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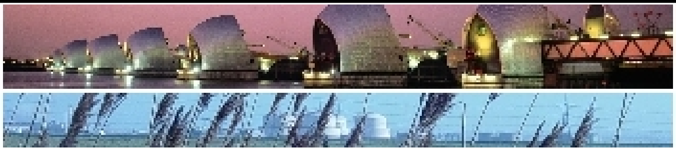
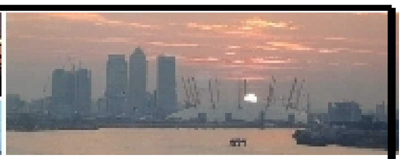


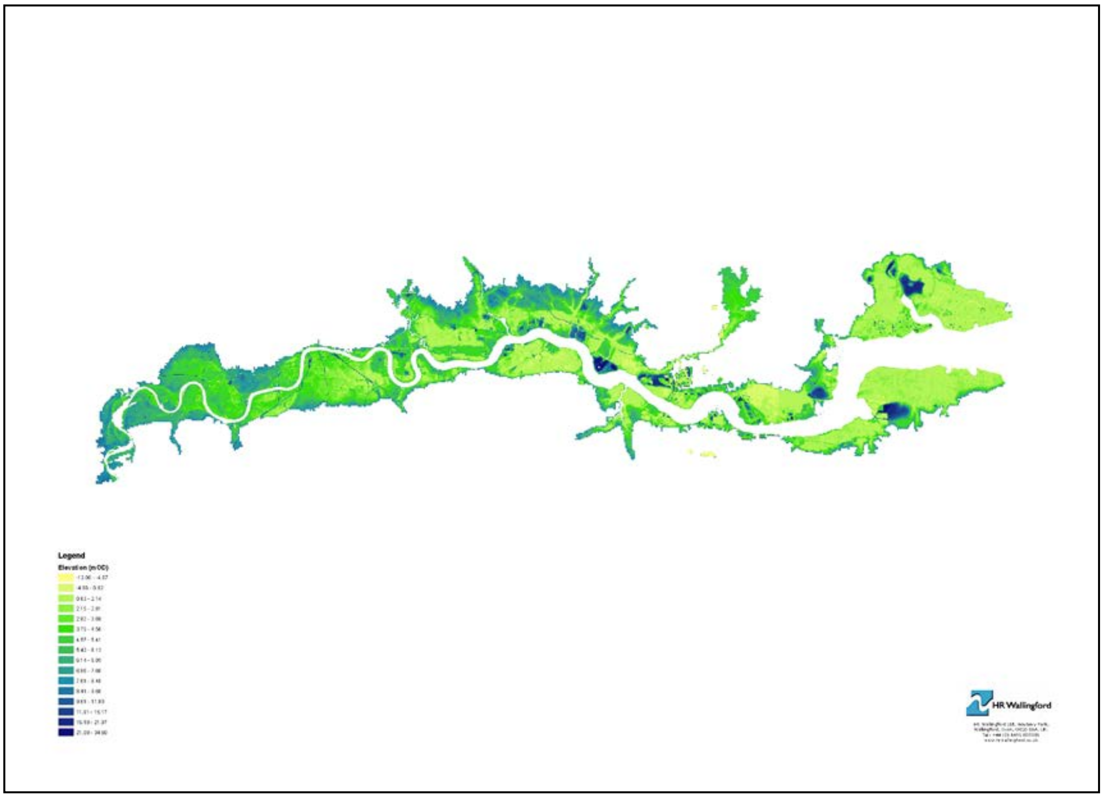


Thames Estuary 2100

Rapid flood spreading methodology (RFSM)

Final Report

Technical Note DT 4



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Thames Estuary 2100

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SUMMARY

This report describes the successful development and validation of a new generation flood spreading model – the so-called RFSM (Rapid Flood Spreading Model). The RSFM has been developed to support probabilistic analysis of risk within the context of the RASP analysis framework and hence is capable of carrying out multiple realisations of flood inundation scenarios within a runtime several orders of magnitude below the standard hydrodynamic models whilst yielding sufficiently accurate assessment of flood inundation.

The report recommends that the RSFM should be embedded within the RASP HLM+ software and adopted within the IA 8/10 (TE2100 theme number) V3 and beyond.

For further information regarding the content of this report please contact either Paul Sayers (HR Wallingford) or Owen Tarrant (Environment Agency).

GLOSSARY OF TERMS

Accumulation area: Topographic depressions present in the floodplain relieve where the water is stored in case of flooding. They form the basic entities in which the RFSM is based on.

Accumulation point: The lowest point present in a given accumulation area.

Communication level: It represents the lowest level that the water must reach in a given accumulation area to spill into another accumulation area.

Flood area: An independent hydraulic area within the floodplain. It is assumed that the water can not flow from one flood area to another.

Pathway: The trajectory that the flow follows across the floodplain.

RASP: Acronym of Risk Assessment for Flood and Coastal Defence for Strategic Planning – and the basis for the IA System Model (see www.rasp-project.net)

RFSM: Acronym of Rapid Flood Spreading Methodology.

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1 INTRODUCTION

The RASP HLM+ framework embedded within the IA System Tool provides a probabilistic analysis that enables sources, pathway and receptors to be integrated and risk assessed. The accuracy of the results from the IA Model is very sensitive to the accuracy of the flood spreading methods used. The highly simplified parametric spreading methods used in NaFRA and early versions of the IA Model have been shown to be insufficiently representative to support the more strategic scale analysis of risk required as part of the TE 2100 project.

This project (DT 4) was therefore commissioned to support the development of a new breed of flood spreading tools capable of analyzing the many combinations of defence failure and loading conditions demanded by the RASP methods in an acceptable timeframe and to reasonable level of accuracy.

This report outlines the development of the revised spreading method and its validation against a range of more traditional TUFLOW runs.

2 PROJECT OBJECTIVES

The project objective set out within the proposal for services under the DT4 contract is as follows:

To produce…a rapid flood spreading technique, proven against existing results, suitable for application to the Thames embayments, together with guidance for application.

A number of subsidiary objectives were also defined as follows:

- To review the drivers for the rapid flood spreading and the particular performance issues to be met.
- To review the modelling options.
- To develop a selected approach
- To apply, refine and validate the preferred approach against more detailed models within the Greenwich Embayment
- To provide a report including guidance on model application
- To aid transfer of techniques to DT and IA themes for inclusion in decision support tools

Note:

Application to the whole of the TE 2100 study area was not a requirement.

3 FUNCTIONAL REQUIREMENTS FOR THE RSFM

3.1 Introduction

Existing inundation models are either too inaccurate or too slow to run to be utilised within the context of a probabilistic analysis. Therefore, a new generation model was required. The function requirements for the new model can be summarised as follows:

- ***Run time*** - To provide results in an affordable lapse of time
- ***Topography and grid size*** - To be capable of working with an appropriate grid size for the purpose of economic damage estimations
- ***Physical processes*** – To be capable of sufficiently accurately representing the key physical processes of the flow
- ***Boundary conditions*** - To be capable of being run many times with different boundary conditions
- ***Numerical stability*** - To be numerically robust
- ***Reliability of output results*** - To be accurate enough to enable a credible assessment of economic risk

These functional requirements are discussed in more detail below.

3.2 Functional requirements - Run time constraints

For any given system of defences there as 2^n states that system may take for any given load. Combined with a need to consider a full range of loading conditions the number of inundation realisations can be seen to rapidly grow.

Therefore the runtime of the inundation model is critical to the run time of the risk model as a whole. Although not know explicitly it is anticipated that a runtime on excess of 5secs would be too greater and hence this was adopted as standard requirement.

3.3 Functional requirement - Representation of topography

Typically the topographic gradients in the study area are gentle. Floods in these areas tend to be dominated by 2-D processes, so the spreading model has reflect this. The floodplain is, however, clearly delimited by high ground, with an average floodplain width of about 3kms.

3.4 Functional requirement - Grid size

The model should be independent of grid size and should allow the user to define this appropriately. However it is recognised that:

- The grid size must be small enough to make reasonable use of the detailed LiDAR data available in the study area
- the run time is a limiting factor – refined grids are likely to increase run time
- the simplifications adopted to develop the model make its use with highly refined grids inappropriate (but feasible) as the physical processes occurring at these detailed scales are not be captured by the model

Taking account of these issues it was agreed that the model should be suitable to work with grid sizes covering from 25 to 100 m (25, 50, 100 m). As an exception, depending on the flood area dimensions and terrain features, the model will cope with finer grid sizes up to 10m.

3.5 Functional requirement – Representation of the key physical processes

No requirement was define a priori regarding the physical processes to be included within the model. It was however recognised that it to accommodate the run time requirement the complexity of the model would need to be minimized and the governing equations used must reflect only the important physical processes.

3.6 Functional requirement - Boundary conditions

The number of different boundary conditions used within a RASP type analysis is huge. The RFSM must therefore have the ability to efficiently and automatically modified the boundary conditions used.

Note:

It is assumed that the "boundary conditions" for the RFSM can be described in terms of spatially defined inflow volumes entering the floodplain. The generation of these inflow volumes would come from external models. The RFSM then takes the inflow volumes, spreads the water and returns the water depths to evaluate damages. This process will be repeated for each flood scenario to run.

3.7 Functional requirements – Reliability of the output results

To support an economic assessment of risk the RFSM must provide an estimation of the spatially varying flood depth within the floodplain for each given defence system state and load combination.

Velocity outputs are not essential (although should be considered a nice to have).

4 INUNDATION MODELLING A REVIEW OF OPTIONS

4.1 Introduction to possible options

Methods to model inundation vary in their complexity and accuracy: from quick methods that need minimal information and take virtually no time to run; to those which require detailed data and have a long computation time. This section provides an overview of potential options to simulate flooding – from simple to complex.

The Greenwich embayment, in the Thames region, has been used to demonstrate the output from each of the modelling methods and options described.

Note:

It is assumed that the reader is familiar with GIS, hydraulic terminology and available software packages.

4.2 Inundation modelling - A review of options

4.2.1 Option 1 - GIS (spatial queries – no modelling of flow physics)

Description: In this method the ground surface is intersected with a projected water surface (i.e. expected flood water level) to produce a flood extent map (see Figure 1).

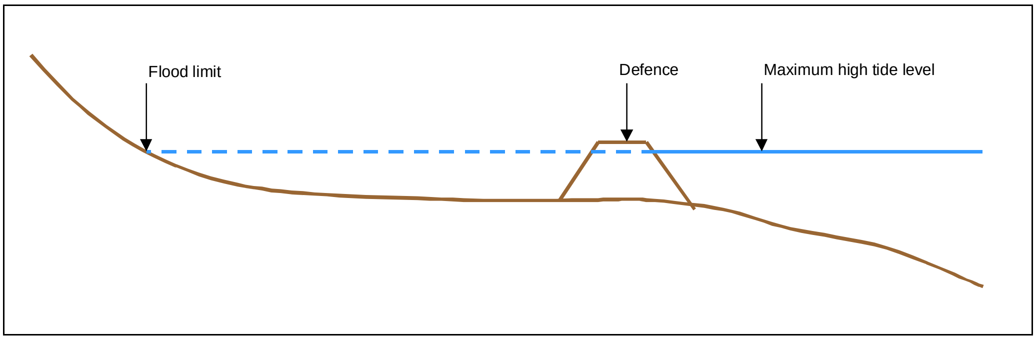

Figure 1: Projected water level

Any ground level below the water level surface is assumed to be flooded. Figure 2 shows an example of the output of this method where the blue areas represent the flood areas.

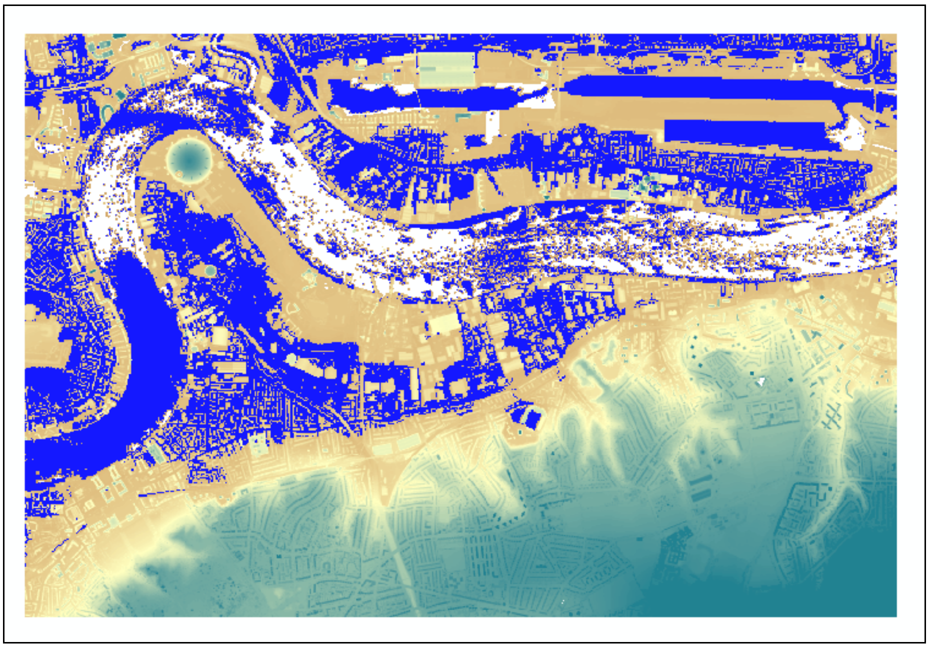

Figure 2: Flooding using a simple (no physics) GIS method

Data requirements:
Limited – topography, source of flood waters and volume.

Output:
Flood extent and water depth.

Advantages:
- Quick and easy to setup.
- Uses standard GIS package such as Arcview or MapInfo functionality.

Disadvantages:
- Flooded areas are overestimated (and not necessarily hydraulically linked).
- No physics are explicitly modelled
- No information on local velocities or speed of flood spreading is provided

4.2.2 Option 2 - GIS (modified spatial queries – limited physics)

Description:
This method is similar to the one described above but it allows the presentation of some physics in modelling the spread of water by simulating the effects of parameters such as friction (e.g. simplifying Manning's equation) as shown in Figure 3.

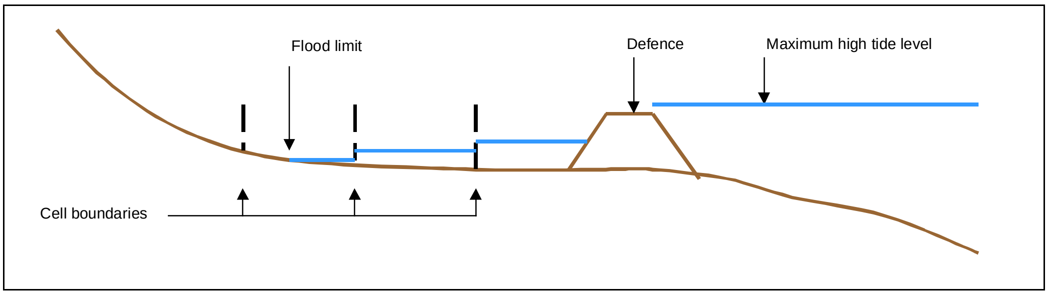

Figure 3: Flooding using GIS method (some physics)

A source of flooding (i.e. Breach) can also be modelled and areas that are not linked to the flood source can be eliminated from the flooded areas. Figure 4 shows an example of the output of this method. As shown in Figure 4, the flooded areas which are noticeably different for those predicted by Option 1.

Data requirements
Limited – topography, source of flood waters and volume.

Output:
Flood extent and water depth information.

Advantages:

- Relatively quick and easy to setup.
- Involves some of the physics in spreading the flood water.
- Uses standard GIS package such as Arcview or MapInfo functionality

Disadvantages:

- Mass and momentum not necessarily conserved
- No information on local velocities and speed of flood spreading.

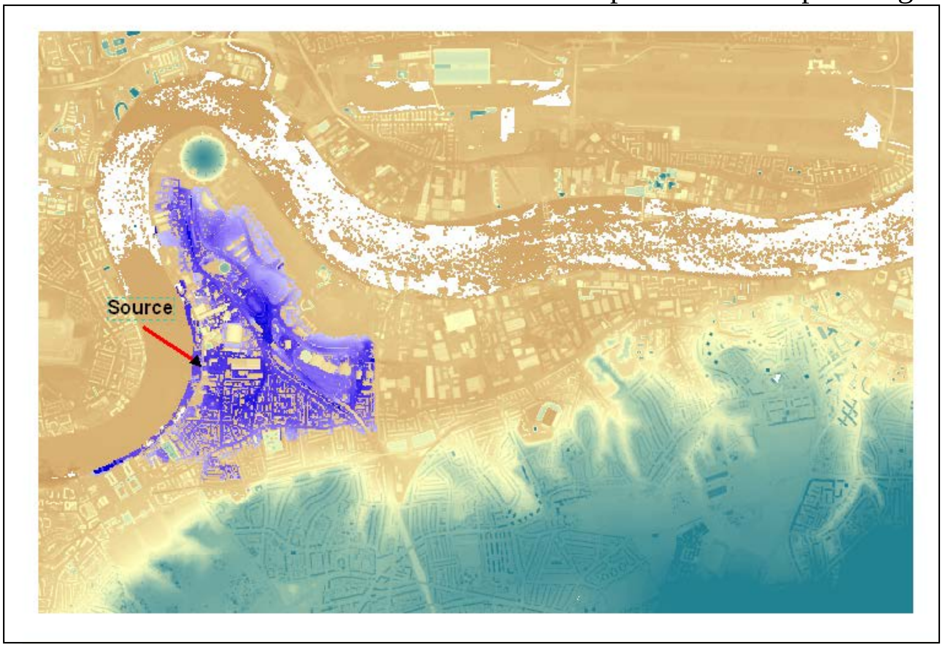

Figure 4: Flooding using GIS method (some physics)

4.2.3 Option 3- Quasi two dimensional methods (flood basins)

Description:
These methods [see Reference 1] model the spreading of flood water by splitting the flooded areas into relatively small flood cells (compartments) where water can flow from one to the other based on the capacity of each flood cell. Friction and 'weir' effects can also be modelled between flood cells. Figure 5 shows an example of splitting the Greenwich embayment into smaller flood cells.

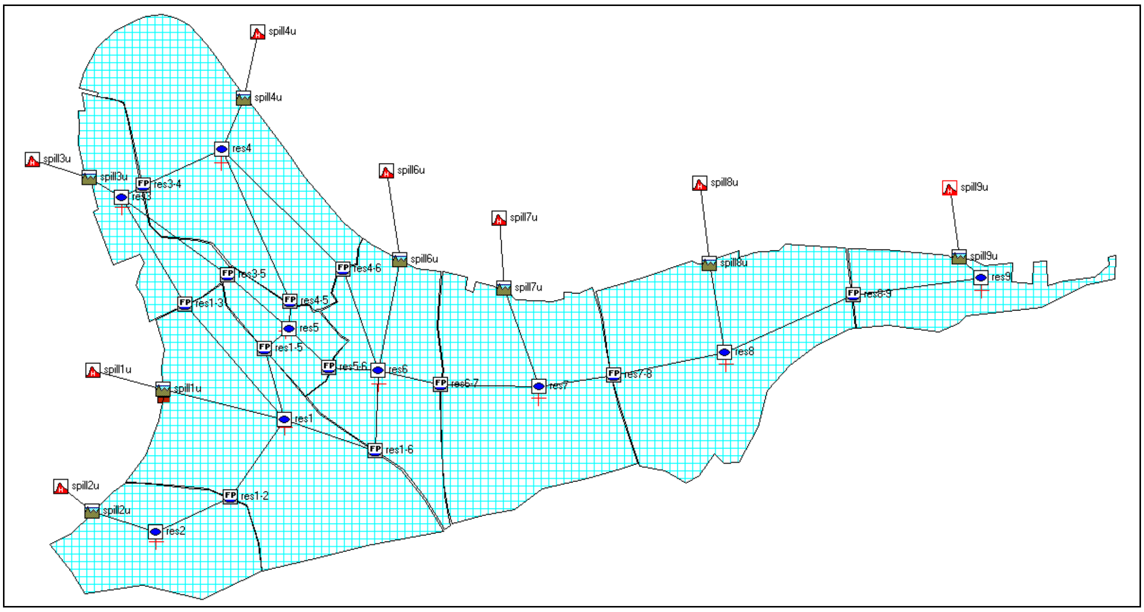

Figure 5: Example of splitting floodplains into flood cells (from Reference 2)

Data requirements:
Limited – topography, source of flood waters and volume.

Output:
Flood extent, water depth and indicative information on speed of flood spreading.

Advantages:

- Involves a higher level of physics in spreading the flood water than the above two methods.
- Some indicative information on the speed of spreading can be obtained.
- Uses standard GIS package (such as Arcview or MapInfo) and hydraulic model (such as InfoWorks) fucntionality.

Disadvantages:

- Momentum is not conserved.
- More time to setup than either Options 1 or 2.
- Flooded areas might not be linked to the source of flooding or to each other (depending on the nature of the model setup).

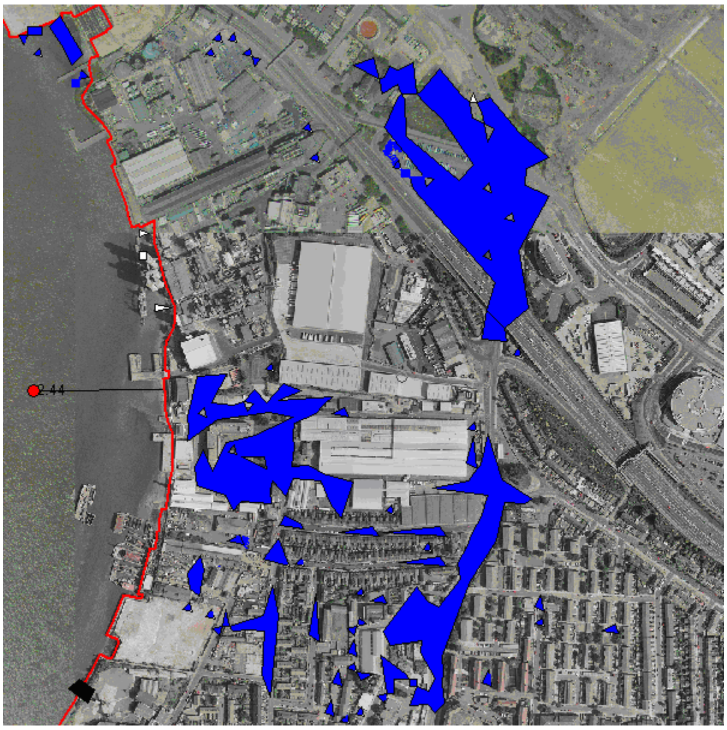

Figure 6: Flooding using Quasi two dimensional methods

4.2.4 Option 4 - Quasi two dimensional methods (Raster routing methods)

Description:

These methods [see Reference 3] are similar to the methods describe din Option 3; however, in this case the flood cell size is much smaller than that used above. The cell size is obtained from directly from the ground model data. Figure 7 shows an example of the output of this method where the blue areas represent the flood areas.

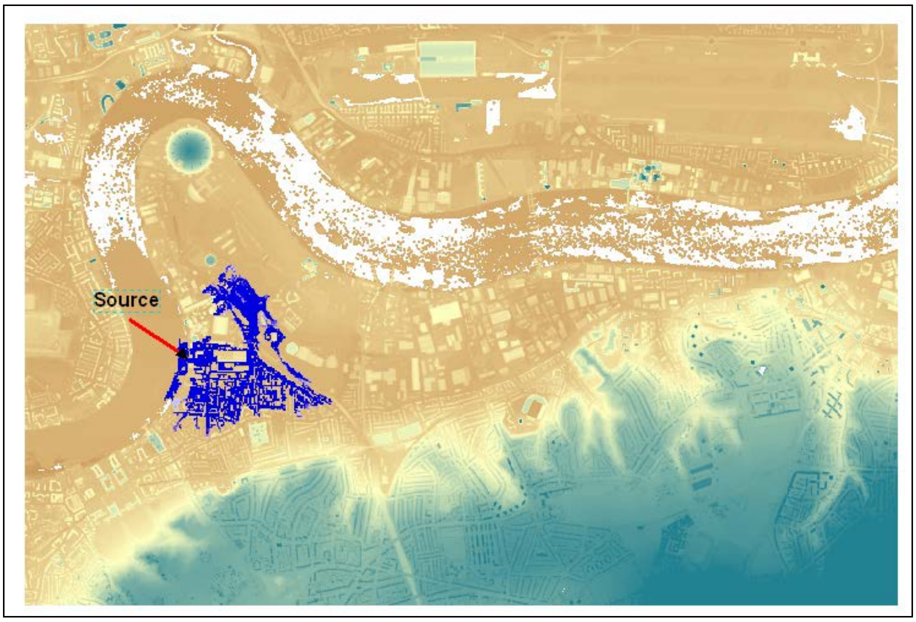

Figure 7: Flooded areas using the quasi two dimensional methods

Data requirements:

Detailed DTM, inflow hydrographs and locations.

Output:
Flood extent, water depth, flow velocities and time of inundation.

Advantages:
- A higher level of physics in spreading the flood water compare to Options 1-3.
- Some indicative information on the velocity of spreading can be obtained.
- Uses standard GIS package such as Arcview or MapInfo functionality and any raster routing model such as LISFLOOD.

Disadvantages:
- Difficulty ensuring conservation of momentum terms when seeking fast model run times.
- Extended setup times compared to Options 1 and 2
- If explicit schemes are used to solve the flow equations, incompatible cell size and time step can cause instabilities in the model. This can constrain the selection of time step and cell size combinations and lead to excessively long run time.

4.2.5 Option 5 - Full two dimensional methods

Description: These methods model the flood spreading by solving the full two dimensional shallow water equations (i.e. conserving mass and momentum). Examples of models which use this technique are Telemac [see Reference 4] and TUFLOW [see Reference 5]. Figure 8 shows an example of the output of this method.

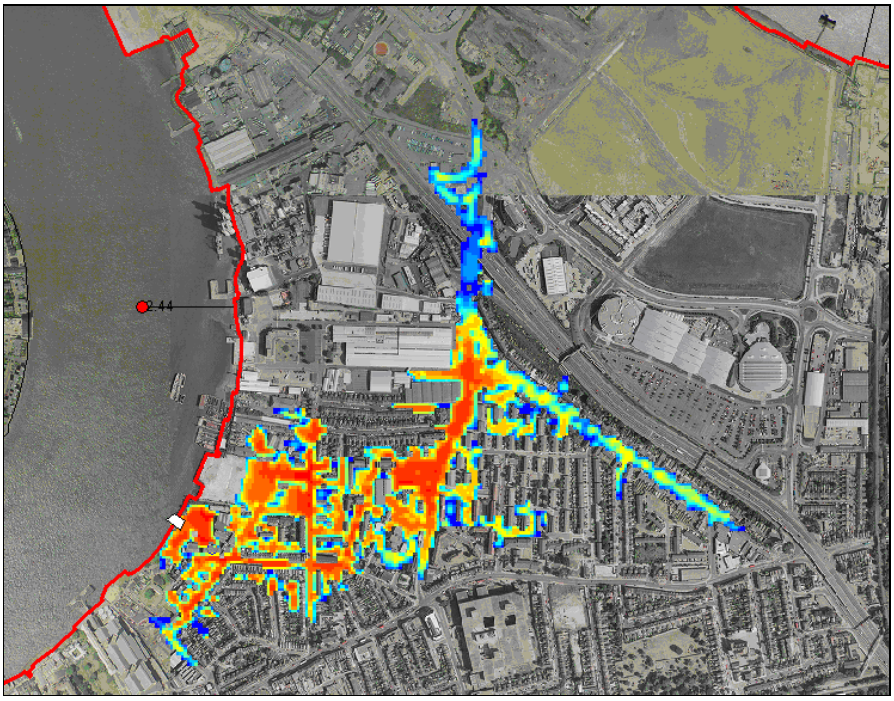

Figure 8: Flooded areas using the two dimensional methods

Data requirements: The data required for this method is ground levels for the study area (best as a digital ground model) and hydraulic data to setup the hydraulic model. The work can be done a using standard GIS package such as ArcView or MapInfo and a 2D model such as Telemac and TUFLOW.

Output: Flood extent map such as the one shown in Figure 8, and information on water depth, local velocities and speed of flood spreading.

Advantages:

- Solves the full 2D shallow water equations (i.e. conserves mass and momentum).
- More accurate information on local velocity and the velocity of spreading can be obtained.

Disadvantages:

- Run times are relatively long.
- Requires more time to setup than all of the above methods.

4.3 Review recommendations

It is clear that selecting a method to spread the flood water would depend mainly on the aim of the flood risk assessment study. Within the approach to flood risk analysis proposed under IA8/10 Theme of the TE2100 project, the main requirements that the rapid spreading model should cover have been detailed in previous chapters of this report. Mainly they are:

- Short setting up time
- Short run time
- Flexibility
- Numerical robustness
- Enables sufficient accuracy for the intended use

And the expected results from the model are:

- Estimations of the flood depths achieved along the floodplain

Table 1 shows a summary of the features of the methods described previously. Looking at Table 1 and taking into account the main requirements the new model must fulfil, it can be stated that the rapid spreading model should combine features from several methods. It should be as easy to set up as the GIS methods but it should provide results, in terms of water depths, with a level of accuracy on the order of quasi two dimensional or raster routing methods. Another interesting goal to achieve would be to conserve volume, i.e. to assure that the volume at the end of the simulation matches the inflow volume to the floodplain.

Since momentum, velocities and temporal evolution are not priority objectives, the proposed rapid spreading method will fit between the GIS methods and the quasi two dimensional methods. But it will also have some characteristics typical in more complex methods, such as the use of refined regular or irregular grids and also mass conservation.

Method	Setup time	Run time	Mass conservation	Momentum conservation	Water depth	Local velocity	Speed of spreading
GIS (No physics)	Quick	None	No	No	Yes	No	No
GIS (Some physics)	Quick	None	No	No	Yes	No	No
Quasi two dimensional	Short	Short	Yes	No	Yes	No	Indicative
Raster Routing Fine grid	Long	Long	Yes	No	Yes	Indicative	Indicative
Raster Routing Coarse grid	Long	short	Yes	No	Yes	Indicative	Indicative
Two dimensional fine rectangular grid	Long	Long	Yes	Yes	Yes	Yes	Yes
Two dimensional coarse rectangular grid	Long	Short	Yes	Yes	Yes	Yes	Yes
Two dimensional irregular grid	Long	Long	Yes	Yes	Yes	Yes	Yes

Table 1: Features of flood spreading methods

None of the aforementioned methods is fully suitable for its use in the IA8 Systems Model and therefore a new flood propagation model has been developed.

5 DESCRIPTION OF PROPOSED METHOD

5.1 Introduction.

The proposed approach has been developed specifically to carrying out flood spreading calculations in the context of a probabilistic risk assessment. It is able to deal successfully with multiple flood scenarios and provide estimated flood depths within the floodplain capable of supporting reliable estimates of associated damage.

5.1.1 Overview of governing equations

In traditional models the St. Venant equations, which are a simplification of the complete Navier-Stokes equations, are used to describe the flow. These governing equations, in Cartesian coordinates and neglecting diffusive terms can be written as follows:

$$\frac{\partial}{\partial t}[H]+\frac{\partial}{\partial x}[F]+\frac{\partial}{\partial y}[G]=[S]$$

$H : conserved\ variables$

$F : convective\ terms\ x-axis$

$G : convective\ terms\ y-axis$

$S : source\ terms$

where one possible formulation for the vectors is:

$$[H]=\begin{bmatrix} h \\ hu \\ hv \end{bmatrix} \quad [F]=\begin{bmatrix} hu \\ hu^2+0.5gh^2 \\ huv \end{bmatrix} \quad [G]=\begin{bmatrix} hv \\ huv \\ hv^2+0.5gh^2 \end{bmatrix} \quad [S]=\begin{bmatrix} R \\ g(S_{ox}-S_{fx}) \\ g(S_{oy}-S_{fy}) \end{bmatrix}$$

$h : water\ depth$

$u : velocity\ x\ axis$

$v : velocity\ y\ axis$

$g : gravity\ acceleration$

$R : Mass\ source\ terms\ (Rain,\ sewer\ system,\ etc)$

$S_o : slope\ of\ the\ terrain$

$S_f : friction\ term$

These equations form a coupled non-linear system of hyperbolic partial differential equations. The accuracy of this kind of model for the simulation of surface flows has been proved over the years. The analytical solution of the equations for 2-D cases is not obvious, however, and is possible only in some very simplified 1-D cases. Therefore, a numerical method needs to be used to solve the equations. Within the context of the rapid spreading method being developed here the numerical solution of these full equations is not appropriate (given current computational power) and must be simplified.

5.1.2 Overview of simplifying assumptions

Governing equations

A number of simplifying assumption have therefore been made to the governing equations, namely:

- The in flow into the floodplain (from given overtopping or breach event) is not inertial (i.e such as the flow generated after a sudden dam break),
- The influence of the convective terms *(F and G in the above equations)* can be neglected.
- The main driver of the water movement is the source term.

On first view these simplification could lead to the use of a to LISFLOOD or similar models, where the flow is directed by the slope and the friction of the terrain following the Manning's or equivalent equations. Nevertheless, it is known that the friction will represent only a fraction of the contribution to the momentum term due to the slope of the terrain. Therefore a further simplification has been applied:

- It can be considered without a critical loss of accuracy that the main driver is only the slope of the terrain.

Further simplification is however to achieve the functional specification discussed earlier. In particular the likely setup time must be reduced setup times and the computation speed improved (the reliance on an explicit time step limit determines the long run times of models such as LSTFLOOD and JFLOW). It has therefore been assumed that:

- For the purposes of a risk assessments it is not essential to have the detailed temporal evolution of the flood depths.

- An estimation of the maximum depths, which will be used for assessing economic damages.

These assumptions mean that the flood spreading routine can be simplified to obtain only a snap shoot of the maximum depths, avoiding complicated temporal calculations.

In summary the new spreading model will therefore account only for:

- The slope of the terrain.
- Only a single output will be provided - the maximum flood depths.

Model setup and mesh generation

The mesh generation must be a simple process, not dependent on the user, but able to reflect the full resolution of the available topography data. The model must also have the ability to implement revised boundary conditions automatically (as the number of scenarios to run will be large).

5.2 Methodology.

5.2.1 General overview

The RFSM is a water spreading tool indicated to perform economic damage risk calculations in floodplains very rapidly. In order to reduce the calculation time and based on the assumption that the flow is mainly driven by the slope of the terrain, the hydraulic problem is split in different steps. Each one of these steps is developed to carry out specific tasks in the more efficient way. Basically, these steps are:

i) Pre-processing activities
ii) Accumulation activities
iii) Pathway module

The pre-process is devoted to create the calculation mesh and to include the defences (sources of flooding) in the model. The floodplain is divided in different areas, the so-called "accumulation areas" which will be the basic elements of the mesh. These entities represent topographic depressions in the floodplain where the water from the river is accumulated in case of flooding. The division of the floodplain in accumulation areas is maintained by the assumption that the flow is considered not inertial and therefore the water will pond according to the topographic features. A database with a volume/level function for each accumulation area is generated and will be used in the following steps. Moreover, the relation between every accumulation area and its neighbours is identified. This relation is based on the so-called "communication levels", which are the ground levels at which the water will spill from one accumulation area to another. This step depends only on the original topographic data, therefore the finer the input grid is, more accumulation areas will be obtained. Finally, the last task carried out during the pre-process is to link the defences, i.e. the sources of flooding, to the accumulation areas.

The accumulation model spreads the input volume to the floodplain among the accumulation areas, according to the volume/level databases obtained from the pre-process. The input volume must be calculated externally, for instance, by a breach module or a rain forecast. The results obtained from the accumulation model represent a snap shoot of the estimated final location of the water in the floodplain.

The flow chart showing how the RFSM works can be observed in Figure 9 below. The blue boxes represent the stages of the RFSM, the green boxes the input data, the orange box the intermediate results, and finally, the red box is the final result provided by the RFSM. This will be the value used to evaluate economic damages.

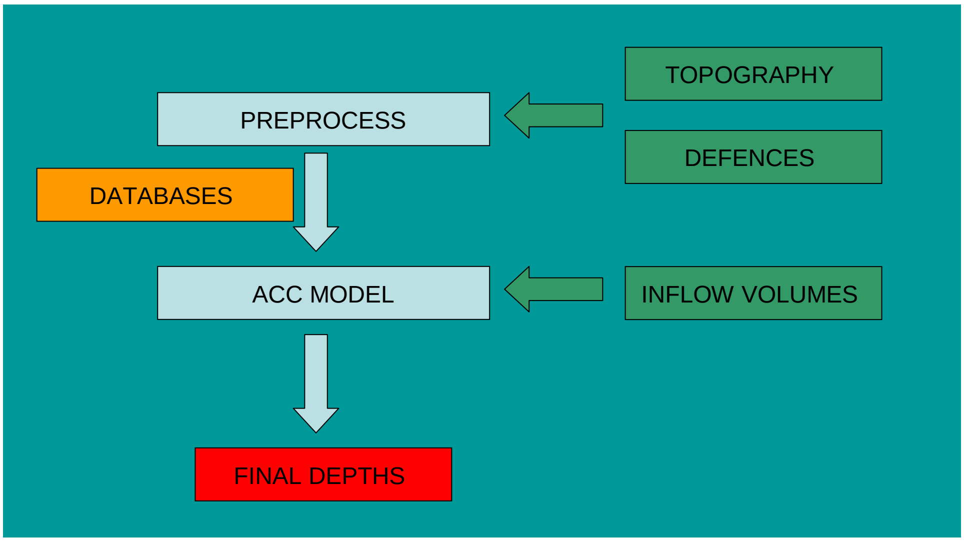

Figure 9: Overall flow chart. RFSM.

5.2.2 Preprocess

The main aim of the pre-process is to extract all the relevant topographic information contained in the input data. This process is based on the following two assumptions:

- the flow pathway follows the steepest slope of the topography, from the source of flooding to the accumulation area(s)
- the pathway will remain the same independent of the event severity

These assumptions mean that the flow in complex situations is simplified. In real situations, depending on the flow rate, secondary pathways can appear besides the main one. This can result in an overestimation of flooding in the main pathway areas whilst in secondary pathway areas the flooding could be underestimated. Anyway, under the perspective of multiple scenario models, where the probabilistic integration has a big influence in the final results, this issue is considered to be not significant as it will appear only in very specific cases.

The input data for the pre-process is:

- Topography: At the moment raster datasets are used as input. This means that the grid points are even spaced. But different grid sizes can be used in different embayments. The raster datasets are made up of DEM cells, which are square entities with a grid point in their centre.
- Defences: location of the mid point of the defence.
- Flood areas: The floodplain is divided into hydraulically independent areas, the so-called flood areas or also called embayments. The spreading algorithm will run per flood area.

The floodplain is split into smaller units called accumulation areas, representing depressions in the topography where the water is accumulated. The lower point of each one of these depressions is called accumulation point. This division of the floodplain is automatic and unique, depending only on the input topographic data, or in other words in the ground elevations and the grid density. Therefore the user is freed of the tedious work of setting up the mesh. Each accumulation area belongs to a specific flood area and a function of level versus stored volume is built for all of them.

Apart from that, the information regarding the communication levels between accumulation areas is stored in a database. These communication levels represent the ground levels at which the water coming from one accumulation area is spilling to another. The databases containing the communication levels and the level-volume functions are the basis of the accumulation method.

The pre-process is carried out in several steps.

Step 1 Searching the accumulation points

The first task is to locate the accumulation points. This identifies the low points in each embayment. Examples of this calculation can be seen in Figures 10 and 11 for the Greenwich embayment and two different grid densities.

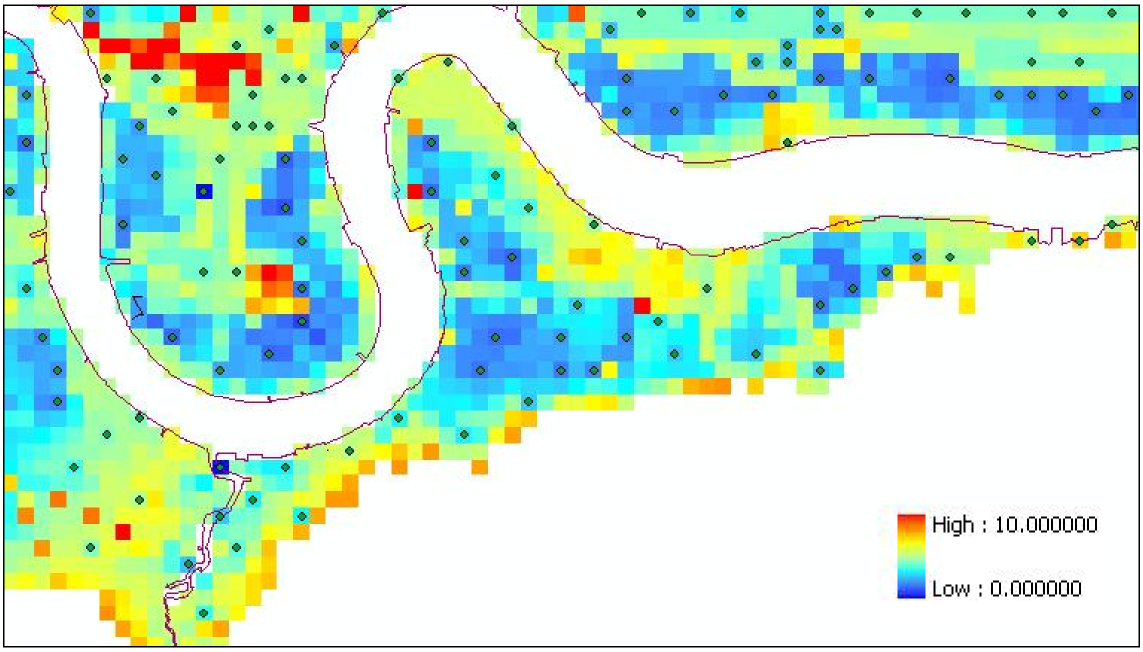

Figure 10: Identifying the accumulation points (100 DTM)

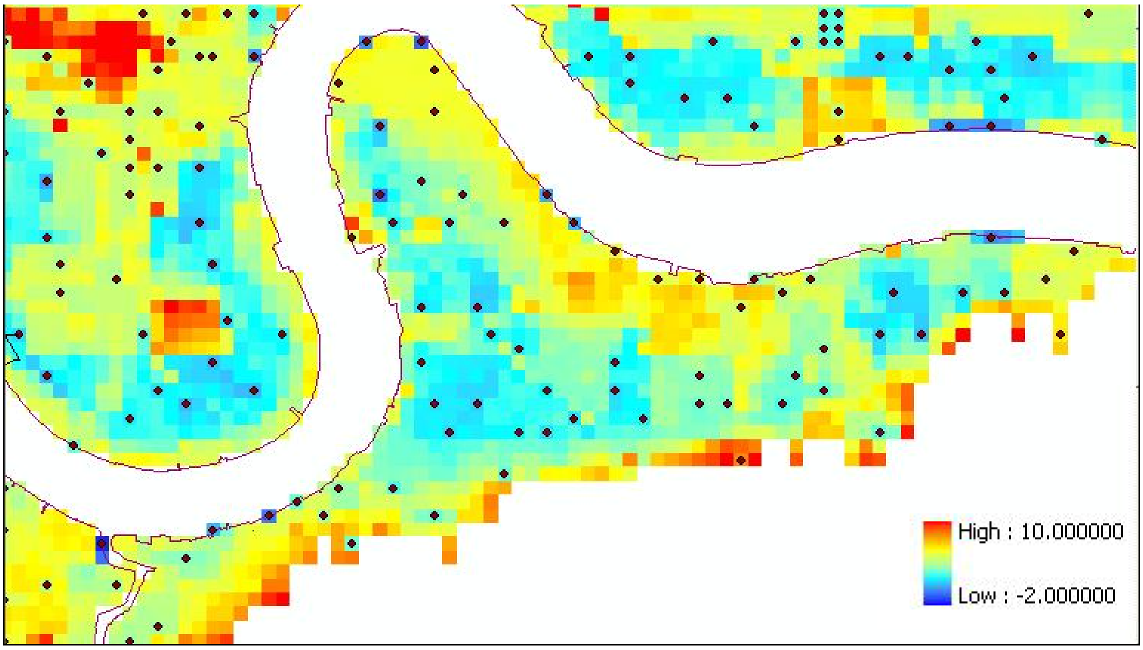

Figure 11: Identifying the accumulation points (~60 DTM)

Step 2 Building the accumulation areas

Every DEM cell will have an accumulation point associated. From each cell in the grid and following the steepest downstream slope in any of the eight possible directions (N, S, E, W, NE, NW, SE, SW), an accumulation point is reached. All the DEM cells associated to one accumulation point will form an accumulation area. An example of the accumulation areas generated in the Greenwich area can be shown in Figure 12 below.

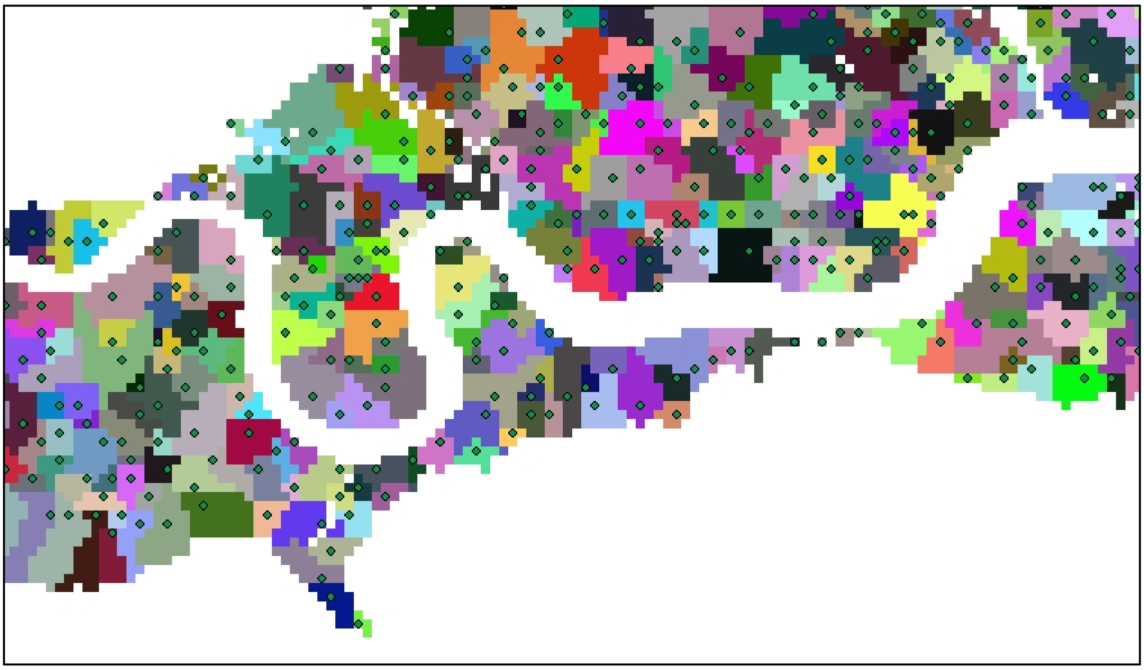

Figure 12: Identifying the accumulation areas (100 DTM)

Step 3 Searching neighbours/communication points between accumulation areas

For each accumulation area, the neighbour accumulation areas are worked out. Among the DEM cells between two neighbour accumulation areas, the lowest ground level is selected. This will be the communication level between them. An sketch showing two accumulation areas and the communication point between them can be seen in Figure 13.

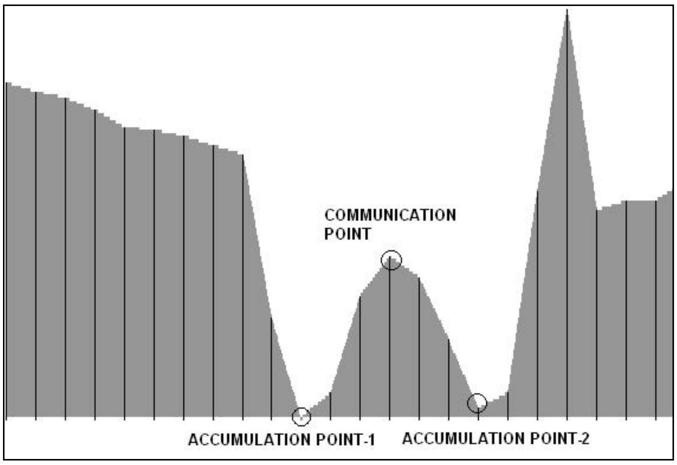

Figure 13: Communication point between two accumulation areas

Step 4 Building the databases.

Two databases are built:

- Level-volume database: It contains the volume stored in an accumulation area till every ground level of its DEM cells. Therefore, all the topographic information contained in the original DEM is stored in this database. Moreover, additional data is added regarding the volumes stored till the communication levels. An example of this database can be shown in Table 2 below:

ACC AREA	LEVEL	VOLUME
1	1	0
1	1.2	100
1	1.3	200
1	1.35	400
1	1.4	650
1	1.5	1100
1	1.65	1600
1	1.7	1800
1	1.8	2300
1	1.9	2900

Table 2: Level-volume database

- Neighbour database: For each accumulation area it contains the list of its neighbour accumulation areas and the communication level between them. The number of lines per accumulation area will be always less or equal than the number of lines in the previous database. An example of this database can be observed in Table 3 below:

ACC AREA	LEVEL	NEIGHBOUR
1	1.35	2
1	1.7	3
1	1.9	4

Table 3: Neighbour database

Step 5 Including the defences in the model.

Every defence is associated to the nearest accumulation area from its mid point. Therefore, every defence will have a unique accumulation area associated. All the inflow volume from a defence into the floodplain will discharge into the accumulation area associated to the defence.

5.2.3 Accumulation model

The accumulation model represents the core process of the RFSM. It uses the inflow volumes calculated by the RASP HLM+ breach model and the databases generated in the pre-process to spread the water in the floodplain. The results obtained from the accumulation model represent a hypothetic snap shoot showing the final situation of the water, i.e. the water at rest.

The accumulation method uses a stepping algorithm to distribute the water in the floodplain. The general flow chart of the algorithm can be seen in Figure 14. That algorithm will be repeated in a flood area basis. The method conserves water mass, but does not take into account the momentum.

Basically, each step a volume is distributed in the floodplain according to the volume of water already stored in the accumulation areas. In the first step the volume of water to spread in the floodplain will be the inflow volume provided by the RASP HLM+ method. The adjacent areas to the sources of flooding are activated, or in other words, they will be filled up in the current step. The capacity of the active accumulated areas is then calculated. It will be the volume of water that can be stored in them till the next communication point. If for instance, these accumulation areas have enough capacity to store the initial inflow volume, the simulation would end at the first step. If, on the opposite it is not the case, then the volume of water already distributed in the first step (the capacity of the active areas in the first step) is subtracted from the total inflow volume. The difference will be the so-called excess. In the next step the new volume to spread and the active accumulation areas are updated. The new volume to spread will be the excess from the last step. This process is repeated again until the excess is nil.

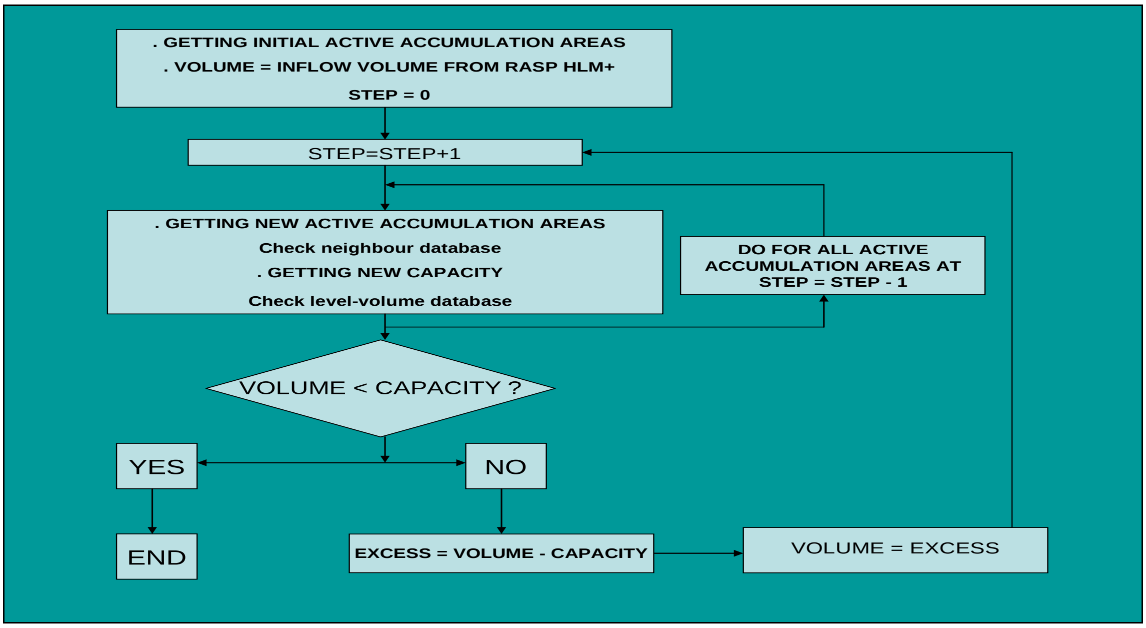

Figure 14: General flow chart. Accumulation model.

In short, the accumulation model algorithm is based in the tasks described below that will be repeated every step. Each accumulation area has associated two variables that must be explained, inflow volume and excess. The inflow volume refers to the volume that spills into a certain accumulation area. On the other hand, the excess is the water volume that is impossible to store in a specific accumulation area without spilling to another. The detailed flow chart of the algorithm can be seen on Figure 15.

Task 1 Activate accumulation areas

The accumulation areas that have some inflow volume are activated.

Task 2 Calculate the capacity of the active accumulation areas

For each activated accumulation area, the capacity available till the next communication point is obtained looking up in the neighbour database the next communication level. This communication level has a volume associated, that can be obtained from the volume database. The capacity available will be the difference between this value and the volume stored beforehand in the accumulation area.

$$Capacity = V_{nc} - V_s$$

$$V_{nc} : Volume\ till\ the\ next\ communication\ point$$

$$V_s : Volumen\ already\ stored\ in\ the\ accumulation\ area$$

Task 3 Check the relation between capacity and inflow volume

For each activated accumulation area, the inflow volume in compared with the available capacity. Two possible situations can happen:

- For every active accumulation area the capacity is greater than the inflow volume. The excess is set to zero in all the accumulation areas. Go to task 5.

$$\forall \ Accumulation\ areas \rightarrow Capacity > Inflow\ volume$$

- At least there is one active accumulation area where the capacity is smaller than the inflow volume. There are therefore some accumulation areas with volume excess. Go to task 4.

$$\exists \ Accumulation\ areas \rightarrow Capacity < Inflow\ volume$$
$$Excess_i = \sum (Inflow\ volume)_j - Capacity_i$$
$$i = 1...n,\ number\ of\ \ accumulation\ areas$$
$$j = 1...m,\ number\ of\ \ neighbours$$

Task 4 The active accumulation areas with excess are filled up

The active accumulation areas with some excess are filled up till the next communication point looking up the neighbour table. The inflow volumes in these accumulation areas are set to zero.

Task 5 The active accumulation areas without excess are filled up

The active accumulation areas without excess are filled up following the level-volume database. The inflow volumes to these accumulation areas are set to zero.

Task 6 The compatibility of levels with the river is checked. Open river boundary

For each accumulation area filled up in the previous two tasks, the compatibility of levels is checked with the river levels. The flood levels in the floodplain for a given scenario can never be higher than those achieved in the river. For this reason, if there is any accumulation area with higher levels than the river, the accumulation routine caps its level to the river level, which is supposed to be the maximum possible value. The remaining volume is not spread and is supposed to go back to the river.

Task 7 Searching new accumulation areas to fill

Two situations can occur:

- There are not accumulation areas with excess. Go to task 7
- There are some accumulation areas with excess. For each of these accumulation areas with excess the following process is carried out. Looking up the neighbour database and following the decision process shown in Figure 15 the excess of volume is converted into inflow volume. The possible situations at this stage are:

    - If the water level of the neighbour is lower, then the excess will be its inflow volume.
    - If the water level of the neighbour is equal, the excess is split between the two accumulation areas. Therefore they will have an inflow volume that

will be half of the original excess. This process can be extended to situations with more than 2 accumulation areas with the same level, simply dividing the excess by the number of accumulation areas.

Eventually, the excess is set to zero. Go to task 1.

Task 8 End of the accumulation method algorithm.

The final water levels for all the accumulation areas are retrieved and passed to evaluate damages. All the water spilled into the floodplain is stored in the accumulation areas, therefore the mass conservation is assured by definition.

$$Inflow\ volume = \sum_{i}^{n} V_{si}$$

V_{si} : *Volumen stored in the accumulation area i.*

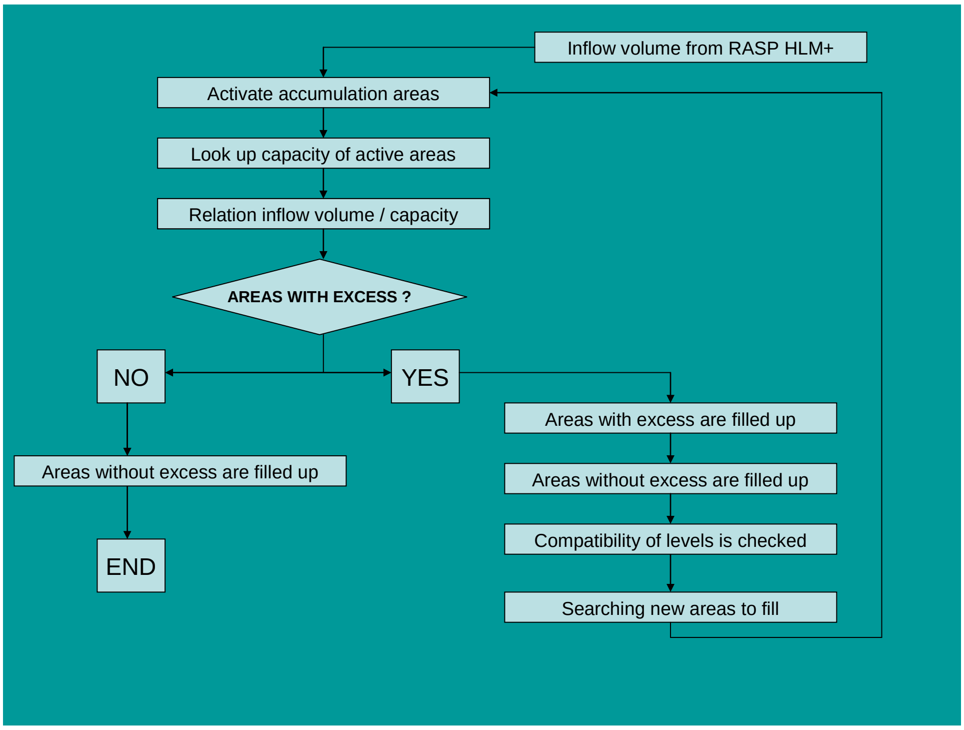

Figure 15: Detailed flow chart. Accumulation model.

The process of getting new active accumulation areas is governed by the databases provided by the pre-process. When an active accumulation area (source) is filled up till its next communication level (looking in the neighbour database), the water level of the neighbour must be checked. As stated before, depending on the water level of the neighbour, two situations can arise:

- The neighbour level is lower than the level of the source → the source is deactivated and the neighbour is activated.
- The neighbour level is the same than the level of the source → both accumulation areas are active and therefore are joined.

This process is showed as a flow chart in Figure 16 below. The situation when the neighbour level is higher than the source level is not physically possible. Therefore it cannot take place during the normal running of the RFSM.

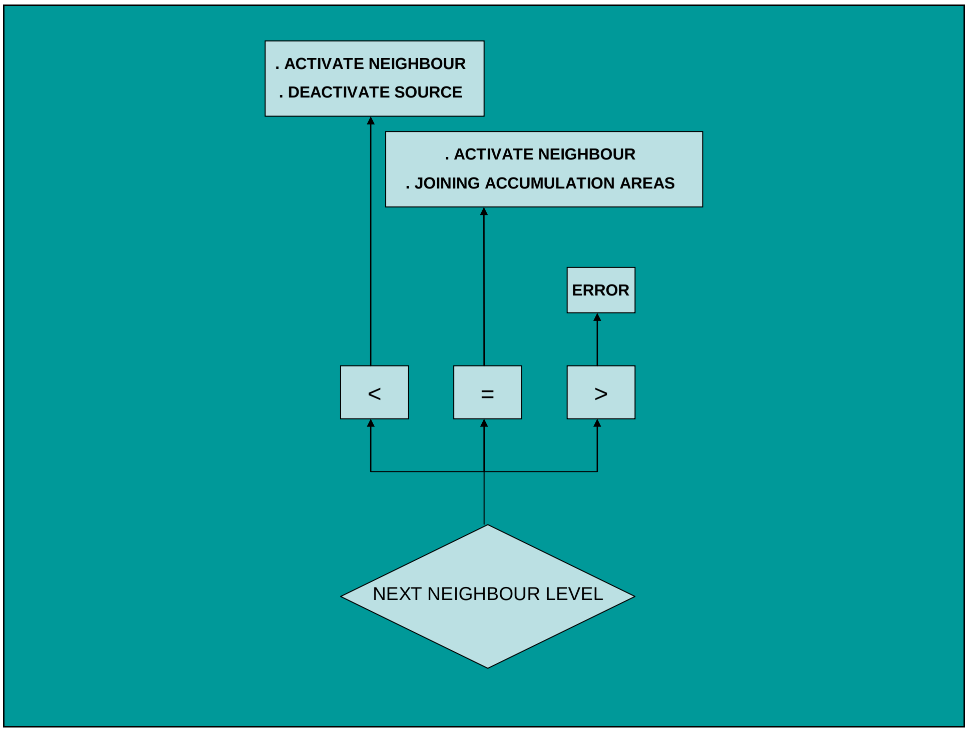

Figure 16: Detailed flow chart. Accumulation model.

It is important to highlight that the results provided by the methodology presented before will show the final situation of the water in the floodplain. As a first approximation these values can be considered appropriate for the evaluation of risks.

6 FITNESS FOR PURPOSE – FLOOD EXTENT AND DEPTH

6.1 Introduction

Comprehensive testing of the model has been undertaken within the DT4 project (HR Wallingford 2006). This note summarises this testing, full details are provided in HR Wallingford, 2006.

In order to check the accuracy and reliability of the new spreading methodology, a number of test cases have been set up:

- Breach only (model covering the main estuary with breached defences at five locations).
- Complex topography (local flood modelling in the vicinity of Greenwich)
- Economic damage (assessing the sensitivity of economic damage results to the flood spreading methods).

6.2 Breach only (estuary wide modelling)

Setting up the model/Obtaining input data

To assess the reliability of the RFSM a combined ISIS-TUFLOW model of the Thames was used. Five breaches were specified at different locations along the estuary (see Figure 17 and Table 4). The location (British National Grid) and characteristics of the five breaches are detailed in Table 4. Within this Appendix the results from Breach 3 (Royal Docks) are presented, the full results for all breach locations are provided in HR Wallingford (2006). A detailed map showing location of Breach 3 and the 'gauging stations' used to monitor flood depths in this location is shown in Figure 18.

Table 4 Breach data

Breach number	Breach level (m aOD)	Defence crest level (m aOD)	Breach width (m)	National Grid 'x' co-ordinate	National Grid 'y' co-ordinate
1 (North Kent)	3.98	6.43	150	573655	179308
2 (Dartford)	4.56	6.21	150	556746	176105
3 (Royal Docks)	3.94	5.18	120	540248	179815
4 (Hammersmith)	4.77	5.54	120	523961	176102
5 (Isleworth)	5.27	5.94	120	516752	176099

In the combined ISIS-TUFLOW model, the Thames has been modelled as 1-D with ISIS, whereas the floodplain has been modelled as 2-D with TUFLOW. In these simulations, in order to perform a comparison between models with realistic data, typical tide and river boundary conditions have been introduced to run the combined 1-D/2-D model (ISIS-TUFLOW model). The flow rate through each breached defence has been recorded to calculate the net inflow volume through them. This net inflow volume was then used as input data for the RFSM.

The RFSM has been run using two different mesh densities. The coarser using only the ground levels of the cell centres available in the TUFLOW grid (100m even spaced rectangular grid), whereas the finer using all the ground levels available in the original TUFLOW grid (50m even spaced rectangular grid).

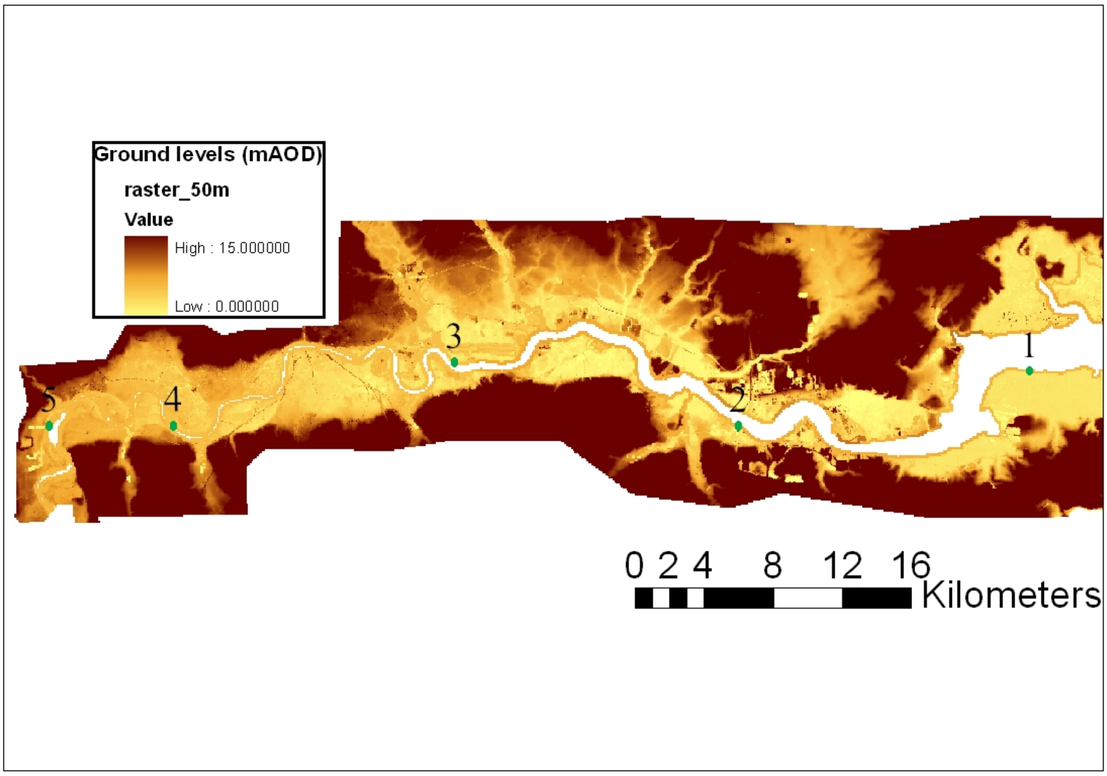

Figure 17: Breach locations in the Thames Estuary.

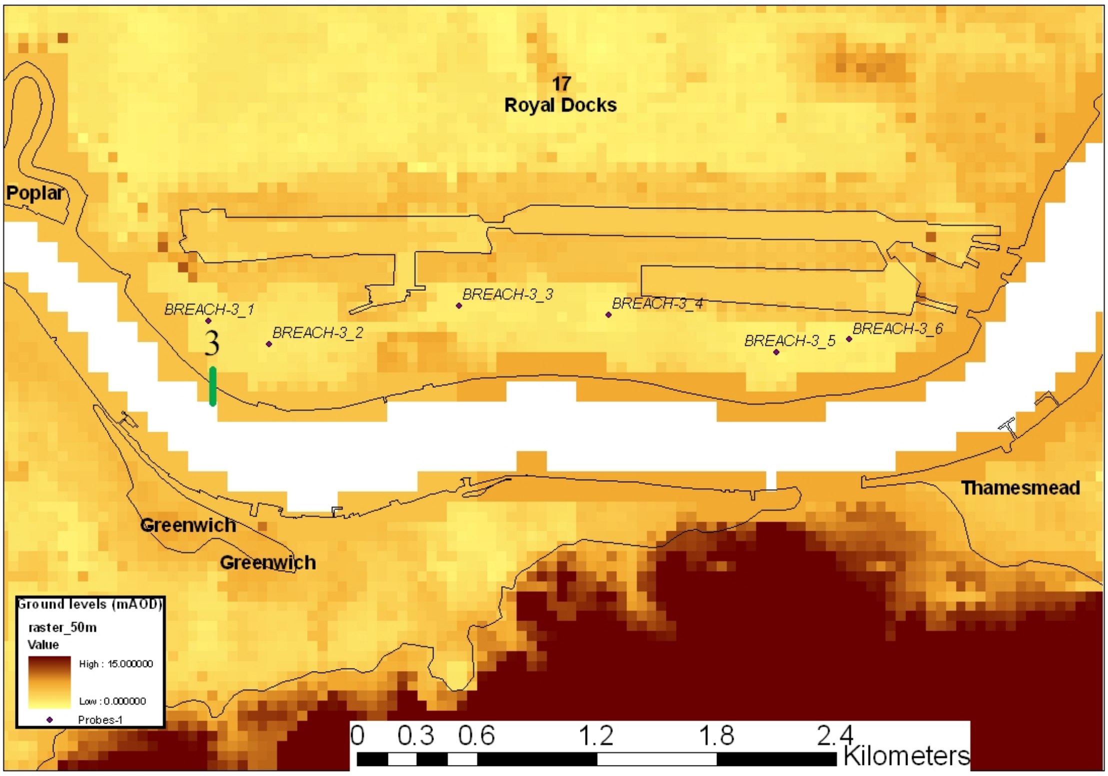

Figure 18: Royal Docks embayment. Gauging locations for breach-3.

The breach test cases were run using a low RP event, estimated to be around 100 years. This event was considered severe enough to reach the breach levels set up in each one of the five breach locations, but without overtopping the defences.

After setting up the breaches in the 1-D/2-D model, the model was run and the flow rates through each one registered. The lapse of time between two flow measurements was set as 5 minutes. After obtaining all the flow data, it has been integrated over the whole time series to obtain the net inflow volume flowing into the floodplain. The volume obtained by means of this integration (assuming linear interpolation between two flow measures) is shown in the Table 5 below:

Table 5 Volumes through the breached defences registered by TUFLOW.

Breach number	**100-year Volume (m^3)**
Breach01	74,048
Breach02	604
Breach03	178,790
Breach04	206,976
Breach05	59,112

A GIS software package has been used to check if these values correspond to the net volumes accumulated in the floodplain at the end of the simulation. Surprisingly, the results showed that TUFLOW does not conserve volume. The resolution of the TUFLOW volume conservation was beyond the scope of this testing exercise. TO enable a fair and consistent test, the net volumes used as input for the RFSM were the actual volumes present at the end of the TUFLOW simulations.

Results

In the following section the results are first presented and compared in terms of plots with the maximum and final depths obtained with TUFLOW, versus the depths obtained with the RFSM. Graphs that depict final flood depths at the gauging stations are then shown. Finally, a graphic displaying the flooded area and the mean depth is shown for each test case.

The results for breach 3 (Royal Docks) can be seen in Figures 19 to 23. The agreement between the results obtained with both models is high. The results for the RFSM in terms of depth (see Figure 22) and flood extent (see Figure 23) are well matched to the TUFLOW output.

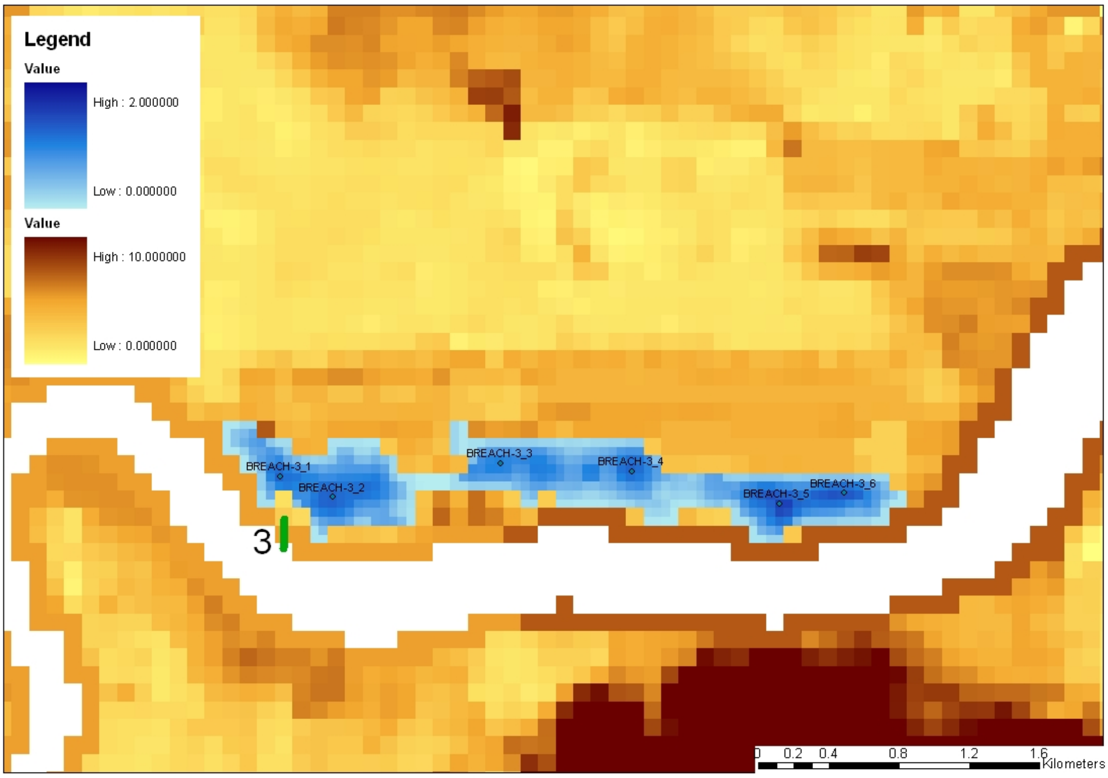

Figure 19 Breach-3. Final depth TUFLOW (mAOD). Estimated RP 100.

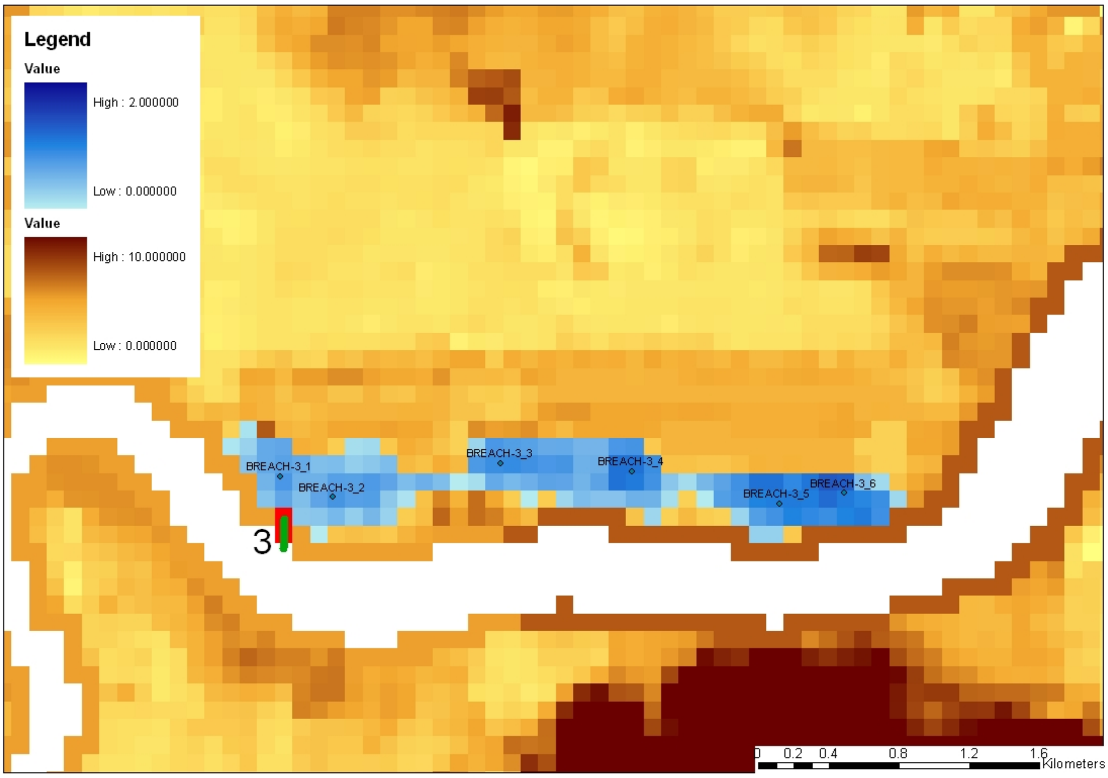

Figure 20 Breach-3. Depth RFSM (mAOD). 100m grid. Estimated RP 100.

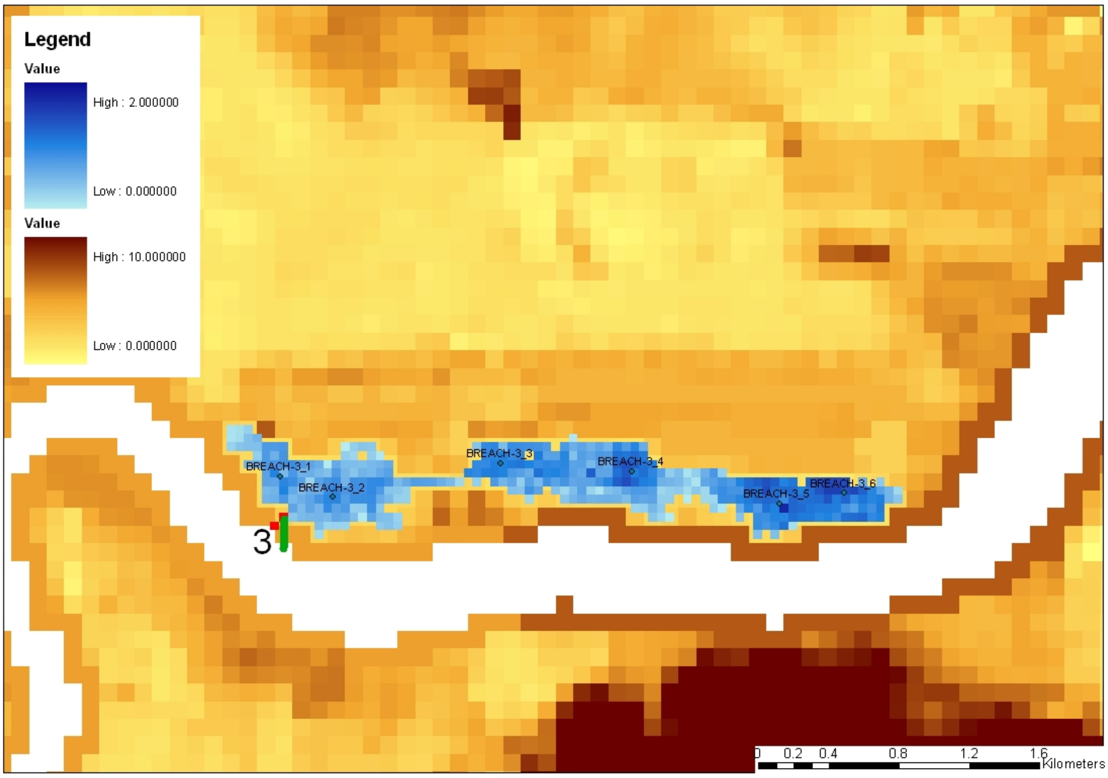

Figure 21 Breach-3. Depth RFSM (mAOD). 50m grid. Estimated RP 100.

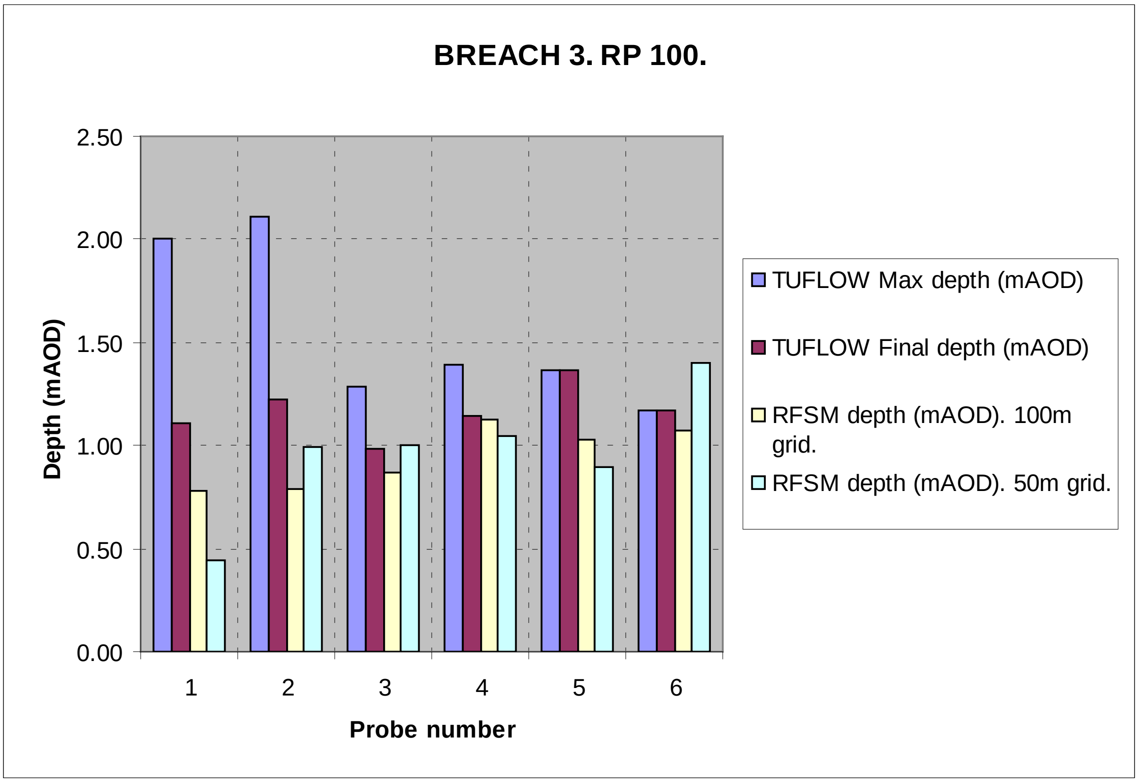

Figure 22 Breach-3. Depth (mAOD). Gauging points.

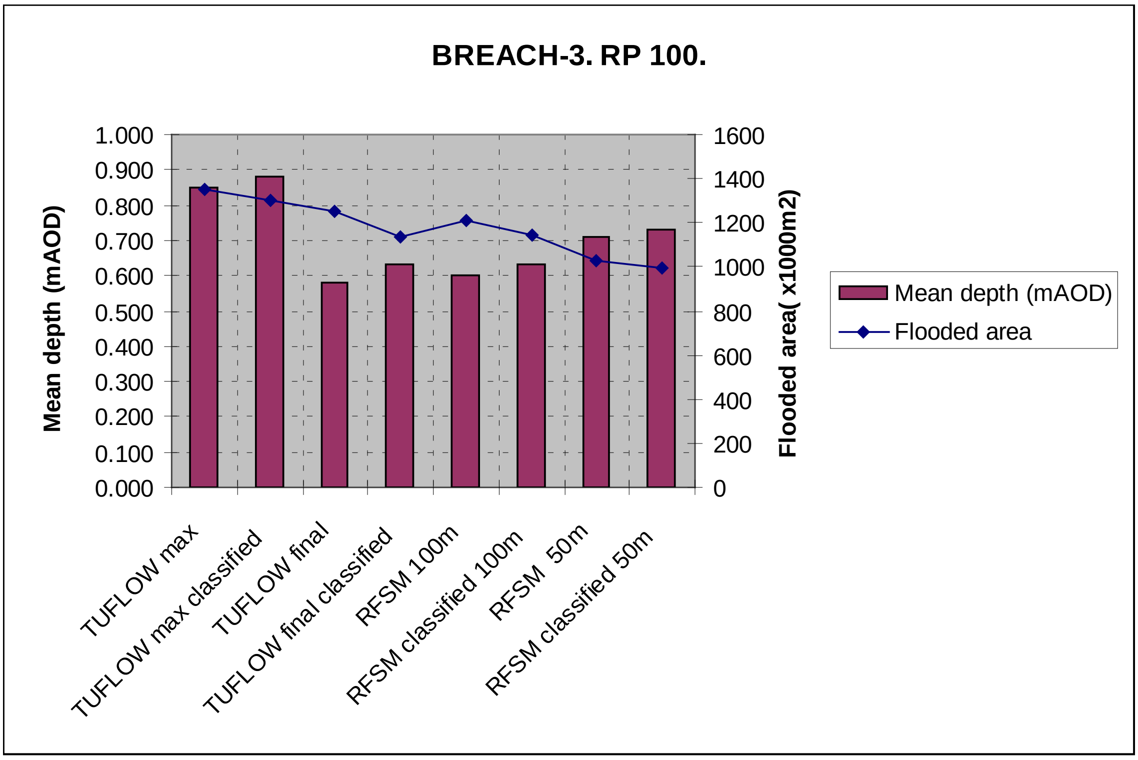

Figure 23 Breach-3. Flooded area and mean depth.

6.2.1 Greenwich test cases

Setting up the model/Obtaining input data

To test the RFSM in complex situations with refined meshes a local Greenwich model has been established (Figure 24). To obtain the input data to be used by the RFSM, two sections have been set up in the TUFLOW model to register the inflow at specific time intervals. The integration of the inflow series over the whole duration of the event has provided the net inflow volumes to use in the RFSM.

In this case, as previously, the net volume calculated from the inflow data provided by TUFLOW did not match the total volume stored at the end of the simulation. The same procedure of using the final TUFLOW volumes was therefore adopted.

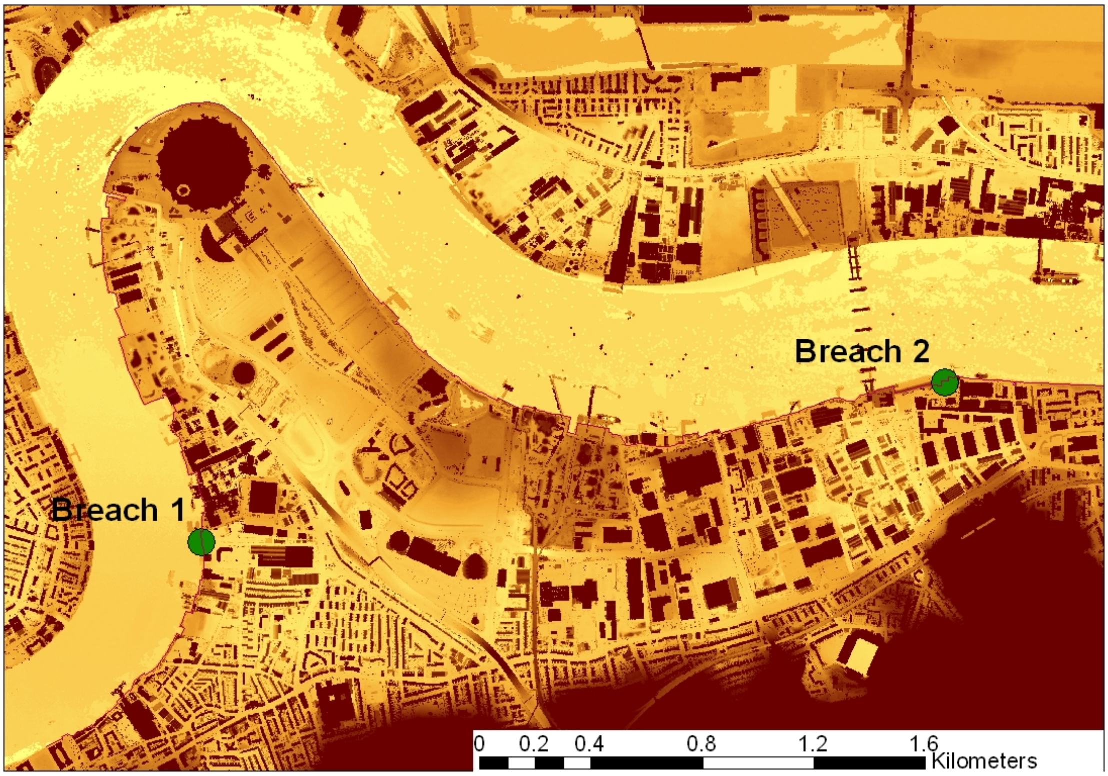

Figure 24: Greenwich embayment. Breach locations.

To accommodate the complex topography a 10m grid has been used within the RFSM. To investigate the uncertainty related to the mesh density, two coarser meshes have been also run with the same input data, both with 100m cell size. The difference between the 100m models lies in the original topographic data. The first one has been built from unfiltered data of the area, i.e. with the buildings included in the terrain, the second has been made from the filtered data, i.e. without buildings.

A series of gauging points have been set up in the Greenwich area to register the water depth achieved in each one of the simulations. The probe locations for breach 1 and breach 2 are shown in Figures 25 and 26.

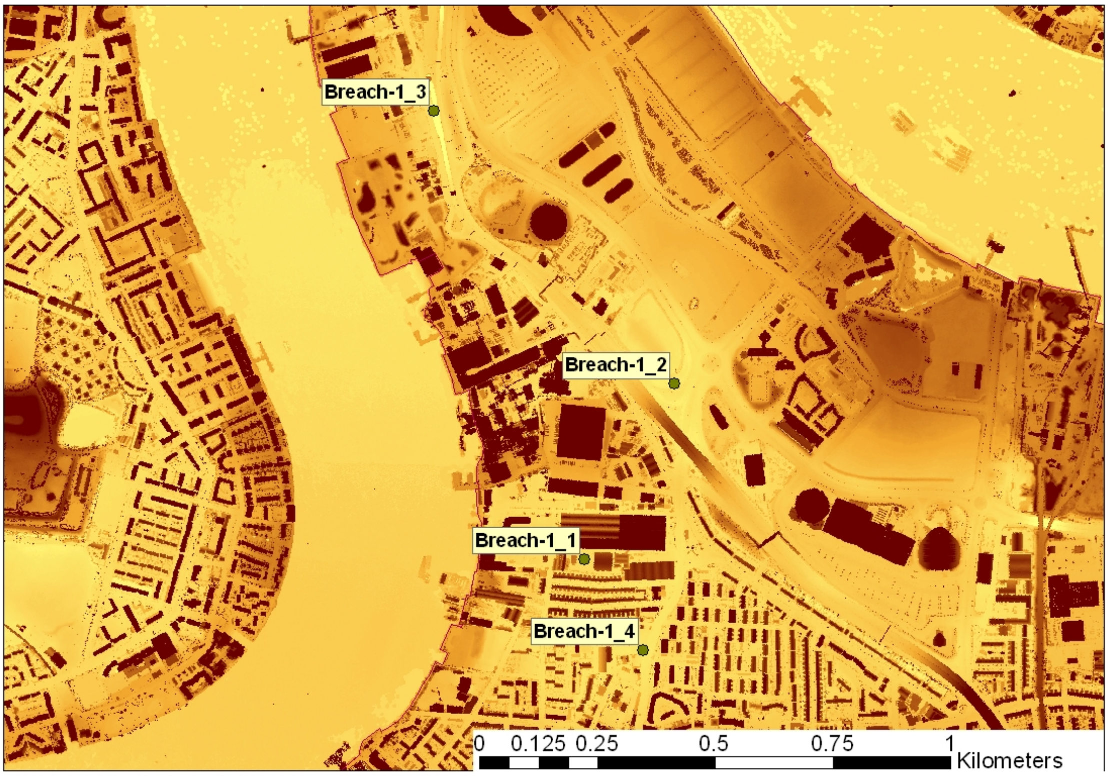

Figure 25: Greenwich embayment. Breach-1. Gauging points.

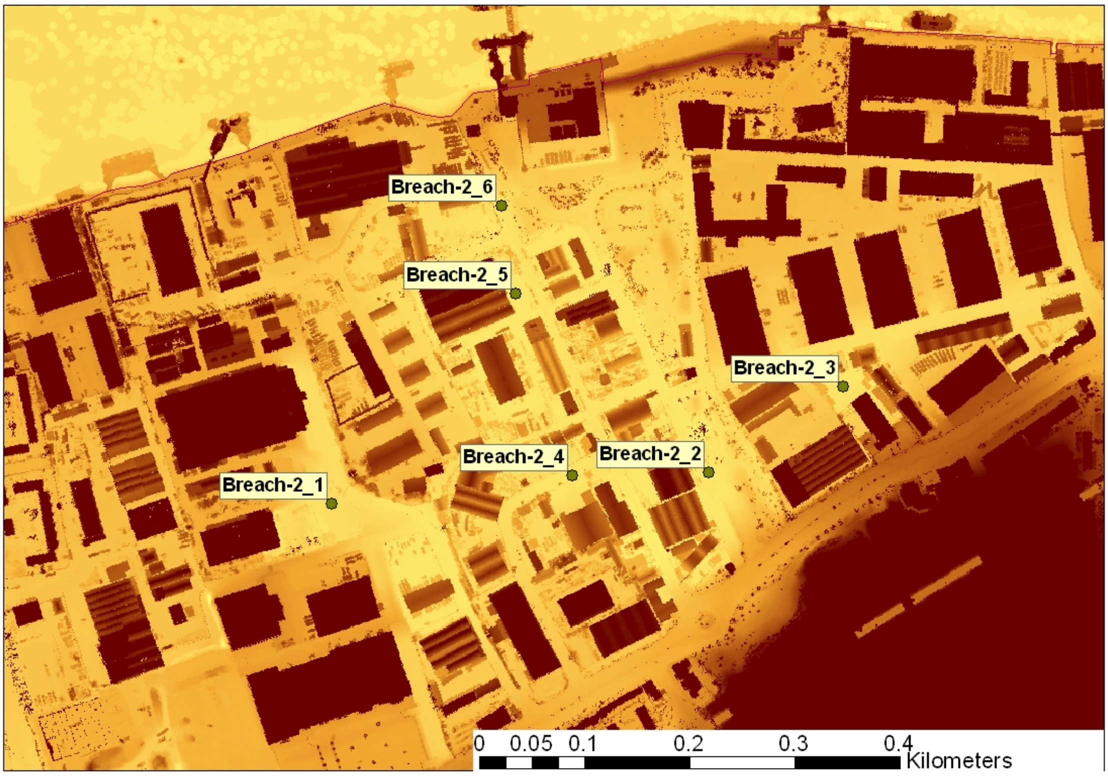

Figure 26: Greenwich embayment. Breach-2. Gauging points.

Results

The results obtained with TUFLOW for the breach 1 can be observed in Figures 11 (maximum depth) and 12 (final depth). The results obtained with the 10m unfiltered grid with the RFSM are presented in Figure 13. Finally, the results obtained with the 100m unfiltered and 100m filtered grids are shown in Figures 14 and 15 respectively. The quantitative results for the water depth obtained at probe locations is presented in Figure 27 and the flood extents in Figure 28.

The level of agreement between TUFLOW and RFSM when using the refined mesh is very encouraging. At first sight, the flood extents look exactly the same, which is corroborated by the flood extent graphic (see Figure 27) and when looking at the water depths obtained in the gauging points (see Figure 26). The flood extent obtained with the RFSM is slightly smaller in comparison to TUFLOW, but well within acceptable limits.

This test case is the demonstration that the main driver of the flooding in this type of cases is the slope. Hence, the assumptions that underpin the RFSM are reasonable and logical. The use of very complex models to obtain water depths in order to evaluate damages associated with flooding events is not necessary if the knowledge of the temporal evolution is not a critical issue.

Alternatively, it is also interesting to check how the topographic discretization can affect the final results provided with any model. In this case, the flood extents obtained with the 100m unfiltered and filtered meshes show big discrepancies. These results highlight the importance of selecting the appropriate topographic data to be used in the spreading models.

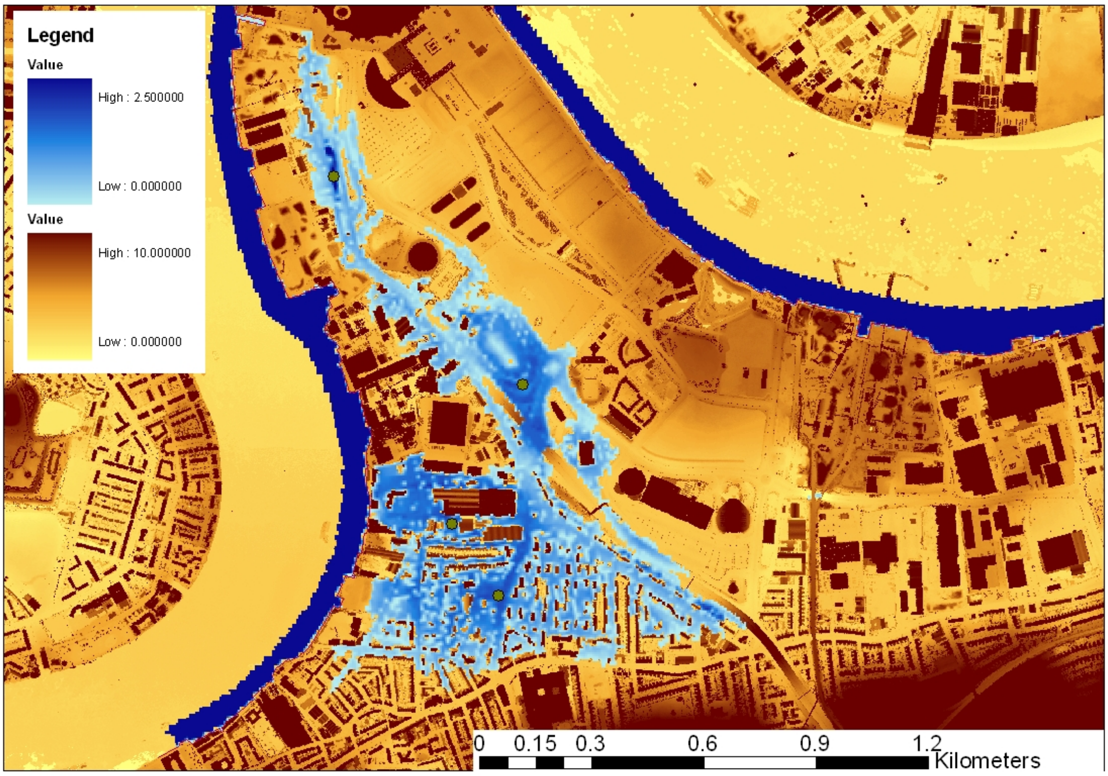

Figure 27: Greenwich. Breach-1. Maximum depth TUFLOW (mAOD).

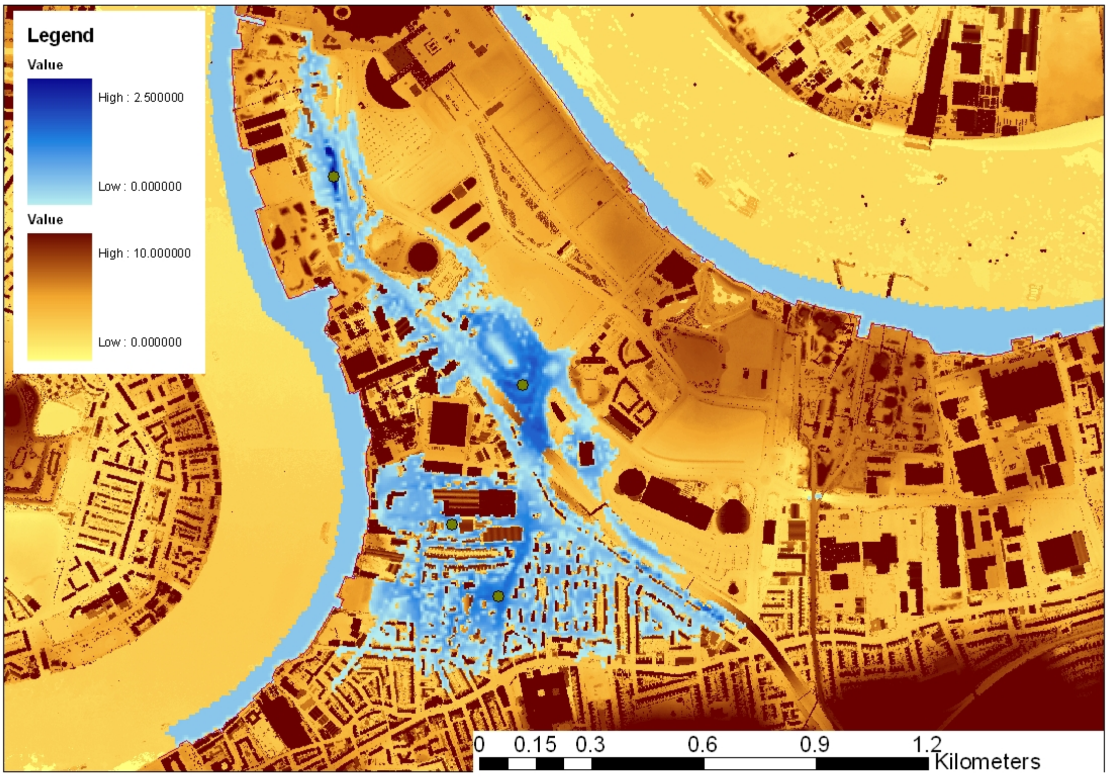

Figure 28: Greenwich. Breach-1. Final depth TUFLOW (mAOD).

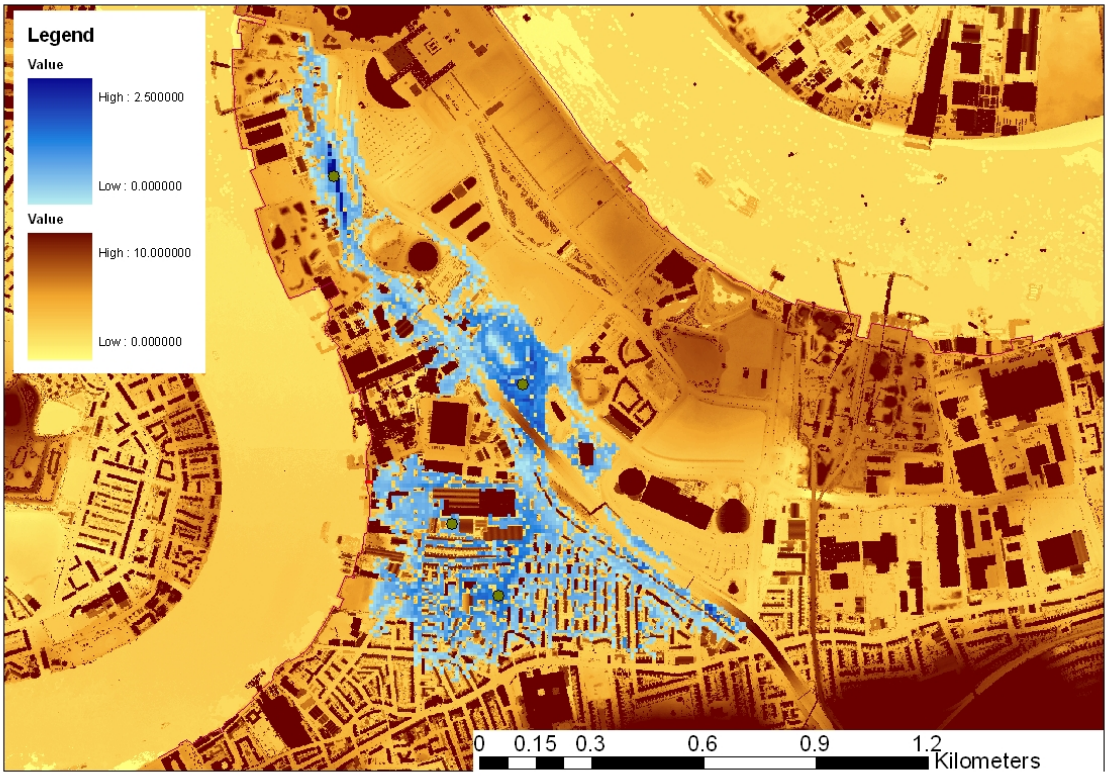

Figure 29: Greenwich. Breach-1. Depth RFSM (mAOD). 10m unfiltered grid.

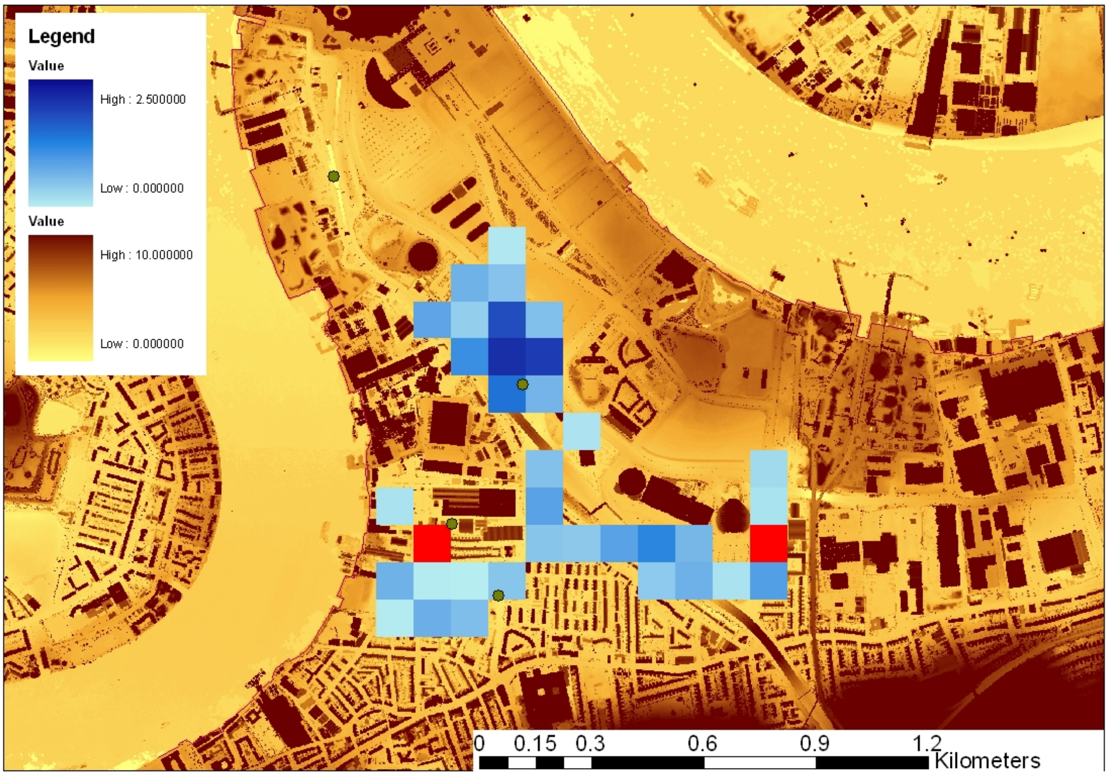

Figure 30: Greenwich. Breach-1. Depth RFSM (mAOD). 100m unfiltered grid.

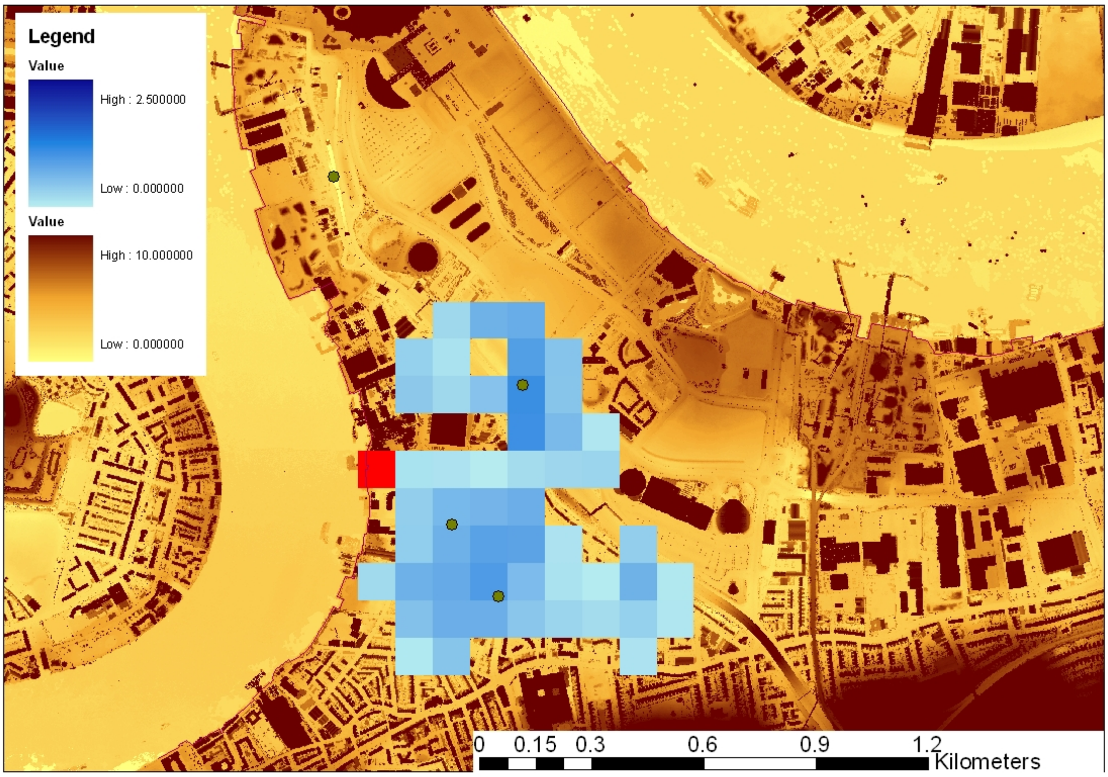

Figure 31: Greenwich. Breach-1. Depth RFSM (mAOD). 100m filtered grid.

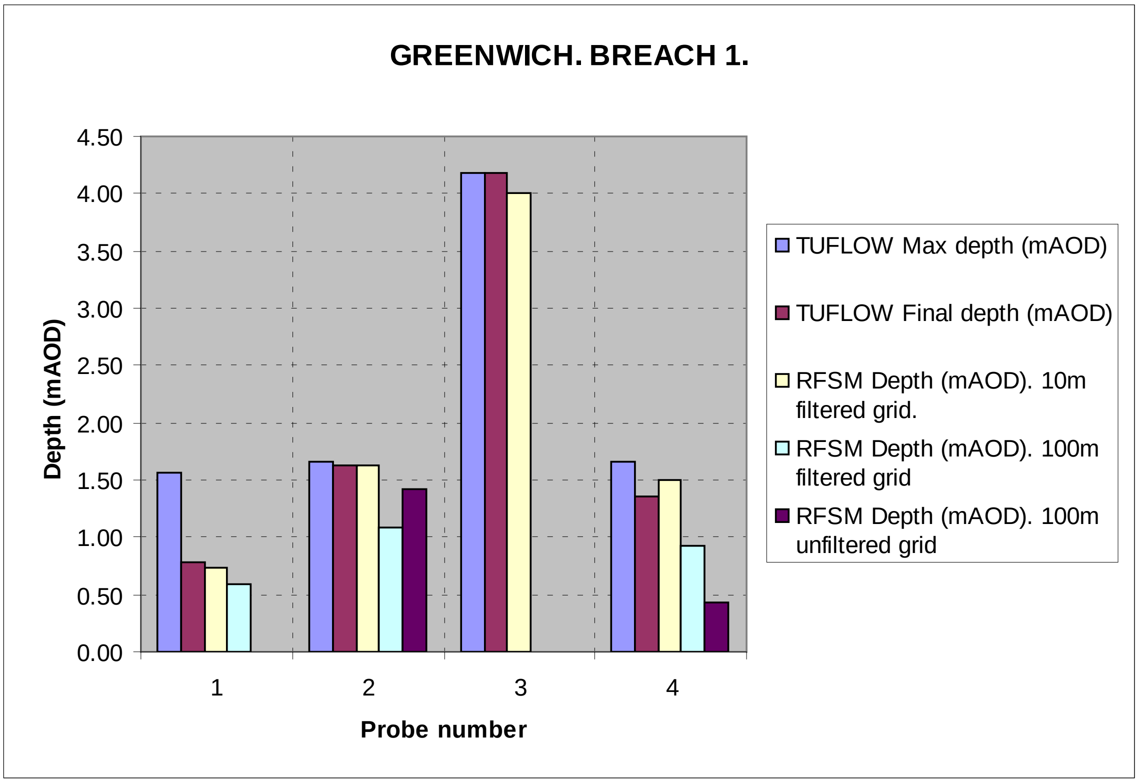

Figure 32: Greenwich. Breach-1. Depth (mAOD). Gauging points.

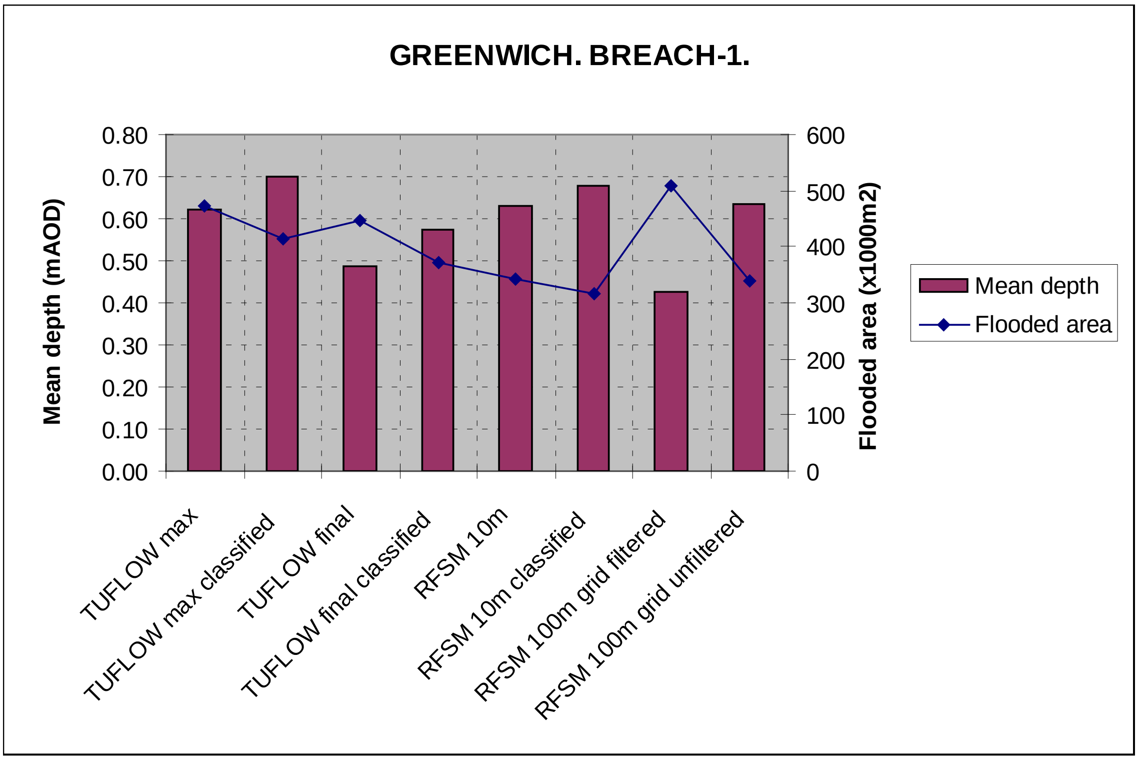

Figure 33: Greenwich. Breach-1. Flooded area and mean depth.

The results obtained for breach-2 are presented from Figure 18 to Figure 24. The flood extent resulting from the TUFLOW run (see Figures 18 and 19) is very similar to that obtained using the RFSM (see Figure 20), principally when using the refined mesh.

In terms of depth, the results obtained with the refined mesh using the RFSM are almost identical to those provided by TUFLOW. The influence of the local terrain features is clearly highlighted with these results. Neither the inertial terms, nor the friction terms, have the same influence in the evolution of the flooding.

It is interesting again to compare the results obtained with the 100m grids created from the unfiltered and filtered meshes. Due to the blockage effect of the buildings, the water in the floodplain is more disperse when using the unfiltered mesh, in contrast with the concentrated distribution when the filtered mesh is used. More research will be needed to find the proper compromise of permeability to assign to the buildings in future developments of the RFSM.

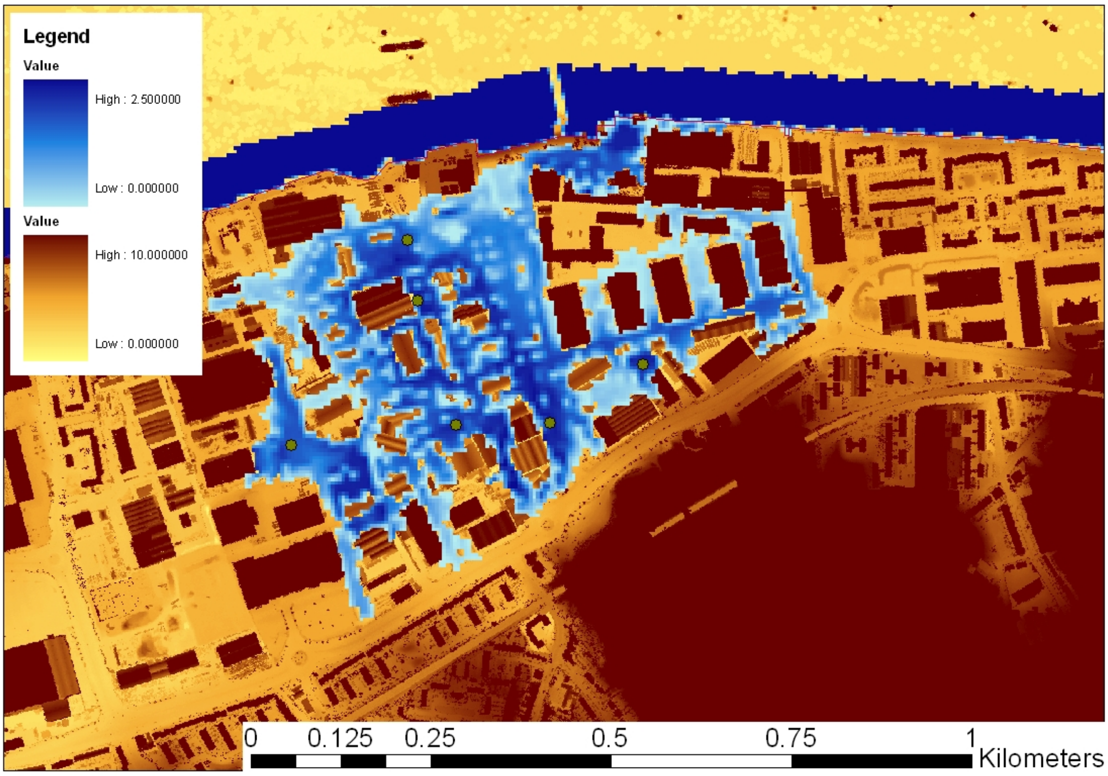

Figure 34: Greenwich. Breach-2. Maximum depth TUFLOW (mAOD).

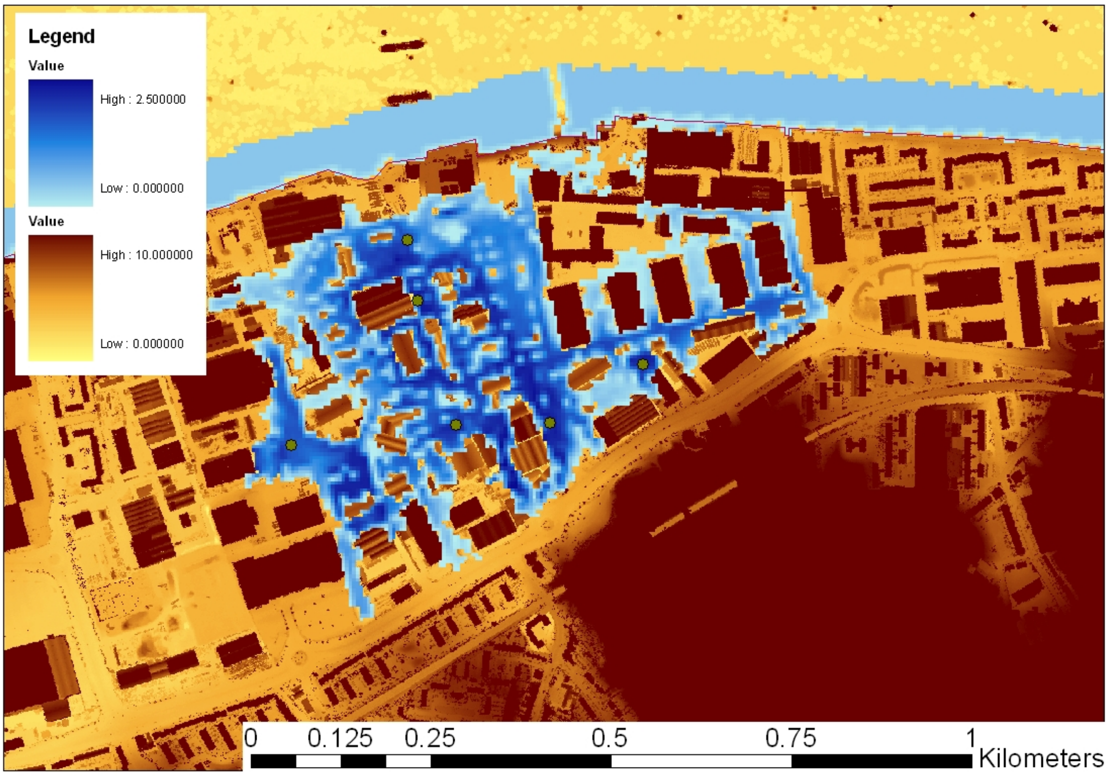

Figure 35: Greenwich. Breach-2. Maximum depth TUFLOW (mAOD).

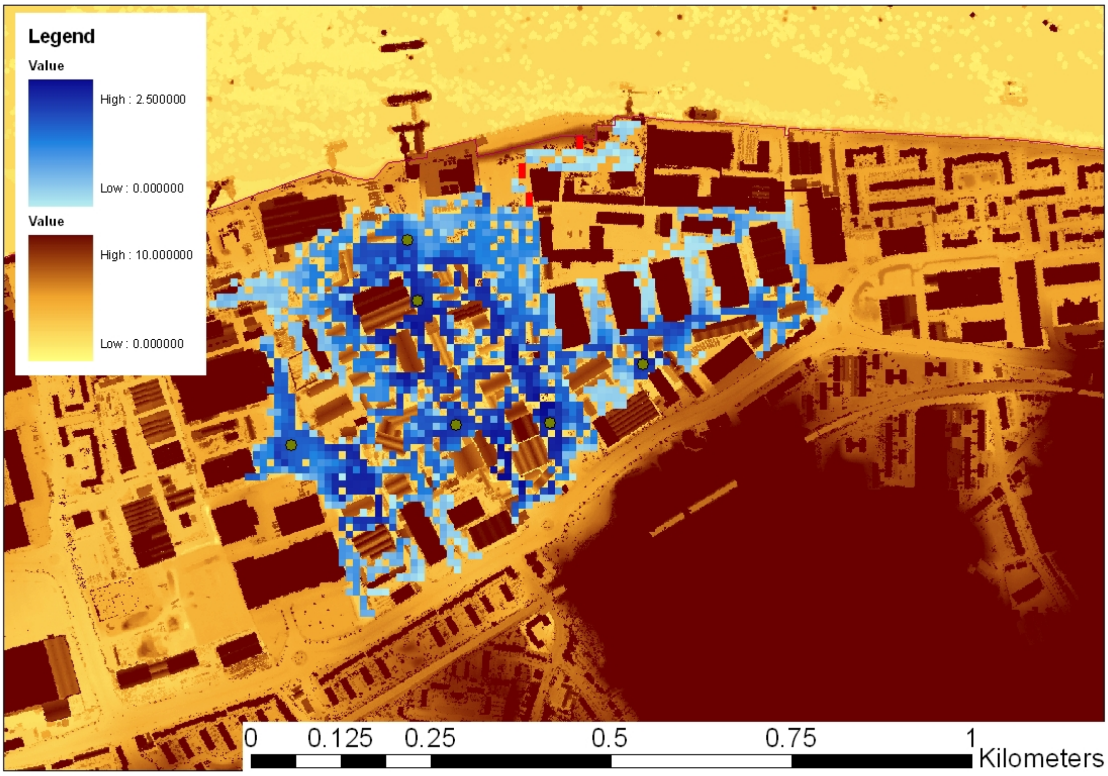

Figure 36: Greenwich. Breach-2. Depth RFSM (mAOD). 10m unfiltered grid.

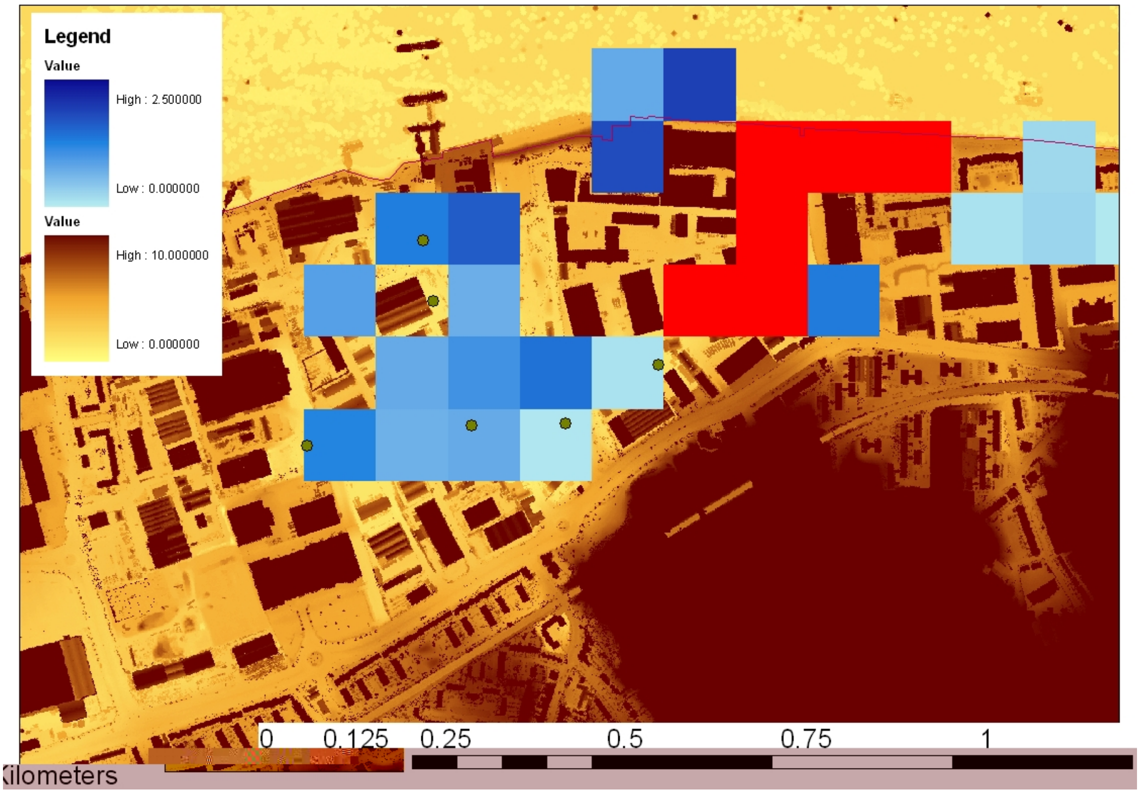

Figure 37: Greenwich. Breach-2. Depth RFSM (mAOD). 100m unfiltered grid.

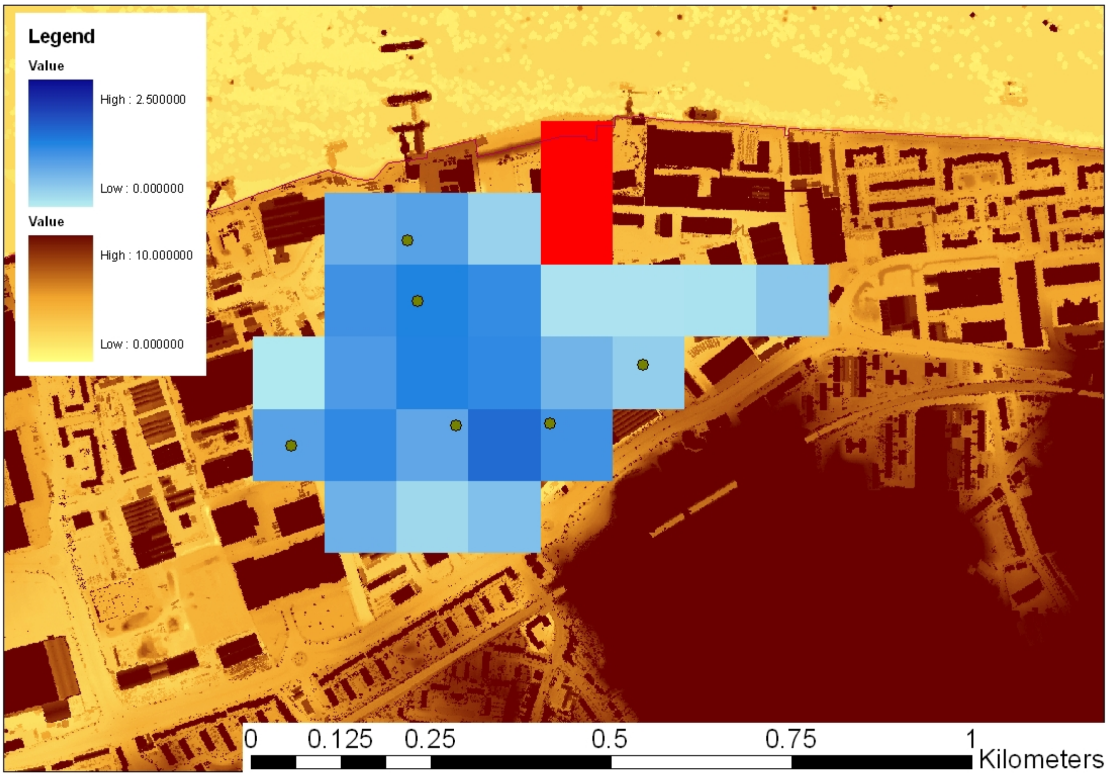

Figure 38 Greenwich. Breach-2. Depth RFSM (mAOD). 100m filtered grid.

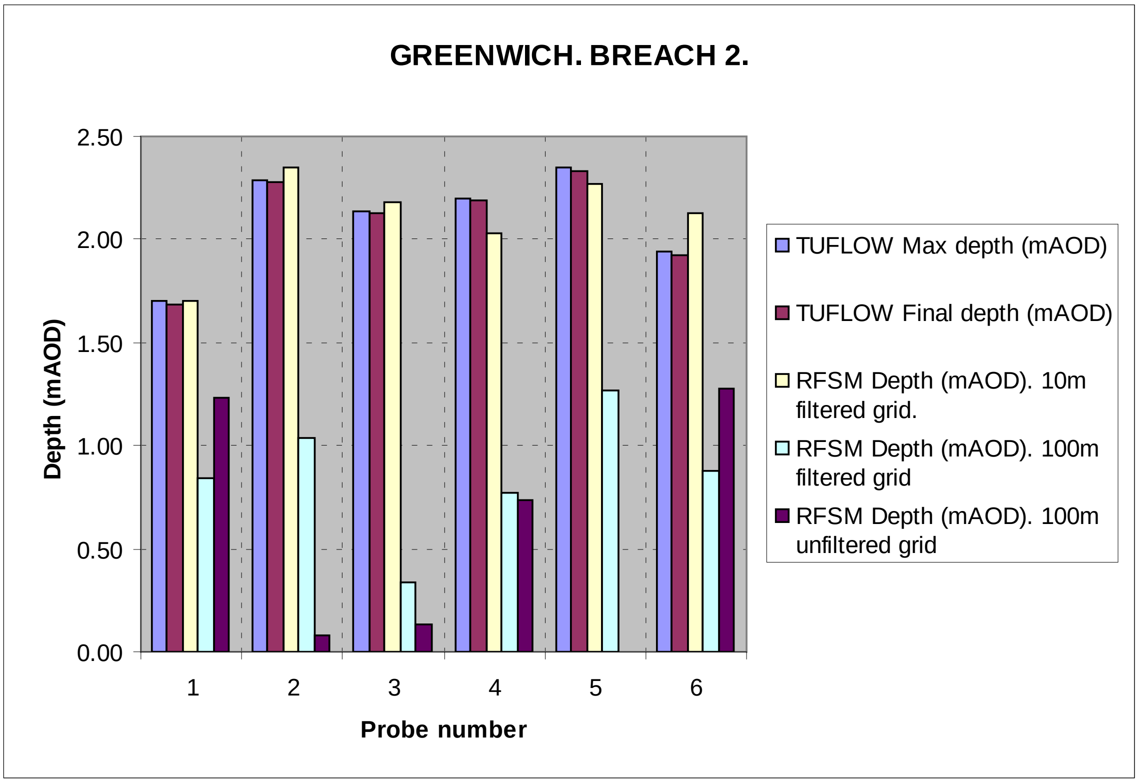

Figure 39 Greenwich. Breach-2. Depth (mAOD). Gauging points.

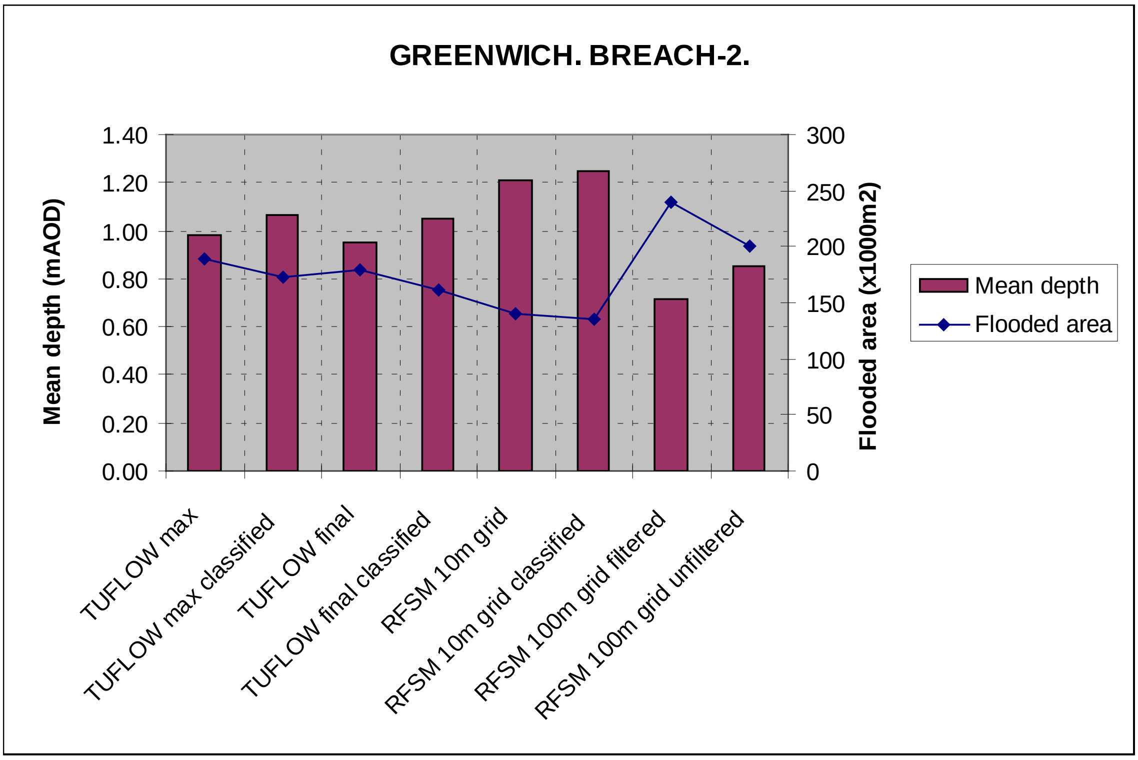

Figure 40: Greenwich. Breach-2. Flood area and mean depth.

7 FITNESS FOR PURPOSE - ECONOMIC APPRAISAL

7.1 Introduction

To assess the sensitivity of economic damages to the method of flood spreading, the test cases detailed above have been extended to include estimates of economic damage. The depth damage relationships for each Impact Cell used within the IA8/10 model have been allied to the RFSM within a self contained software tool. Using this tool the inundation results detailed above have been translated to economic damages. Results are provided for the estuary wide model Breach 3, Royal Docks, (full details for all models are provided in HR Wallingford (2006).

7.2 Results for Breach 3 (Royal Docks)

The results for breach 3 are shown in Figure 41. The total damage and mean values (NB the mean value per flood cell is the total damage divided by the flooded cells that have properties inside), both for 100m and 50m grid are of similar magnitude for the final TUFLOW results lending confidence to the use of the RFSM for economic appraisal. This is particularly evident at the 50m grid scale where differences are indistinguishable.

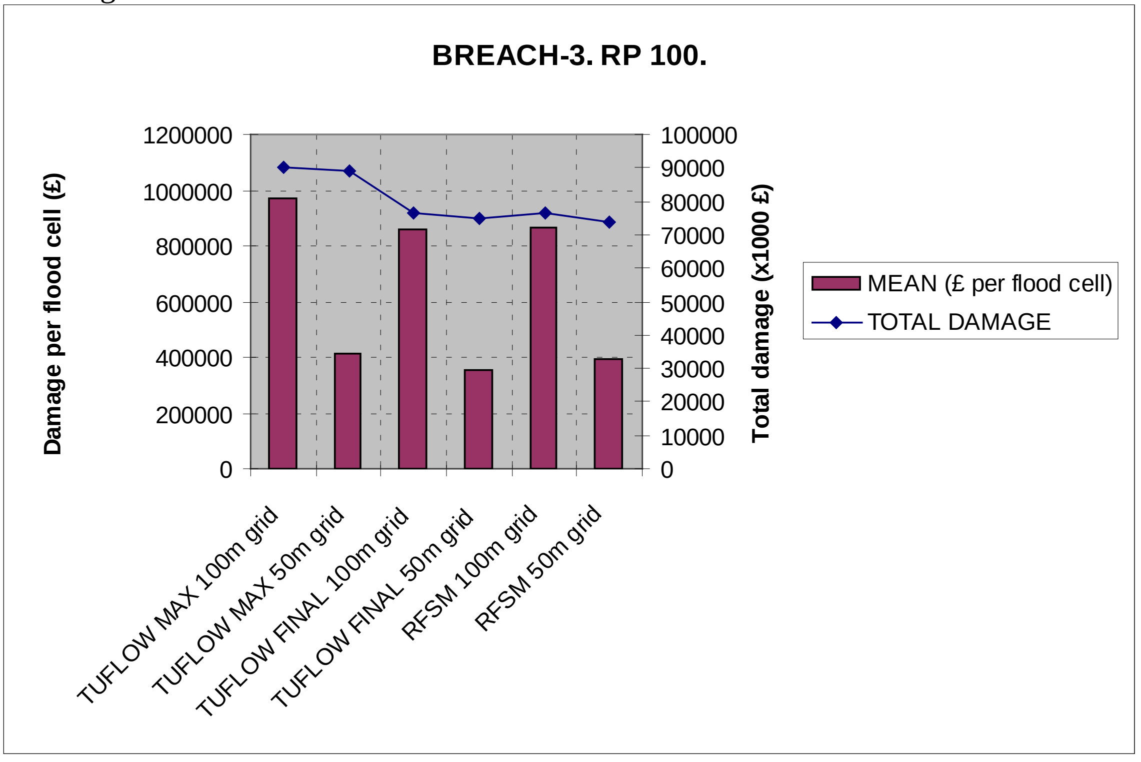

Figure 41: Breach-3. Economic damage. Estimated RP 100.

8 OVERALL PERFORMANCE EVLAUTION OF THE RSFM

This chapter provides a summary of the observed performance of the RSFM against the functional requirements described earlier.

Run time: The cases that have been tested have shown that the model is fast enough to fulfil the original requirements of speed. A summary of the run times registered for the test cases detailed in section 6 of this report are provided in Appendix D. Except in one case, all the runs times are below 1 second. Therefore the RFSM results fall within the specified threshold, as the original time limit per run was set to 5 seconds. Moreover, it has to be borne in mind that the run times shown in this report were obtained from preliminary versions of the code. In the current versions the code is optimized, hence, the run times are expected to be much lower.

Topography: The RFSM has demonstrated its ability to simulate inundations in floodplains caused by breaching or overtopping of fluvial/coastal defences. Therefore it can be stated that the model is appropriate for its use in floodplains that present the features specified in the requirements section and addressed in the limitations and assumptions chapter, as it is the case for the Thames Estuary.

Grid size: The RFSM has been tested with different grid sizes, ranging from 100m to 10m. The differences in flood extent and economic damages as a function of the inflow volume and the grid size can bee seen in Figures below. These Figures represent the percentage of difference between the final results obtained with TUFLOW and the obtained with the RFSM. The conclusions that can be drawn from these graphics are the following:

- The maximum differences are associated with the 50m grid. There is a simple explanation for this behaviour. Although TUFLOW plots out by default the results in a grid with the points in the corners, faces and centres of the cell, only the cell centres play a role in the actual calculations (this was confirmed after a verbal conversation with Bill Shyme, one of the developers of TUFLOW). Therefore, TUFLOW has been run only in a 100m grid, and therefore are comparable with the obtained with a 100m grid with the RFSM.

- Considering only the test cases with 100m grid and 10m grid, except in two cases the differences in the results are below 20%. The bigger differences (around 40%) with the 100m grid occur in breach 2 for the test cases with estimated RP 1000 and 10000 years. So, in fact, they represent just one location. In this case, the flow is quite complex, with several main pathways. Moreover, the uncertainty about the mass conservation in TUFLOW might be the cause of these differences. But, in general terms, for the 10m grid and 100m grid the results can be considered satisfactory.

- All the flood extents calculated by TUFLOW, except in one case, are larger than those calculated by RFSM. Again, the uncertainty in the actual volumes that TUFLOW is using along the temporal simulation could be the cause of this tendency. It is recommended to carry out comparisons of the RFSM with finite volume models, which by definition assure mass conservation.

- As an initial value, the discrepancies in flood extent between TUFLOW and the RFSM can be set around 10-20 % (there is still a need to solve the mass conservation uncertainty issue).

- Regarding the final economic damages (see Figure 42), the typical values for the differences associated with the 10m and 100m grid (considered the more representative for comparison purposes) can be set around 15%, with some exceptions with a bigger difference. Nevertheless, in this case there is not a marked tendency. Some extreme values are higher using the RFSM than TUFLOW, whereas others are lower. It is supposed that these extreme values will be averaged in the context of multiple scenario analysis. Moreover, the results provided by TUFLOW are not considered 100% reliable as a reference to compare with. Therefore, the RFSM is supposed to produce results with a lower value of uncertainty for the annual expected damage.

- In terms of maximum economic damages, the differences between TUFLOW and the RFSM seem to be in the range of 0-50%. This means that the results provided by the RFSM will underestimate the maximum damages. This was an expected result, as at the moment the RFSM calculates an estimation of the final depths in the floodplain. Anyway, this comparison has been made with only against TUFLOW results, which moreover, do not offer too much confidence. It is recommended to test the RFSM against other models.

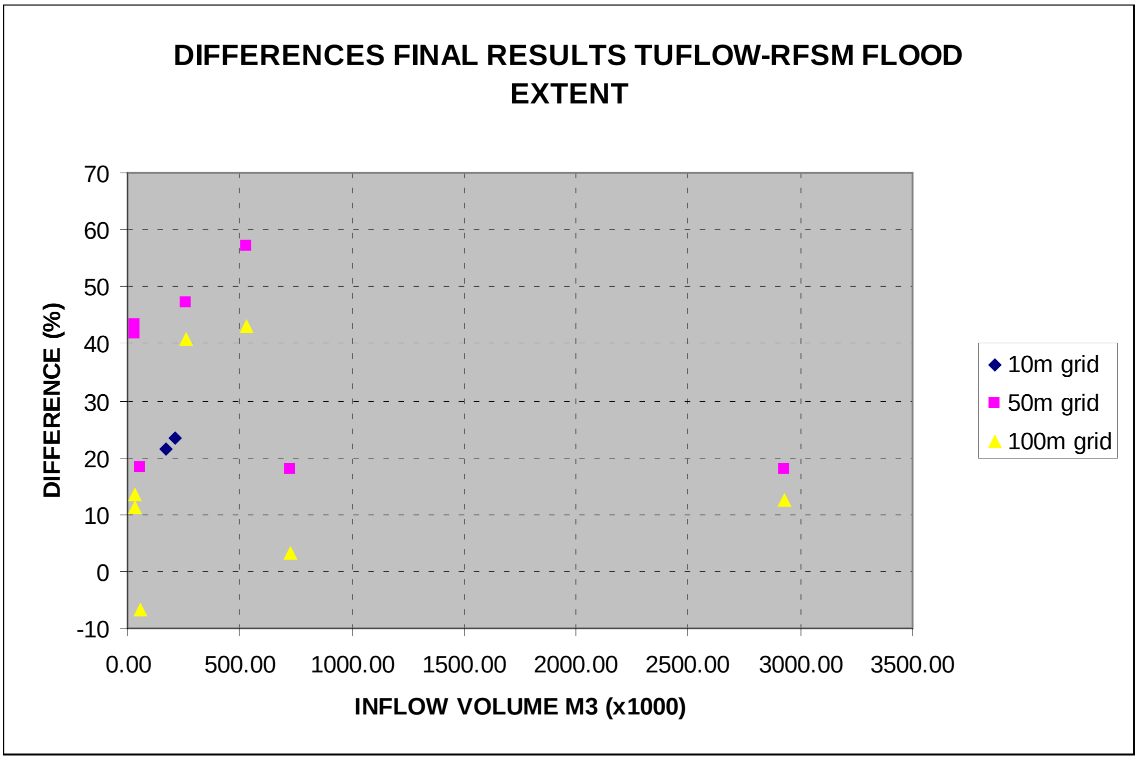

Figure 42. Differences between TUFLOW and the RFSM in flood extent for 3 grid sizes.

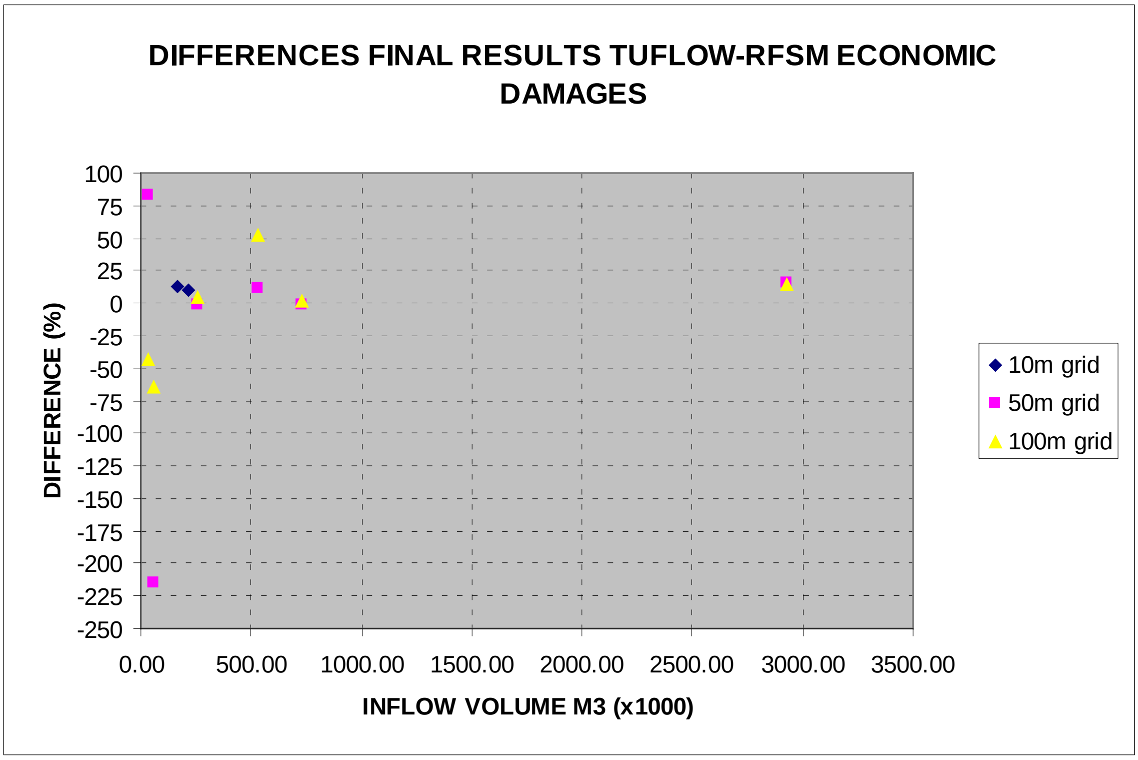

Figure 43. Differences between TUFLOW and the RFSM in final economic damages for 3 grid sizes.

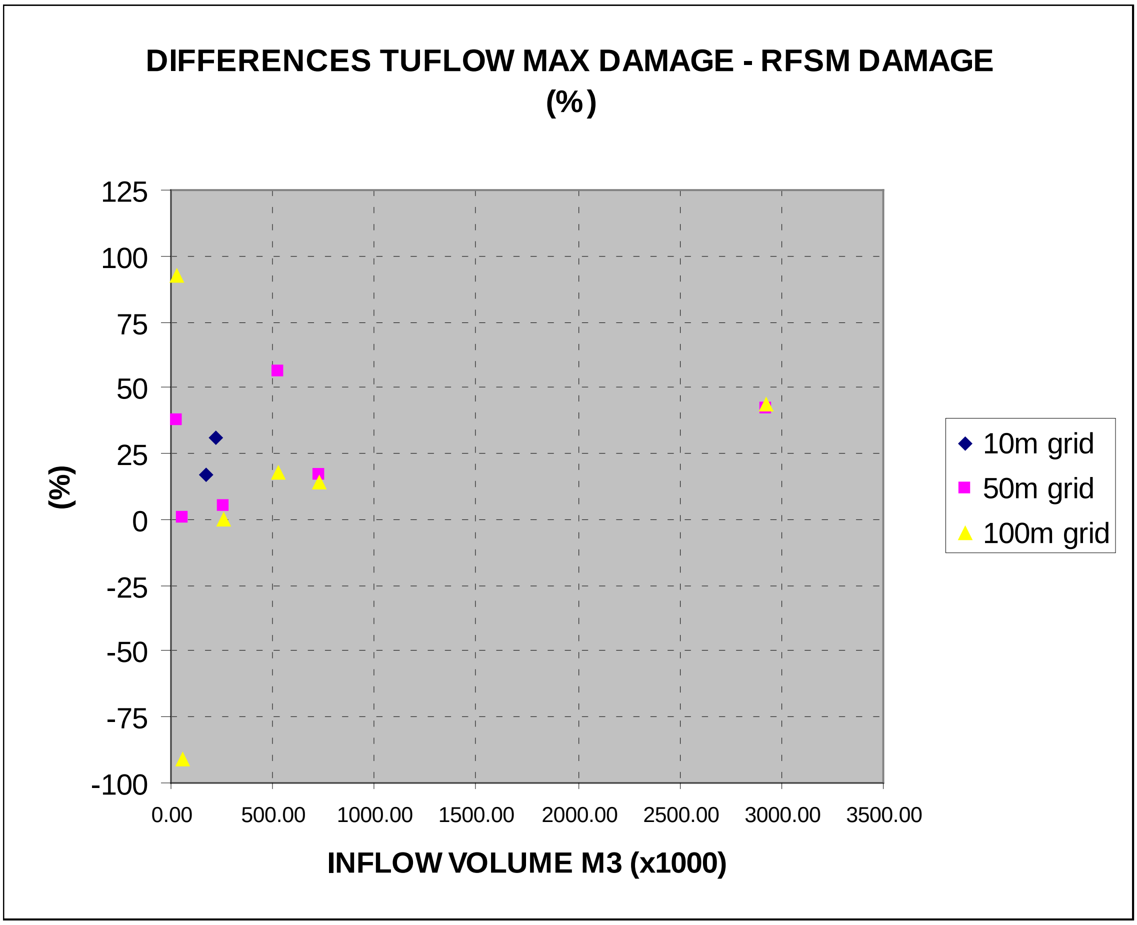

Figure 44. Differences between TUFLOW and the RFSM in maximum economic damages for 3 grid sizes.

- Physical processes to include: The gravity has been considered the main factor to include in the model. The results provided by the model show that this hypothesis is fit for purpose.

- Boundary conditions: The model is capable of loading volumetric batches of boundary conditions in one go. Therefore it fulfils the requirements originally specified about this issue.

- Output results: The model provides estimations of the final depths in the floodplain with the aim of carrying out probabilistic damage calculations.

9 LIMITATIONS OF USE

The basic simplification within the model (described earlier) limit the applicability of the model. General guidance on these limitations is provided below:

- The model should be used only in fluvial or coastal floodplain areas with certain topographic features:

    1. The area should be delimited by the flood defence line and the terrain high ground.
    2. The *average* longitudinal slope of the terrain must be gentle.

- The model is not recommended for application in flows where the inertial terms play an important role.

- The approach considered for the flow is based in several basic assumptions stated below:

    - The flow pathway follows the steepest slope of the topography, from the source of flooding to the accumulation area(s).
    - The pathway followed by the flow will remain the same independent of the event severity.

    If these criteria are not considered true the model will not be reliable.

- At present the boundary conditions can be described in one of two ways only:

    - Volumetric boundary condition: the net inflow volumes through the sources of flooding are implemented in the model. The net volumes spilling into the floodplain must be calculated from an external breach/overtopping model.
    - Open boundary: The river/sea levels are implemented in the model. These levels can never be exceeded in the floodplain.

- At present the only output that the RFSM is an estimation of the final depths in the floodplain.

- Mass conservation is assured in the RFSM. In contrast with this, momentum is not conserved, as the velocities do not play any role in the algorithm.

10 GUIDANCE OF USE

The only user defined parameter is the grid size to use.

The topographic data introduced in the model must match exactly the actual outline of the embayments. Therefore the defence line and the high ground limits of the embayments must be defined carefully to avoid errors (for example considering areas in a river bed as part of the floodplain)

A 50m grid size is likely to provide a reasonable compromise between accuracy and speed within the context of the TE2100 studies.

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11 CONCLUSION

A number of conclusions may be drawn as follows:

- ***Objectives achieved*** - The objectives originally set for the project, as detailed in the contract, have been achieved with the development of the Rapid Flood Spreading Methodology presented in this report.

- ***Assumptions are reasonable*** - The assumptions within the RFSM are shown to be reasonable and comparisons of the RFSM with TUFLOW have demonstrated that the RSFM is a reliable and efficient flood spreading approach.

- ***Model results (flood extent and depth) have been validated*** - The hydraulic results provided by the RFSM agree in general terms with those obtained with TUFLOW, but they tend to be less diffusive. One of the reasons for this lack of diffusivity is the uncertainty related with mass conservation that TUFLOW has shown and is detailed in this report. It is recommended to test the RFSM with other hydrodynamic models in well-posed test cases where the mass conservation is assured.

- ***Model results (economic damage) appear reasonable*** - The damage calculations provided by the RFSM represent a step forward compared with the previous spreading model included in RASP HLM+ and used in the IA 8/10 V2 model. The economic results show that the model is appropriate for its use in the IA 8/10 V3, particularly when viewed in the context of uncertainties that are prevalent in the derivation of the depth damage relationships, breach widths, water levels etc. At the moment, the global damage calculations obtained by the RFSM are expected to be lower than the obtained using estimated maximum depths, but in the order of the obtained using estimations of final depths.

- ***Run time is adequate*** - In the preliminary tests the run times have been shown to be low and within target bounds (although this can not be confirmed until integrated within the IA model). The run times experienced to date range from virtually zero seconds to 2.5 seconds. Therefore it can be stated that the RFSM meets easily the run time requirements.

- ***A co-funding success*** – The effort and resources devoted to this project have been supported by a number of funding sources. As such it has been possible to make a significant initial contribution to the development of flood spreading models (an area that will continue to be an important area of development over the coming years).

12 RECOMMENDATIONS

The RSFM tested here provides a significant step forwards in supporting crediable probability risk analysis. However, the RSFM is only the first step towards such a goal and a number of significant improvements are possible, including:

- ***To embed the RSFM within the IA 8/10 System Model*** - The RFSM will be incorporated within RASP HLM+ and used in the IA 8/10 V3 model. The improvements of the RSFM over the existing flood spreading approach within the RASP HLM+ are considerable and the resultant model will be the first step towards a model capable of combining probabilistic treatment of defence failure scenarios with a fast but accurate flood spreading model with which to assess the consequences of flooding. The resulting IA 8/10 model will be a powerful flood risk assessment model within the context of the HLOs and beyond.
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- ***Static variable grid size*** - There is not need to have a single grid size within the RSFM. In the first application through the IA 8/10 V3 it is recommended an intermediate grid size is used. An appropriate starting point would be a grid with 50m square DEM cells to build the accumulation areas across the whole study area. The DEM cell size could be lowered down to 25m in some embayments if more detailed is required. Even finer resolutions could be considered but this would increase run times, and the improvement in accuracy is probably not worth while given the size of other uncertainties. However as the IA model moves forward to V4 and beyond this could be explored further.

- ***Dynamic variable grid size*** - Enable the model to use different grid sizes depending on the severity of the event under consideration. The use of very refined meshes for an embayment with high inflow volumes does not make sense as it will act just as one pond. Therefore, to further restrict the run time, a variable grid size could be used depending on the inflow volume. This approach would enhance the performance of the model in terms of run time.

- ***Including multi-sources*** - Following the current approach the model can be easily completed by adding other source terms apart from the slope of the terrain. Volumetric source terms as rain or sewer systems can be easily incorporated in the model. With these improvements the model would be able to couple underground water with surface water models, therefore giving better guidance on the appropriate decisions to improve flood risk management. Moreover, due to its speed to carry out massive calculations, it could cope with real time simulations in case of extreme meteorological events.

- ***Improved diffusivity*** - In the comparisons with full hydrodynamic models, the RFSM has shown a lack of diffusivity that could cause errors in the estimation of damages. A simple way of introducing more diffusivity in the model is to modify the original topography to generate a virtual one. The model would run using the virtual topography and the results translated into the original one.

- ***Reuse of results and case management*** - One of the advantages of the RFSM is that the model does not need to rerun cases with incremental inflow volume. This simplification is based on one of the assumptions taken to develop the model: the pathway will remain the same independently of the severity of the event. In other words, if the cases are ranked by inflow volume, they can be run in one go using only the highest inflow volume leading to a significant reduction in the run time associated with multiple realisations as required in the RASP model.

- ***Inclusion of building*** - Introducing buildings in the model would be another improvement. Nevertheless, the best way to do it (porosity, bottom elevation, friction, etc) is not already specified and more research will be needed in this area.

- ***Adopting non-uniform meshes*** - Working with non-uniform meshes would represent another advantage for the model. The model would be more flexible as it could use irregular meshes in the same flood area (at the moment, the mesh size is fixed per flood area). This could be used in associated with the suggested mesh improvements above. To implement this improvement it would be necessary to develop a GIS tool to generate the connectivity matrix between irregular polygons (At present this is not necessary as the rasters are structured grids). The floodplain could be divided in irregular polygons taken account of the streets, properties, etc. The GIS tools would generate then the connectivity matrix. The rest of the pre-process would remain the same that is currently used. This new approach would remove the limitation of using even spaced grids.

- ***Code parallelization*** - The RFSM has been designed to work on a flood area basis. As the accumulation algorithm is run per flood area, the parallelization of the model would be relatively straight forward. This presents the opportunity for running the model on a multiprocessor basis and hence reducing runtimes.

13 REFERENCES

[1] **Infoworks RS 'Help' Documentation, Version 6.0. Source:** *Wallingford Software, United Kingdom.*

[2] "**Embayment Inundation Modelling Report. Stage 2a" Source:** Environmental Agency 2004.

[3] "**A simple raster-based model for floodplain inundation"** Bates, P.D., De Roo, A.P.J. **Source:** *Journal of Hydrology*, n 236, p 54-77.

[4] "**TELEMAC: A new numerical model for solving shallow water equations"** Galland, J.-C. (Maritime Hydraulics Branch, Direction des Etudes et Recherches, Dept. Lab. Nat. d'Hydraulique, EDF, Chatou, France); Goutal, N.; Hervouet, J.-M. **Source:** *Advances in Water Resources*, v 14, n 3, June 1991, p 138-48.

[5] "**TUFLOW: Two & one-dimensional unsteady software for rivers, estuaries and coastal waters"** Shyme, W.J. (WBM Oceanics Australia); **Source:** IEAustr 2D Seminar, Sydney, Feb 2001.

14 ACKNOWLEDGEMENTS

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APPENDIX A STABILITY TESTS.

Stability Testing

To test the robustness and stability of the RFSM several preliminary test cases were tested along the Thames Estuary. The results obtained in these test cases are presented in the following Figures as plots showing the depths provided by the RFSM. In the majority of the test cases the inflow volume used as input for the RFSM were set as 1 million m3, which was considered severe enough to carry out this stability analysis. The performance of the model during these stability tests was completely successful (the model did not crash in any case) and the accumulation algorithm demonstrated its reliability.

Apart from that, several direct comparisons between the RFSM and TUFLOW were also performed. The direct comparisons are the Figures 102 and 103, and Figures 104 and 105. The first direct comparison was run in the Bermondsey embayment with 1 million m3 as inflow volume. The second direct comparison was run in the Greenwich embayment and two breaches were set up. The inflow volumes trough these breaches were 70k m3 and 20k m3.

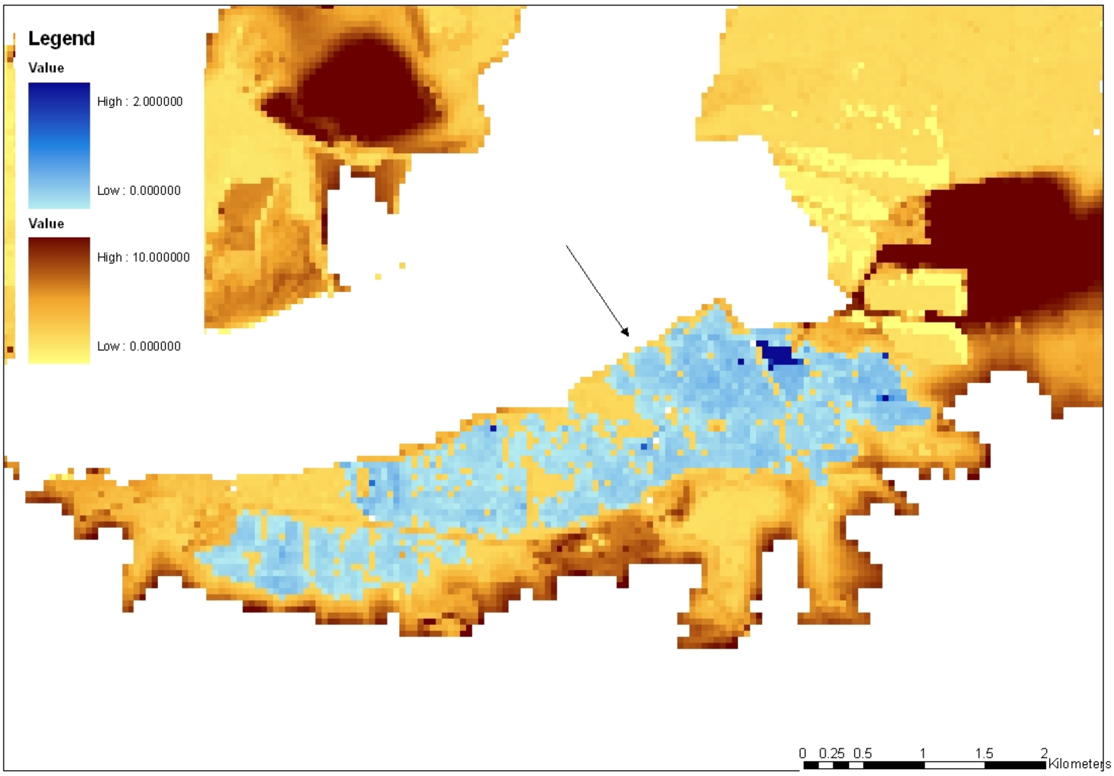

Figure A1: Preliminary test case 1. Shorne Marshes embayment. Inflow volume: 1 million m3.

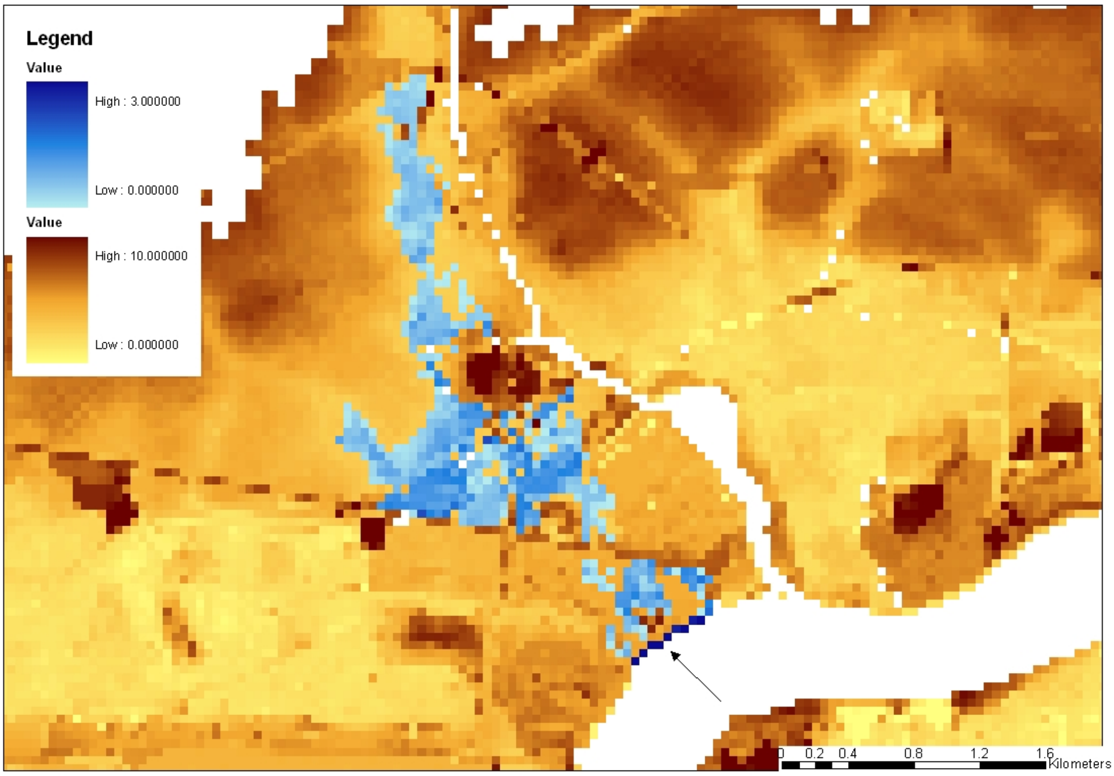

Figure A2: Preliminary test case 2. Roding embayment. Inflow volume: 1 million m3

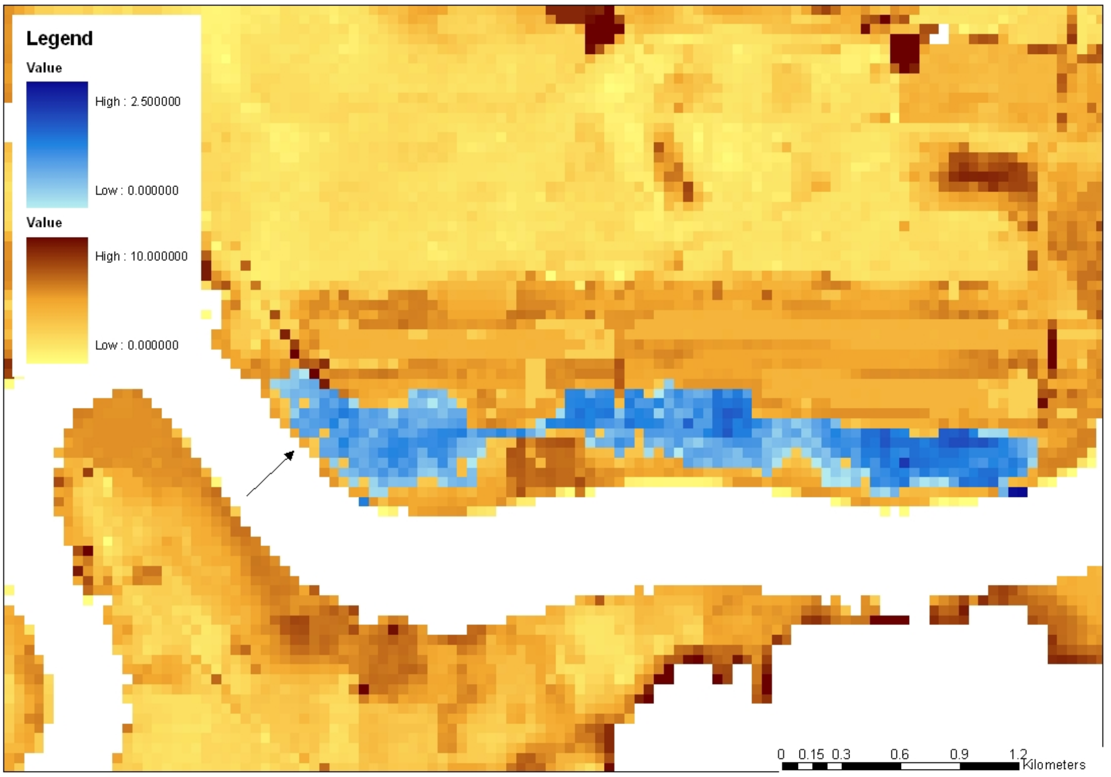

Figure A3: Preliminary test case 3. Royal Docks embayment. Inflow volume: 1 million m3

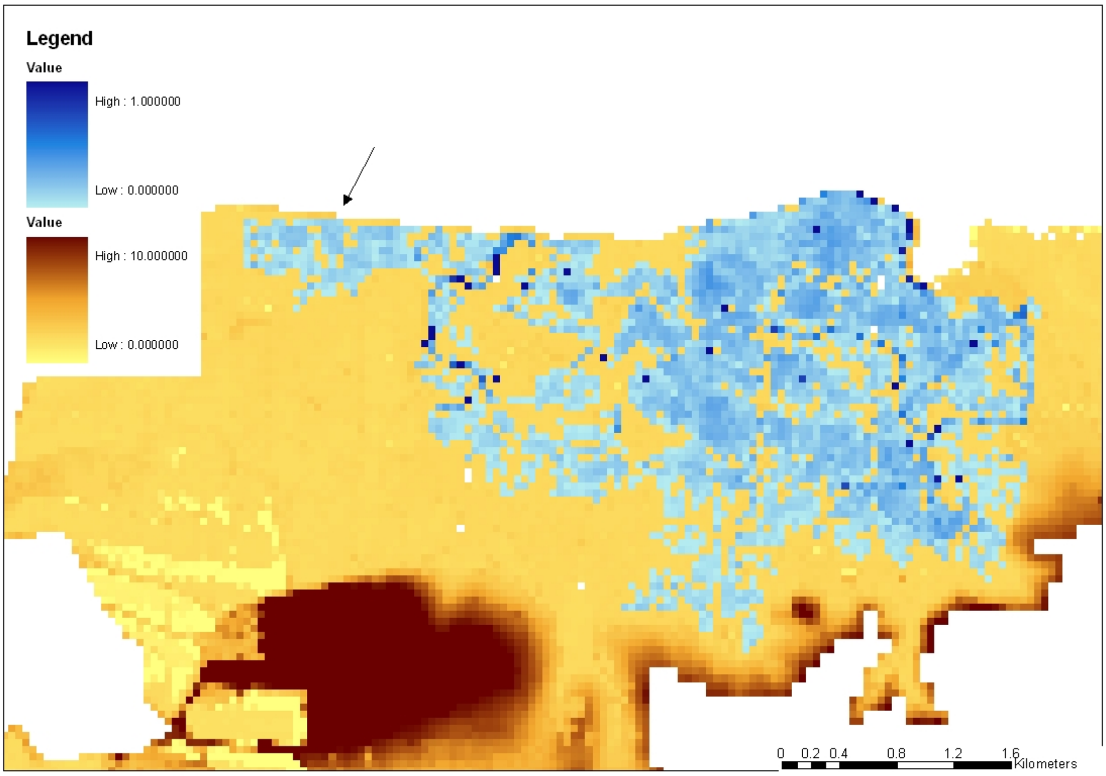

Figure A4: Preliminary test case 4. North Kent Marshes embayment. Inflow volume:1 million m3

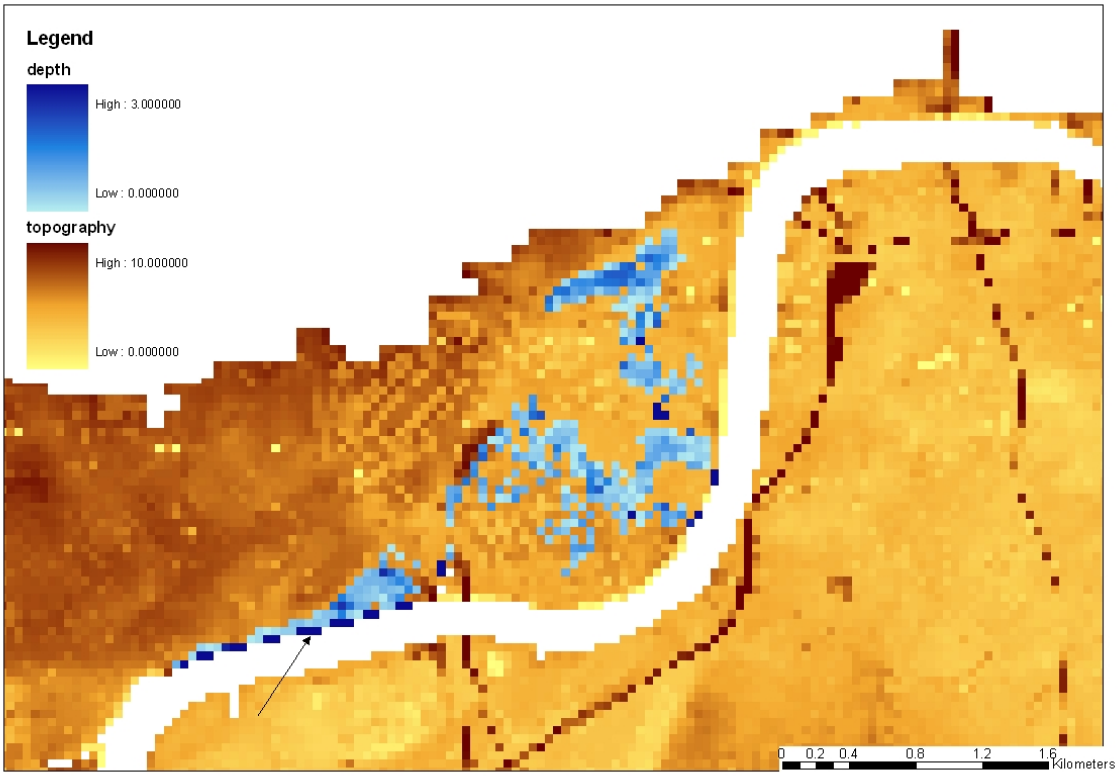

Figure A5: Preliminary test case 5. Westminster embayment. Inflow volume: 1 million m3

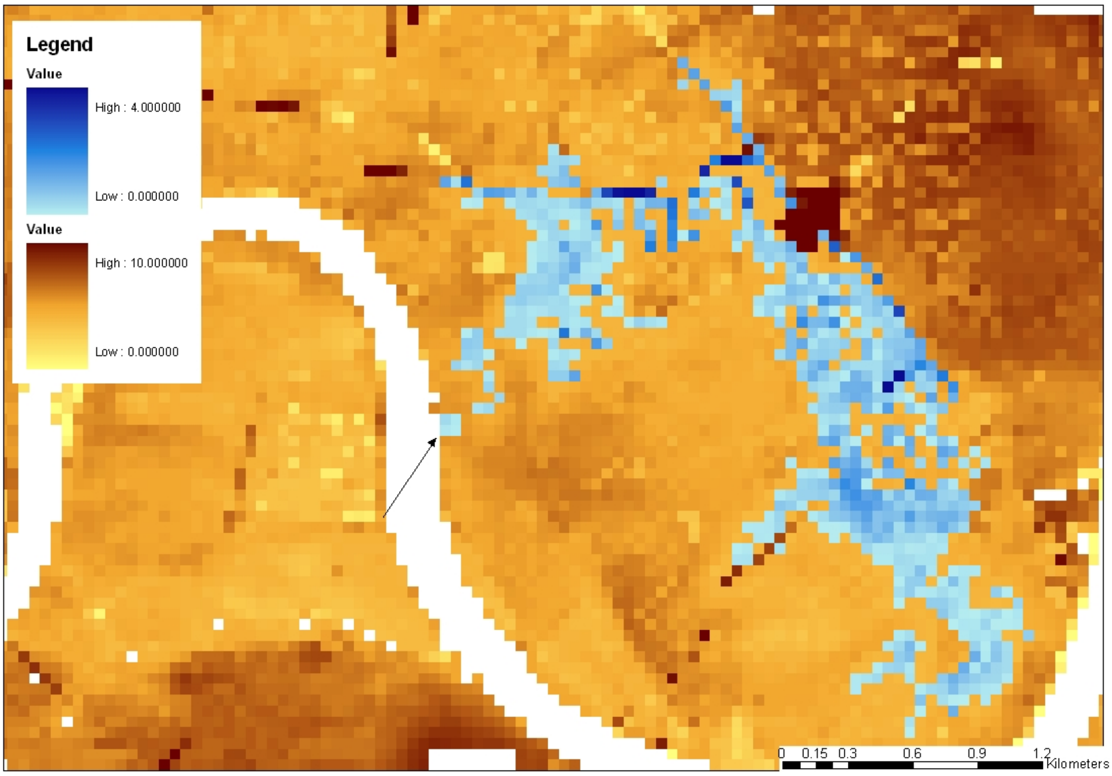

Figure A6: Preliminary test case 6. Hammersmith and Fulham embayment. Inflow volume: 1 million m3.

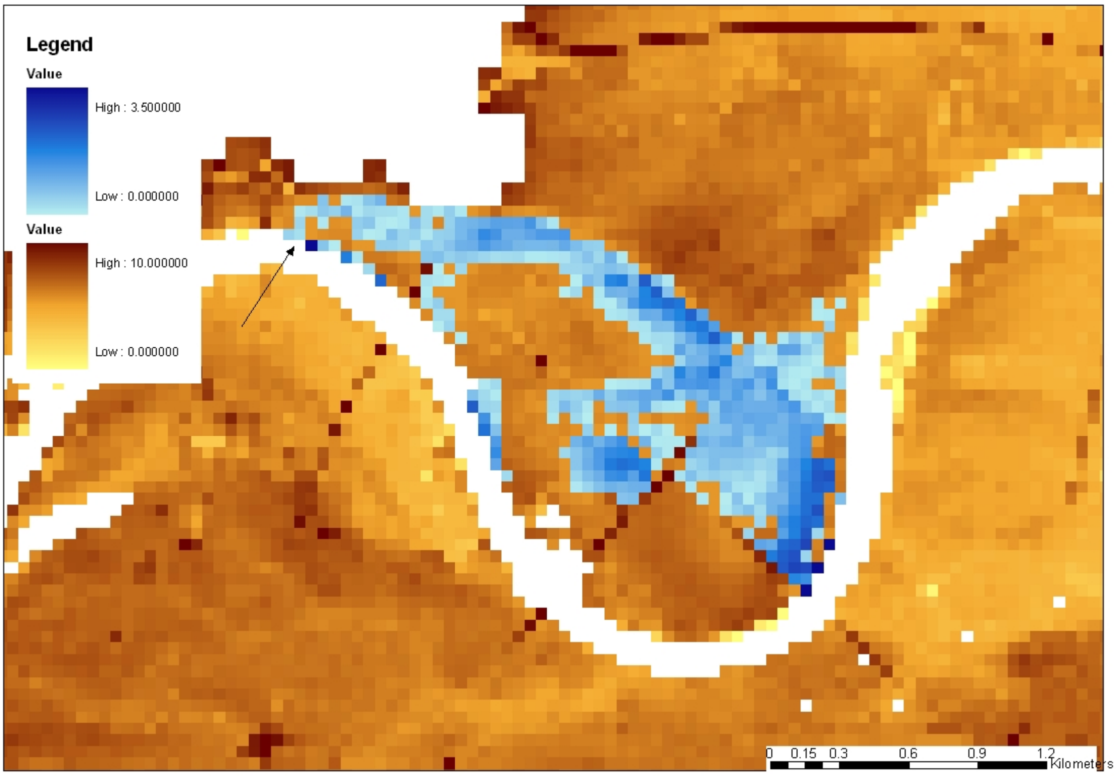

Figure A7: Preliminary test case 7. Chiswick embayment. Inflow volume: 1 million m3.

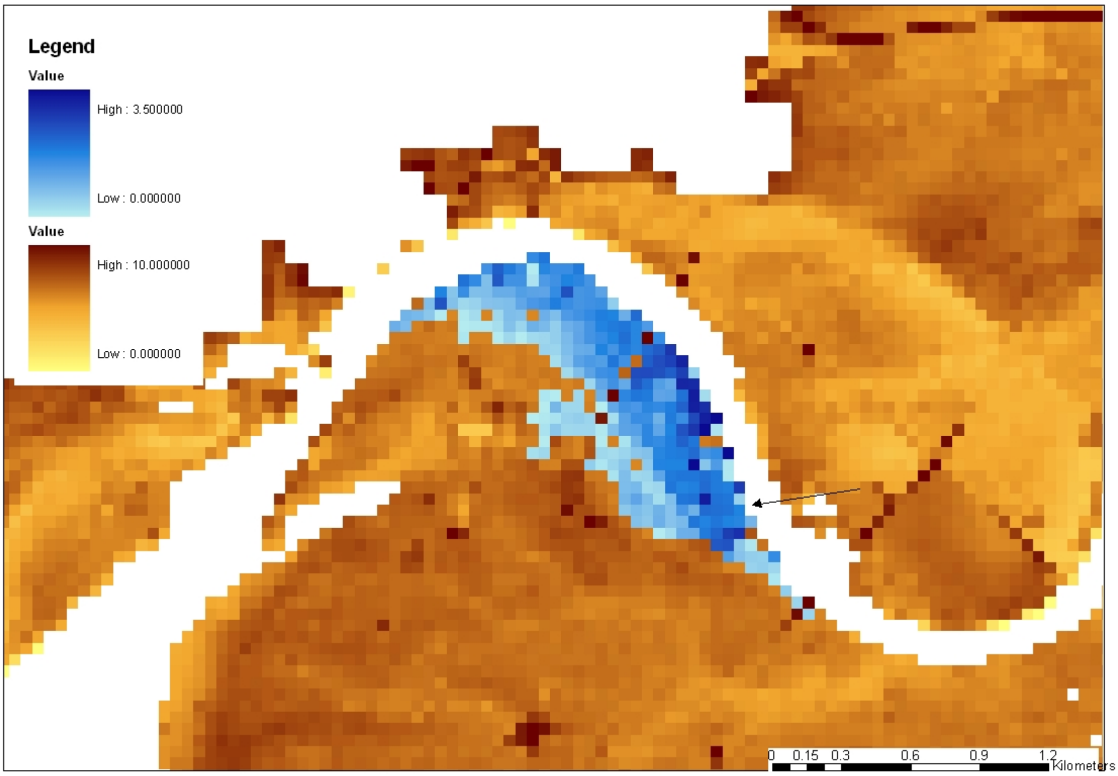

Figure A8: Preliminary test case 8. Kew embayment. Inflow volume: 1 million m3.

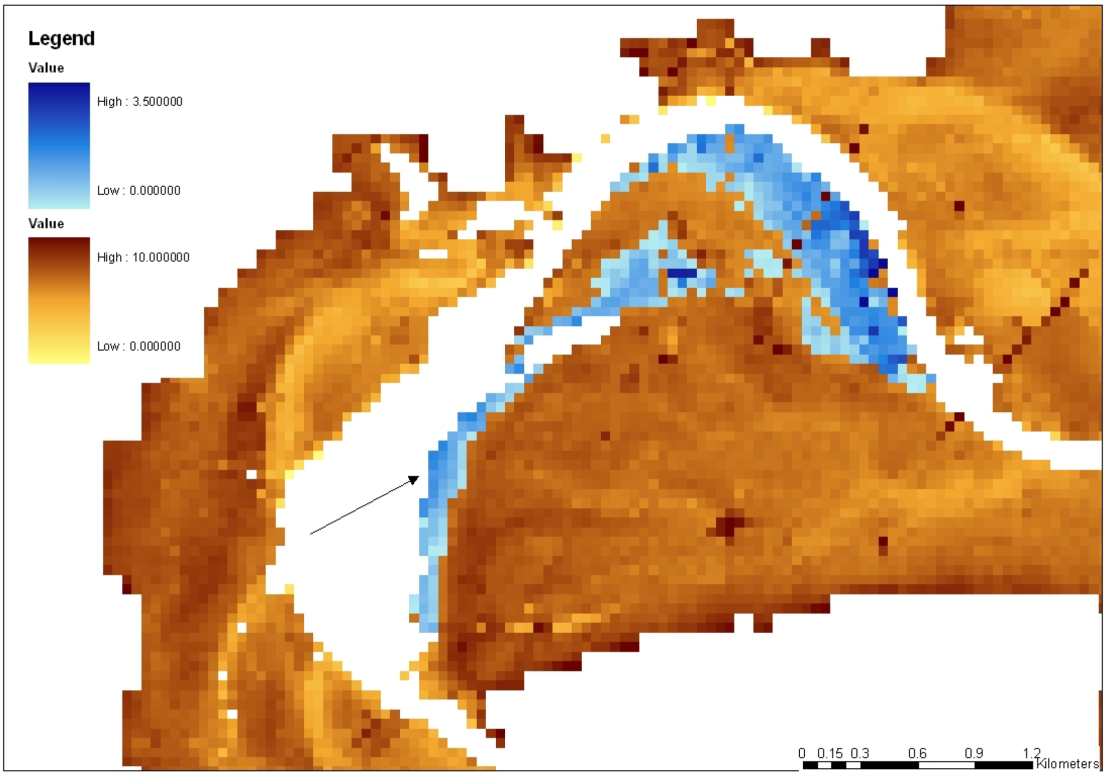

Figure A9: Preliminary test case 9. Kew embayment. Inflow volume: 1 million m3.

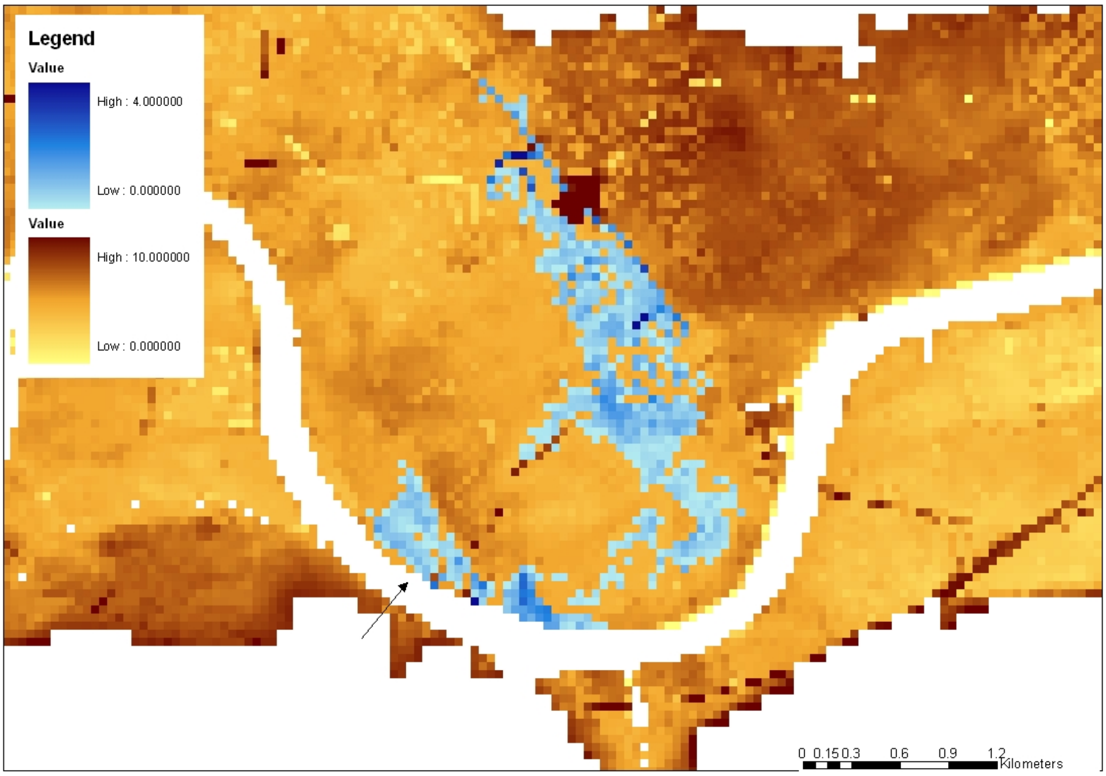

Figure A10: Preliminary test case 10. Hammersmith and Fulham embayment. Inflow volume: 1 million m3.

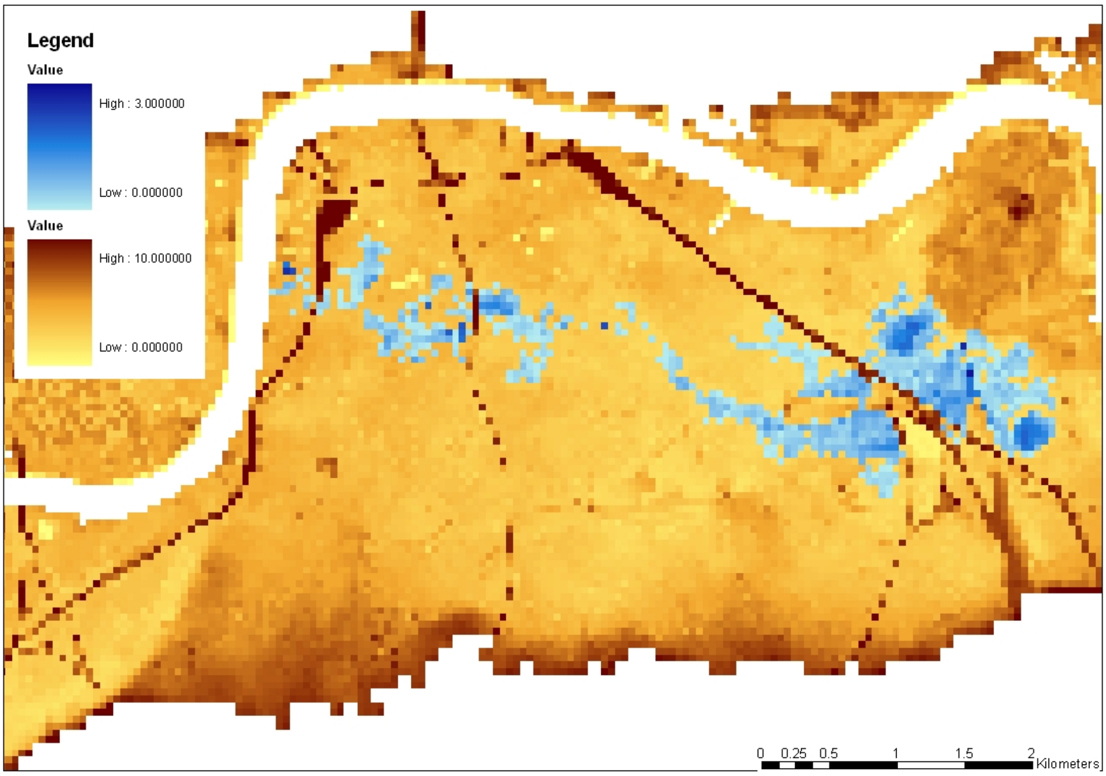

Figure A11: Preliminary test case 11. Bermondsey embayment. Inflow volume: 1 million m3.

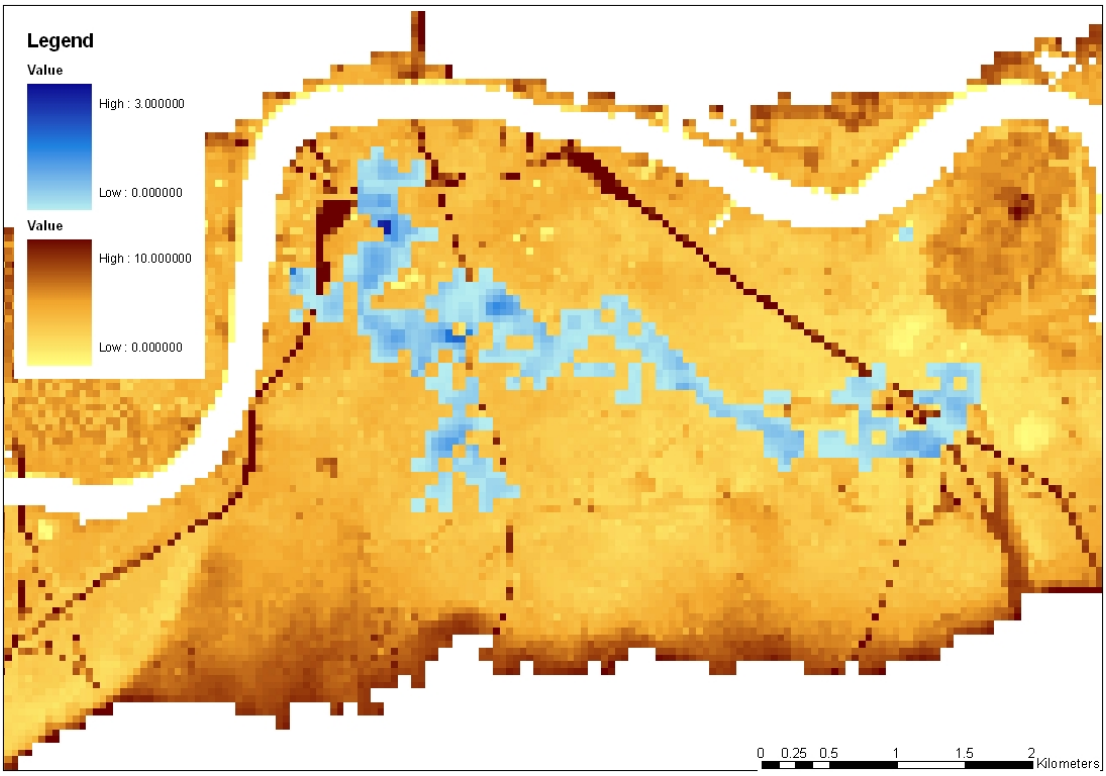

Figure A12: Bermondsey embayment. TUFLOW results. Inflow volume: 1 million m3.

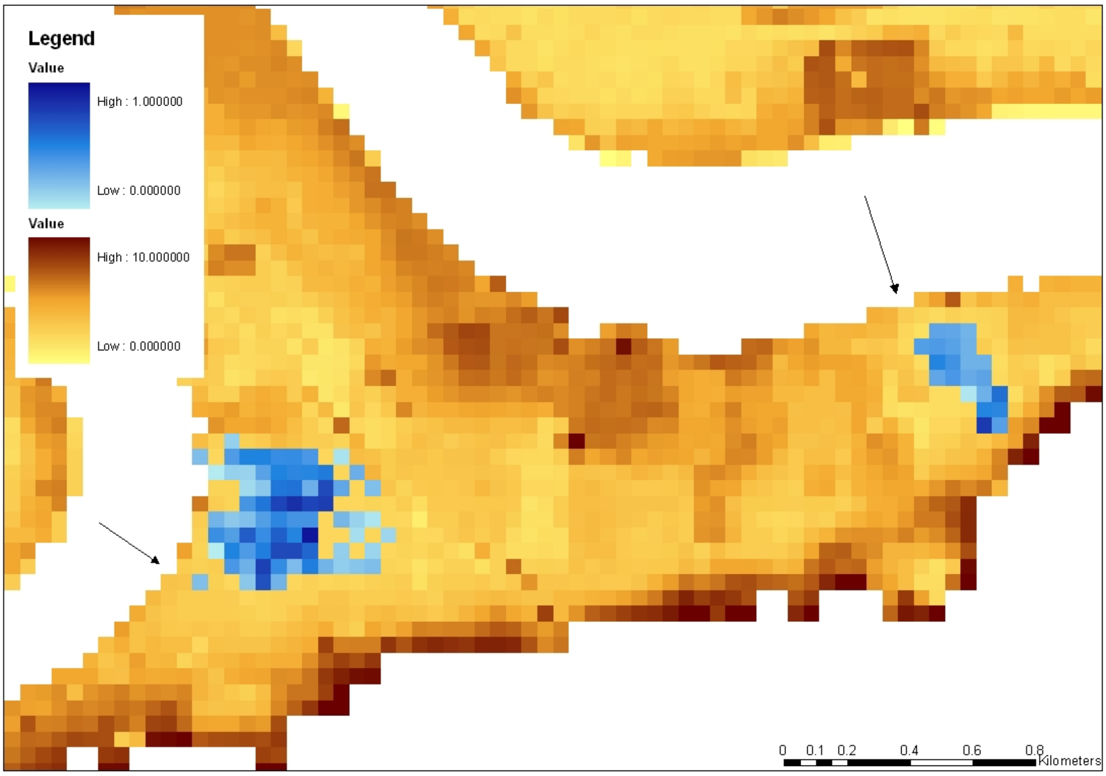

Figure A13: Preliminary test case 12. Greenwich embayment. Inflow volume: 70k and 20k m3.

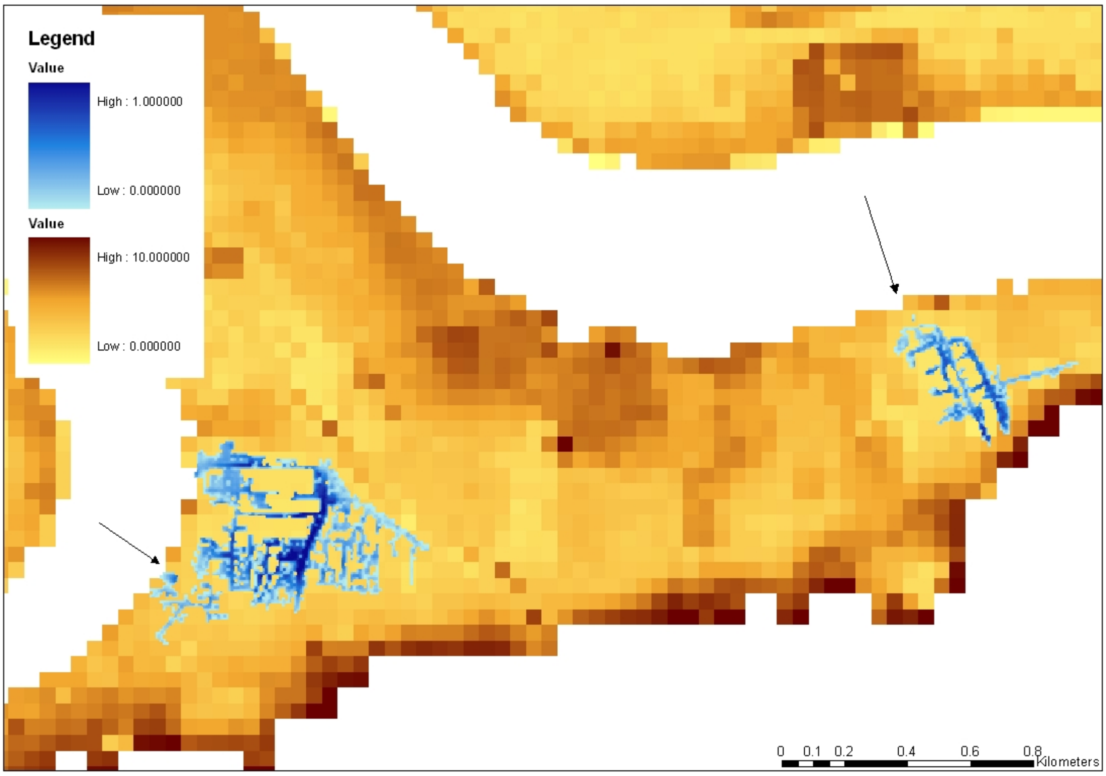

Figure A14:Greenwich embayment. TUFLOW results. Inflow volume: 70k and 20k m3.

APPENDIX B. FLOODING CALCULATIONS.

BREACH	INFLOW (m3)	AREA (m2)	MIN DEPTH (m)	MAX DEPTH (m)	RANGE	MEAN (m)	STD	VOL (m3)
TUFLOW max								
1		610000.000	0.001	0.636	0.635	0.112	0.122	68484.998
3		1350000.000	0.032	2.150	2.118	0.851	0.559	1148799.973
4		290000.000	0.001	0.996	0.995	0.250	0.244	72417.498
5		210000.000	0.002	1.098	1.096	0.336	0.324	70650.001
TUFLOW max classified								
1		260000.000	0.101	0.636	0.535	0.214	0.126	55520.000
3		1302500.000	0.103	2.150	2.047	0.880	0.548	1145632.500
4		187500.000	0.102	0.996	0.894	0.368	0.228	68990.000
5		152500.000	0.113	1.098	0.985	0.454	0.306	69255.000
TUFLOW final								
1		485000.000	0.001	0.553	0.552	0.066	0.077	32087.500
3		1250000.000	0.004	1.549	1.545	0.581	0.372	726070.000
4		180000.000	0.004	0.702	0.698	0.185	0.179	33290.000
5		150000.000	0.041	1.071	1.030	0.361	0.289	54200.000
TUFLOW final classified								
1		117500.000	0.100	0.553	0.453	0.156	0.106	18380.000
3		1135000.000	0.102	1.549	1.447	0.633	0.351	718277.500
4		102500.000	0.105	0.702	0.597	0.292	0.171	29945.000
5		122500.000	0.113	1.071	0.958	0.428	0.278	52457.500
RFSM final 100m								
1	32087.290	420000.000	0.002	0.510	0.508	0.076	0.105	32087.901
3	726070.100	1210000.000	0.009	1.336	1.327	0.600	0.317	726082.993
4	33289.880	160000.000	0.008	0.624	0.616	0.208	0.185	33308.599
5	54199.970	160000.000	0.034	1.052	1.018	0.339	0.231	54275.298
RFSM final 50m								

1	32087.290	275000.000	0.002	1.175	1.173	0.117	0.208	32097.750
3	726070.100	1025000.000	0.008	1.746	1.738	0.708	0.343	726085.000
4	33289.880	105000.000	0.001	1.064	1.063	0.317	0.242	33297.500
5	54199.970	122500.000	0.007	1.465	1.458	0.443	0.348	54239.750
RFSM final classified 100m								
1		60000.000	0.178	0.510	0.332	0.304	0.112	18237.900
3		1140000.000	0.119	1.336	1.217	0.634	0.294	722695.000
4		120000.000	0.109	0.624	0.515	0.261	0.184	31300.000
5		140000.000	0.136	1.052	0.916	0.382	0.216	53440.900
RFSM final classified 50m								
1		62500.000	0.101	1.175	1.074	0.375	0.319	23447.750
3		995000.000	0.109	1.746	1.637	0.728	0.328	724377.500
4		87500.000	0.103	1.064	0.961	0.372	0.229	32522.500
5		110000.000	0.117	1.465	1.348	0.487	0.339	53611.750

Table B1: Statistical summary. Flooding calculations. Estimated RP 100.

BREACH	INFLOW (m3)	AREA (m2)	MIN DEPTH (m)	MAX DEPTH (m)	RANGE	MEAN (m)	STD	VOL (m3)
TUFLOW max								
2		700000.00	0.01	2.01	2.00	0.43	0.44	300360.00
TUFLOW max classified								
2		535000.00	0.10	2.01	1.91	0.55	0.44	292205.00
TUFLOW final								
2		660000.00	0.00	1.82	1.82	0.39	0.40	258925.00
TUFLOW final classified								
2		490000.00	0.10	1.82	1.72	0.51	0.40	250997.50
RFSM								
2	258923.8	390000.00	0.01	2.45	2.44	0.67	0.60	259729.00
RFSM classified								
2		340000.00	0.14	2.45	2.31	0.76	0.59	257364.00
RFSM 50m								
2	258923.8	347500.00	0.00	2.65	2.64	0.75	0.56	259102.50
RFSM 50m classified								
2		310000.00	0.10	2.65	2.55	0.83	0.53	257437.50

Table B2: Statistical summary. Flooding calculations. Estimated RP 1000.

BREACH	INFLOW (m3)	AREA (m2)	MIN DEPTH (m)	MAX DEPTH (m)	RANGE	MEAN (m)	STD	VOL (m3)
TUFLOW max								
2		170000.000	0.011	1.416	1.405	0.444	0.406	75515.000
TUFLOW max classified								
2		132500.000	0.113	1.416	1.303	0.555	0.396	73482.500
TUFLOW final								
2		140000.000	0.011	1.371	1.360	0.380	0.383	53155.000
TUFLOW final classified								
2		102500.000	0.103	1.371	1.268	0.501	0.381	51380.000
RFSM								
2	53155.890	80000.000	0.011	1.502	1.491	0.669	0.475	53515.800
RFSM classified								
2		60000.000	0.503	1.502	0.999	0.876	0.359	52549.300
RFSM 50m	53155.890							
2		60000.000	0.029	1.859	1.830	0.888	0.536	53296.250
RFSM 50m classified								
2		55000.000	0.169	1.859	1.690	0.966	0.492	53109.750

Table B3: Statistical summary. Flooding calculations. Estimated RP 10000.

OVERTOPPING	INFLOW (m3)	AREA (m3)	MIN DEPTH (m)	MAX DEPTH (m)	RANGE	MEAN (m)	STD	SUM	VOL (m3)
TUFLOW max									
1		9280000.00	0.00	3.40	3.39	0.58	0.52	2163.68	5409200.00
TUFLOW max classified									
1		7650000.00	0.10	3.40	3.30	0.70	0.50	2133.89	5334725.00
TUFLOW final									
1		7052500.00	0.00	2.02	2.02	0.41	0.34	1169.97	2924925.00
TUFLOW final classified									
1		5867500.00	0.10	2.02	1.92	0.49	0.33	1145.06	2862650.00
RFSM									
1	2924923.854	6170000.00	0.00	1.92	1.92	0.48	0.38	294.04	2940360.00
RFSM classified									
1		5450000.00	0.10	1.92	1.82	0.53	0.37	290.53	2905250.00
RFSM 50m									
1	2924923.854	5795000.00	0.00	2.26	2.26	0.51	0.40	1174.81	2937025.15
RFSM 50m classified									
1		5237500.00	0.10	2.26	2.16	0.56	0.39	1163.30	2908250.12

Table B4: Statistical summary. Flooding calculations. Thamesmead overtopping.

BREACH	INFLOW (m3)	AREA (m2)	MIN DEPTH (m)	MAX DEPTH (m)	RANGE	MEAN	STD	SUM	VOL (m3)
TUFLOW max									
1		473475.00	0.00	5.32	5.32	0.62	0.49	11753.30	293832.50
2		188675.00	0.00	2.59	2.59	0.98	0.67	7418.52	185463.00
TUFLOW max classified									
1		414700.00	0.10	5.32	5.22	0.70	0.47	11647.30	291182.50
2		172850.00	0.10	2.59	2.49	1.07	0.64	7388.84	184721.00
TUFLOW final									
1		445900.00	0.00	5.32	5.32	0.49	0.42	8664.27	216606.75
2		179300.00	0.00	2.58	2.58	0.95	0.67	6795.29	169882.25
TUFLOW final classified									
1		372500.00	0.10	5.32	5.22	0.57	0.40	8537.83	213445.75
2		161200.00	0.10	2.58	2.48	1.05	0.63	6763.50	169087.50
RFSM 10m grid									
1	216000.00	341800.00	0.00	7.42	7.42	0.63	0.50	2160.09	216009.00
2	170000.00	140600.00	0.00	2.61	2.61	1.21	0.69	1700.02	170002.00
RFSM 10m grid classified									
1		317200.00	0.10	7.42	7.32	0.68	0.49	2148.09	214809.00
2		135800.00	0.10	2.61	2.51	1.25	0.66	1697.77	169777.00
RFSM 100m grid filtered									
1	216000.00	510000.00	0.02	1.08	1.06	0.43	0.29	21.69	216949.01
2	170000.00	240000.00	0.04	1.50	1.46	0.71	0.42	17.13	171326.01

RFSM 100m grid unfiltered									
1		340000.00	0.00	2.12	2.12	0.64	0.54	21.60	216015.00
2		200000.00	0.06	1.92	1.86	0.85	0.58	17.09	170912.99

Table B5: Statistical summary. Flooding calculations. Greenwich.

APPENDIX C. ECONOMIC DAMAGES.

RP 100 BREACH	AREA (m2)	MIN (£ per DEM cell)	MAX (£ per DEM cell)	RANGE	MEAN (£ per DEM cell)	STD	TOTAL DAMAGE (£)
TUFLOW MAX 100m grid							
3	930000	260	5260680	5260420	969678	973181	90180100
4	180000	6133	3044560	3038430	638776	719044	11498000
5	30000	11402	696374	684973	250929	315276	752788
TUFLOW MAX 50m grid							
3	540000	44	4181970	4181930	411113	521430	88800300
4	117500	1554	2629940	2628390	241317	450631	11341900
5	22500	608	209075	208467	52245	73893	470205
TUFLOW FINAL 100m grid							
3	890000	4836	5260680	5255850	860652	909169	76598000
4	100000	34369	1303780	1269410	513974	385112	5139740
5	10000	535958	535958	0	535958	0	535958
TUFLOW FINAL 50m grid							
3	525000	1349	4181970	4180620	357151	457994	75001700
4	75000	59	1124610	1124550	164339	256169	4930160
5	10000	18859	129365	110506	71444	48024	285774
RFSM 100m grid							
3	880000	93	5052180	5052090	867920	943253	76377000
4	40000	17870	362326	344456	205980	132034	823920
5	30000	43831	721076	677245	299430	300382	898291
RFSM 50m grid							
3	467500	1976	4146600	4144620	394614	529183	73792800
4	22500	320	4086870	4086550	788430	1233540	7095870
5	10000	28264	311962	283698	117068	116067	468271

Table C1: Statistical summary. Economic damages. Estimated RP 100.

RP 1000 BREACH	AREA (m2)	MIN (£ per DEM cell)	MAX (£ per DEM cell)	RANGE	MEAN (£ per DEM cell)	STD	TOTAL DAMAGE (£)
TUFLOW MAX 100m grid							
2	20000	112788	1661390	1548600	887087	774299	1774170
TUFLOW MAX 50m grid							
2	5000	66475	3205620	3139140	1636050	1569570	3272090
TUFLOW FINAL 100m grid							
2	20000	111253	1640730	1529470	875989	764737	1751980
TUFLOW FINAL 50m grid							
2	5000	65582	3179310	3113720	1622440	1556860	3244890
RFSM 100m grid							
2	20000	109899	3162800	3052900	1636350	1526450	3272690
RFSM 50m grid							
2	2500	3116430	3116430	0	3116430	0	3116430

Table C2: Statistical summary. Economic damages. Estimated RP 1000.

RP 10000 BREACH	AREA (m2)	MIN (£ per DEM cell)	MAX (£ per DEM cell)	RANGE	MEAN (£ per DEM cell)	STD	TOTAL DAMAGE (£)
TUFLOW MAX 100m grid							
2	110000	4946	2190990	2186040	718163	868930	7899800
TUFLOW MAX 50m grid							
2	27500	2455	3707170	3704720	804455	1126710	8849010
TUFLOW FINAL 100m grid							
2	110000	4747	2041170	2036420	655178	813541	7206960
TUFLOW FINAL 50m grid							
2	27500	2383	3594260	3591880	745740	1081180	8203140
RFSM 100m grid							
2	70000	20350	4030800	4010450	1039700	1367160	7277910
RFSM 50m grid							
2	2500	3900530	3900530	0	3900530	0	3900530

Table C3: Statistical summary. Economic damages. Estimated RP 10000.

OVERTOPPING	AREA (m2)	MIN (£ per DEM cell)	MAX (£ per DEM cell)	RANGE	MEAN (£ per DEM cell)	STD	TOTAL DAMAGE (£)
TUFLOW MAX 100m grid							
	4950000	1153	28313300	28312200	706050	1469810	349495000
TUFLOW MAX 50m grid							
	3412500	448	27290900	27290500	246999	858088	337153000
TUFLOW FINAL 100m grid							
	4050000	716	12614900	12614100	592495	883418	239961000
TUFLOW FINAL 50m grid							
	2797500	67	7733810	7733740	201783	418889	225795000
RFSM 100m grid							
	3330000	50	7390520	7390460	568377	685055	189270000
RFSM 50m grid							
	2162500	72	6134180	6134110	224234	390982	193962000

Table C4: Statistical summary. Economic damages. Thamesmead overtopping.

Greenwich BREACH	AREA (m2)	MIN (£ per DEM cell)	MAX (£ per DEM cell)	RANGE	MEAN (£ per DEM cell/10m grid basis)	STD	TOTAL DAMAGE (£)
TUFLOW MAX							
1	236650	0	83158	83158	9234	10668	21851900
2	87900	1	125702	125701	13880	16785	12200100
TUFLOW FINAL							
1	216000	0	75724	75724	7684	9048	16596650
2	85425	1	125483	125483	13380	16501	11429900
RFSM							
1	157300	3	86824	86821	9568	10742	15051100
2	63400	10	126268	126258	16050	18658	10175500

Table C5: Statistical summary. Economic damages. Greenwich.

APPENDIX D. SPEED TESTS.

CASE	ACCUMULATION AREAS	MESH SIZE (m)	SOURCES	TOTAL VOLUME (m3)	TIME (s)
RP100 BREACH-1	2844	100.00	1	32087.29	0.14
RP100 BREACH-3	2844	100.00	1	726070.10	~0.00
RP100 BREACH-4	2844	100.00	1	33289.88	~0.00
RP100 BREACH-5	2844	100.00	1	54199.97	0.02
RP1000 BREACH-2	2844	100.00	1	53155.89	~0.00
RP10000 BREACH-2	2844	100.00	1	258923.80	0.02
RP100 BREACH-1	1586	50.00	1	32087.29	0.02
RP100 BREACH-3	251	50.00	1	726070.10	0.02
RP100 BREACH-4	240	50.00	1	33289.88	0.03
RP100 BREACH-5	29	50.00	1	54199.97	0.03
RP1000 BREACH-2	606	50.00	1	53155.89	~0.00
RP10000 BREACH-2	606	50.00	1	258923.80	0.02
OVERTOPPING THAMESMEAD	2844	100.00	18	2924923.85	0.27
OVERTOPPING THAMESMEAD	498	50.00	18	2924923.58	0.88
GREENWICH BREACH-1	3252	10.00	1	216000.00	2.42
GREENWICH BREACH-2	3252	10.00	1	170000.00	0.41

Table D1: Duration of the spreading calculations with the RFSM preliminary version.