In this paper a newly developed three-dimensional hydrodynamic model has been used to investigate the consequences of the site redevelopment of Llanwern and flooding prevention measures. The 3D model includes hydrodynamic pressure without static pressure assumption. Two possible flooding risks have been analysed—tidal flooding from the south and fluvial flooding from the River Usk. Modelling results show that the consequences of the redevelopment and flood prevention measures are minimal on the surrounding area.

1. INTRODUCTION

A three-dimensional (3D) hydrodynamic model has been developed for flood study and applied for Llanwern flood risk assessment. The case in this paper is for the proposed redevelopment of part of Llanwern steelworks. The development will comprise approximately 600 acres of the western half of the Llanwern steelworks site, which was used for storage of core materials and heavy steel production by Corus before work came to an end in 2001. Fig. 1 shows the overall layout plan. Following environmental improvement and infrastructure works, construction of around 4000 housing units and approximately 1.5 million square feet of industrial units is planned.

With the rapid increase in computer power in recent years, 3D models can now be applied to free-surface hydraulic engineering problems. In order to model the flood process in the development area, a 3D flood model including hydrodynamic pressure has been developed based on a 3D flow model developed in Halcrow. The full 3D Reynolds-averaged Navier–Stokes equations including hydrodynamic pressure have been solved in the flood model. A technique of flooding and drying, first developed by Falconer and Owens, was used in the present model.

In this paper, section 1 provides a strategic overview of potential sources and implications of flooding at the Llanwern regeneration site. In section 2 detailed assessment of potential flooding is presented. Finally, flood propagation modelling and proposed measures to enable the development to proceed are presented in section 3.

2. BACKGROUND

Theoretically, the Llanwern regeneration site is currently at risk from predominantly tidal flooding due to its low ground level (Fig. 1); however there is also a risk of fluvial flooding from the north of the site at Llanwern village along Monks Ditch. The following descriptions will consider potential fluvial/surface water flooding from tidal flooding across Caldicot Levels and from the River Usk.

Significant flooding has occurred in Llanwern village and has been associated with fluvial flooding from Monks Ditch. Corus has previously alleviated flooding at Llanwern village by diverting some of the Monks Ditch flow to the company’s drainage system and increasing the volume of water pumped from its surface water drainage system. A preliminary economic appraisal of potential flood alleviation measures for Llanwern village was undertaken and concluded that the present value of benefits available is not sufficient to provide a viable capital works scheme. At this stage it was considered that elevated flood levels are primarily due to a lack of conveyance within the channel through Llanwern village.

There are two siphons along Monks Ditch at the northern and southern ends of the site. During periods of high flow, water can be diverted from Monks Ditch to the site drainage system. The surface water drainage system within the site comprises a number of culverts and open channels that run through the site from north to south. They channel water from watercourses north of the site, excess production water and surface water to the main east–west ditch (which flows from west to east at the southern end of the site, see Fig. 1) and then via a series of oil interceptors and settlement lagoons to the pumping station. The water is then pumped via a pipeline to discharge into the estuary. The infrastructure within the pumphouse is currently powered by electricity. There is currently significant capacity within the surface water runoff system. Heavy steel production, which required some 16 million gallons of water per day, has now ceased and the current water requirement for the production of steel strip is only around 6 million gallons per day. As part of the development the existing culverts will be developed as a series of open channels to enable the control of fluvial flow and surface water runoff. These open channels will be designed to prevent impacts upstream and downstream of the site and therefore will not increase flood risk to the adjacent areas.
The low-lying land between the Llanwern site and the coast is predominantly in agricultural use and is drained by an extensive system of manmade ditches and channels (known as reens). The Caldicot and Wentloog Levels Internal Drainage Board (IDB) states that there are approximately 104 km of reens under its management on the Caldicot Levels. The main reens of the Caldicot Levels, which are also managed by the IDB on behalf of the Environment Agency (EA), exceed 54 km in length. The drainage system carries surface water to the sea where it is discharged via outlets known as Pills, which are equipped with tide flaps, and through the intertidal area via Pill channels. The EA and IDB carry out various works including cutting down vegetation on the banks twice a year, clearing the channels and maintaining and operating the sluices to provide a balance between providing sufficient water to the agricultural land for crops and preventing flooding. The Llanwern area has not been flooded by the tide since the mid-1800s. However, there are a number of areas that are prone to flooding: localised flooding around the electrical substation and highway immediately south of the Llanwern site; flooding around Goldcliff; Chapel Lane and the sea doors. It is considered that the proposed development will not have an impact on flooding/flood risk downstream of the site.

3. FLOOD PROPAGATION MODELLING

3.1. Possible tidal flooding

The Caldicot Levels comprise 7100 ha of reclaimed alluvial plain situated adjacent to the Severn Estuary. The area lies below mean high water spring tide level and forms a strategic infrastructure corridor with significant and varied land uses. Tidal inundation of these lowlands is prevented by various flood defence structures that were generally erected between 1947 and 1966. The sea defence embankments provide a relatively high standard of protection against surge tide flooding, but wave action results in significant and relatively frequent overtopping of the defences. During a storm in February 1990 wave overtopping was observed and significant damage to the defences resulted. This damage resulted in near-breach conditions at several points along the embankment. It has been established that the standard of service against breach for the defences is approximately 20 years, falling way below the 100–300-year Department for Environment, Food and Rural Affairs (DEFRA) indicative standard. Analysis has identified a current annual breach probability of 5% (i.e. 20-year return period), increasing to 20% by 2050. This analysis was checked against historic records including video footage of the 1990 and 1998 overtopping events. The 1990 event caused severe damage to the defence, resulting in near-breach conditions.

Following an assessment of a wide range of options it was proposed that the existing sea defences be improved by raising the existing defences by capital improvements, to be designed in advance of each phase of the work. Phase 1 of Caldicot Sea Defence Improvements involved the construction of a wave return wall on top of the existing defences. In more sheltered areas, earthwork improvements to the existing embankments are recommended.
3.2. Possible flooding from River Usk

The existing standard of protection provided by the majority of informal defences along the east bank of the River Usk, between the confluence with the River Severn and the M4 motorway, is 1 in 50 years; however, in places the standard of protection provided is as low as 1 in 20 years. The ground levels adjacent to the river are higher than those in the urban hinterland, resulting in potential flood damage some distance from the river; however, the area at risk from flooding is bounded by the railway embankment which runs parallel to the River Usk. There are locations where roads pass under the railway embankment, allowing the possibility for flood waters to encroach eastwards. These locations are some distance from the river’s edge and it is considered that the volume of flood waters that could be conveyed through the openings during a potential overtopping period of 2 h would not cause flood damage to properties on the eastern side of the railway.6

3.3. FLOOD3D modelling

A 3D flood model (FLOOD3D) has been developed at Halcrow and used to establish the consequences of tidal flooding following a breach in the existing sea defence embankment immediately to the south of the site. This model is based on complete 3D Reynolds-averaged Navier–Stokes equations, including hydrodynamic pressure. These equations can be written as

\[
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{v} \cdot \nabla \mathbf{v} + \mathbf{w} \cdot \nabla \mathbf{w} \right) = -\nabla p + \frac{\partial}{\partial x} \left( \frac{\mu}{\sigma x} \frac{\partial \mathbf{u}}{\partial x} \right) + \rho \mathbf{g}
\]

\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} + \mathbf{w} \cdot \nabla \mathbf{w} \right) = -\nabla p + \frac{\partial}{\partial y} \left( \frac{\mu}{\sigma y} \frac{\partial \mathbf{v}}{\partial y} \right) + \rho \mathbf{g}
\]

\[
\rho \left( \frac{\partial \mathbf{w}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{w} + \mathbf{v} \cdot \nabla \mathbf{w} + \mathbf{w} \cdot \nabla \mathbf{w} \right) = -\nabla p + \frac{\partial}{\partial z} \left( \frac{\mu}{\sigma z} \frac{\partial \mathbf{w}}{\partial z} \right) - \rho \mathbf{g}
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{v} \cdot \nabla \mathbf{v} + \mathbf{w} \cdot \nabla \mathbf{w} = 0
\]

where \(x, y, z\) are the coordinates of a fixed Cartesian system; \(\mathbf{u}, \mathbf{v}, \mathbf{w}\) are the velocity components in the \(x, y, z\) directions, respectively; \(p\) is the ratio of pressure to the constant density \(\rho\) of the fluid; \(\mathbf{g}\) is acceleration due to gravity; \(\mu^h\) and \(\mu^v\) are the coefficients of horizontal and vertical eddy viscosity, respectively. The origin is located at the undisturbed level of the free surface, with \(z\) upward. The kinematic boundary condition on the water surface is

\[
\frac{\partial h}{\partial t} + \mathbf{u} \cdot \nabla h + \mathbf{v} \cdot \nabla h + \mathbf{w} = 0
\]

where \(h\) is elevation of the water surface above datum.

For incompressible fluids such as water it is sufficiently accurate to use the condition \(p = 0\) along the free water surface—that is, pressure is set to zero on the water surface.

The sigma coordinate transformation is used to transform the equations and the corresponding boundary conditions from the physical domain to the calculation domain. The time-splitting method is used to separate advection and diffusion terms from the pressure terms in the governing equations. The pressure variable is further separated into hydrostatic and hydrodynamic pressures so that computer rounding errors can be largely avoided. The resulting hydrodynamic pressure equation is solved by a multi-grid method, while the hydrostatic pressure equations are solved very efficiently by an alternating direction implicit (ADI) scheme. Roe’s scheme is used for the convection terms, producing accurate results. Details of the model can be found in the paper by Li and Fleming.7 For the flooding study, a technique of flooding and drying firstly developed by Falconer and Owrens4 was used in the present model. In theory a full 3D model should produce more accurate results than a 2D model or a quasi-3D model.

A digital terrain model with a 20 m grid spacing was used to run FLOOD3D with results to be provided at 10 min intervals. Five vertical layers were used in the model. The model took 15 min to simulate 1 h of flood wave propagation for grid points of 500 × 500 in horizontal plan and five grid points in the vertical direction.

3.4. Modelling bathymetry

Existing coverage of the EA Lidar detecting and ranging (Lidar) survey data of the study area is limited to a corridor up to 1 km wide along the coast; Corus topographic data were available within the site from a site investigation undertaken in August 1959. A standard digital terrain model (DTM) was produced using Interferometric Synthetic Aperture Radar (IFSAR), which compares two or more radar images collected at slightly different geometries. The survey was flown in summer 2002, with data points every 5 m and vertical accuracy of: RMSE 1.0 m; 95% 2.0 m, mean 0.7 m, standard deviation 0.7 m. Fig. 2 shows a contour plot of the DTM. The levels shown compare well with site levels provided by Corus (average level at redevelopment site = +5.2 m Ordnance Datum Newlyn (ODN)).

3.5. Modelling of breach in the sea defence embankment at Goldcliff

The purpose of these model runs was to assess the extent and depth of flooding following a breach in the sea defence embankment at Goldcliff (Point A2) to the south of the Llanwern site (see Fig. 1). A summary of input data used in the model is provided in Table 1.

The breach Point A2 was selected using the DTM to identify the lowest point along the coast to the south of the development site that would provide a flood route to the site.

A 1-in-200-year return period event has been considered in line with DEFRA’s indicative standards of protection, while 100 years of sea level rise has been included in line with recent DEFRA recommendations to consider 100-year timescales during a strategic review of hard defences.

Water levels were calculated using Halcrow’s Shoreline and Nearshore Database System (SANDS) using tidal constituents for Newport, South Wales from UK Admiralty Tide Tables.
A time series of tides for year 2004 was generated. The highest water level for this time series was defined and data from five tidal cycles around the highest water level were extracted. The extreme water level (8.96 m ODN for Point A2) was superimposed on top of the predicted water levels, and these extreme water levels were used as input boundary data for the FLOOD3D model. It has been assumed that any waves propagating through the breach in the defences will be dissipated over the wide floodplain.

Two scenarios were considered, which both assume no change in the existing defences or topography.

- Existing case—to assess the depth of flooding and how flood water propagates over the Llanwern site and the surrounding area.
- Using the results from the above model run, to determine the level to which the Llanwern redevelopment site needs to be raised to prevent flooding.

The FLOOD3D model provided velocity plots and plots of flood propagation/depth of flooding at 10 min intervals once the tide level was above the level of the breach. The model was run assuming that the breach would remain open for a period of 48 h before resources could be mobilised to repair the breach.

3.5.1 Existing case. The progression of the flood water is shown in Fig. 4 and the maximum depth and extent of flooding for the existing case is shown in Fig. 5. The proposed Llanwern regeneration site is the area between the four stars. It can be seen from Fig. 5 that if the existing ground levels remain unchanged then some areas of the development site will
be subject to flooding. The model shows that flood waters will reach the site 4 h after the breach.

3.5.2. Raise ground levels around proposed development site to prevent flooding. The progression of the flood water and the maximum depth and extent of flooding for this scenario are shown in Figs 6 and 7, respectively. To prevent flooding of parts of the development site an embankment at a level of +6.6 m ODN will need to be installed along the southern edge and the north-east corner of the site.
The consequences of flooding on the surrounding land following installation of an embankment around the development site are minimal with no new areas being flooded and an increased depth of flooding of up to 200 mm in places (see Fig. 8) compared to flooding in the existing case. The areas affected are predominantly agricultural with low residential density and industrial use to the east. During extreme flooding conditions it will still be possible to access/egress the

![Fig. 6. Goldcliff sea defence embankment breach: progression of flood water modelled if the levels were raised around the proposed development site to prevent flooding](image)

![Fig. 7. Goldcliff sea defence embankment breach: maximum water depth during 48 h if the levels were raised around the proposed development site to prevent flooding](image)
development site from the west using the existing road network to access the A455.

3.6. Modelling flooding from the River Usk

The FLOOD3D model was used to assess the extent and depth of flooding from the River Usk. The extreme water level at the entrance to Newport Docks is +9.21 m ODN, which is the 1-in-200-year return period water level, plus 100 years sea level rise. In the absence of additional information it has been assumed that this is the extreme water level at the two breach locations along the River Usk. In both cases a breach level of +6.0 m ODN was used.

The location of breaches 1 and 2 were identified using the DTM. Breach 1 is the lowest point along the River Usk to the west of the development site, which would provide a flood route to the site. Breach 2 was considered as an alternative since the level of the ground between this breach and the development site is lower than the potential flood route from breach 1 and therefore may result in increased flooding, although the breach is further from the site.

The two scenarios mentioned in section 3.5 were again considered; again, both assuming no change in the existing defences or topography. The model was run assuming that the breach would remain open for a period of 48 h before resources could be mobilised to repair the breach.

3.6.1. Existing case. The progression of the flood water for both breaches is shown in Figs 9 and 10; in both cases flood waters will reach the site 3 h after the breach. Plots of the maximum extent and depth of flooding (Figs 11 and 12) show that if the existing ground levels remain unchanged then some parts of the development site will be subject to minor flooding.

3.6.2. Raise ground levels around proposed development site to prevent flooding. To prevent flooding of the development site following a breach at the River Usk it will be necessary to construct an embankment at a level of +8.5 m ODN at the western end of the site and to raise the embankment at the southern edge of the site to +6.1 m ODN. The progression of flood water and the maximum depth and extent of flooding are shown in Figs 13–16.

For breach 1 the consequences of flooding on the surrounding land following installation of the embankment will be a very small increase in the area of land flooded and an increased depth of flooding over approximately 50% of the flooded area between the site and the River Usk, see Fig. 17. Of this area, the majority has a maximum increase in flood depth of up to 200 mm, while the remainder (approx. 10%) has a maximum increase of up to 600 mm with a localised area of up to 800 mm. The model shows that for the existing case this area is already under an average of 1.5–2.0 m depth of water and therefore the resultant increase is considered to be minimal in the context of the overall flooded area. The areas affected are predominantly residential, industrial and a retail park immediately to the west of the site.

For breach 2 the consequences of flooding on the surrounding land following installation of the embankment will be minimal, with no new areas being flooded and an increased depth of flooding of up to 200 mm in places, see Fig. 18. The areas affected are predominantly agricultural with low residential density and industrial use to the east.

For breach 1 and breach 2, following construction of flood defence embankments, the proposed evacuation route will be either along the southern feeder road, which is aligned west–east along the southern border of the

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**Fig. 8.** Goldcliff sea defence embankment breach: difference in flood water depth between the existing case and with levels raised to prevent flooding.
Fig. 9. River Usk breach 1: progression of flood water in the existing case

Fig. 10. River Usk breach 2: progression of flood water in the existing case
Breach location
Breach level: +6.0 m ODN

Bathymetry: m
Flood water depth: m

0.00
0.25
0.50
0.75
1.00
1.50
2.00
130
120
110
100
90
80
70
60
50
40
30
20
10
5
0

Fig. 11. River Usk breach 1: maximum depth and extent of flood water in the existing case

Fig. 12. River Usk breach 2: maximum depth and extent of flood water in the existing case
Fig. 13. River Usk breach 1: progression of flood water modelled if the levels were raised around the proposed development site to prevent flooding.

Fig. 14. River Usk breach 1: maximum water depth during 48 h if the levels were raised around the proposed development site to prevent flooding.
Fig. 15. River Usk breach 2: progression of flood water modelled if the levels were raised around the proposed development site to prevent flooding.

Fig. 16. River Usk breach 2: maximum water depth during 48 h if the levels were raised around the proposed development site to prevent flooding.
development site and which connects to Junction 23a of the M4 (this road will need to be raised to prevent flooding during extreme events) or to the north of the site via a new bridge that would need to be constructed over the railway line.

4. CONCLUSIONS

A 3D model for flood propagation has been developed and applied to investigate the consequences of site redevelopment and flooding prevention measures. This paper demonstrates
that the 3D flood model can be used for practical design on a PC. The present model includes hydrodynamic pressure without a static pressure assumption. As a result of the modelling and studies it can be seen that the consequences of the development and flood prevention measures are minimal on the surrounding area. The majority of the surrounding area comprises open space and commercial property. This area would already be subject to flooding if an event were to occur.

To prevent flooding of the proposed development site during a 1-in-200-year return period event (including 100 years sea level rise) from the River Usk and following a breach in the flood defence embankment immediately to the south of the site, an embankment will need to be installed along the southern edge and the north-east corner of the site at a level of +6.6 m ODN and another embankment will need to be installed at a level of +8.5 m ODN along the western edge of the site. Installing these embankments will have negligible impact on the flood risk of the surrounding area. However, it will have a minor effect on the depth of flooding in areas already subject to flooding.

REFERENCES