Interactive Simulation and Visualisation of Realistic Flooding Scenarios

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Abstract Floods are a permanent threat for urban environments and coastal regions. Due to the numerous environmental and climatological factors that cause floods, their prevention and prediction is complicated. Flood protection and prevention plans are assessed by computational models. The related risk analysis communication demands simulations of accurate inundation models and their interactive visualisation. In our new Dutch Knowledge for Climate project we work closely together with industrial partners with whom we develop a platform that supports this communication. Our research focuses on real-time flow simulations, their interactive visualisation and steering techniques for flooding scenarios. Our goal is an interactive, realistic problem-solving environment for flooding discussions amongst decision makers, water boards, hydrologists and the general public. Most important in this research are sophisticated algorithms that promote this goal. Related work in the field is done on small-scale examples and abstract computational models. We work on large-scale, high-resolution, realistic computations while maintaining interactivity. For this we use aerial terrain LiDAR point clouds of The Netherlands and most recent, complex Computational Fluid Dynamics (CFD) models. The rendering system will apply a combination of new point cloud compression algorithms and spatial Level-of-Detail data structures. Fast CFD simulations will be achieved by subgridding and parallel processing of

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S. Zlatanova et al. (eds.), *Intelligent Systems for Crisis Management*, Lecture Notes in Geoinformation and Cartography, DOI: 10.1007/978-3-642-33218-0_7,

non-linear calculation models. Additionally, the integration of various geo-information (i.e. precipitation) is key to educated flooding decision-making. In this paper we describe in detail our project goals, our current progress and upcoming related research tracks.

1 Introduction

Floods are a permanent threat for urban environments and coastal regions worldwide. Therefore in Europe, The Netherlands are particularly threatened. Dikes at the coast are securing the inside of the country from floods while channels distribute water inside the country in a controlled way. Floods and high sea levels are a constant danger to this controlled ecosystem. The challenge for computational science is the construction of accurate simulations with models as close to reality as possible. The results of these simulations are flooding assessments of use cases, as a basis for flood protection and flood prevention concepts. The output of such simulations is large in size, therefore it needs to be visualized effectively to promote discussions of fore-mentioned concepts. Additionally, for applicable concepts, simulation and visualisation need to work on large-scale data and with an interactive speed.

Our dataset is a large-scale terrain- and bathymetry scan of The Netherlands, available as the AHN- and AHN-2 datasets. The size of the data sets demands new ways in visualisation, simulation and interaction. The main research question connected to the topic is as follows:

Which algorithms and data structures promote a multi-source, content-rich, interactive visualisation and simulation for flooding-aware environmental discussion?

Several topics and their related research questions, together with their available approaches and our initial sketches, are further presented. They form the basis of our future research. From the practical point of view, we are developing our own rendering system towards a multi-source decision support system (DSS) with two main purposes:

- enable water experts to explore better flood protection mechanisms on large scales;
- promote the discussions between water experts and decision makers in developing efficient worst-case-scenario and evacuation plans.

The following sections discuss in detail our 4 main research tracks. An overview of first results concludes the current progress of the presented topics. A final section will lay out the next steps of our research and development.

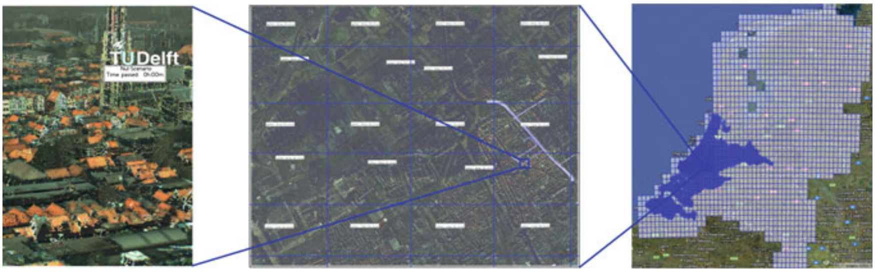

Fig. 1 Tile overview: overview of all AHN-2 point cloud tiles (*right*), in relation to the region of Delfland (*mid*) and the marketplace of Delft (*left*)

2 Large-Scale Point Cloud Rendering

The available terrain datasets used in our approach are represented as massive, unordered, roughly labelled 3D point clouds. Such point clouds receive growing attention in natural hazard management [20, 26]. These point clouds are part of the AHN-2 dataset[1] which is an aerial LiDAR[2] scan of the whole Netherlands. The scan consists of unordered point clouds which are geo-referenced as “Rijksdriehoekscoördinaten”. Due to the data size the dataset is divided into around 44.000 separate tiles (Fig. 1), which consist of point clouds themselves. These point clouds have an average resolution of $30\frac{points}{m^2}$ and a precision of 0.05 m. Moreover each tile is separated into ground data (e.g. terrain) and additional data (i.e. buildings, trees). For the visualisation purpose a single or multiple tiles are linked to an aerial photograph. This colour information in return increases the memory consumption of each dataset.

Rendering concepts like Surfels [14] and QSplats [19], describe efficient ways of large-scale point visualization. We currently apply in our system circular splats as rendering primitives to compensate for locally-poor sampling densities. Alexa et al. [1] describe in their paper the generation of minimal samples for closed point set object perception via Moving-Least-Squares (MLS) surfaces, which is another way to efficiently render point cloud objects with varying sample densities. Gobbetti and Marton [7] prove the efficiency of large-scale point cloud rendering for static structures. Wand et al. [22] explore new ways of multi-resolution point cloud rendering by focussing on dynamic, efficient data structures for such data sets. We apply rendering techniques similar to Wand et al., with the difference that they store the full high-resolution base point set as bottom leaf layer. Lower resolution levels contain additional, simplified samples. Our approach, which is explained in further sections, distribute the points of the dataset over all levels of detail, therefore avoiding the generation of additional samples. Maeno et al. [11]

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[1] AHN-2—Actueel Hoogtebestand Nederland 2nd version (http://www.ahn.nl).

[2] LiDAR—Light Detection and Ranging (http://www.lidar.com).

discuss in their paper large-scale data management and rendering techniques for heterogeneous terrain point clouds. Our focus in this field is on optimized data structures and rendering algorithms rather than data management.

Due to the amount of data, processing time as well as the memory consumption of each point, the data can not be managed in full scale by a single machine while maintaining reasonable framerates. Therefore, the handling of a dataset demands ways of data reduction. The corresponding research questions we hereby try to address are:

How do data reduction techniques contribute to interactive flooding visualisation and simulation?

Which techniques and designs are suitable for large-scale, interactive and realistic flooding simulations and visualisations?

2.1 Current Rendering and Visualisation

We created a prototypical 3D real-time rendering system to visualise AHN-2 datasets and the output of related flooding simulations. The system works with OpenSceneGraph and our internally-developed virtual reality framework "VRmeer". This program is extended during our research to apply new insights for subsequent user studies. While following paragraphs provide an overview of the used algorithms and techniques, more detailed information can be found in the paper of de Haan [6].

Our current algorithms are based on a spatial subdivision of points by employing a hierarchical, paged tree-data structure. The layout of the data structure can vary between octrees and quadtrees. The layout choice depends on the variation of the dimensional extent of the available tiles. For large, flat terrain the variation of x- and y-values is high while the variation of the z-axis is very low (for the used coordinate system we refer to Fig 2). Therefore, a quadtree is the preferred layout. For urban environments, the variation in all 3 dimensions is equal, thus an octree layout is the optimal choice. The tree depth depends on the overall number of points that needs to be shown.

This tree structure is used for Level-of-Detail (LoD) rendering. The necessary distance information for the LoD is stored for each point. When displaying the points only nodes (or leaves) of required resolution levels are shown. The arrangement of the points inside the tree is controlled via point cloud re-sampling. This re-sampling is done in a homogeneous manner, meaning that for N tree levels each N points are assigned to complementary nodes. This combination of spatial subdivision and Level-of-Detail can be seen in Fig. 3.

The water of the flooding scenarios is represented in one of 3 different ways. A first way is the conversion of a water depth map (one output of the simulation) to a colour texture. This is done by representing the integer-format water height by a saturation transfer function of blue, representing the water depth. The colour

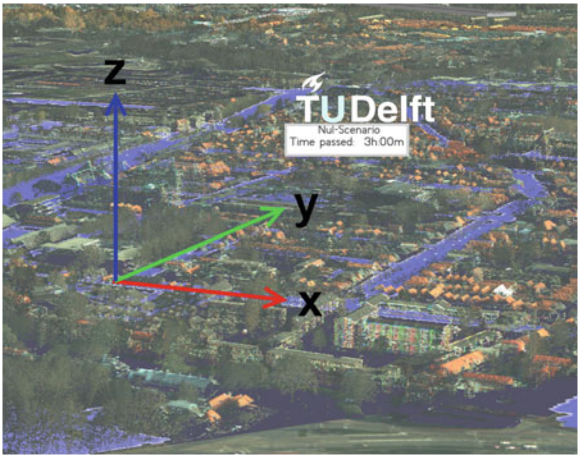

Fig. 2 Coordinate system: used global coordinate system with the z-axis orthogonal to terrain plane

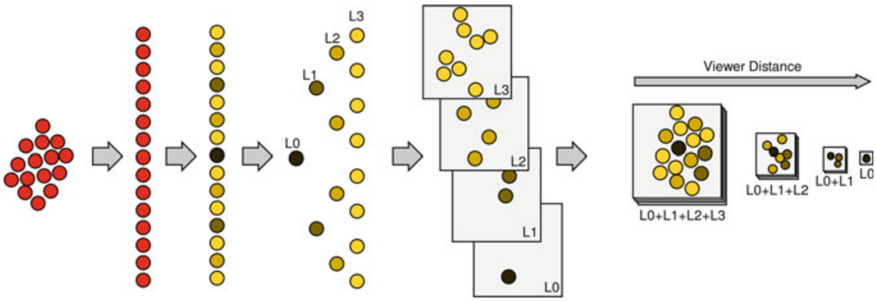

Fig. 3 Level-of-Detail: transformation from unordered points to tree-ordered LoD-cells containing points

values for each cell are then used in a separate overlay plane. This can be seen in Fig. 4a. The velocity vector information of the water is stored in addition to the water depth. This information is used in a second way of water visualisation. In this version, a shader program animates wave movements at each point (Fig. 4b). The drawback of these visualisation techniques is that the position of the overlay plane is set, leading to a visually homogeneous water depth. We therefore apply a third possibility of water visualisation. By transforming the depth map to a mesh that represents the actual 3D information of the water depth, it is easier to see the real flood impact. The mesh therefore fully- or partially-covers the terrain objects, depending on the simulation result and the height of each object (Fig. 4c). A comparative sketch of both methods, a fixed plane compared to a mesh, can be seen in Fig. 5.

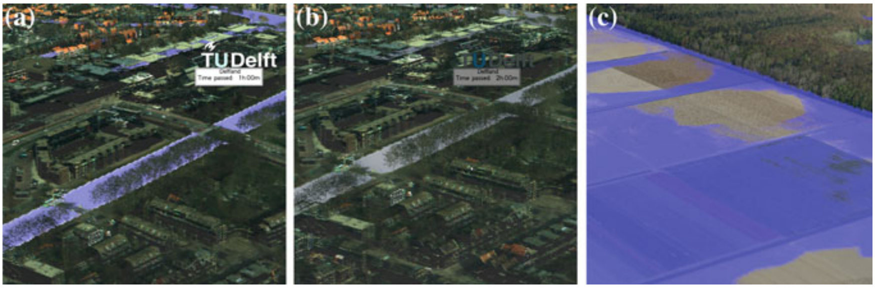

Fig. 4 Water visualisation modes: our 3 modes of water visualisation. Water depth as *blue-colour* saturation transfer function on a static plane (**a**), realistic wave animation on a static plane (**b**) and a water mesh resembling the correct water depth (**c**)

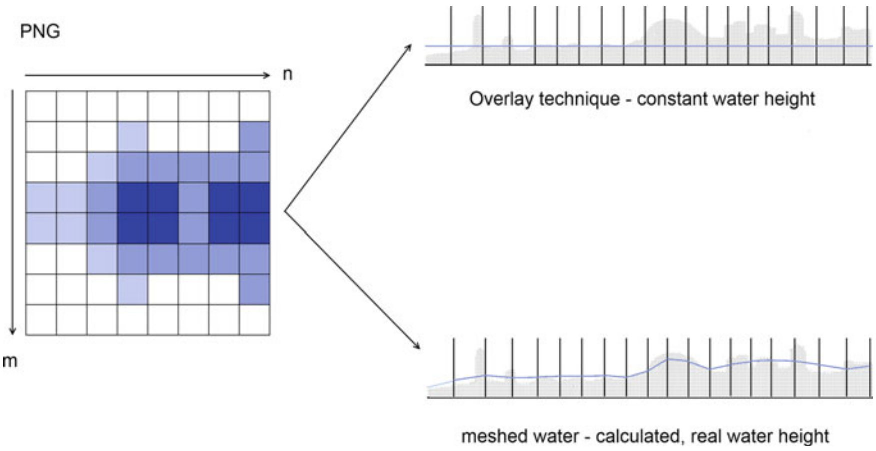

Fig. 5 Differences in water visualisation: sketch of the difference between the plane-based water visualisation and the meshed water

2.2 Drawbacks and On-Going Work

Although being a good starting point, the fore-mentioned algorithms of the system have some drawbacks. Generally, the visual quality of the visualised terrain heavily depends on the sampling-scheme of the point cloud. Issues connected to the point cloud sampling are:

- unnecessary high amount of points in overlapping regions of multiple tiles;
- high objects in urban environments are not well captured due to non-feature-adaptive sampling of the points;
- unnecessary high amount of points in low detail levels of homogeneous areas in the point clouds.

To overcome this sampling problem, we are working on more adaptive sampling schemes and feature-adaptive metrics for point clouds. Additionally, due to the fixed subdivision, there is a non-continuous transition between the different levels of detail. The reason for this behaviour are the discrete detail levels. This behaviour can irritate the user during the navigation in a dataset. We are currently working on a continuous Level-of-Detail technique, which improves the performance of the system and solves the transition issue.

In order to be able to render larger regions (i.e. whole provinces) or multiple data sets (i.e. historical changes in the landscape or multiple simulations at once) new ways of data reduction need to be followed. One of these ways is Labelling. We pursue a more precise labelling of the point cloud to efficiently re-sample the dataset and to chose the optimal tree container structure. We will apply new metrics during the re-sampling to obtain the optimal points for each level of detail.

3 Interactive and Adaptive Flooding Simulation

The American Geophysical Union (AGU) published an extensive summary on challenges in water monitoring on large scales in 2011 [25]. Here, a particular challenge is the need for accurate and fast water simulations that operate on large scales or global level. The available AHN-2 datasets are such large-scale regions on local level, due to the high resolution. The runtime of flooding simulations generally depends on the data size. Therefore, algorithms for data reduction and Level-of-Detail are beneficial to visualisation as well as simulation. Current systems (i.e. ArcGIS) rarely make use of data reduction techniques and, to our knowledge, no use of data compression. Consistent flooding simulation packages that combine modern parallel execution technologies with accurate computational models are rare. This is due to the non-linear nature of complex CFD models. Fast simulation execution times on complex CFD models are essential for our research to promote computational steering, as described by Liere et al. [21]. Our related research question is:

How can we achieve interactive, adaptive, accurate flooding simulations?

One prototypical sample project in the field is the Virtual Dike 3D water simulator [12]. This application shows the parallel potential of water simulations as well as the integration of counter-measure models in the simulation [16]. Chen et al. use the parallel OpenSees 3D simulation tool for calculation and steering of seismic wave propagation. The basis of our development is the realistic 1D/2D 3Di flooding simulation solver [8, 15]. The visualisation is created by first deriving precise bathymetry levels from the tiled AHN-2 data source. This bathymetry map is successively refined with a subgridding algorithm [3] to reduce the overall data size and therefore the calculation time. Afterwards, new water levels and velocity vectors are computed on grid cell level and saved in an appropriate exchange format. In the final step, the simulation is visualised according to Sect. 2. The whole process can be seen in Fig. 6.

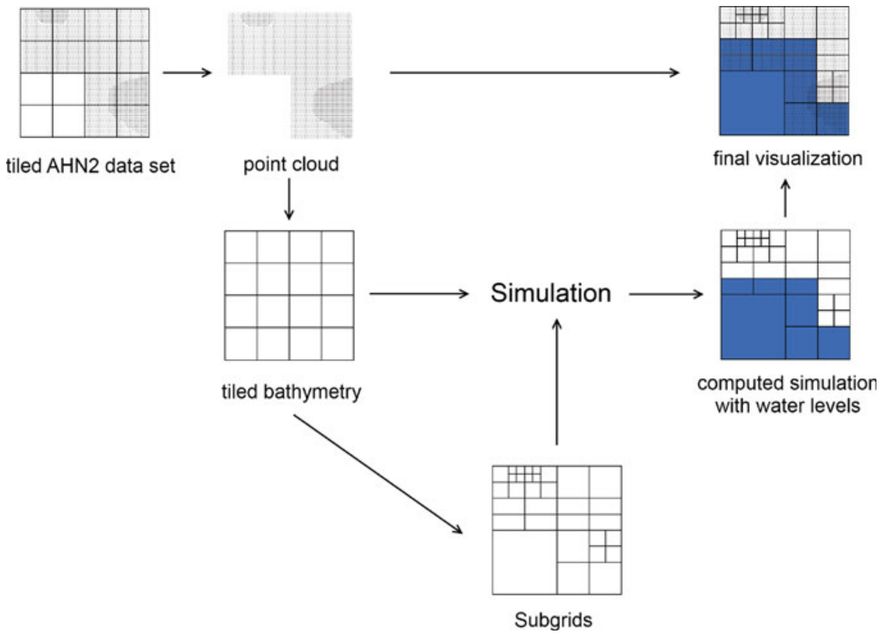

Fig. 6 Simulation pipeline: data flow- and transformation chart for our simulation

From our point of view, data reduction (i.e. information clustering with subgrid methods) and parallel processing (i.e. GPU-based CFD) are required for an accurate, full-scale, interactive simulation visualisation. Additionally, in-situ integration of additional, related data sources (i.e. precipitation) can be realized at the same time on modern, data-parallel architectures.

4 Geo-Information Integration

Flood occurrences, their progression and their impacts depend on numerous environmental factors. Consequently, flood simulation results should be reviewed depending on their environmental circumstances. Additionally, the discussion of flooding counter-measures depends on geographic context factors (i.e. landuse, polder extents) as well as the simulation result. Decisions are made based on disaster probability, effort and benefit. General geo-information is often available as image- or volume information. They can be easily integrated into modern GIS systems, that use meshes to visualise the environment. In contrast to these systems, our system is based on highly-detailed point clouds. There is only little algorithmic knowledge on the mapping and on-the-fly computation of mentioned geo-information on point clouds. Additionally, the efficient integration of meshes (i.e. counter-measures) into a point cloud-based simulation and visualisation system is a novelty in the field of GIS systems. Even standard GIS operations like colouring and clipping are hard to perform efficiently on large-scale point clouds. These points, the combination of map images, structural meshes and the point cloud-based terrain, are parts of our algorithmic research. We want to find new algorithms to enrich the highly-detailed point cloud with context data.

Another one of our research paths is the integration of environmental phenomena that are affecting flood occurrences. A specific environmental effect of major importance for floods in urban environments is precipitation. Our simulation system takes precipitation events into account. This is done by rising the local water depth on point basis. Currently, position and amount of precipitation is set by the user. Our work focuses on the integration of meteorological predictions as input to the simulation and the combination of visualisation and simulation of this effect. Research questions that are to be answered in this context are:

Which techniques are suitable to combine heterogeneous context information data structures and point cloud terrains?

How can we handle different sizes and boundary conditions of input data of environmental effects?

How can we visually combine environmental input- and output-data with a point-based terrain in a coherent way to promote the understanding of floods?

The main issue of the third question is the coherent visualisation of environmental effects. On the example of precipitation it can be seen that the visualisation of rainfall as particle systems, floods as meshes and terrains as point clouds is challenging. By choosing unsuitable visual representations of these data, users might get confused regarding the interplay of these processes instead of gaining insight from additional information.

While hereby specifically addressing issues regarding precipitation integration, challenges with the integration of other environmental effects (i.e. infiltration) are alike. We therefore expect that gained insights during the research (on basis of precipitation) are transferable to other environmental effects.

5 Multi-Scenario Comparative Simulation Visualisation

Available publications on flood assessment (i.e. precipitation affecting climate change [17], flood warning by taking rainfall and river discharge into account [13]) are use-case driven. They are based on pre-defined environmental conditions and pre-set flooding parameters. The interaction with the visualisation and simulation is limited. Changes in the simulation (e.g. adaptation of parameters) can not be done during calculation. Instead, the simulation needs to be stopped and re-calculated from the start with the new parameter set. Our goal is to develop an interactive, scenario-driven Decision Support System (DSS) based on formerly mentioned technologies, algorithms and concepts. This approach offers the possibility for peer-group users to collaboratively interact with the scene as well as with the simulation. The plan is to enrich the visualisation with new interaction possibilities and to create an on-the-fly adaptable simulation. This allows water experts to try out new prevention structures in-place and immediately see the planning result.

This concept is referred to as computational steering. We refer to this term by considering:

- a meaningful, multi-modal visualisation;
- a real-time, accurate CFD calculation;
- a multi-user interaction.

Our connected research question to this topic is:

How can multiple flooding scenarios be facilitated in a comparative visualisation and simulation?

An example in the field of computational steering of flooding scenarios is an application called "WorldLines" [23, 24]. This is a prototypical sample application that shows initial solutions to challenges connected with scenario-driven data exploration. The major differences between WorldLines and our DSS will be the spatial extent of each scenario as well as realism and complexity of the simulation calculations. As stated earlier, the large-scale, high-resolution AHN-2 point clouds as well as the complex, real-world-applicable CFD simulation demands new concepts. Thus, these concepts are aligned and embedded in a target-group-related steering system.

Another related example of computational steering is the 3D seismic wave visualisation by Chen et al. [4]. Here, frequency-band analysis and frequency displacement are used for information filtering. The results are visualized by direct volume rendering.

The final system has to deal with changing simulation parameters, water levels and terrain point clouds. These changes can be user- as well as time-dependent. A challenge closely linked to this approach is also the simulation visualisation of historical scenarios. These setups are often used in flooding research to understand the occurrences of floods as well as evaluation of new protection mechanisms. While historical flooding data is commonly taken to assess and evaluate new simulation methods, historical flooding events are rarely used for further studies. The challenges in historical flooding simulation and visualisation are:

- scanning, monitoring and storage of historical flood occurrences and causes;
- meaningful visualisation and animation of time-dependent data;
- time-dependent river discharge rates, demanding flexible, adaptive simulations;
- adaptive models, because floods and extreme precipitation change terrain and infrastructure (i.e. real estate damage, soil erosion).

The challenges are addressed partially by the following research publications. The Darthmouth Flood Observatory runs an exhaustive surface water data record of worldwide historical flooding events, visualised by highly accurate maps. Lienert

Fig. 7 Delfland: use case dataset "Delfland" in bird's eye perspective

et al. [10] researched the usage of historic flooding data as context information for current flooding simulations in a flood prediction system to support the understanding and decision-making process of current and future flooding events. This research led to a large-scale database of historic floods' measurements, visualised by 2D maps [9]. Brass and Blanchard [2] visualised 5 historic, precipitation-based floods in Texas for assessing the influence of social factors, like personal experience and profession, in the human ability to recognise and rate flood risks. Ribarsky et al. [18] lay out in their paper the needs for the visualisation of dynamic, time-dependent, modifiable terrains, buildings and other geoinformation for the purpose of weather research. Clevis et al. [5] used geoarchaeological simulations to re-track the motion of water to subsequently gain insight into former terrain shapes and archaeological sites that are destroyed by soil erosion. As a conclusion it can be seen that each above-mentioned challenge is approached separately in different approaches. Due to our demands, we will address multiple above-listed challenges during our research. Of particular interest for us are the last 2 listed bullet points.

6 Recent Results on Use Case "Delfland"

This section presents our recent results on a part of the dutch municipality Delfland. The dataset consists of 55 tiles, measuring a physical extent of 67.26 km^2 and being 8.2 GB big. It includes point cloud information, aerial photos and 1 simulation dataset.

The computer for the runtime measurements is an Intel Quad-Core processor and an NVIDIA Quadro FX 3700 graphics card. The dataset in bird's eye perspective (Fig. 7), where all tiles are rendered exclusively in the coarsest LoD,

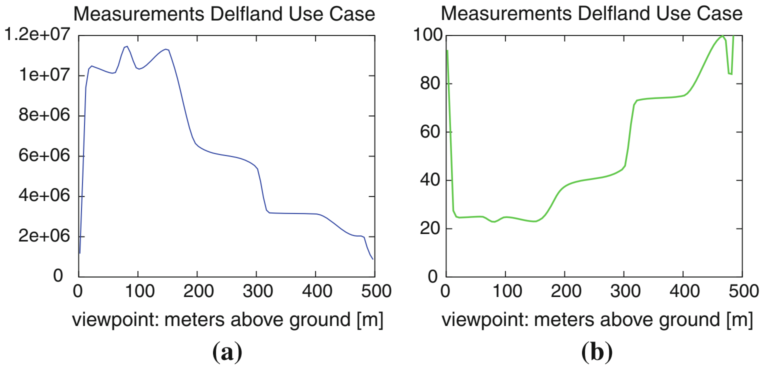

Fig. 8 Measurement plots: plots of the number of vertices in main memory (**a**) and the frames per second (**b**) in respect to the view distance, approximated in meters above ground level. This is because the Level-of-Detail choice depends of the distance "view point—vertex position". The measurements were taken in bird's-eye perspective

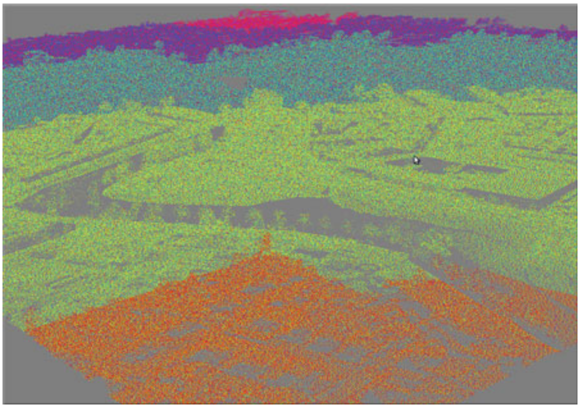

Fig. 9 Level-of-Detail in point clouds: a typical "wide-angle" view. The colouration shows the maximum loaded level of detail, from *blue* (level 0—farthest) to *red* (level 4—closest). It can be seen that a large amount of level-0-points are loaded, even in distances that can not be seen. That results a slow rendering in this viewpoint

is running with an average speed of 90 fps, showing 772.000 vertices. While approaching ground level with the viewpoint, the frame rate drops consecutively while loading new levels of detail, from 90 to 20 fps. This happens because more points in higher detail levels are loaded. This behaviour can be seen in Fig. 8. The frame rate drops sharply when choosing a wide-angle view at near-ground view positions (around 11 fps with more than 20 million points in the view). An example of a wide-angle view is shown in Fig. 9. This is because all tiles in viewing direction need to be loaded, in their respective LoD. Nevertheless, the wide-angle view is important because it provides the best insight on the inundation situation in urban environments. Initial user studies have shown that most experts choose the wide-angle view for the assessment of flooding situations. Because of this regular usage of a wide-angle view, the explained performance behaviour is a point for improvement in the future.

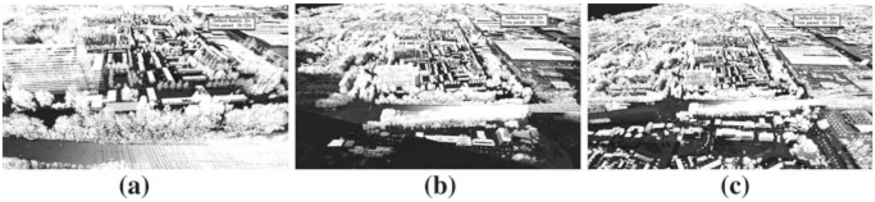

Fig. 10 Non-continuous transition problem: the image series show the abrupt change from a start viewpoint (**a**) to an end viewpoint (**c**) while loading the tiles in (**b**)

Another unappreciated behaviour is the abrupt appearance of new tiles or tiled LoD-nodes, as described in Sect. 2. This can also be seen in Fig. 10.

7 Future Research and Assessment

Due to the presented state of each research track it can be seen that there are open questions which demand experiments and new algorithmic approaches. We will focus our future efforts on the improvement of the simulation in terms of speed by experimenting with GPU Computing technology in combination with our detailed CFD models. Our future progress can be expected in the concepts of:

- interactive, realistic, large-scale flooding simulations;
- point cloud-based terrain visualisation, derived from LiDAR data;
- point-based GIS operations;
- computational steering of large-scale simulations based on complex computational fluid dynamics (CFD) models;
- integration of precipitation and other environmental factors into a coherent fluid dynamics simulation visualisation.

Currently, water experts assess and use the system on professional workshops. They discuss pre-calculated flooding scenarios of chosen areas. The system has therefore, at the moment, an educational purpose to improve the understanding of floods.

The system is also used in museum installations to educate the public on flooding, based on large-scale, historic, pre-computed flooding scenarios. In this context, hydrologists at the TU Delft use the system to assess their CFD calculation models via comparison with real, historic floods.

Our vision is to use the software in the future as an immediate-response system of occurring floods to coordinate and control public safety. This is reflected in our focus on large-scale, interactive Simulation Visualization algorithms.

Acknowledgments This work is supported by the federal Dutch project for water- and climate knowledge "Kennis voor Klimaat", grant IGF-IGF26G. The work is embedded in the water planning project of "3Di". The work is carried out in close collaboration with Deltares; Nelen & Schuurmans; BiG Grid, advanced ICT research infrastructure for e-Science; SARA Computing and Networking Services; the TU Delft CiGT department, particularly Dr. Ir. Guus Stelling, and the TU Delft OTB department.

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