Inundation of the Ziltendorfer Lowland during the Odra flood 1997 and its impact on the main river – a numerical study

Hilmar Messal and Heinz-Theo Mengelkamp

ABSTRACT

The inundation of the Ziltendorfer Lowland, a farmland polder with some villages, during the major flooding event in July 1997 in the Odra watershed, is simulated with the two-dimensional hydrodynamic model TRIM2D. Inflow and outflow through three consecutive embankment breaches make up a complex flow regime which governs the inundation and the water level in the Odra river. With reasonable assumptions for the dam breach genesis the inundation and depletion are simulated in good agreement with the observed flooding front positions. Simulations with a one-dimensional hydrodynamic model for "dam breach" and "no dam breach" scenarios confirm analytical considerations of an increase of the water level downstream in the main river for the "dam breach" scenario because of an outflow from the Ziltendorfer Lowland into the Odra river during the peak flooding period.

Key words | embankment breach, flood, inundation, lowland, Odra, Ziltendorfer Lowland

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INTRODUCTION

In July 1997 two heavy rainfall episodes in the upper reaches of the Odra catchment caused severe flooding in the Czech Republic, Poland and the most eastern part of Germany, with more than 100 fatalities and large material losses. From 4–10 July a quasi-stationary low pressure system developed over the upper Odra and its tributaries. Warm and humid air was continuously transported from the Mediterranean to the eastern part of Central Europe and lifted over cooler air from the North, bringing long-lasting widespread precipitation of up to 500 mm in 5 days. A second period of intensive rain followed from 18–22 July over the Sudete Mountains. There was also unusually heavy rainfall along the German–Polish boarder affecting the middle and lower reaches of the Odra. The Odra and its tributaries burst their banks at several locations. The two flood waves originating from these precipitation events had merged when they reached the German–Polish boarder south of the city of Eisenhuettenstadt (Figure 1). On 23 and 24 July two embankment breaches flooded the Ziltendorfer Lowland, a polder north of Eisenhuettenstadt (Figure 2), inundating an area of 55 km² with water depths reaching up to 5 m height. On 26 July three small embankment breaches from the inside let some of the water flow back to the main river, increasing the water level rapidly downstream.

Simulating such a complex inundation process and its impact on the main river requires an appropriate numerical model. Simulation models for floodplain inundation range in complexity from relatively simple regression models that relate known flood elevations to river position and flood-plain location (Townsend & Walsh 1998) to one-dimensional (Ackermann *et al.* 1999) and two-dimensional (Galland *et al.* 1991) models which solve some simplified set of the Saint Venant equations. Bates & DeRoo (2000) developed a model called LISFLOOD-FP which consists of a one-dimensional kinematic wave approximation for channel flow and a two-dimensional diffusion wave
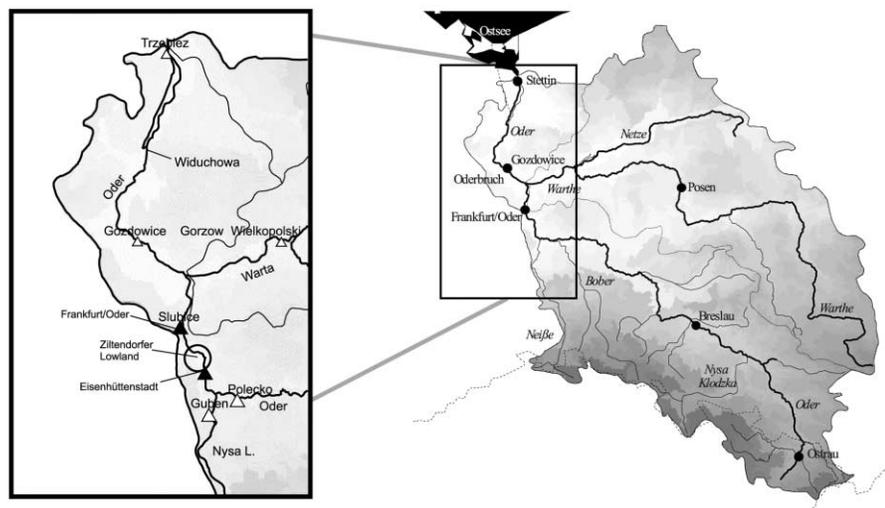
Figure 1 | The Odra catchment and the location of the Ziltendorfer Lowland.

representation of floodplain flow. Thomas & Williams (1995) and Younis (1996) describe solutions of the full three-dimensional Navier–Stokes equations for open channel flow. These models, as well as a number of mostly one-dimensional models which are published on the internet (e.g. MIKE11, www.dhisoftware.com or HEC-RAS, www.hec.usace.army.mil/software/hec-ras/hecras-hecras.html), have been verified with continuous pure embankment overflow. An evaluation of three numerical models for predicting river flood inundation is given by Horritt & Bates (2002). Obviously, because of such rare events and/or incomplete data coverage little is known about simulations of the effect of dam breaches.

The consecutive dam failures make the inundation of the Ziltendorfer Lowland a highly three-dimensional discontinuous process. Moreover, over the flat lowland small errors in water level may cause large errors in the inundation front position. High resolution digital orographic data are therefore to be integrated into an appropriate numerical simulation model. To simulate the inundation and depletion of the Ziltendorfer Lowland we have selected the three-dimensional model TRIM3D (Casulli & Cattani 1994; Casulli 1999) and applied its two-dimensional depth averaged version called TRIM2D hereafter. Although being designed for coastal and estuarine areas (Cheng et al. 1993) TRIM2D is capable of simulating hydrographs in relatively large stream reaches (Jones et al. 2002).
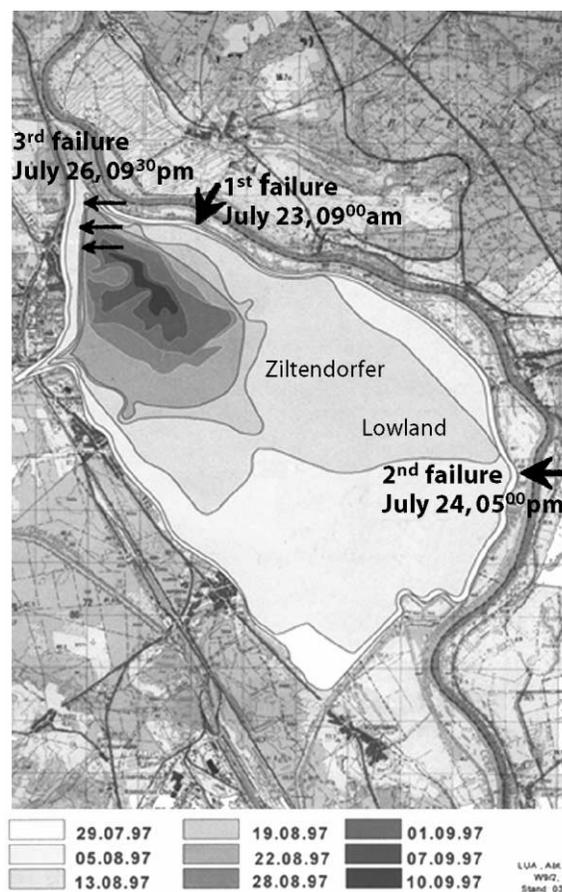

Figure 2 | Dates and location of embankment failures and inundation front positions. (Original map by Landesumweltamt Brandenburg, Das Sommerhochwasser an der Oder 1997, Studien und Tagungsberichte, Report No. 16, page 24, changes by the authors).

After a description of the Ziltendorfer Lowland inundation event in the next section the paper proceeds with a brief outline of the model TRIM2D and its setup in the third section. Adaptation of the model to the flooding situation by some scenario studies is described in the next section followed in the fifth section by the simulation of the Ziltendorfer Lowland inundation event in 1997. Based on analytical considerations we then analyse the impact of the inundation and depletion on the main river in the subsequent section before conclusions are drawn in the final section.

FLOODING OF THE ZILTENDORFER LOWLAND

The Ziltendorfer Lowland is a fertile lowland between Eisenhuettenstadt and Frankfurt/Oder (Figures 1 and 2) covering an area of about $60 \, km^2$ and being protected by embankments. The Ziltendorfer Lowland is part of the flood area of the Odra. During the 1997 flooding event some $55 \, km^2$ were inundated with an estimated retention volume of about 150 million m^3 (Engel & Oppermann 1998). More than 2,000 people were evacuated. The embankment protecting the Ziltendorfer Lowland broke on 23 July at 9 am at the northeast corner of the Ziltendorfer Lowland (Figure 2) with an estimated inflow of about $500 \, m^3/s$. At 5 pm the next day a second dam failure occurred further upstream at Aurith at the eastern periphery with an estimated inflow up to $700 \, m^3/s$ (Landesumweltamt Brandenburg, 1998). Due to the relative higher water levels at the second dam failure location the inflow through the first embankment breach turned to an outflow very soon ("bypass flow"). The larger inflow through the second breach, however, caused an increase of the water level in the Ziltendorfer Lowland, reaching its maximum on 26 July. An overflow of the embankment in the northwest corner of the Ziltendorfer Lowland was followed by three almost simultaneous breaches around 9 pm on 26 July. Depletion of the Ziltendorfer Lowland began straightaway, raising the water level in the main river to its maximum value. The inflow into the Ziltendorfer Lowland through the second dam breach at Aurith stopped on 17 August. Normal water levels were attained around 16 September.

SETUP OF THE MODEL TRIM2D

The hydrodynamic model TRIM3D (Casulli & Cattani 1994; Casulli 1999) was selected as an appropriate model to simulate the inundation and depletion of the Ziltendorfer Lowland. Designed for coastal and estuarine flow simulations TRIM3D (TRIM = Tidal, Residual and Intertidal Mudflat) solves the shallow water equations using a semi-implicit finite difference numerical scheme (Casulli 1999). Terms affecting the numerical stability are treated implicitly, while the remaining terms are treated explicitly. This formulation controls the numerical instability and improves the computational efficiency (Cheng & Casulli 2001). TRIM3D is capable of handling large local changes in water surface elevation and velocity and does not become unstable as model cells change from active (wet) to inactive (dry) during the course of the simulation (Jones et al. 2002). The numerical algorithm allows for the simulation of flooding and drying in low lying areas since the finite volume scheme is used for the discretization of the mass conservation equation. TRIM3D has been successfully applied to prepare an atlas of currents and water levels in the Sylt-Rømø-bight at the eastern shore of the North Sea (Behrens et al. 1997) and also in the Greifswalder Bodden (Horstmann & Wolf 1997). To keep the demand on computing resources down we used the two-dimensional depth averaged model version TRIM2D. TRIM3D is reduced to two dimensions by specifying only one vertical layer.

The simulation area encompasses the main river channel from Eisenhuettenstadt to Frankfurt/Oder and the Ziltendorfer Lowland (Figure 2). Two-dimensional hydrodynamic modelling requires high-accuracy, spatially dense elevation data and the river geometry (bathymetry). Cross sections of the river bed were available every 500 m and 200 m for the upper and lower section, respectively. (The cross sections have changed during the flooding event; here, those from the time before the event were used.) These data were interpolated onto a grid with 30 m horizontal resolution and combined with elevation data which were digitized from topographic maps on a scale of 1:10000 and interpolated onto the same 30 m grid. The interpolated orographical data were corrected for non-interpolated realistic embankment heights. Figure 3 shows the digital
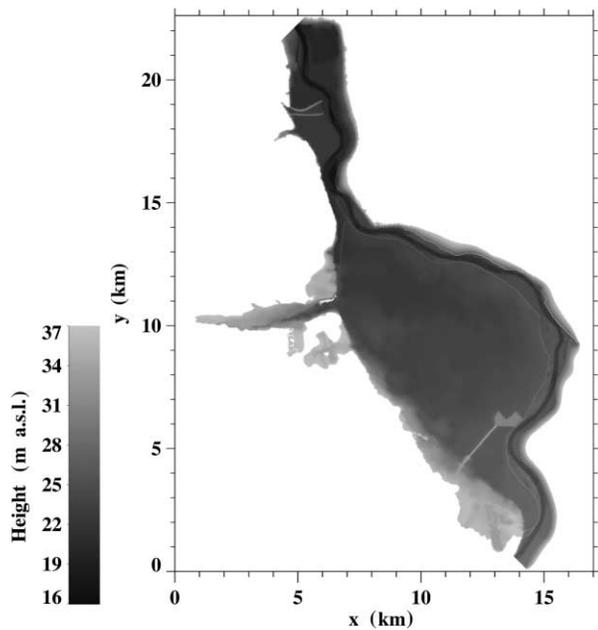
Figure 3 │ Digital elevation model of the Ziltendorfer Lowland.

elevation model of the Ziltendorfer Lowland and the main river channel on the right hand side.

The simulation covers the time period from 1 July to 1 September 1997. The observed water depth time series at the gauging stations Eisenhuettenstadt and Frankfurt/Oder served as upper and lower boundary conditions, respectively (Figure 4). During the first two hours of the

initialization phase water depths at the boundaries were slowly increased from zero to the observed depths as on 30 June followed by a 22 h real time simulation to reach steady state conditions. From 1 July on water depth data at the boundaries were provided on 15 min intervals. These data were interpolated on the 3 s fixed simulation time step. The two prognostic variables are velocity and water depth, from which discharge was calculated at selected grid points.

Manning's roughness coefficients were prescribed as a function of water depth at each grid point (Table 1). These values were estimated by use of a one-dimensional Saint Venant model for the main river. This model was adapted to the flooding situation by changing Manning's coefficients and comparing observed and simulated discharge at different gauging stations (Ewertowski 2002).

Embankment breaches mean a sudden change of the orography which technically cannot be handled during a continuous model run. A restart option has been added to the model code allowing continuation of the simulation with the flow field as calculated for the last time step before the embankment breach but with a changed orography.

The geometry of the openings has been estimated from pictures and from personal information as no recording of the opening incident took place. Table 2 shows the chronology of the simulation and the width of the embankment openings. The second dam break was widened
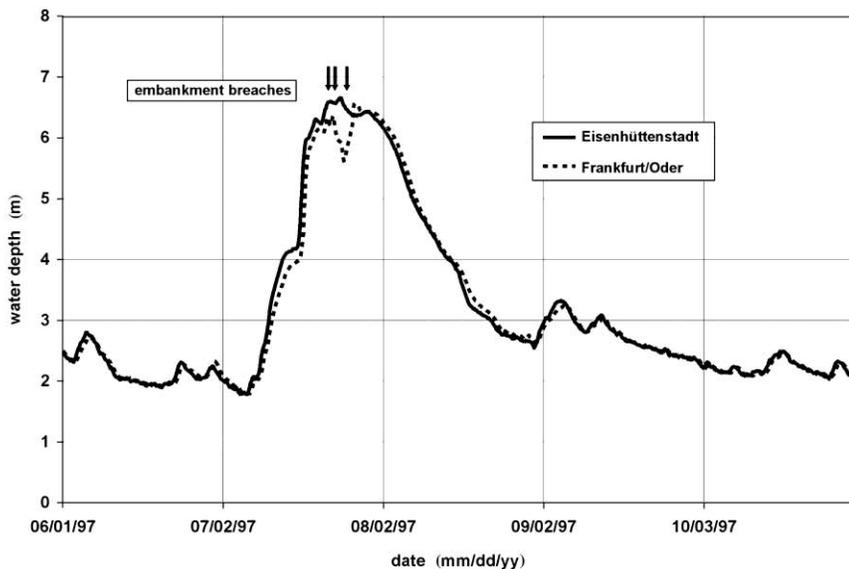

Figure 4 │ Water depths at the gauging stations Eisenhuettenstadt and Frankfurt/Oder used as boundary conditions.

Table 1 │ Manning's coefficient

Water depth (m)	0.25	0.75	2.00	7.50	20.00
Manning's coefficient	0.0852	0.0597	0.0371	0.0275	0.0244

from an initial 95 m to 165 m over 24 h. The third dam break was simulated in three steps. Starting with a 60 m wide opening, another 60 m wide opening was added 3.5 h later. Three days later three openings of 90 m width were reported at the respective location.

Because of the uncertainty in time and width of the dam failures a simple sensitivity analysis was made assuming the third dam break had a width of 270 m instantly on 26 July. Different from the original scenario the discharge peak at Frankfurt/Oder on 27 July increased from 3,600 m^3/s to an unrealistic value of 4,000 m^3/s.

SIMULATION OF THE ZILTENDORFER LOWLAND INUNDATION

Water depths and the flooding extent for selected points in time are presented in Figure 5 (a–g). Normal water depths on 1

July (a) clearly show the main river channel. On 23 July immediately before the first embankment breach all the area in between the embankments and some polder in the very north are inundated (b). Three hours later (c) after the first embankment failure inundation of the Ziltendorfer Lowland started from the north, reaching a maximum water depth just before the third dam break on 26 July at 09:30 pm (d). At the end of the simulation the depletion phase (e-g) has not finished yet. Corresponding to the dates of observations as indicated in Figure 2 we deduced the inundation front position during the depletion phase from the simulated water depths (Figure 6). There is no objective measure but a coincidence of the front positions is readily identifiable.

The flow rate at the three embankment openings (Figure 7) indicates a bypass flow from the second to the first opening and later from the second to the third breach. The intake flow at the first opening converts to an outflow shortly after the second dam breach on 24 July. With the breaches on 26 July from the Ziltendorfer Lowland into the western arm of the river the flow through the first dam opening gradually decreases while a bypass develops from the second to the third opening. With the widening of the third opening on 30 July the flow through the first embankment breach converts to an inflow again. While

Table 2 │ Dam breach genesis

Real time		Simulation time			
Date	Time	Hours	Days	Event	Width of the opening (m)
30 June	05:00 pm	0.0	0.0	Simulation start	0
1 July	05:00 pm	24.0	1.0	Stationary steady state	0
23 July	09:00 am	544.0	22.7	1. Dam break	120
24 July	05:00 pm	576.0	24.0	2. Dam break (a)	95
25 July	05:00 pm	600.0	25.0	2. Dam break (b)	165
26 July	09:30 pm	628.5	26.2	3. Dam break	1 × 60 = 60
27 July	01:00 am	632.0	26.3	3. Dam break	2 × 60 = 120
30 July	01:00 am	704.0	29.3	3. Dam break	3 × 90 = 270
1 September	01:00 pm	1508.0	62.8	End of simulation	

the intake flow through the first and second opening consecutively decreases the Ziltendorfer Lowland depletes through the third opening. The process ends around 18 August.

As a sum of all inflow and outflow rates (Figure 8) the total volume of water in the Ziltendorfer Lowland (Figure 9) shows a maximum of 133 million m^3 on 24 and 25 July, which corresponds with an estimated volume of 150 million m^3 (Engel & Oppermann 1998). Calculating the total volume of water from water depths at each

grid point immediately before the third dam break on 26 July results in 128 million m^3. The number of 130 million m^3 seems to be a fairly reasonable estimate for the retention potential of the Ziltendorfer Lowland.

IMPACT OF THE FLOODING ON THE MAIN RIVER

Based on analytical considerations we construct the hypothetical hydrographs at Eisenhuettenstadt (upstream of the Ziltendorfer Lowland) and Frankfurt/Oder
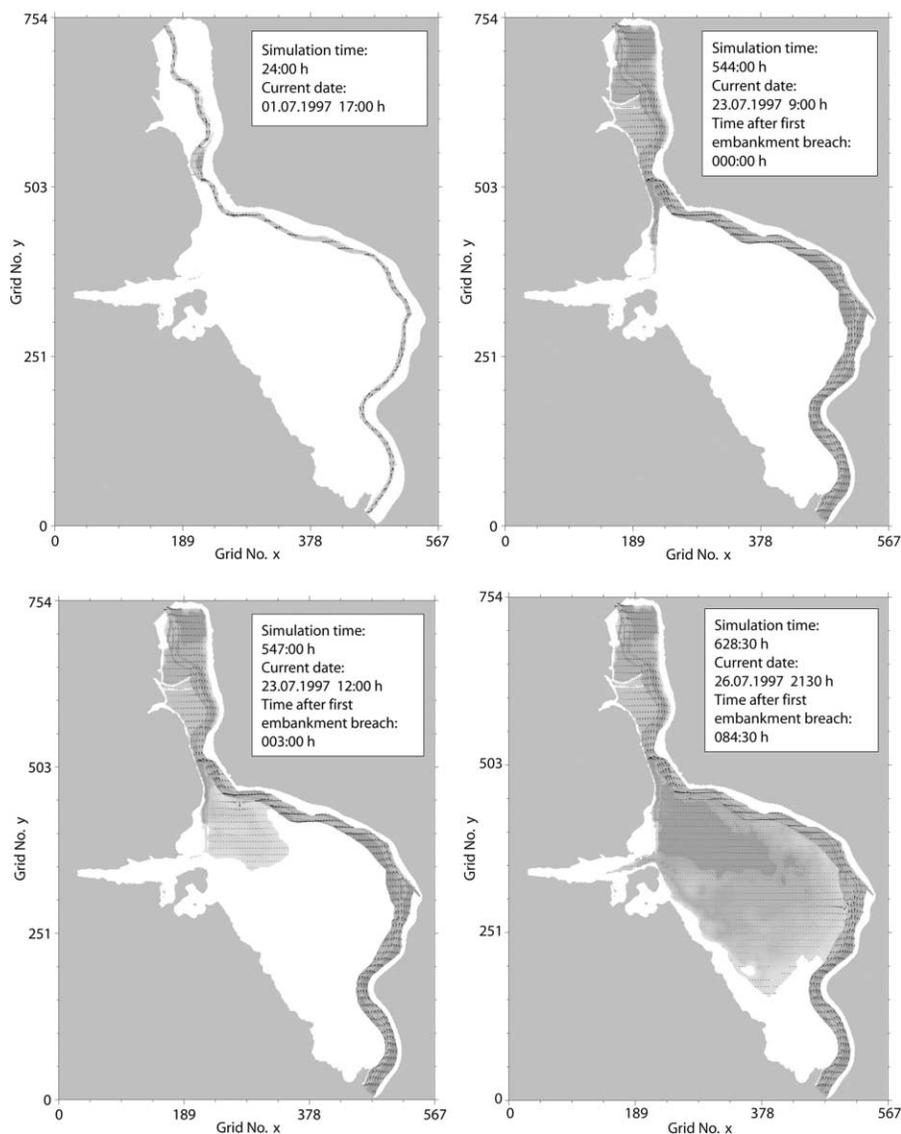

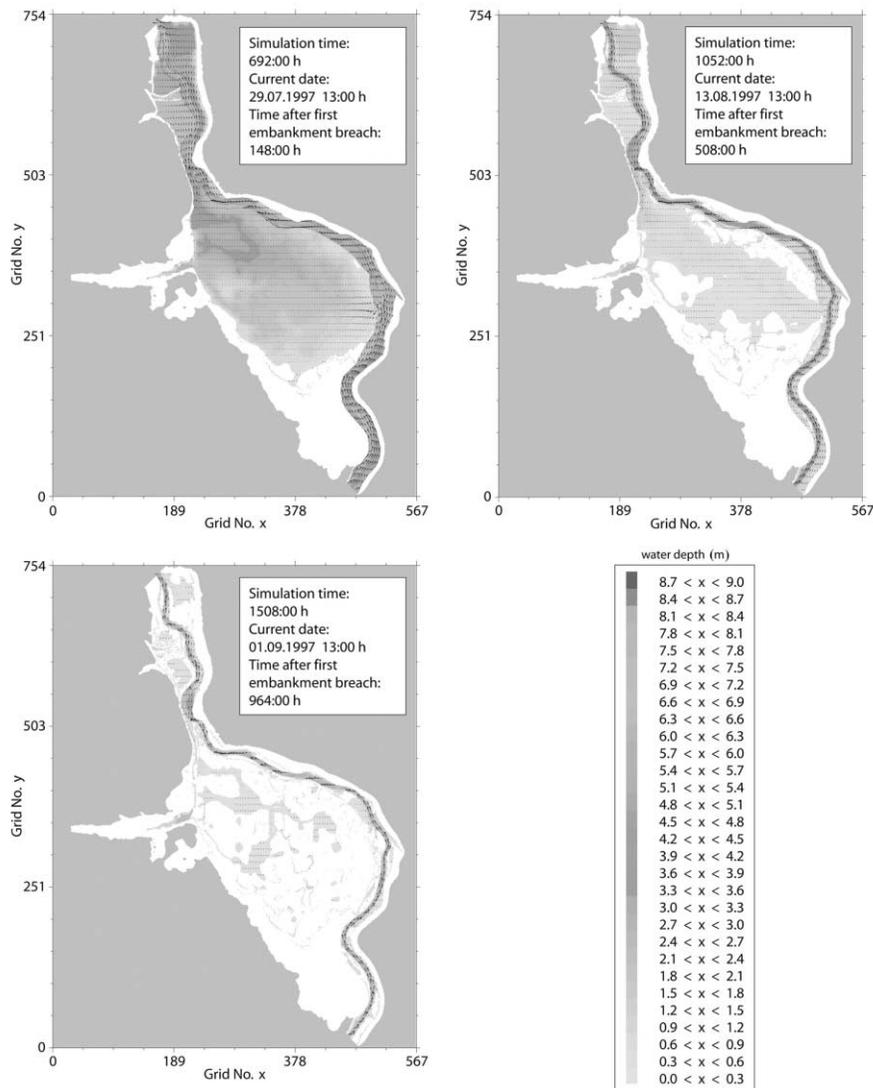**Figure 5** │ Flooding situation at different simulation points in time.

Figure 5 (*continued*).

(downstream) for the case of no embankment failures. Let us start with the observed water depths which include the flooding effects (Figure 10). For the water depth at Eisenhuettenstadt we assume a linear connection (dashed line) between the peak values on 24 July (before the second dam break) and 30 July (after the third dam break). With the assumption of an unchanging difference between water depths at Eisenhuettenstadt and Frankfurt/Oder from 23–30 July we then construct the hypothetical water depth at Frankfurt/Oder (dotted line). We also assume that the total amount of water is the same between the observed and the hypothetical curve before and after the crossing early on 27 July (retention equals runback) and that the hypothetical water depth approaches the observed one slowly during the depletion phase. This results in the dotted line for the time after 30 July. From this analysis we conclude that 1) the Ziltendorfer Lowland inundation lowered the water depth at Eisenhuettenstadt upstream during the period 24–30 July, 2) the third embankment breach on 26 July into the Brieskow lake increased the water depth in the main river at Frankfurt/Oder to a value above the "no breaches" scenario and 3) that this increased water depth at Frankfurt/Oder extends to mid-August.
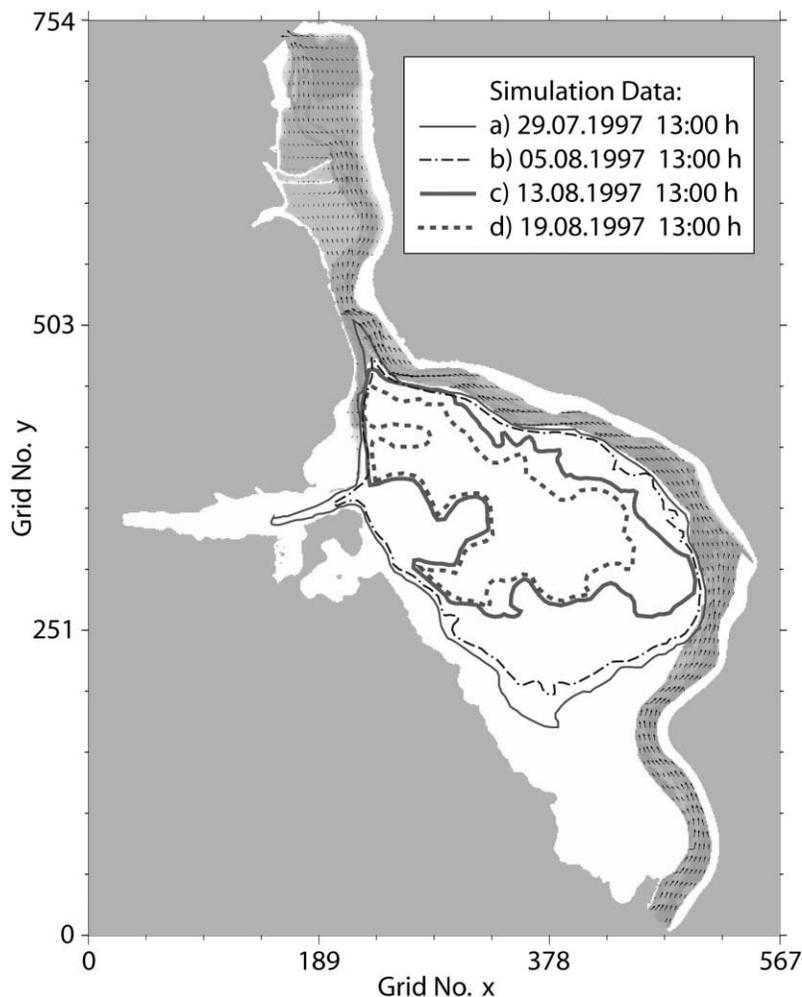
Figure 6 | Inundation front positions deduced from simulations.

In order to verify these analytical considerations simulations were performed for "dam break" and "no dam break" scenarios. The setup of the model TRIM2D as described in the third section does not allow such simulations because the upper (Eisenhuettenstadt) and lower boundary (Frankfurt/Oder) are affected by the inundation process. A "no dam break" scenario requires boundaries far enough from the Ziltendorfer Lowland not to be influenced by the flooding. Additionally, computer resources would be enormous for two scenario runs with TRIM3D, even in a two-dimensional version.

The one-dimensional hydrodynamic model MODRIM (Ewertowski 1998), originally designed for the lower Odra stretch close to the Baltic Sea, was extended upstream to the

gauging station Polecko 25 km south of Eisenhuettenstadt. Water levels at this station and at Police roughly 200 km downstream of Frankfurt/Oder close to the Baltic Sea served as upper and lower boundary conditions, respectively. The river geometry is described by a total of 217 cross sections, of which 120 were surveyed after the 1997 flooding event.

Manning's roughness coefficients are dynamically adapted depending on water depth. The surface roughness coefficients are estimated for different stretches separately and also separately for the centre of the main river channel and for border areas through model calibration for the period 9 March to 19 May 1994. This period also saw a major flooding event. Manning's roughness coefficients for the channel centre near the Ziltendorfer Lowland range
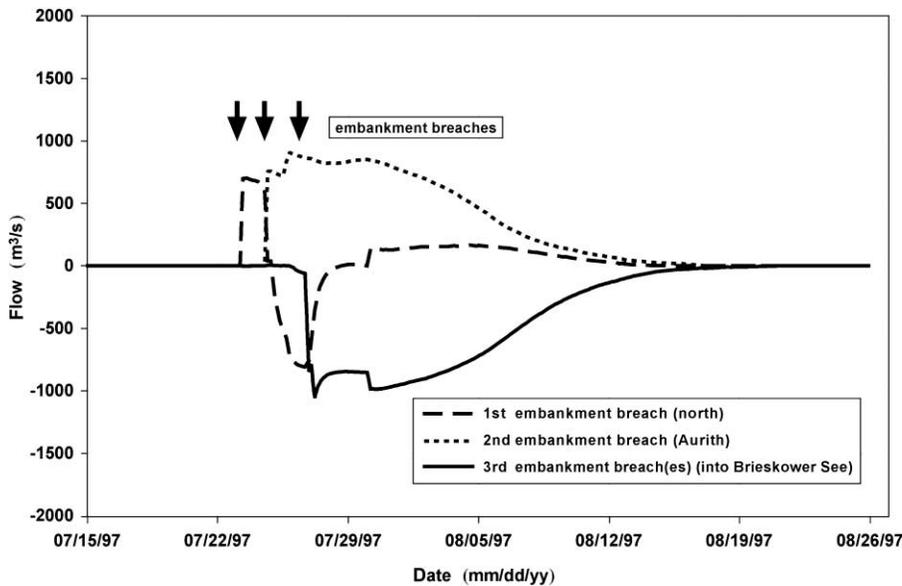
Figure 7 │ Flow rate through dam breaches.

from 0.024–0.085 and for the flood plains from 0.031–0.111. For verification purposes the period from 9 February to 20 May 1999 was simulated. This period included the March 1999 major flooding event. There was reasonable agreement between observed and simulated water depths and flow rates at the gauging stations along the river.

For the 1997 flooding event water depths at Polecko and Police from 1 July to 26 August were used as boundary conditions. Additionally the inflow from the Warta river at Gorzow and from the Lausitzer Neisse at Gubin were prescribed. The "dam break" scenario was defined by prescribing at the respective model nodes the outflow and
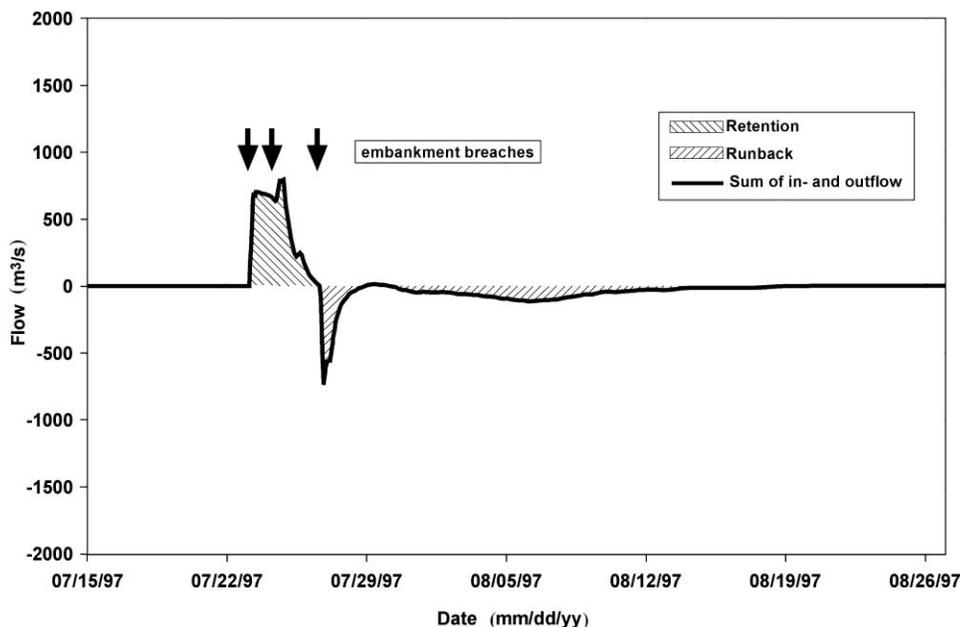

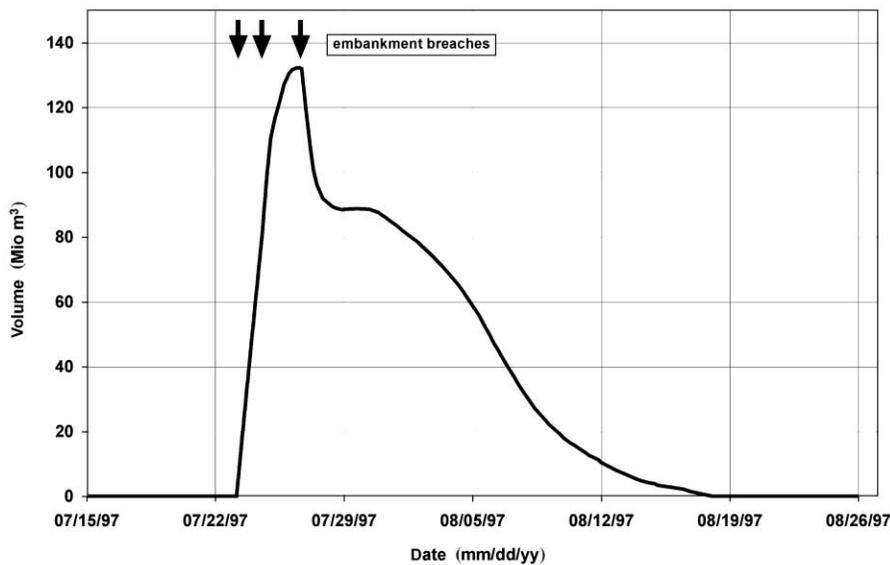**Figure 8** │ Total inflow and outflow of the Ziltendorfer Lowland.

Figure 9 | Total amount of water in the Ziltendorfer Lowland.

inflow through the Ziltendorfer Lowland as shown in Figure 7. The observed water depth at Frankfurt/Oder from Figure 4 is shown in Figure 11 as a solid line. The dotted and chain dotted lines are the simulated water depths for the "dam break" and "no dam break" scenario, respectively. Obviously, the effect of the first dam break is overestimated, showing the simulated water depth at

Frankfurt/Oder dropping faster then the observed one. Also the decay of the third dam break effect appears to happen faster. For our purpose of verifying the analytical consideration for the "no dam break" scenario we concentrate on the chain dotted line. It appears that the overall shape coincides with the analytically derived curve. The difference in the absolute value can be attributed to
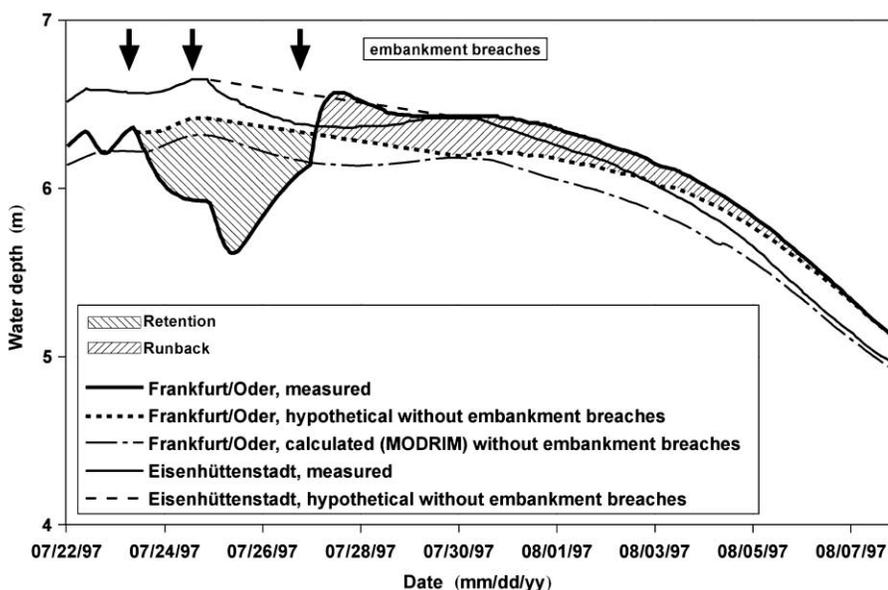

Figure 10 | Water depth at Frankfurt/Oder (measured, hypothetical and simulated) and at Eisenhuettenstadt (measured and hypothetical).
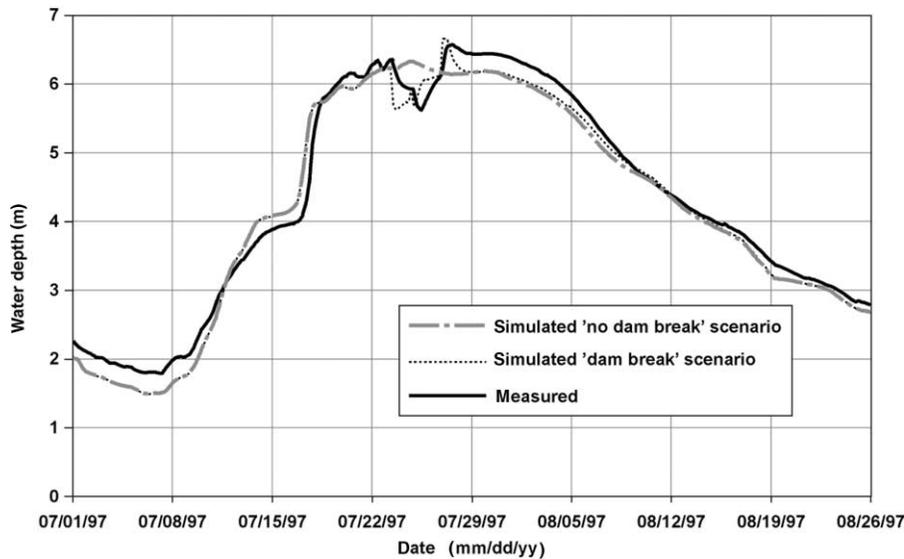
Figure 11 | Water depth at Frankfurt/Oder (solid: measured, dotted: simulated "dam break" scenario, chain dotted: simulated "no dam break" scenario).

uncertain relations between water depth and discharge at the boundaries. These relations provided by Polish and German authorities were not always consistent. The MODRIM simulations, however, approve the conclusions drawn from analytical considerations.

CONCLUSIONS

The inundation of the Ziltendorfer Lowland during the Odra flood in July 1997 has been simulated with the two-dimensional hydrodynamic model TRIM2D. The embankment breaches genesis is estimated from eyewitnesses' accounts. They seem to realistically reflect the actual situation as the simulated and observed inundation front position show good agreement.

The analysis of the impact of the inundation on the main river is based on analytical considerations and one-dimensional hydrodynamic simulations. The inflow into the Ziltendorfer Lowland through the first and second embankments leads to reduced water depths in the main river. The outflow into the main river through the third embankment breach led to higher water levels in the main river downstream. At the gauging station Frankfurt/Oder the observed water depth exceeds the hypothetical depth for the "no dam breach" case during the flood peak period.

Large required computer resources for the two-dimensional simulations make them inappropriate for real time applications. However, scenario simulations for flood-prone areas would allow quick estimates of embankment breach consequences during catastrophic events.

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