River Inundation Modelling for Risk Analysis

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Zusammenfassung

Im Beitrag werden die Ergebnisse einer räumlich-zeitlichen Überflutung außerhalb von Flussquerschnitten im Polderbereich Mehrum dargestellt. Diese Aufgabe ist Teil des DFNK-Projektes “Simulation des Hochwasserablaufs und von Überflutungsvorgängen unter besonderer Berücksichtigung von Deichversagen, Bebauung und Infrastruktur“. Der Polder Mehrum liegt am Rhein in Nordrhein/Westfalen. Die Studie untersucht den Überflutungsprozess im Poldergebiet resultierend aus einem angenommenen Deichbruch. Das Untersuchungsgebiet wird durch ein zweidimensionales hydrodynamisches Modell simuliert, wobei zur Lösung der Flachwassergleichungen die Finite Element Methode genutzt wird. Das Rechennetz wurde innerhalb des Flussgebietes aus Querschnittsprofilen im Abstand von jeweils 100 Metern und innerhalb des Polders aus 10 Meter x 10 Meter Rasterdaten gebildet. Zur Kalibrierung des Modells wurden die Durchflussdaten in den Orten Ruhrort und Wesel, die einen Abstand von ca. 33 Km aufweisen, herangezogen. Zur Einbeziehung des Dammbruches wurden nicht-reflektierende Randbedingungen genutzt. Im Ergebnis konnten räumlich-zeitliche Überschwemmungsvorgänge quantifiziert werden. Aus diese Informationen können von den Behörden Not- bzw. Evakuierungspläne auf der Grundlage von Deichbrüchen abgeleitet werden.

Abstract

This paper presents the results of an engineering study on flood inundation, carried out for the Polder Mehrum area, as part of the DFNK project. Mehrum is situated along the River Rhine, in Germany. The study investigates the inundation process in the polder area, resulting from a dyke breach due to overtopping. The flow field is simulated using a two-dimensional hydrodynamic model, solving the shallow water equations by the finite element method.

The computational mesh is constructed from (i) measured river bathymetry data, taken 100m apart; and (ii) topographical data, provided on a 10m x 10m raster grid, for the polder area. Flow data are obtained from two gauging stations, Ruhrort and Wesel, located 33km apart and are used as boundary conditions for model calibration and verification purposes. In addition, since the downstream boundary condition is not known *a priori*, a non-reflecting downstream boundary condition is used for simulations involving dyke breaching.

Computed results of inundation depths, flood arrival times and flood duration are presented. This information can be used to assist agencies in developing emergency and evacuation plans and analysing risk potential in the event of flooding due to dyke breaching.

Introduction

The River Rhine is about 1,320km long, and has a catchment area of 185,000 km^2, of which 54% is in Germany. Typical of such river systems is the existence of polders. The polder areas have traditionally been used for agricultural purposes due to the richness of the alluvial soil and the inhabitants in these areas are protected from flood waters by the construction of dykes. These and other activities, like river straightening schemes etc, have resulted in lower capacities and higher peak discharges, leading to increased risks of flooding. Hence, there is a need to accurately model flood inundation due to dyke breaching. The information obtained from such a model will be useful for developing emergency measures.

A map of the area under investigation is shown in Fig. 1. The stretch of the River Rhine to be modelled is situated in the Lower Rhine region and is approximately 33km long and lies between the towns of Ruhrort and Wesel. The entire area to be modelled, including the polder is approximately 50km^2.

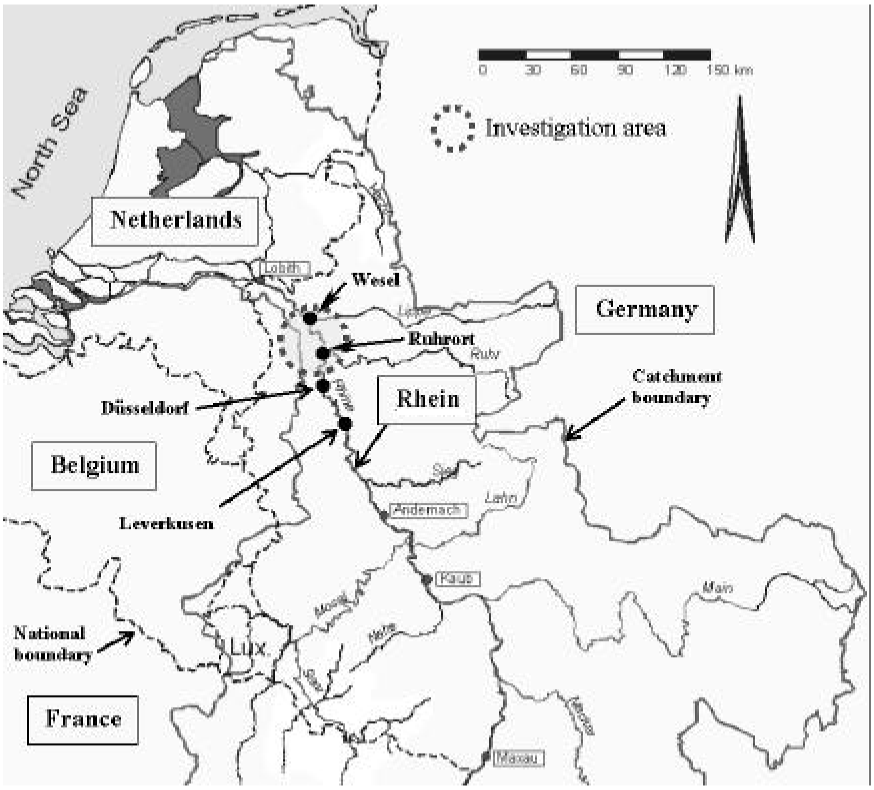

Figure 1: Investigation area.

Han, Lee and Park (1998) have used a coupled, 1-D and 2-D model to simulate flood inundation due to dyke breaching. The authors used a 1-D model for calculations in the main channel and a 2-D diffusion model for the calculation of overland flow. The 1-D and 2-D models are coupled by a dyke breaching model that feeds information of the breach outflow at each time step to the 2-D model. This approach is not always possible, for example, in situations where the flow in the main channel exhibits a strong meandering pattern. In such a situation, 2-D numerical models have to be used (for example, see D'Alpaos, Defina and Matticchio 1994).

It should be mentioned that, in order to accurately predict the discharge through the breach, a dyke breaching model that correctly simulates the dyke breaching process is needed. This is because dyke breaching events (as compared to dam breaking) are rarely instantaneous, and therefore the outflow depends on the time development of the breach. The problem is further complicated by the fact that breaching can occur either in overtopping or piping modes. This aspect of the problem is currently under investigation at the institute as part of an overall research project to study risk potentials associated with dyke breaching, and is not addressed here.

This paper presents some findings on an engineering study of flood propagation due to dyke breaching in the Polder Mehrum area. For the present simulations, the breach formation has been assumed to be linearly varying with time. The present calculations are made using the shallow water equations using a solver developed at the University of Latvia (User Manual 2001).

Governing equations and numerical scheme

The two-dimensional, time dependent shallow water equations are given in conservation form by the following equations:

$$\frac{\partial z}{\partial t} + div\,\vec{q} = 0$$

$$\frac{\partial \vec{q}}{\partial t} + \left(\vec{q}\nabla\right)\vec{v} + \vec{v}\,div\,\vec{q} + gh\nabla z + \frac{g q \vec{q}}{C_s^2 h^2} + m\nabla\left(h\nabla\vec{v}\right) = 0 \qquad (1)$$

where z is the free surface elevation, q is the discharge per unit width, t is time, h the water depth, v is the vertically averaged velocity, g acceleration due to gravity, m the horizontal turbulent diffusion coefficient and C_s the Chezy coefficient. The vector notation is used to describe quantities in the x- and y- directions respectively.

The numerical scheme essentially follows the method of D. Ambrosi et al. (1996). The scheme is implicit and therefore ideal for simulating large systems with long durations. An equation splitting scheme is used at every time step, where the various contributions from the advection, diffusion and propagation components are solved independently (Benque et al. 1982). The advection step is solved by the characteristics method (1982). Spatial discretization is obtained using the standard Galerkin finite element method.

Two types of boundary conditions were specified at the downstream boundary: (i) water surface elevation as a function of time, under non-breaching conditions; and (ii) a relation between elevation and discharge, approximated by the following relation (Vreugdenhil 1989):

$$z - z_o = \frac{q_n}{\sqrt{gh}} \qquad (2)$$

under breaching conditions, where q_n is the discharge per unit width in a direction perpendicular to the downstream boundary and z_o is a reference elevation. For both non-breaching and breaching conditions, the discharge was specified as a function of time at the upstream boundary.

Computational mesh

Measured data for the river consists of bathymetry measurements, taken perpendicular to the main channel, at 100m intervals. The measurements extended beyond the dykes, on both sides of the river banks. Is convenient to use the dyke nodes as boundaries for the model, as this ensures that dyke points remain unchanged during adaptation, thus maintaining the integrity of the dyke line.

The original data is not suitable for the production of a computational mesh as the triangles that would be produced will be too distorted. Therefore, the data was first reduced to a 75m x 75m raster grid, before triangulation. The mesh was further refined to ensure a regular shape of the triangles and also to obtain a smooth transition between the elements.

Data for the polder area consists of measurements of ground topography available in 10x10m raster. The raster points were similarly reduced and the same procedure for triangulation and adaptation was carried out.

The final computational mesh was obtained by combining the elements generated for the river and polder areas, taking care to maintain the integrity of the dyke line, separating the polder from the river. Finally, the elements were further adapted according to the Courant number criteria:

$$\Delta t = \frac{\Delta x}{u + \sqrt{gh}} \qquad (3)$$

in order to obtain control over the computation time-step. Typical values of u (= 2m/s) and h (= 6m) were used in the analysis. Elements having time-steps of less than three seconds were removed and the median time-step was found to be 5.7s. The foregoing exercise in mesh adaptation resulted in an optimum mesh structure, both with respect to computational and physical requirements. This consideration is important especially when the computation has to be carried out for a large system over a long period of time.

The final mesh, shown in Fig. 2, has approximately 4,000 nodes and 7,500 elements. Chezy coefficients of 65 and 40 were used for the river and polder areas respectively.

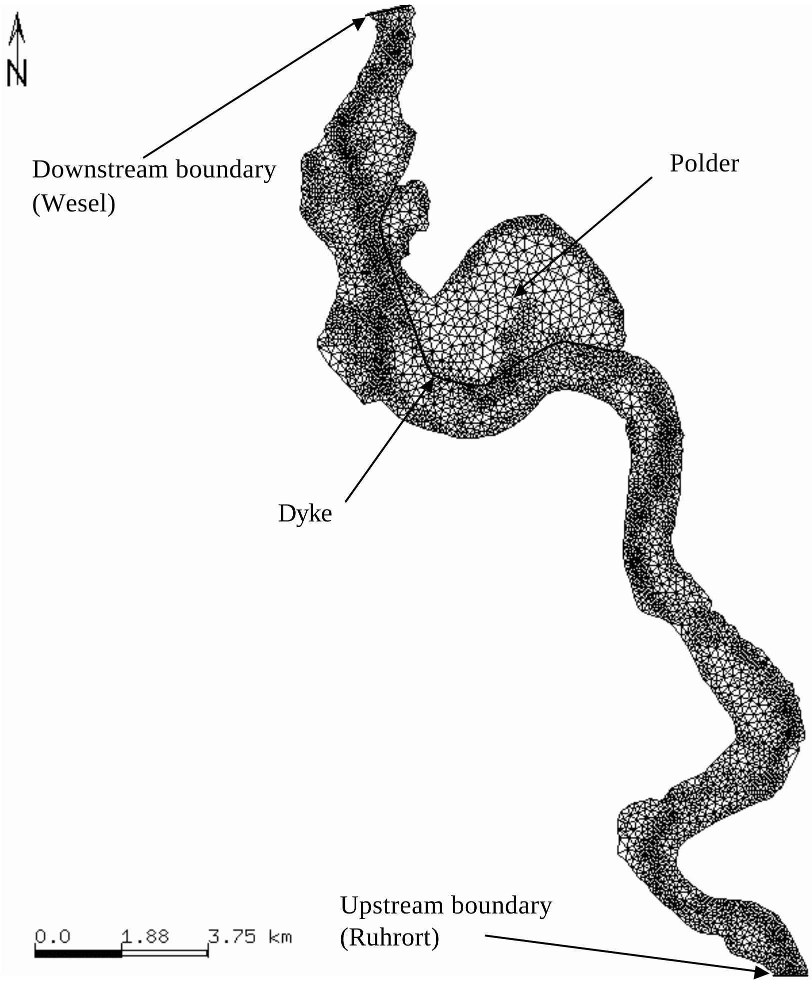

Figure 2: Computational mesh.

The former value was obtained from calibration and the latter value was adopted taking into account the increased roughness that would be encountered for overland flows within the polder area. A value of $0.1 m^2/s$ was used for the horizontal turbulent diffusion coefficient.

A computation time-step of 50s., approximately 10 times the Courant criteria (based on the median time-step) was adopted. This value of time step was chosen as a compromise between maintaining the accuracy of the computations as well as keeping the computation time down to practicable limits. The average computation time, using a Pentium III 600 processor, required for a complete (19 days) simulation is about 9hrs.

Results

A water surface elevation versus time relationship was specified at the downstream boundary, for simulations under non-breaching conditions. Together with the prescribed discharge at the upstream boundary, these are the 2 boundary conditions used for calibration. As mentioned previously, eqn (2) was used as the downstream boundary condition under breaching conditions. An initial run was also made using eqn (2) as downstream boundary condition under non-breaching conditions. The results are compared with that obtained using a specified elevation versus time relationship mentioned earlier. This exercise was carried out to ascertain that correct results were obtained when using eqn. (2). The simulations were carried out using data obtained from the gauging stations for the period 23/1/95 – 11/2/95. No appreciable differences between the 2 sets of results were observed.

The next step was then to run the model, under breaching conditions. In this case, eqn. (2) has to be used as the downstream boundary condition, since the water elevation here is not known *a priori*. At 31/1/95 00:00hr, a dyke breach was simulated by the lowering of about 200m of the top of dyke level to the local ground elevation, in approximately 30mins. The water surface elevation at the downstream (Wesel) boundary is compared with that for the non-breaching case in Fig. 3. As shown in the figure, there is a small but significant drop in the water surface elevation, causing the peak to be decreased by about 0.2m.

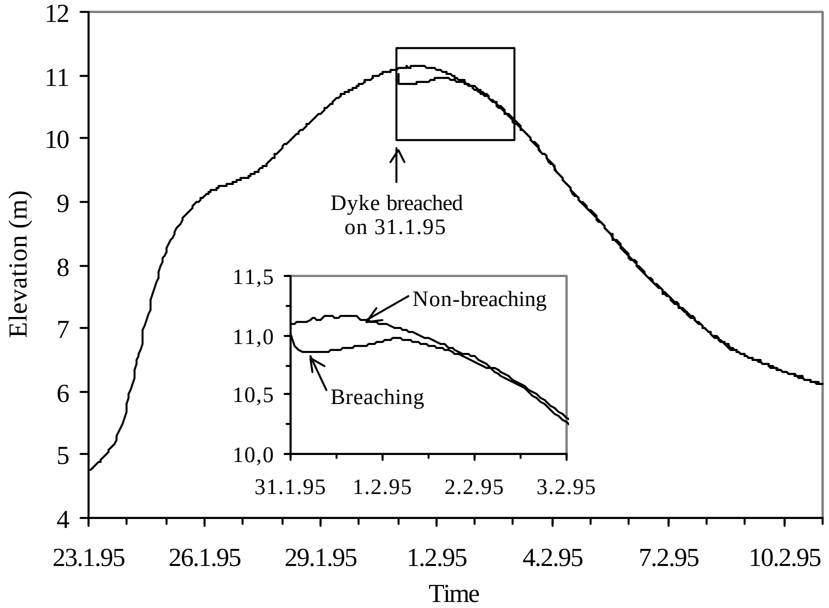

Figure 3: Decrease in water surface elevation at Wesel due to dyke breaching.

Flood propagation over the polder area is depicted in Fig. 4. The figure shows that, following breaching, the polder area is generally inundated after 36hrs. After this time, flow reversal takes place, as the water surface elevation in the polder exceeds that in the main channel, due to the recession of

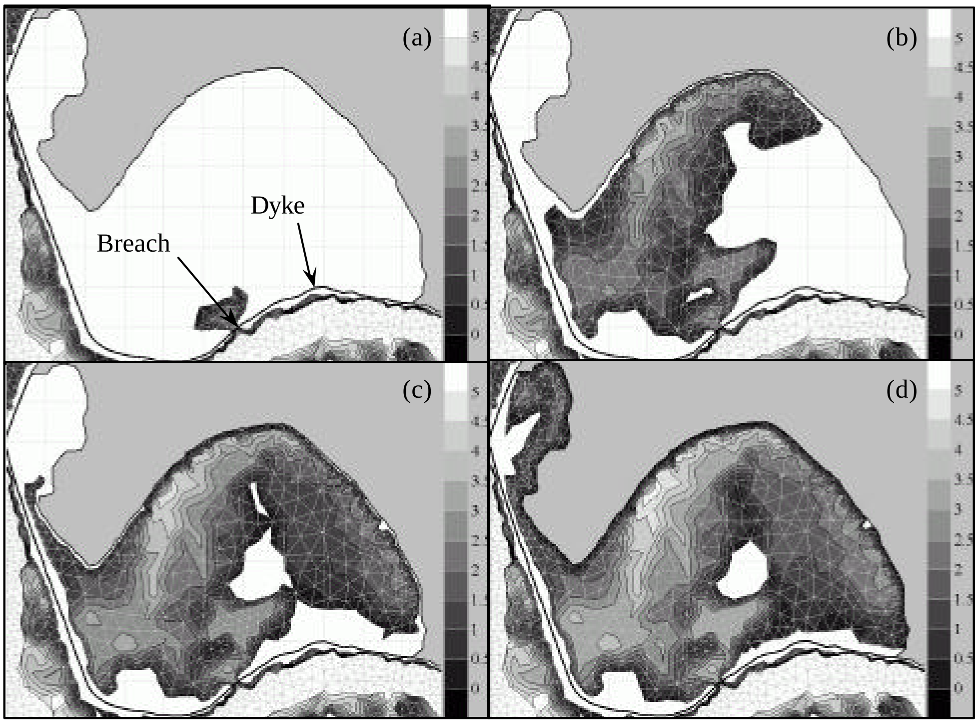

Figure 4: Flood propagation in the polder area: (a) 31/1/95 00:30 (b) 31/1/95 12:30 (c) 31/1/95 20:30 (d) 1/2/95 12:00.

the flood wave in the main channel. This process is shown by a plot of the time variation of the elevations on either side of the dyke in Fig. 5. The elevation in the main channel for the non-breaching case is also included in the figure for comparison.

Also shown in Fig. 5 are results of calculation for a breach created on 27/1/95. As indicated in the figure, the flood propagates throughout the extent of the polder area in about 3 days. After this time, the water level in the polder continues to rise, as the stage in the main channel is still increasing. A comparison of the water surface elevation in the polder for the 2 breaching scenarios shows that the peak elevation is lower when the dyke breaching occurs when the stage in the main channel is close to is maximum level. Consequently, the peak elevation in the polder area is also lower.

The variation of total depth with time is depicted in Fig. 6 for 3 inhabited areas in the polder, for the breach created on 31/1/95. The total depth corresponding to the deepest part of the polder is also included for comparison. The deep area experiences a permanent inundation, with a water surface elevation close to the final breach level, after the passage of the flood wave. The inhabited areas, which are generally located at higher elevations, either dry out after the passage of the flood wave (Löhnen and Gottesmickerhamm) or are unaffected (Mehrum). In addition, Fig. 6 also gives information on flood arrival times, expected inundation depth and the length of time that is expected that the areas concerned will be inundated.

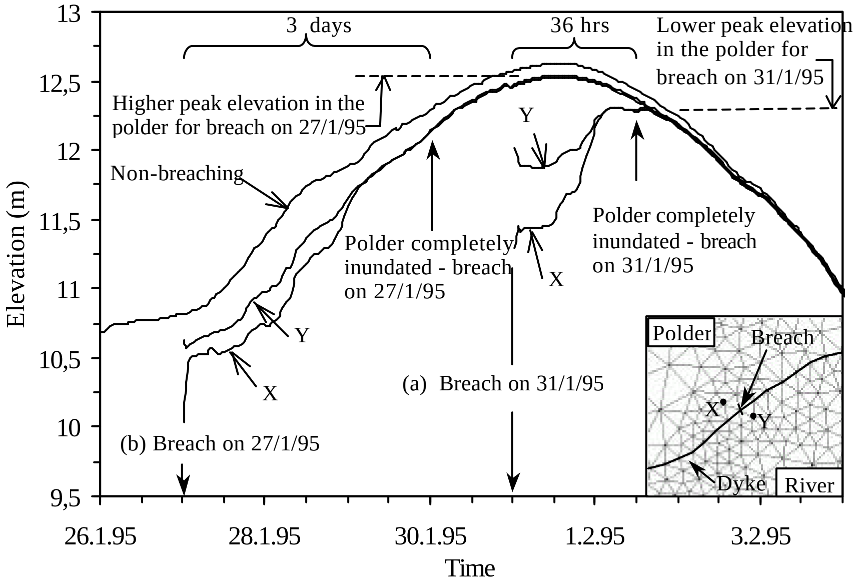

Figure 5: Variation of the water surface elevation on either side of dyke (location X in polder area and location Y in main channel) for breach on (a) 31/1/95 and (b) 27/1/95. The final breach elevation is 9.2m.

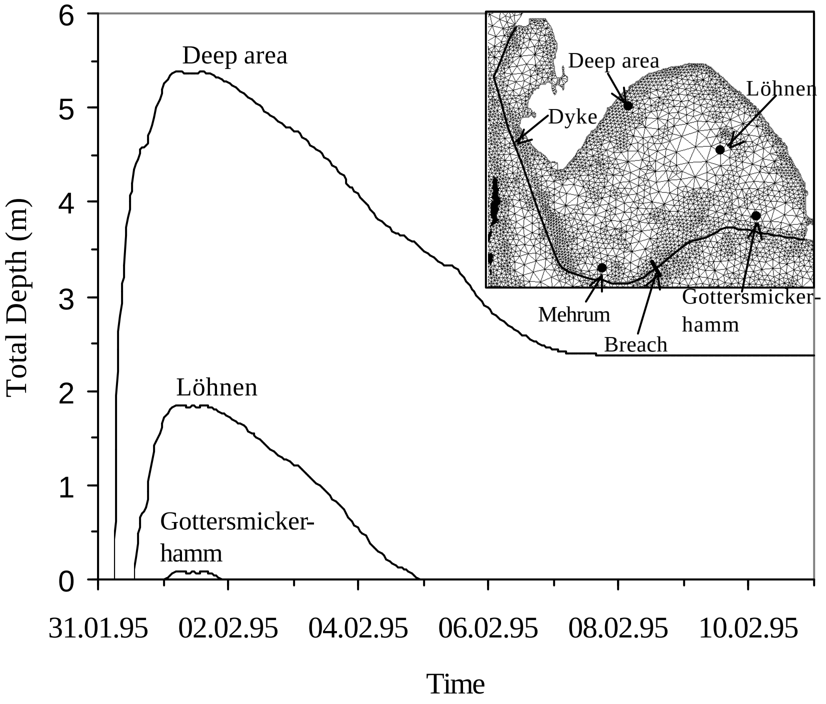

Figure 6: Variation of total depth with time. (Note that Mehrum is unaffected)

Conclusions

An engineering investigation was carried out to simulate flood propagation in the stretch of the River Rhine between the towns of Ruhrort and Wesel. The simulation used a 2-D finite element model, based on the shallow water equations. A breach in the dyke was created to simulate flood inundation in the Polder Mehrum area. The results yield information on flood arrival times, inundation depths and durations of inundation. This information can be used by agencies in the development of emergency and evacuation plans and in analysing risk potential in the event of flooding due to dyke breaching.

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