scenarios to be inputted on the system. Water level, significant wave height, wave period and mean wave direction values can all be adjusted for different scenarios to indicate a possible threat to the coast. An example of this coastal flood warning can be seen in Figure 15.

eThekwini's FEWS now incorporates ocean modelling (Delft3D FM), Offshore wave modelling (SWAN), nearshore wave modelling (X-Beach) and inundation (SFINCS) which are all interlinked and coupled. The models can be used to test prehistoric events and possible scenarios and is running operationally for forecasting currents, waves and inundation. Figure 16 below shows a summary of the Coastal FEWS setup.

Data inventory, data collection and process understanding relevant to the location of interest, are extremely important for model validation and calibration. Fortunately, eThekwini already has extensive monitoring in place that can be used to validate these models. These include tide gauges, ADCP's, wave buoys, radar, and beach cameras, which are all already incorporated within eThekwini's FEWS.

An indication of the network of instrumentation on the coastline of eThekwini can be seen in Figure 17.

Forecasts and models are never guaranteed; therefore, it is important to observe real time data on the ground during any flood event. This vast network of instrumentation makes eThekwini's FEWS one of the most advanced in the world.

CONCLUSION

A lot of effort has been made over the past 5 years to focus on the coastal side of FEWS. Achievements have been successful to develop, configure, calibrate and implement the numerous ocean and coastal models as described above. eThekwini's FEWS currently incorporates an advanced combination of ocean, offshore and nearshore modelling techniques to ultimately provide a realistic approach to forecasting coastal inundation. This paper was a brief overview of the current model setup for the coastal aspect of FEWS and much more detail can be found on each model from the eThekwini FEWS Team.

RECOMMENDATION

Many considerations and alterations can still be made on all of the models mentioned above. Future development and calibration of eThekwini's coastal FEWS can include the following:

- More test simulations of the Delft3D FM model against more current survey data for velocity magnitude and direction
- More accurate bathymetry as model input for the Delft3D FM around the continental shelf
- Refine grid further at the coast to include incoming currents in the harbour
- Continue calibration and validation of SWAN model with measured data from wave buoys
- Make SWAN model less computationally heavy for FEWS
- Validate nearshore wave transformation with a 2D X-Beach model and data (if available)
- Investigate the need for multiple 1D X-Beach models along the promenade
- Investigate the possibility to replace X-Beach with a Bayesian Network System (pre-trained database) to translate nearshore waves
- Assess sensitivity to uncertainties in the nearshore bathymetry (which is highly dynamic) - use different transect along the coast for X-Beach
- Extend SFINCS model to the entire eThekwini coastline
- Compound SFINCS modelling for both inland and coastal inundation in 2D

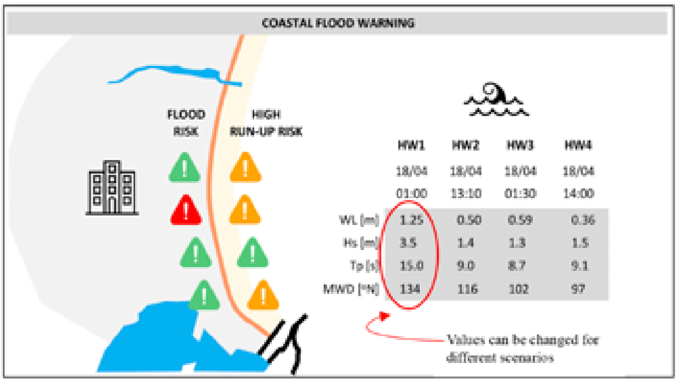

FIGURE 15: *Coastal Flood Warning Interactive Display for "what if" scenarios for the main beachfront area of Durban*

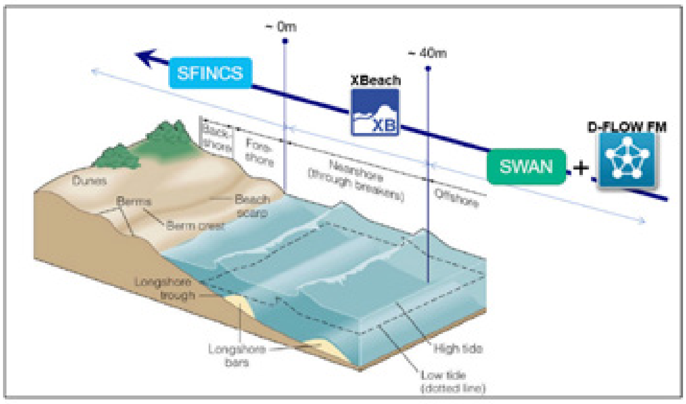

FIGURE 16: *Summary of models that have been coupled in eThekwini's FEWS for the modelling and forecasting Durban's Ocean and nearshore waters, adapted from Brooks/Cole Publishing (2014).*

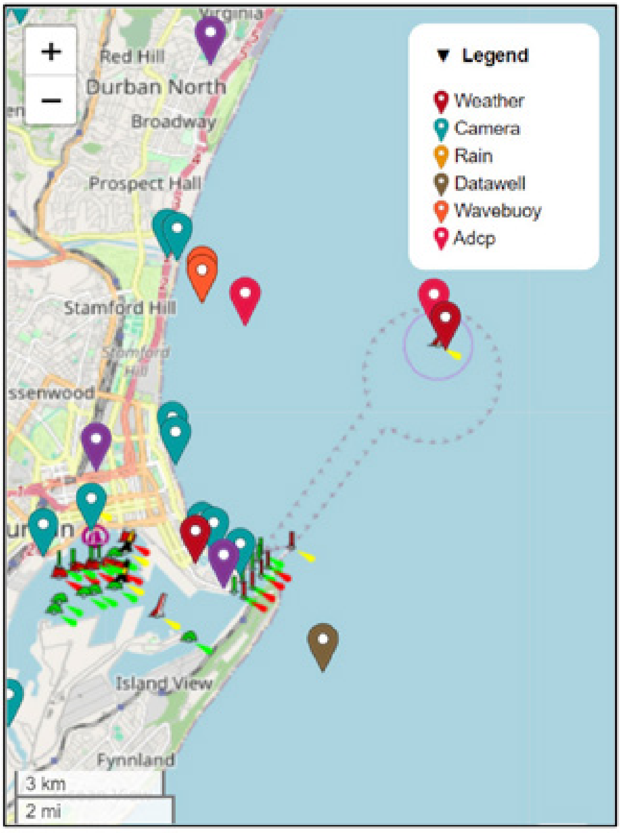

FIGURE 17: *eThekwini's instrumentation on the coast of Durban's main beachfront area*

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