D 2.2 Integrated modelling framework for hazard assessment in coastal regions

Work Package 2

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Contents

1. Summary of what the report contains and its aims

PEARL Work Package (WP) 2 addresses estimation of hazards from hydro-meteorological events. The major part of the work concerns the use of modelling systems to simulate different kinds of floods resulting from storm-surges, pluvial (rain-induced) and fluvial (river) processes as well as waves and climate change. There is a need for innovation in a procedure that can be used to address coincidence of 2 or 3 types of floods that can happen either simultaneously or are causally linked and also those that can happen unexpectedly over a short time scale. This is driven by the next generation of integrated (innovative) flood mitigation measures. The present report outlines the integrated modelling approach undertaken in PEARL.

The *modelling technologies* include an open source, general purpose, computational fluid dynamics code - Fluidity, an atmospheric form ATHAM-Fluidity, the wave model SWAN, the Max Planck (MPG) climate model and the pipe/sewer system SWIM model. The urban models will be extended to include underground water systems, providing a single unified integrated solution framework for urban flooding. The suit of models also includes various DHI models.

The modelling framework seeks to advance:

a) Capabilities in estimation of hazards;
b) Modelling of different components of hydro-meteorological events, for example, combined storm surge and pluvial flooding.
c) Improvements in predictive capabilities over a wide range of spatial scales, from metres to several kilometres, which are needed for better assessment of flood impacts.

Key benefits:

a) The existing academic literature/work needs advancements in modelling and prediction of individual components of hydro-meteorological disasters.
b) Development of innovative concept for analysing interactions between different systems, and gaining better knowledge of flood evolution.
c) Better hazard and risk assessment.

2. Overview of the present document

The present document is structured in the following way, Section 2.1 provides summary, Section 2.2 discusses the background and state of the art in numerical modelling of floods, Section 2.3 discussed integration of different modelling methods and techniques, Section 2.4 discusses model coupling issues and Section 2.5 discusses how to generate a range of simulations concerning different processes of extreme events.

2.1 Summary

The present report describes an advanced methodology and numerical models to cope with emerging challenges of complex interactions of flooding from “all sources” leading to increased flood risk in coastal regions. Therefore, the work concerns development of methods and software tools for modelling and prediction of urban pluvial (surface including underground sewers), fluvial (river) and coastal flooding under conditions in which they can occur at the same time (coincidental flooding). Such knowledge and tools aim to support practitioners and researchers in both improved design of enhanced resilience to flooding and for flood emergency management. The developed models and methodologies will be tested and validated on the Greve case study, in Denmark. Dissemination of the research results includes scientific publications and open source software tools for prediction and for real time simulations, and case studies to demonstrate the developed models and tools in selected coastal cities. The work provides contribution towards innovative modelling solutions for flood hazard assessment.

2.2 Background and state of the art

Recent flood disasters (e.g. Xynthia storm in France in 2010 and the Great East Japan Earthquake and Tsunami in 2011 and the Great East Japan Earthquake and Tsunami in March 2011, hurricane Irma in the Caribbean in 2017) have caused significant socio-economic consequences. Floods of various origin (coastal, fluvial, pluvial and groundwater) destroyed or heavily affected functions of critical infrastructure networks and caused severe financial and social effects. In the EU because of climate change, risk of flooding and inundation increases particularly in coastal regions due to the combined effects of all flood generating processes mentioned above. More frequent occurrence of these problems and resulting consequences in coastal cities indicates that existing engineering technologies, approach and tools cannot provide effective solutions to meet the future challenges. Advanced methodology and new software products are needed. This includes both rainfall forecasting at fine temporal and spatial solutions and integration and prediction of urban pluvial (surface), fluvial (river) and coastal floods. In urban areas reliable prediction at street/property level at fine temporal scale for at least 2-3 hours lead time is needed. Such methodologies and supporting knowledge and integrated solutions are in its infancy.

Precipitation forecasts are usually produced by numerical weather prediction models (NWP) that have an updating cycle of 6 hours. Assimilating weather radar data into their initialization is not a trivial task. An alternative is to use fine scale rainfall prediction from weather radar data, e.g. Wang et al., (2011). For short lead times (1-3 hours), radar based forecasts have been shown to outperform NWPs, since radar can capture the initial precipitation. The best results in fine scale rainfall prediction are obtained when the radar based nowcasting is enhanced by merging with data obtained by “ground truth” (i.e., dense network of raingauges) and assimilated into a high resolution atmospheric model such as the one developed as part of the present work. However, radar based predictions degrade faster than NWP predictions as lead time increases because the radar nowcasting leaves the development/decay unresolved. The best solution can be found in combining downscaled NWP forecasts (Gires et all (2011) and radar forecasts Wang et al. (2011)).

The paper of Wang et al (2012) presents the results of the development of such methods at Imperial College. This research will be further enhanced within PEARL project.

Classified by spatial dimensions, there are 1D, 2D and 3D flood models. The 1D, 2D and 1D/2D coupled models are relatively well developed for simulating major and minor systems (or above-ground and below-ground systems). Some typical commercial urban flood modelling software products are DHI products such as MIKE URBAN and MIKE FLOOD and MWH (previous HR Wallingford) – FloodWorks (see also, Hunter et al., 2008; Vojinovic and Tutulic, 2008). There are also other non-commercial modelling tools (such as SIPSON) which have been developed based on research projects (Maksimovic et al., 2009).

To date, the use of 3D models has not been explored much. This may be particularly relevant for cases where vertical inertia is important and the use of 3D warrants its application. Moreover, it can provide some additional information that is unavailable from 1D and 2D simulations, for example, information on 3D velocity fields, water level changes and unsteady dynamic load on structures which are in contact with fluids. This may benefit the research in flood modeling, pollution transport, dispersion of flow structure inlets, fluid structure etc. With 3D models, it is possible to get much better information about local flow structures close to isolated objects like houses and long linear objects like dikes. However, there is considerable challenge with these tools which is associated with computational time. Modelling experts estimated that the simulation time needed by a 2D surface flood model is approximately x^3 times that of a 1D model that has a simulation time of x minutes. The simulation time is a limiting factor for real-time applications (e.g., control of systems and emergency management).

The present work deals with an integrated methodology of rainfall prediction with hydrological modelling and multiple spatial / temporal scales of hydraulic models for coincidental urban flood prediction and warning as well as integrations with coastal flooding from storm surges and/or waves. Some of the key challenges for innovative development are:

- Integration of pluvial, fluvial and oceanographic models
- Prediction of coincidental urban floods
- Multi-scale modelling and 3D.
- Demonstrations in case studies and flood prediction

2.3 Approach

The diagram given in Figure 1 illustrates part of the framework with the key tasks such as setting up of individual models, their coupling and reduced order modelling is shown in Figure 2.

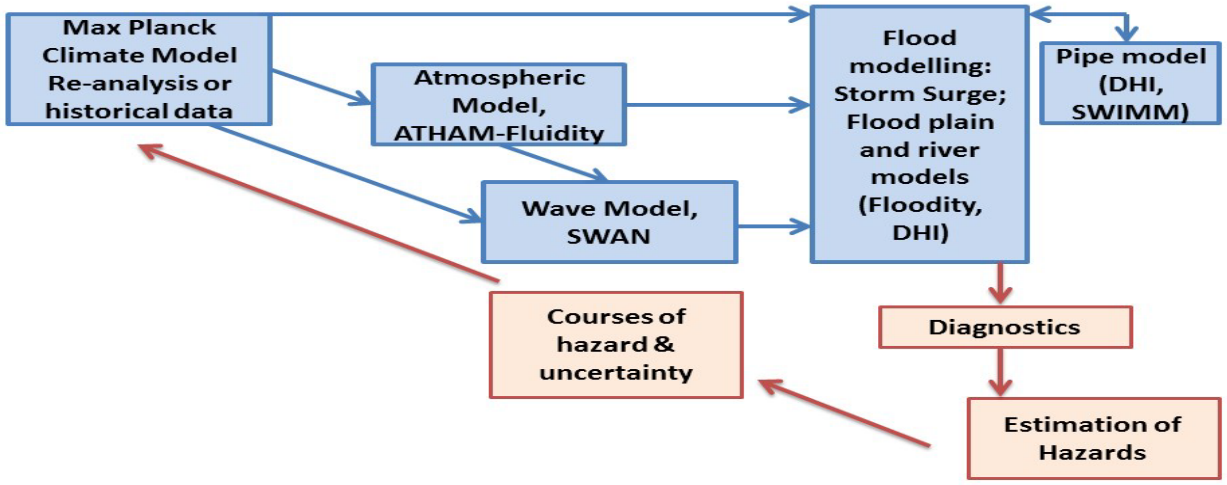


Figure 1: PEARL hazard modelling and estimation framework

One way coupling between the modelling components assumed in this work. **Max Planck Climate Model**: Here global climate model results are generated but with a focus of the resolution around EU. **Atmospheric Model**: New gen. unstructured mesh atmospheric model. **Wave model**: Spectral wave model SWAN used. **Flood modelling**: Use of adaptive unstructured mesh flooding model. **Pipe model**: models for the transport of water through pipe/flooding system. **Blue** are the models and **brown** are associated with hazard assessment. **Diagnostics**: Use of diagnostics such as provided by paraview that enable the model results to be analysed e.g. identify areas of potential hazard – a hazard map. **Estimation of hazards**: The diagnostics thus enable us to help determine the estimation of the hazards. Courses of hazard and uncertainty: Indicates a backward progression through the models (akin to an adjoint) to determine what the potential courses of hazard are. **Atmospheric models (REMO and ATHAM-Fluidity model)**: These models are used for simulations of atmosphere processes (ocean forcing and rain) for selected case studies (application to Denmark case). This will enable us to gain a more detailed understanding of underlying processes of extreme events. Outputs from the simulations will deliver not only highly resolved precipitation data in space and time as input for hydrological models but also wind, temperature and pressure fields as input for ocean storm surge model. **Wave model (SWAN)**: It will be used to analyze wave conditions on different temporal and spatial scales from the long-term overall wave conditions at the ocean model scale to the local extreme event wave conditions at the scale of the flood protection constructions. The input for SWAN will be generated by the atmospheric model. Temporal and regional distribution of the wind with a time resolution of one hour will used for the simulation of the wave spectrum with SWAN. In addition, water levels and flow velocities coming from the Storm Surge Model will be used to take into account their non-linear effects on the local wave spectrum. **Flooding model (DHI_MIKE, FLOODITY)**: A multi-scale integrated urban flooding modelling framework which will have the capabilities for one dimensional (1D), two-dimensional (2D) and three-dimensional (3D) flooding modelling. It has an adaptive multi-scale mesh spatially and temporally and the necessary coupling abilities to simulate individually and coincidence of urban pluvial (heavy precipitation) and coastal flooding (high sea level and/or storm surge)

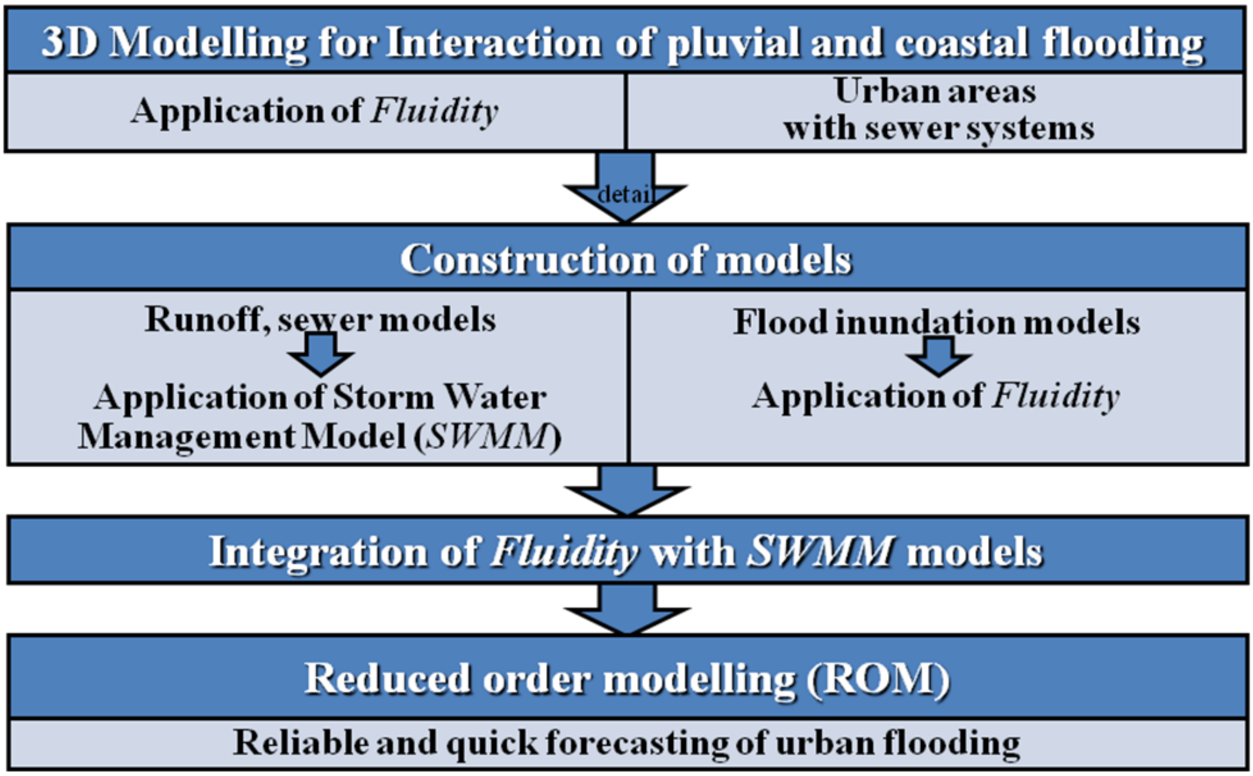


Figure 2: Integration of SWMM, Fluidity and ROM.

Integration of pluvial, fluvial and coastal models
Fluidity-ICOM is a powerful 3D unstructured mesh ocean model developed at the Department of Earth Science and Engineering, Imperial College London and it is an open source model. It is a multi-phase computational fluid dynamic model. It solves the Navier-Stokes equations on arbitrary unstructured finite element meshes. This allows accurate and computationally efficient representation of complex forms. Applying anisotropic mesh adaptivity, computational resource is dynamically focused on flow complexity as it develops to reduce computational time. It includes a single model of ocean basin and coastal zone that is capable of resolving down to building scale and it can be used for 3D tsunami and other flooding modelling applications (http://amcg.ese.ic.ac.uk/index.php?title=Fluidity). In this project, Fluidity-ICOM will be used to model ocean basin and coastal zones, including resolution down to the building-scale. Urban flood models will be extended to include below-ground component, providing a single unified integrated solution framework for urban flooding. When higher accuracies are required, the full model can be simulated in an operational mode on many thousands of cores, providing the best and most rapid results, linked with near real-time data (which outside the scope from PEARL). This capability can eventually be linked with media (e.g. smart-phones), to inform city disaster planning and advise the public.

WP2 aims to develop an integrated methodology based on Fluidity-ICOM that incorporates rainfall models together with multiple spatial and temporal scales for urban flood prediction and warning to improve capabilities for assessment of flood hazards.

This will include the following aspects:

a) Development of models with 2D and 3D capability. Validate the models by comparing the results with commercial packages such as DHI-MIKE FLOOD and other commercial models.

b) Development of the multi-scale capability to model ocean basin and coastal zones, including resolution down to the building-scale.
c) Simulations of co-incidence between high seawater level, intensive rainfall/runoff, and (or) high river stage (or large discharge).
d) Development of the integrated capability to model coastal and urban floods and their potential interactions.

Modelling urban runoff
In order to model different situations for the present and future climate scenarios, frequency analysis for the historical data and future scenarios will be made. Meanwhile, the necessary real time hydrological data will be measured in order to calibrate the established models. Outputs of this will serve as inputs into the urban flood models.

Rainfall forecasting
To predict short term rainfall in local urban areas with fine temporal and spatial resolutions, which is vital to make timely prediction of urban flooding, the ATHAM-Fluidity model will be used.

Uncertainty

Identify uncertainty models for precipitation measurements:
1. Gauge bias and variance for different conditions and integration periods,
2. Interpolation variance for different temporal integration periods.

We will look at extreme scenarios (see Figure 3) and together with a selection of historical events we will produce gridded rainfall maps. This is to be used as input into the urban-hydrologic and hydraulic models. See also deliverable 2.1 (hazard assessment framework) for the modelling concepts and tools for the simulation of individual and combined events.

The approach we propose within the PEARL WP2 framework is shown in Figure 1 If one can identify what constitutes a hazard (e.g. loss of life and or damage to properties) then from this one may - in principle - work backwards through the models shown in Figure 1 to identify the most likely causes of this hazard in a method akin to adjoin sensitivity analysis. This would also highlight what co-incidence events are most likely to cause the greatest hazard. However, none of the models used here have an adjoint capability. Thus, we will attempt to perform this analysis entirely through ensemble methods.

Frequency analysis of historical data and future scenarios
We will perform the frequency analysis of precipitation, river stage and high tides, estimate the probability of coincidence of intensive precipitation or runoff with high river stage and extreme high tide in the sea. Impacts of changes in climate, population and land uses affect rainfall patterns (IDF Curves), urban runoff and urban pluvial floods, and probability of coincidence of intensive precipitation, high river stage and extreme high tides in the sea on urban flooding. A framework for modelling climate change impacts on urban runoff and urban drainage have been developed by Nie et al, (2012) for the EU-FP7 project PREPARED to enable changes and tested in a case study. This approach will be modified and demonstrated in the case studies of the present project.

Rapid Modelling
Rapid Reduced Order Modelling will be used to help investigate the vast range of scenarios to help investigate probability density functions of solutions. It should be pointed out that this can be done as follows:
a) Non-intrusively ROM NIROM can be applied to each model within the framework because it simply works from the snapshots of each model within the framework. This enables it to construct a model of each of the full models within the framework.

b) NIROM may also be used to construct two way coupled models even if it only has one way coupling between the model components.

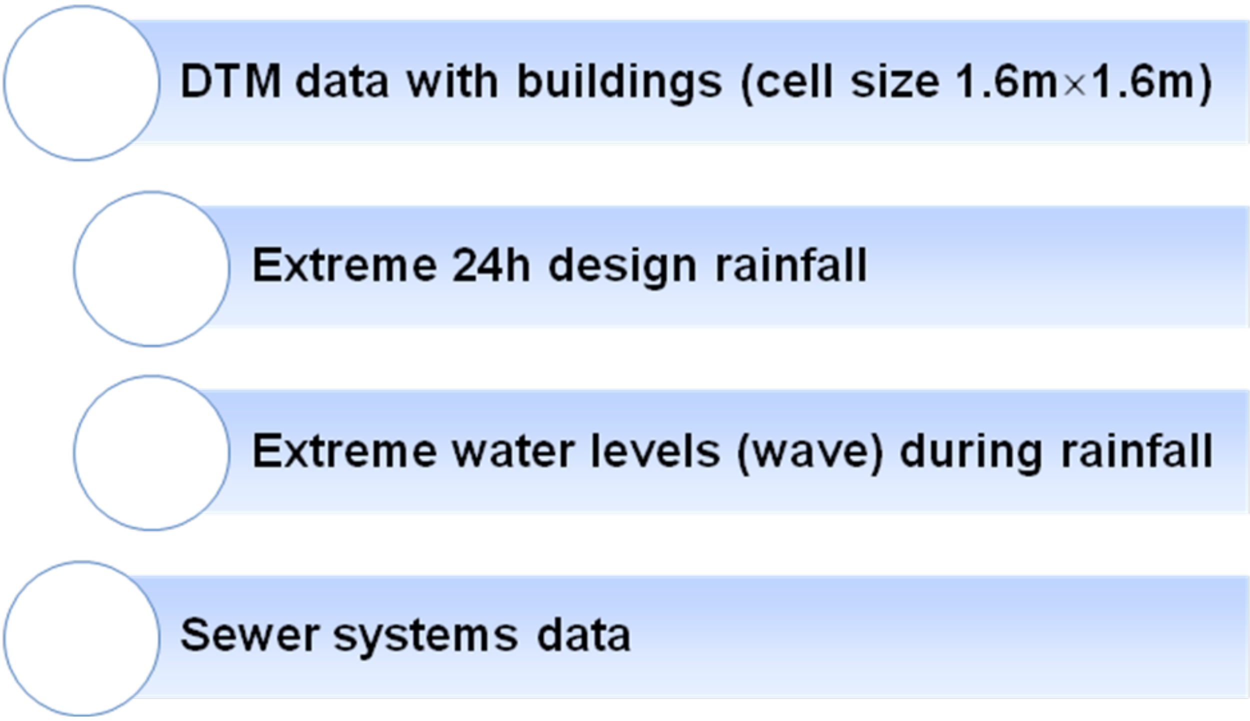


Figure 3: Data Collection and customization.

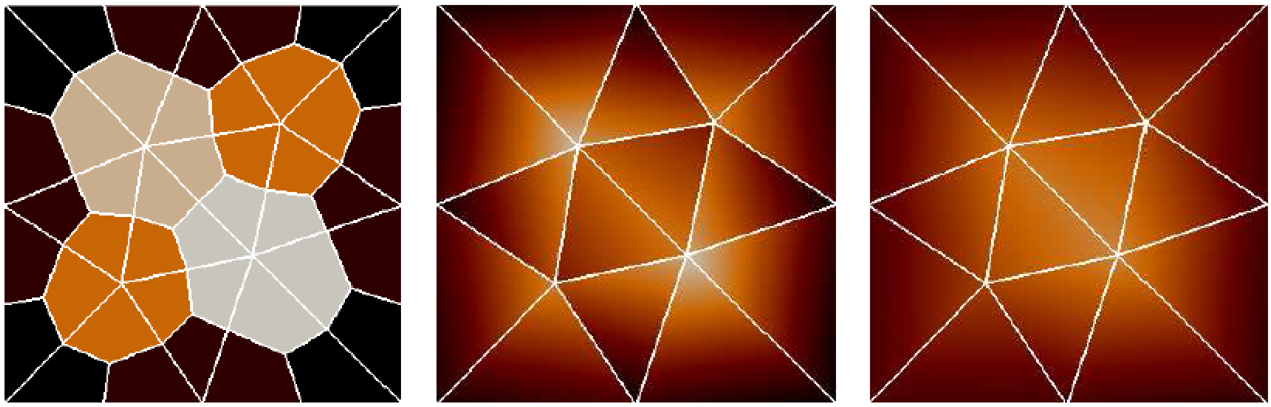
2.4 Integration of models - mapping fields between models and mesh to mesh interpolation

A key aspect of the exchange of data between models is the mesh to mesh interpolation. This is rather a hard problem and one may need to consider: 1) the key balances in the governing equations that may need to be maintained when interpolating information from one mesh to another - not respecting these may result in inaccurate results or even ultimately failure/unstability of the models (Maddison et al. 2011) 2) conservation of key quantities e.g. the integral of the flux of information (e.g. momentum, heat, precipitation) provided by one model is the same as that received by another.

High order Control Volume (CV) coupling: A general, higher-order, conservative and bounded interpolation for the dynamic and adaptive meshing of control volume fields dual to continuous and discontinuous finite element representations are ultimately the key here. Existing techniques such as node-wise interpolation are not conservative and do not readily generalise to discontinuous fields, whilst conservative methods such as Grandy interpolation are often too diffusive. The new method uses control-volume Galerkin projection to interpolate between control volume fields. Bounded solutions are ensured by using a post-interpolation diffusive correction. Example applications of the method to each of the arrows showing the coupling in Figure 1 are key to this work. The robustness of the interpolation for pure advection of a cylinder heavy side functions is shown in Figure 5 and the procedure outlined in Figure 4.

Mesh adaptivity: Dynamic, adaptive meshing is often used during numerical simulations of transient fluid flows to improve accuracy, Peraire et. al. 1992, Pain et. al. 2001. The mesh is refined in regions where properties are changing rapidly in space and (usually) coarsened in regions where the properties change more slowly in order to improve accuracy whilst minimising computational effort. The mesh may change every time-step depending on the error metrics used

to control refinement and coarsening. This inevitably means that data must be mapped from one mesh to another using an interpolation algorithm George et. al. 1998. The interpolation must be done efficiently, to minimise computational overheads, and in such a way that the field being re-meshed remains bounded. The method must also be conservative when dealing with fields constrained by a conservation law (e.g. mass).



(a) (b) (c)

Figure 4: Illustration of the Galerkin CV projection defined by in 2D. (a) A 2D control-volume function is shown with both element and control-volume meshes overlaid. It is a linear combination of control-volume test functions that are constant across a given control-volume and zero on all others. (b) A projection of the control-volume function in (a) to a discontinuous finite element representation. The finite element solution varies linearly across an element and is discontinuous across element boundaries. (c) Projection of (a) to a continuous finite element representation.

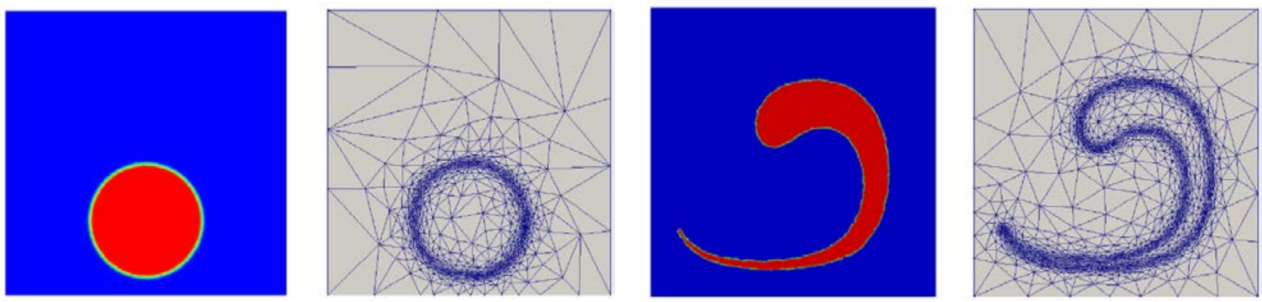


Figure 5: Scalar field and mesh as computed after a quarter of a turn corresponding to 200 adapts using control-volume Galerkin - initial concentration and mesh - final concentration and mesh.

Although within PEARL we consider only one way coupling between major modelling components the future work will include the two way coupling. This requires the use of a model coupler, such as the Platform SALOME from the EU-project NURESIM (Nuclear Reactor Simulations) which is able to couple models with unstructured as well as structured meshes. The major strength of couplers like this is that when you couple your model to the coupler you are able to couple to any of the models within the coupler. This is often the only practical way of coupling many models together.

Interpolation is of vital importance in the numerical modelling of physical problems, in particular those concerning mesh to mesh exchange of information between models as well as mesh adaptivity. Conventional methods such as point-wise interpolation methods do not readily generalise to discontinuous fields and moreover suffer from being non-conservative. However, recent methods have enabled conservative mesh to mesh interpolation based on a super-meshing approach (Farrell et al. 2009) in which a super-mesh containing both meshes that will exchange

information is produced and from this an optimal finite element mesh to mesh can be established. This approach is conservative and moreover can also be made to produce bounded solutions by way of a diffusion algorithm. Very recently this approach has been extended to work for high order interpolation involving control-volume CV or finite difference FD methods.

Thus, the way is clear to exchange conservatively and with high order accuracy and with boundedness or physical realism (if required) information between FEM (including discontinuous FEM fields), CV and FD meshes. This is at the heart of the integration of models, enabling one way coupling as well as both weak and strong two way coupling between these models to be realized. One typically attempts to conserve quantities conserved by the models and quadratic quantities which are conserved by the fundamental continuum equations (e.g. potential vorticity) are not necessarily conserved.

The approach to interpolation within PEARL although it has the ability to interpolate using the latest accurate and conservative methods it is also pragmatic and simple interpolation methods that can be used and where necessary more complex methods can be used. For example, if the dimension of the interpolation is N then one could select the nearest N+1 points to the point we wish to interpolate variables too and use a simple inverse distance weighting to obtain the interpolated value(s) at that point. This simplicity also preserves boundedness of the variables which can have significant advantages.

2.5 Integration of models for individual and coinciding events

Historically, flood risk management across Europe has mainly focused on fluvial and coastal flooding; however, recent events have revealed the imminent risk imposed by urban pluvial flooding. This project also aims to advance capabilities in modelling flooding in urban areas from all sources by placing emphasis on mutual interactions during coincidental flooding from one or more input sources. The uncertainties associated with urban pluvial flood models and forecasting systems however, are still too high, thus limiting their operational use. Although significant progress has been made in all individual types of flooding: fluvial, pluvial and coastal flooding, models that address the interaction of various types of flooding are few and limited.

We aim to develop an integrated modelling framework that incorporates rainfall models together with multiple spatial and temporal scales for urban surface flood prediction and warning. This will incorporate short-term rainfall analysis and prediction; probabilities of coincidence extreme events and rainfall - runoff simulations. The integrated modelling framework proposed here is a combination of coastal, river and urban flood model, so that there is no need to separate the coastal flow and pluvial flow. The computational geometry includes the coastal and city bathymetry, buildings, streets, hydraulic structures and flood defences.

3. Climate Modelling (MPI)

The regionally coupled climate model system REMO/MPIOM/HD has been developed at the Max Planck Institute for Meteorology (Mikolajewicz et al., 2005; Elizalde, 2011; Sein et al., 2015). The ocean component of this system consists of the global ocean circulation model MPIOM (Giorgetta et al. 2013), which is a z-coordinate model with free surface and mass flux boundary condition for fresh water. The model allows free positioning of the model grid poles. By placement of the poles in SW Germany and close to the Great Lakes in the USA a set up is obtained, which has a zoom with highest resolution in the southern North Sea (see Fig. 5). The model includes the full luni-solar ephemeridic tidal potential in the implementation of Thomas et al. (2001). By using a global ocean model with a zoom, the problem of having to specify boundary conditions in the interior of the ocean is avoided at the price of extra computational cost. This approach is optimal for investigating the propagation of signals from the open ocean into the coastal or near-costal area of interest. It allows both the propagation of barotropic waves into the domain of interest (e.g. for the investigation of storm surges) as well as the simulation of climatological changes in sea level as a consequence of circulation changes.

Coupled to the zoomed ocean model is the regional atmospheric circulation model REMO (Jacob 2001). The set up is consistent with the EURO-CORDEX domain (Jacob et al. 2013). This atmospheric model component uses sea surface temperature, sea ice conditions as well as surface velocity from the ocean model and delivers fluxes of heat, momentum mass (freshwater), wind speed and atmospheric load to the ocean. The hydrological budget is closed using the hydrological discharge model HD (Hagemann and Dümenil 1997). The inclusion of the effect of atmospheric load from sea level pressure in the ocean model allows a more accurate simulation of variations of the sea surface height.

This model systems needs external forcing with output either from an atmospheric general circulation model or a reanalysis product (e.g. from ECMWF or NCAR). For PEARL a set of CMIP5 simulations with the global climate model MPI-ESM-LR (Giorgetta et al. 2013) has been downscaled for the European coastal domain. The regionally coupled model system was initialized in 1920 with the climate state from an uncoupled spin up. From 1920 to 2005 the realization 1 of the historical simulation of the global climate model was downscaled. For the period 2006 until 2100 two different scenarios where downscaled: The moderate scenario RCP4.5, which is close to 2 degree global warming relative to the preindustrial climate, as well as the high emission business as usual scenario RCP8.5.

For the calculation of sea level response in case of anthropogenic warming some relevant contributions are not included in this model system. This applies especially for the terrestrial cryospheric components (ice sheets and glaciers) and for the glacial isostatic adjustment process.

One focus of the analysis are the extremes of high sea level stand (more details can be found in PEARL deliverable D2.3). The model's ability to reproduce adequate statistics of sea level extremes has been validated in simulations forced with reanalysis data from ECMWF. For the locations, where long, quality controlled tide gauge station data where available, extreme value statistics for both observations and model results were calculated. For most stations the model could well reproduce the observational data.

The analysis of projected changes in sea level extremes has focussed on the periods 1960–1990 of the historical simulation and 2070–2100 of the scenario simulations RCP4.5 and RCP8.5. For these intervals also the extreme values of sea level high stands have been analysed for selected stations.

For the case study site Greve (Denmark) the 10 most extreme (positive) sea level events for each time interval have been identified in the climate model simulation. The associated weather conditions will be modelled with the high resolution atmosphere and flooding models of Cambridge University and Imperial College using the climate model data as forcing. For Genova case study, the weather conditions with the highest precipitation rates have been identified and will be simulated with the Cambridge University model as well.

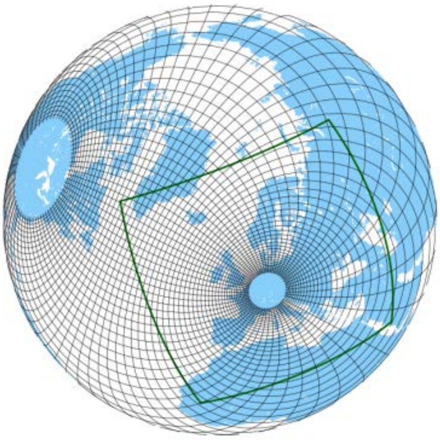


Figure 6: Sketch of grid and domain areas of the coupled model. The grid of the ocean model is indicated by the black lines (only a subset of the grid lines has been plotted).

4. High-resolution atmospheric modelling

4.1 Description of the model

High-resolution atmospheric simulations will be performed using ATHAM-Fluidity, a new solver currently under development at the University of Cambridge as part of PEARL - WP2. This modelling system relies on the dynamical core in use in Fluidity (Ford et al., 2004), to which physical parameterizations required to simulate localised meteorological events are added following, for example, ATHAM (Oberhuber et al., 1998). Once complete, ATHAM-Fluidity will constitute a very unique tool among all available atmospheric models, combining state-of-the-art physical parameterizations for atmospheric processes (i.e. cloud microphysics) with a high-order spatial discretisation operating on general unstructured and adaptive meshes.

4.1.1 The dynamical core

The role of ATHAM-Fluidity's dynamical core is to provide the numerical methods to solve the set of governing equations describing atmospheric transport and motions (a minimum set of equations includes equations for velocity, temperature or potential temperature, and pressure or density). Among other properties, it is required that the dynamical core be sufficiently accurate to capture small variations in atmospheric conditions, conservative to avoid mass (or pressure) losses in the numerical domain, and stable to prevent the development of unwanted numerical errors.

The numerical methods employed in ATHAM-Fluidity rely on a hybrid finite-element approach combining a continuous Galerkin discretisation for pressure and density, and discontinuous Galerkin methods for velocity and other prognostic scalars (temperature, moisture…). These methods are known to meet all the criteria listed above, but have never been extensively used for atmospheric applications due to their high CPU cost. Because of the advanced nature of the approach described here, a number of methodological issues need to be solved to benefit from all the capabilities of ATHAM-Fluidity's dynamical core (this includes for example the development of a higher order conservative spatial discretisation for scalars).

The high CPU cost and complexity of ATHAM-Fluidity's dynamical core are balanced by the important geometrical flexibility it offers. It is indeed able to handle unstructured grids (the 3D numerical domain is then decomposed into tetrahedrons) allowing the discretisation of complex geometries (e.g. rough terrain) without much effort. In addition, the numerical mesh can be dynamically adapted during the course of a simulation: all the numerical effort (high resolution) is then concentrated around the areas of interest, while a comparably inexpensive coarse mesh can be employed everywhere else. As automatic refinement is applied dynamically, with frequent updates of the mesh, large benefits in terms of computational cost can be expected, which makes the approach particularly attractive for otherwise expensive runs.

4.1.2 Physical parameterisations

Simulating meteorological events necessitates the modelling of specific atmospheric processes such as cloud formation (and other cloud processes), solar and terrestrial radiation, atmospheric turbulence and surface exchanges.

The role of the cloud microphysics parameterisation is to model physical processes leading to the formation and evolution of clouds, including the formation of precipitable rain drops and ice/snow crystals. The model adopted in ATHAM-Fluidity distinguishes several condensed water particles (cloud droplets, rain drops, ice crystals…). The size distribution of each of these particle populations is then constructed using information on their mass and number concentrations (2 additional prognostic variables are required for each species considered). The rest of the

parameterization can be seen as a collection of smaller semi-empirical equations (typically 10 to 30) describing individual transformations such as the conversion of cloud droplets to rain, the growth of rain drops by collection of cloud droplets, the evaporation/condensational growth of liquid particles, or the accretion of pristine ice crystals to form snow (Morrison et al., 2005). At the moment, no ice related processes are implemented in ATHAM-Fluidity.

Parameterising turbulence is necessary to model small scale mixing in the atmosphere, for example in the lower part of the boundary layer where heat and momentum exchanges at the surface are determined by turbulent fluxes. ATHAM-Fluidity is based on the Large Eddy Simulation (LES) approach: the larger atmospheric turbulent structures are explicitly resolved on the numerical mesh while only the (dissipative) effect of smaller eddies is parameterised. A very common approach, adopted in ATHAM-Fluidity to parameterise sub-grid scale turbulence relies on a diffusion type closure for which the eddy diffusivity is computed as a non-linear function of the velocity gradient (Mirocha et al., 2010).

Surface fluxes must be modelled by introducing exchanges of energy, moisture and momentum between the surface and the atmosphere. The most sophisticated surface parameterisations consist in standalone models able to represent surfaces of various types (water, dry soil, low vegetation, canopy…) and include specific parameterisations for each of these types (e.g. to model evapotranspiration depending on the vegetation type). In addition, these models solve discretised energy balance equations down to a certain depth below the surface to provide accurate estimates of energy transfers within the soil. Although very detailed, these models may not be appropriate for high-resolution atmospheric modelling and the approach retained in ATHAM-Fluidity makes use of a more simple bulk algorithm designed primarily for ocean surfaces (COARE, (Fairall et al., 2003)). The algorithm is controlled by few input parameters (surface temperature and wave parameters) which may change as the simulation progresses (dynamic coupling between the COARE algorithm and the atmospheric flow field). As a first guess, the algorithm may also be used to model surface fluxes on land by adequately tuning the input parameters (e.g. by converting the wave parameters into surface roughness parameters).

Finally, radiation (both solar and terrestrial) is an important component of the Earth system, warming the atmosphere and surface thereby affecting cloud dynamics. Unlike atmospheric models, radiation cannot be naturally solved in the 3 Cartesian coordinates as it is mostly wavelength and angle dependent. Consequently, radiation solvers are designed as standalone models which are then dynamically coupled to atmospheric codes. Using information on the local temperature, pressure and concentrations of moist quantities as input parameters, they deliver solar and terrestrial radiation fluxes, warming or cooling the atmosphere. Because of the problem complexity and the *a priori* incompatibility between atmospheric and radiation codes, several simplifying hypotheses are necessary to design efficient radiation transfer solvers. In particular, atmospheric radiation codes are typically designed as 1D models operating in the vertical dimension only. Direct coupling with ATHAM-Fluidity and its unstructured mesh is therefore made very complicated. Note that atmospheric radiation is often the most time-consuming process in comprehensive atmospheric models.

4.2 Simulating extreme weather events in coastal areas using ATHAM-Fluidity

ATHAM-Fluidity is designed to simulate localised meteorological events at high resolutions: the simulated geographical areas typically cover between 10x10 km^2 to 100x100 km^2 for targeted spatial resolutions of 100 m to 1 km in the horizontal direction (depending on the extent of the numerical domain) and 10 m to 200 m in the vertical direction. Time steps (giving the temporal resolution of ATHAM-Fluidity) are typically of the order of 10 s to 1 min.

The model is driven by initial and boundary conditions representative of the event of interest. These input data are typically provided by observations, Numerical Weather Prediction models, reanalysis products or large scale atmospheric models (e.g. Regional Climate Models, RCM), and must be interpolated on the high-resolution mesh. Let's recall here that there often is a large disparity between the scales at which ATHAM-Fluidity and, for example, a RCM operate: in this case, the ATHAM-Fluidity numerical domain is smaller than a single grid cell of the RCM so that initial and boundary conditions from the RCM outputs are extracted as single, under-resolved vertical profiles for the entire ATHAM-Fluidity domain.

In order to guarantee that boundary conditions are applied without loss of accuracy (non-conservation of the total mass contained in the domain) and stability issues (generation of spurious numerical oscillations), ATHAM-Fluidity uses damping layers near the lateral boundaries and at the top of the numerical domain. Their role is to progressively relax the solution field within these user-defined damping layers towards the prescribed boundary values and therefore provide a smooth transition between the internal and boundary fields. The use of such damping layers has two important advantages: one can control exactly the inflow and outflow of the domain and therefore control the evolution of the total mass within the domain (mass conservation), and they provide buffer zones damping unwanted numerical waves polluting the solution field.

To complete the set of input data necessary to run ATHAM-Fluidity, one must consider large-scale forcing representing the effects of larger atmospheric patterns on the simulation. Because ATHAM-Fluidity operates at high-resolution but over limited geographical areas, synoptic atmospheric features are introduced via appropriate parameterisations. In particular, limited area models such as ATHAM-Fluidity need information on the large-scale atmospheric horizontal divergence or convergence (typical of cyclonic or anti-cyclonic conditions respectively) as well as on modifications in the background air mass due to the advection of heat and moisture. This information can be provided by large-scale (RCM) models or reanalysis products.

4.3 Coupling with other models from the integrated modelling framework

Coupling between ATHAM-Fluidity and other models within the integrated modelling framework is mostly performed through the exchange of input/output data. We are here only dealing with one-way couplings: ATHAM-Fluidity is not dynamically coupled to any other model described in this document and no direct feedback can be considered (no real time communication between ATHAM-Fluidity and other models is possible).

4.3.1 Inputs from the Regional Climate Model (REMO)

The RCM model is used to provide input initial and boundary conditions to drive the high-resolution ATHAM-Fluidity model. This downscaling procedure, summarized below, is essential to produce realistic high-resolution results representative of identified extreme meteorological events in case study areas. The whole procedure is described in more details in Deliverable D2.3.

As stated in paragraph 4.2, the RCM delivers initial and boundary conditions required to drive ATHAM-Fluidity. Extreme weather events of particular interest in the case study areas (ATHAM-Fluidity will specifically be used for the Greve and Genoa case studies) have already been identified from the RCM outputs based on extreme daily precipitation and extreme sea level criteria (D2.3), and for three different scenarios: a historical scenario (20th century) and two future scenarios (RCP4.5 and RCCP8.5). These extreme scenarios can be used to extract vertical profiles over Greve and Genoa corresponding to selected events of particular interest, and containing all the necessary quantities to drive ATHAM-Fluidity. The extracted soundings must at least include pressure, temperature, relative humidity and wind profiles.

4.3.2 Inputs from the wave Model (SWAN)

The ocean surface parameterization COARE discussed in paragraph 4.1.2 requires input information on the surface temperature as well as on the surface velocity roughness provided under the form of characteristic wave parameters (significant wave height or phase speed of the dominant waves). This dependence of the surface roughness on wave parameters is a new feature of the latest COARE (version 3.0) algorithm (Fairall et al., 2003). Note that the wave parameterisation implemented in COARE still lacks a thorough validation.

Input wave heights and phase speeds can be extracted for specific case study locations from the spectral wave model SWAN, and used as input parameters for COARE. Although originally implemented as constant parameters, the wave information could ultimately be provided to ATHAM-Fluidity as time-dependent parameters.

4.3.3 Outputs for flood (Fluidity) and river (KALYPSO) models

One of the major outcomes of ATHAM-Fluidity as applied to specific case studies (see paragraph 4.2) consists in high-resolution (both spatial and temporal) surface precipitation maps corresponding to extreme meteorological events identified in the RCM.

Once produced, these temporally resolved precipitation maps may be used as inputs to the hydrological models. Because ATHAM-Fluidity and the other models of the integrated modelling framework use different grids (at different resolutions and possibly using different mesh structures) conservative interpolations will be necessary to make ATHAM-Fluidity output data compatible with the hydrological models. Urban floods being simulated using Fluidity, a comparatively simplified coupling procedure is expected.

The production of various precipitation maps showing spatial variabilities (using for example different input scenarios from the RCM), may help identify preferential precipitation/flood patterns, and deliver statistical analyses of pluvial flood events in selected case studies.

4.3.4 Outputs for storm surge modelling (Fluidity-ICOM)

Storm surge simulations performed by Fluidity-ICOM require information on the atmospheric temperature, pressure and wind speed above sea surface. These quantities are especially important to create sea level differences, wind driven waves, and therefore initiate storm surge events. ATHAM-Fluidity can provide localised, high spatial and temporal resolution fields of the above mentioned surface quantities. The well validated COARE algorithm will be key to produce realistic surface conditions for ATHAM-Fluidity and therefore for Fluidity-ICOM.

Storm surge modelling being performed using the same dynamical core as ATHAM-Fluidity (Fluidity), the exchange of input/output data between ATHAM-Fluidity and Fluidity-ICOM should be straightforward.

4.4 Expected outcomes

ATHAM-Fluidity's high-resolution atmospheric simulations will result in two major outcomes: output data for the hydrological and storm surge models, and an analysis of heavy precipitation events corresponding to pre-determined extreme scenarios for two case studies (Greve and Genoa). In the end, an important database of high-resolution data will be created from ATHAM-Fluidity outputs including surface and full 3D characteristic atmospheric variables for two case studies, 3 climate scenarios and several extreme events.

As described in paragraphs 4.3.3 and 4.3.4, 2D surface quantities extracted from the various ATHAM-Fluidity simulations will be used to drive the hydrological and storm surge models (after

proper interpolations). These quantities include surface precipitation rates, temperature, pressure and wind speeds. In addition, modelled surface heat and moisture fluxes may be used for direct comparisons with meteorological data and large-scale model outputs (RCM).

The full 3D model outputs will be further analysed to help understand the physical mechanisms involved in the development of extreme pluvial events. In order to do this, both transient and time averaged quantities will be extracted from selected ATHAM-Fluidity simulations and compared to available meteorological data, reanalysis outputs, and/or results from the RCM.

The two case studies present distinct scientific challenges which may require different analysis methods to be addressed. For instance, the advection of an extra-tropical cyclone (the major contributors to extreme winter weather conditions over western and northern Europe) over Greve may result in rather difficult to predict precipitation patterns in the region. In contrast, precipitation over Genoa will be strongly determined by the topography of the region, the city being surrounded by relatively high mountain peaks. Therefore, while a statistical analysis may give meaningful results for Genoa, a process analysis will be preferred for Greve. Comparisons between results obtained for a variety of ATHAM-Fluidity simulations (at the same location but for different scenarios) will be key to assess the causes and consequences of extreme precipitation events in coastal areas.

5. Stochastic precipitation generator

5.1 Background

For future scenario generation and climate effect studies where an ensemble of predictions is required to quantify uncertainty; sampling from a stochastic model is more efficient than re-running a deterministic atmospheric models with perturbations on forcing and boundary conditions. The parameters of this stochastic model can broadly be divided into four groups:

1. The general moments from the frequency distribution of rainfall intensities
2. The temporal dynamics, expressed by autocorrelation function, length of events and dry spells, power spectra, intensity-duration-frequency curves or other means
3. The spatial behavior, expressed by semivariograms, cross-correlation functions, areal reduction factors or (more rarely) power spectra
4. The dependency of all of the above on external drivers.

While the two first groups are hard to avoid, the importance of group 3 and 4 may vary with the specific challenge at hand. Group 3 in particular depends on the size of the study area versus the (true as well as measured) small-scale variability. Group 4 may or may not be important for an isolated study, but for coupled-hazard analysis it is necessary to provide a link enabling a joint probability distribution to be built.

5.2 Site and data

The work on stochastic precipitation simulation has concentrated on the Greve case study, using a rich set of hourly point rainfall data from the area around Greve and nearby Copenhagen. In addition, radiosonde data from nearby Copenhagen have been downloaded, and are being explored to find suitable forcing variables for the stochastic model. The radiosonde soundings (pressure or elevation profiles) contain the same type of information that would be available from an NWP or climate model.

5.3 First findings and design decisions

The 12h radiosonde data show high degree of temporal autocorrelation for the two first lags (12 and 24 h), indicating that downscaling to hourly data represents most of the information and smaller time scale. For the most rapidly fluctuating properties (i.e. stability and convective indices), the radiosonde data can be augmented with more frequently sampled ground temperature.

Attempts have been made to characterize the geostatistical properties of rainfall fields (item 3 above). Based on the available data set, this is possible for moderate, stratiform events; but not for the extreme convective events which would classify as hazards. Based on this analysis of spatial properties, it has been concluded that a spatial model would bring little extra information on top of what a point process provides, for a study area of Greve's size. In addition to reducing the complexity of the analysis, this also enhances the value of the data set, since the model can now be evaluated on individual stations, rather than spatial surfaces build from the entire spatial collection.

Hence, the stochastic rainfall generator is being built as a point process simulator. Models for parameters in group 1 and 2 above are built based on covariates from the sounding information. This ensures that the rainfall stochastic properties depend realistically on the temporally varying atmospheric state, which enables the co-simulation of pluvial and other weather dependent coastal hazards from atmospheric models as well as radiosonde measurements. Stochastic variability is available at (at least) two levels; the first being the variance in the point process generator itself, the second being the variance in the stochastic model parameters' dependency of the covariates. On top of these, there is always the possibility of capturing uncertainty in the sounding input, either by adding noise, or by generating full ensembles from the atmospheric model.

6. Flooding/storm surge and pipe modelling

6.1 Summary of approach

The work in Work Package 2 will integrate the existing knowledge, methodology and software tools of urban pluvial and fluvial flooding and oceanographic (coastal flow and wave) models into innovative research. It is based on advanced technologies, such as sewer network simplification, flexible mesh, reduced order modelling (ROM), to speed up 3D flooding simulation while maintaining good accuracy, so that it can result in reliable and quick forecasting of urban flooding.

To simulate the complex flow phenomena in urban drainage basins there are two main components for the model coupling system. Firstly, the EPA Storm Water Management Model (***SWMM***) will be modified and applied to simulate processes of surface runoff, soaking, retention and evapotranspiration of precipitation water in urban areas as well as flows in the underground sewage system. Secondly, to simulate the time variation of inundated depth and area, the existing code ***Fluidity*** will be used. The key work in this stage is to achieve integration of ***Fluidity*** with ***SWMM*** models built in the first stage, see Figure 8 for the linkage between the models. Finally, ***Fluidity*** will be extended to include rainfall, wave, and topography (with buildings), connect to underground sewer system to achieve fast and accurate simulation of complex urban flooding, see Figure 7. This coupled model will then be calibrated and validated. Since the results obtained with ***DHI-MIKE*** mdelling were validated in previous published studies (Soledad, 2014) for the same study area, they were used to verify the results obtained with coupled modelling in this research. In addition, for efficient coupled modelling the reduced order modeling (ROM) technology will be used to reduce the time required for simulations.

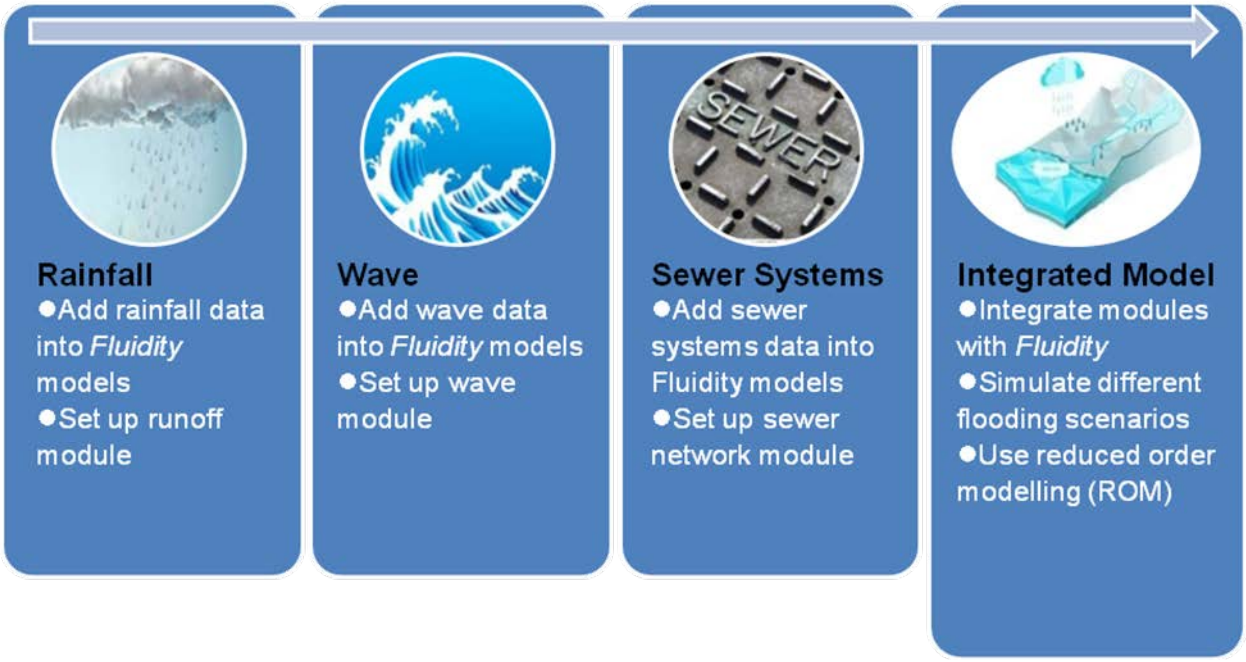


Figure 7: Schematic of flooding modelling system.

6.2 Precipitation

For the design of urban drainage structures (for flood protection), it is necessary to take into account current extreme rainfall events as well as the impact of climate change on future rainfall. For a place where rainfall measurements are available, a frequency analysis can be developed to obtain the IDF (Intensity-Duration-Frequency) relationship. According to the Intergovernmental Panel on Climates Change (IPCC), more intense and frequent extreme rainfall is expected in the future in Denmark, especially during summer periods. Therefore, it was concluded that the design of extreme rainfall in Denmark should include the effects of a changing climate. In northern Europe it was studied by Arnbjerg-Nielsen who pointed out that the increase in design intensities depends on the duration and the return period being studied (Soledad, 2014). According to this author, to obtain the design rainfall it is necessary to apply climate factors, which indicate that design intensities in Denmark are likely to be increased by 10-50% within the next 100 years. For the present research, rainfall data from 83 stations at arbitrary location in Denmark that had more than 10 years of data were included in the analysis. To obtain the IDF curves a regional statistical extreme model was applied (Soledad, 2014).

6.3 Pipe modelling

SWMM conceptualizes a drainage system as a series of water and material flows between several major environmental compartments. These compartments include raingauge, subcatchment, junction, conduit, regulator (orifice, weir or outlet), outfall, pump and storage unit.

In ***SWMM***, flow routing within a conduit link is governed by the conservation of mass and momentum equations for gradually varied, unsteady flow i.e., the Saint Venant flow equations. To solve these equations, ***SWMM*** provides 3 different methods—Steady Flow Routing, Kinematic Wave Routing and Dynamic Wave Routing.

Normally, Dynamic Wave Routing will be chosen, since it solves the complete one-dimensional Saint Venant flow equations and therefore produces the most theoretically accurate results. These equations consist of the continuity and momentum equations for conduits and a volume continuity

equation at nodes.

With this form of routing it is possible to represent pressurized flow when a closed conduit becomes full, such that flows can exceed the full normal flow value. Flooding occurs when the water depth at a node exceeds the maximum available depth, and the excess flow is either lost from the system or can pond atop the node and re-enter the drainage system.

Dynamic wave routing can account for channel storage, backwater, entrance/exit losses, flow reversal, and pressurized flow. Because it couples together the solution for both water levels at nodes and flow in conduits it can be applied to any general network layout, even those containing multiple downstream diversions and loops. It is the method of choice for systems subjected to significant backwater effects due to downstream flow restrictions and with flow regulation via weirs and orifices. This generality comes at a price of having to use much smaller time steps, on the order of a minute or less - ***SWMM*** will automatically reduce the user-defined maximum time step as needed to maintain numerical stability.

Each of these routing methods employs the Manning equation to relate flow rate to flow depth and bed (or friction) slope. The one exception is for Circular Force Main shapes under pressurized flow, where either the Hazen-Williams or Darcy-Weisbach equation is used instead (Rossman, 2010).

Based on results obtained from runoff and pipe modelling using ***SWMM***, data transformation and integration will be carried out by creating links between ***SWMM*** and ***Fluidity*** models, Figure 8.

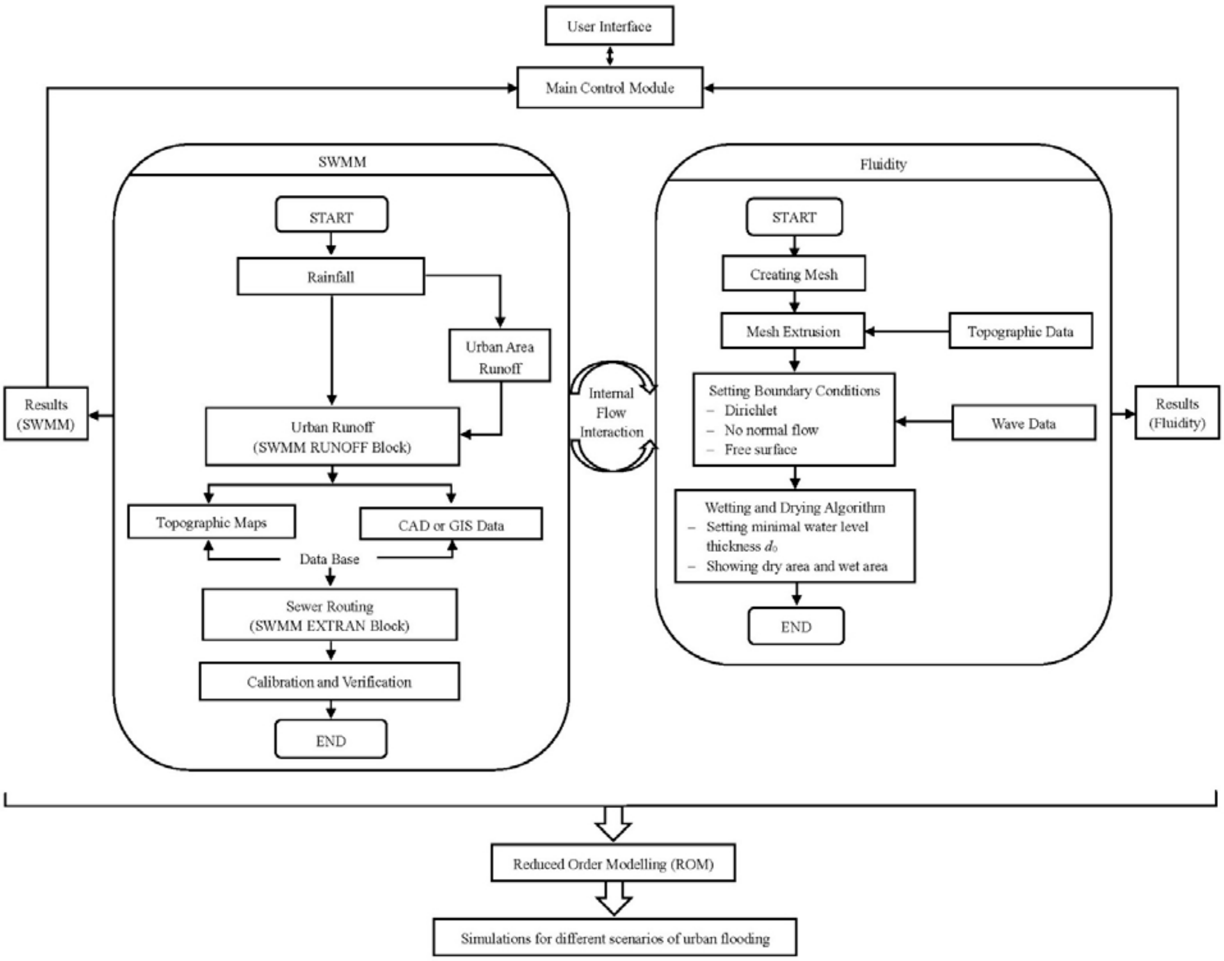


Figure 8: Coupling of pipe SWMM and Fluidity model – a one way coupling approach.

6.4 Rapid reduced order modelling

Reduced Order Modeling (ROM) technology is a rapidly growing discipline, with significant potential advantages in: interactive use, emergency response, ensemble calculations, and data assimilation (Cao et al., 2006; Fang et al., 2009; Hoteit and Kohl, 2006; Vermeulen and Heemink, 2006; Robert et al., 2006). Based on proper orthogonal decomposition (POD), ROM is expected to play a major role in facilitating real-time turn-around with computational results and data assimilation. The surrogate ROM's basis functions are required and these are generated by initially using an ensemble of simulations of the full model. A set of optimal POD bases (orthogonal vectors) is extracted through truncated singular value decomposition. The POD bases are then used to formulate a reduced dynamical system that contains the main features of the flow. This technique can provide a low dimensional Ordinary Differential Equation (ODE) approximation of the PDE models when used in conjunction with a Galerkin projection. Due to fast decrease in leading singular values, dominant components of a large dimensional process can be captured with only a small number of bases e.g. 20~100, thus reducing the computational speed to the order of seconds (Fang et al., 2009).

6.5 How to generate a range of simulations from the climate data (atmospheric and waves and sea height) to deal with extremes

The future extreme sea level events used in this research as boundary conditions were derived from these previous studies and the Max Planck (MPG) climate model (section 4). After introducing the extreme water levels to the model, the rainfall time series can be introduced. At first it is assumed that the extreme sea level events occurs independently of extreme rainfall, therefore rainfall-runoff will not be included in the model. In a second phase, rainfall will be applied to the model in order to analyse the effects where high water levels take place at the same time as significant rainfall. Finally, different scenarios combining intensity rainfall and sea levels were modelled.

7. Events in coincidence

Despite significant expertise in modelling individual components of flooding there are two significant gaps at the international scene: modelling of multiple coincidence and real time forecast of events requiring fine temporal and spatial scale. Recent climate related natural disasters have hit Europe and Japan, and flooding in many other places in the world highlight the need for technologies that can rapidly forecast and manage these events. It also reveals that the currently applied planning and design methods need to be refined and made more robust and reliable. Innovative modelling, predicting and planning tools are needed for critical infrastructures in coastal and estuarine areas. They should be able to integrate multiple coincidental risk scenarios including high ground and surface water level in the rivers and high tide or storm surge in the sea coinciding with heavy storms causing flash (pluvial) floods. Taking into account the joint natural hazards should be combined with failure in operation of critical infrastructures and their dependencies. Although the problem is global, vulnerability and interdependence of critical infrastructure networks are rarely studied. Moreover, reliable methods for prediction and early warning of the interactions of different types of floods are in its infancy especially in the case of the events requiring fine spatial and temporal resolution. Frequent occurrence of these high hazard events in coastal cities calls for development, testing and implementation of new modelling, prediction and emergency management technologies. The principal objective of this project is to reduce vulnerability of coastal areas to coincidental natural disaster events. This objective will be met by developing and testing next generation suit of modelling and prediction tools and demonstrating its applicability in selected case studies. The aim is to enable:

1) Risk and vulnerability assessment — from cause (coincidental hazard) to multiple effects (impacts).
2) Technology development — Develop next generation technologies for fine scale rainfall and flood forecasting under multiple coinciding of land and see based events. Enhanced quick response and emergency management capability.
3) Testing the applicability in case studies.
4) Coupling of models/physics: waves, storm surges, floods, atmospheric dynamics.
5) Generation of a range of simulations from coincident events from and generating extreme events.

8. Conclusions

Work Package 2 is concerned with the development of a novel hazard assessment framework and supporting tools to assess coincidence of two or more flood-related hazards by improving the modelling and predictive capabilities of integrated components. There is also a need to improve predictions especially over a wide range of spatial scales from metres to many kilometres to be able to assess the impact of a flooding disaster, assisting the rescue services, policy makers and scientists involved with risk reduction strategies for coastal and urban flooding. The unstructured and possibly adaptive mesh modelling technology allows these spatial scales to be resolved.

The framework described in this report will be demonstrated on a case study area and it will be presented and discussed in a separate report (i.e. deliverable 2.4).

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