

**PEMBROKESHIRE COUNTY
COUNCIL**

**Haverfordwest Town Centre
Strategic Flood Consequence
Assessment**

Final Report

Notice

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Document History

JOB NUMBER: 5056736			DOCUMENT REF: 5056736-DG-SFCA-3.doc			
Revision	Purpose and Description	Originated	Checked	Reviewed	Authorised	Date
1-D1	Draft	DMH	KIO			
1-D2	Internal draft	DMH	KIO	HR		05-03-08
1	Draft issue to client for approval	DMH	KIO	HR	HR	06-03-08
2	Final Issue	DMH	KIO	HR	HR	20-06-08
3	Re-issue Final – with minor amendments	DMH	KIO	HR	HR	23-10-08

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1 Introduction

1.1 Background

As part of the planning process, under the Compulsory Purchase Act 2004, planning authorities in Wales are required to produce a Local Development Plan (LDP). This will replace Joint Unitary Development Plan (JUDP) as the Development Plan for Pembrokeshire County Council. This means that when it is adopted, planning decisions will mostly be based on the LDP.

The LDP has to show that it is encouraging patterns of development that are economically, socially and environmentally sustainable. Pembrokeshire County Council will produce a 'Sustainability Appraisal Report' comprising a Strategic Environmental Assessment during the process of developing the LDP, explaining how these factors have been considered.

Pembrokeshire County Council (PCC) has engaged Atkins Limited to undertake a strategic level assessment of the flood risk in Haverfordwest in order to inform a Regeneration Framework for the town centre. The SFCA will also provide part of the evidence base for the LDP. We anticipate that this strategic flood assessment will provide a 'risk based' approach to regeneration proposals in central Haverfordwest. This will provide clarity to both the Council and to potential developers. However, we note that the current study does not replace the need to undertake site specific FCAs required under planning policy guidelines (TAN15¹) for planning applications.

It is noted that at the time of writing there is no official WAG guidance on the scope of Strategic Flood Consequence Assessment (SFCA) within the principality.

1.2 The Study Area

The study area is restricted to central Haverfordwest, along the river corridor of the Western Cleddau River and the lower reach of the Cartlett Brook. This area is bounded to the north by Haverfordwest County football ground, to the south by the Priory and the railway station in the east. The extent of the study area is shown in Figure 1.1.

As discussed with PCC's Forward Planning Team, the area bordering the banks of the Cartlett Brook have been considered only insofar as how overland flow from this source during extreme flood events might affect the A40 and areas on the left bank of the Western Cleddau River.

A key factor in considering sustainability will be whether the flood risk within proposed development areas is acceptable and if it can be managed sustainably into the future.

The following detail is taken from the PCC produced document a 'Vision for Haverfordwest'. This document provides the general context, interprets JUDP and Spatial Plan policies, and sets out aspirations for the town over the next 10-15 years.

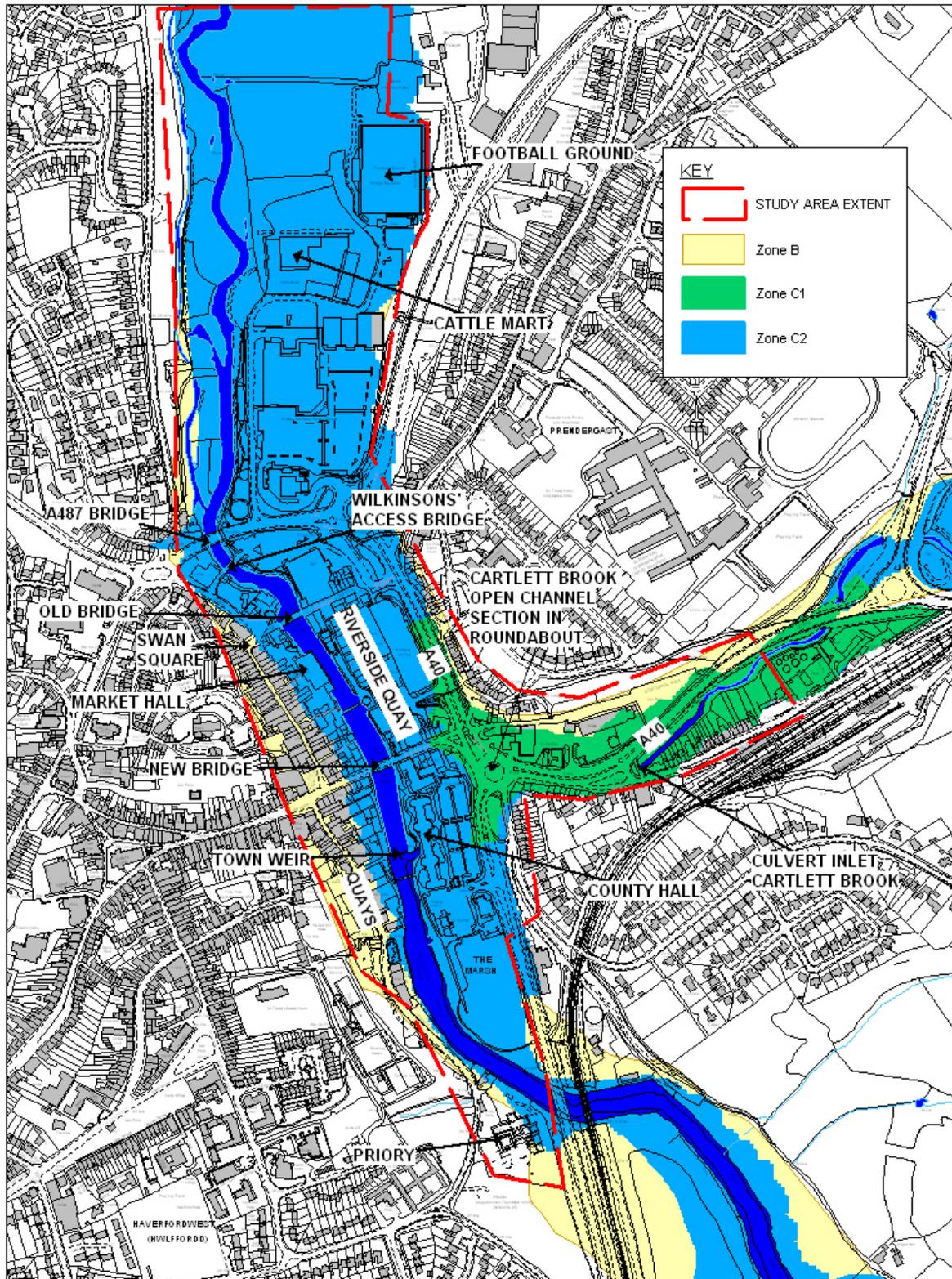
Active upgrading of the core of the town centre – from Swan Square to Castle Square and opening up the riverbank to greater public access, tied in with nearby enhancements to other areas - will be crucial in drawing together the east and west bank parts of the emerging town centre. The role of the historic backdrop of the castle, the Parade area and the inner residential areas offers the prospect of supporting key town centre functions in a way which adds interest and encourages repeat visits.

¹ Planning Policy Wales: Technical Advice Note: 15 Development and Flood Risk: Welsh Assembly Government July 2004

The majority of the study area lies within TAN15 Zone C, either Zone C1 or Zone C2 as defined by the Development Advice Maps included within TAN15, as indicated on Figure 1.1.

Zone C1 is defined as areas of the floodplain that are developed and are served by the significant infrastructure, including flood defences. Within zone C2, defined as areas of floodplain without significant flood defence infrastructure, only less vulnerable development should be considered subject application of the justification test (see Section 2.1.1). Emergency services and highly vulnerable development should not be considered in C2.

Figure 1.1 Development Advice Map and Key Locations Central Haverfordwest



2 Regeneration Framework

The Regeneration Framework for the centre of Haverfordwest will be through necessity, an iterative process. It is anticipated that the consequences of flooding highlighted in this report will inform the development options in Haverfordwest.

A draft Regeneration Framework document (Dec 2007) has been produced which outlines potential changes along the river corridor of the Western Cleddau. However, given that the wider local development planning process is live and as such proposals are open to change, we have assessed all parts of the town centre for their acceptability for all potential development types, as defined under the indicative guidance given in TAN15.

The town has been divided in areas for the purpose of discussion. These areas are presented in Figure 8.1, Section 8 and listed in the table below.

Table 2.1 Breakdown of areas of the town centre considered

• Area A	Left bank, south of A487 bridge. Site of existing Wilkinson's store and associated car parking
• Area B	Left bank - includes site of the existing Riverside Quay development and the A40 Cartlett Road
• Area C	Includes Cartlett Brook, A40 and Council building and car park
• Area D	Right bank -Includes historic ruin of Priory and bottom of Union Hill
• Area E	Right bank – Old Quay & New Quay areas
• Area F	Right Bank between A487 bridge and New Bridge
• Area G	Site of existing Morrison's supermarket, car park and associated retail units
• Area H	Includes Cattle Mart site and football ground

2.1 Planning Policy Guidance – Development and Flood risk

TAN15 sets out the criteria against which the consequences of a development in an area at risk of flooding can be assessed.

As part of this process, TAN15 requires that a flood consequences assessment (FCA) be produced for all developments within the flood risk area. Areas considered to be at flood risk are shown on the Development Advice Map (DAM) produced by the Welsh Assembly Government (WAG). The Environment Agency Wales (EAW) advise as to the requirement for an FCA. Consultation with the EAW is the first step in establishing the flood risk within the requirements of TAN15.

2.1.1 Justification Test

When development is to be considered within Zone C, flooding issues should be considered as a part of the overall planning process. As a result, the TAN15 advises that any development within the zone should be the subject of a FCA in accordance with

Section 7 and Appendix 1 of TAN 15². Any development would first have to pass the justification test as detailed in Section 6 of TAN 15. The local authority will need to ensure that any areas to be included in the local development plan are justified. The criteria as described in TAN15 are repeated below for reference.

1. *Much urban development in Wales has taken place alongside rivers and in the coastal flood plain. It is therefore inevitable, despite the overall aim to avoid flood risk areas, that some existing development will be vulnerable to flooding and fall within Zone C. Some flexibility is necessary to enable the risks of flooding to be addressed whilst recognising the negative economic and social consequences if policy were to preclude investment in existing urban areas, and the benefits of reusing previously developed land. Further development in such areas, whilst possibly benefiting from some protection, will not be free from risk and could in some cases exacerbate the consequences of a flood event for existing development and therefore a balanced judgement is required.*
2. *New development should be directed away from Zone C and towards suitable land in Zone A, otherwise to Zone B, where river or coastal flooding will be less of an issue. In zone C the tests outlined in Sections 6 and 7 will be applied, recognising, however, that highly vulnerable development and Emergency Services in zone C2 should not be permitted. All other new development should only be permitted within zones C1 and C2 if determined by the planning authority to be justified in that location. Development, including transport infrastructure, will only be justified if it can be demonstrated that:-*
 - i. *Its location in zone C is necessary to assist, or be part of, a local authority regeneration initiative or a local authority strategy required to sustain an existing settlement¹; or,*
 - ii. *Its location in zone C is necessary to contribute to key employment objectives supported by the local authority, and other key partners, to sustain an existing settlement or region; and,*
 - iii. *It concurs with the aims of PPW and meets the definition of previously developed land (PPW fig 2.1); and,*
 - iv. *The potential consequences of a flooding event for the particular type of development have been considered, and in terms of the criteria contained in Sections 5 and 7 and appendix 1 found to be acceptable.*

2.1.2 Acceptability Criteria

TAN15 advises that development should be designed to be flood free during the 1% fluvial flood (i.e. that fluvial flood with a 100 to 1 chance of occurring in any year) and the 0.5% tidal/coastal flood (i.e. 200 to 1 chance in any year event). There is, therefore, a frequency threshold of flooding below which inundation of any development should not be allowed. The following table, which should not be regarded as prescriptive, provides indicative guidance as to what that frequency threshold could be for different types of development described in terms of annual probability of occurrence.

TAN15 recognises that *“beyond the threshold frequency proposed development would be expected to flood under extreme conditions. However even with adequate mitigation measures in place it may still not be sensible to allow particular development to take place. For instance it would not be sensible for developments to be built in areas where the velocity and depth of floodwaters was such that structural damage was possible or that people could be swept away by the flood.”*

² Planning Policy Wales: Technical Advice Note: 15 Development and Flood Risk: Welsh Assembly Government July 2004

Table 2.2 Extract from TAN15 A1.14 Indicative Flooding Threshold

Type of Development	Threshold Frequency (Years)	
	Fluvial	Tidal
Residential	1%	0.5%
Commercial/Retail	1%	0.5%
Industrial	1%	0.5%
Emergency Services	0.1%	0.1%
General Infrastructure	1%	0.5%

A table of indicative guidance, referred to as acceptability criteria as given in Appendix 1.15 of TAN15 is presented in Table 2.3, below.

Table 2.3 Acceptability criteria – direct extract from Appendix 1.15, TAN15

Types of development	Maximum depth of flooding	Maximum rate of rise of floodwaters	Maximum speed of inundation of flood risk area (hrs)	Maximum velocity of floodwaters
	(mm)	(m/hr)		(metres/sec)
	Property Access			Property Access
Residential (habitable rooms)	600	0.1	4	0.15
	600			0.3
Commercial and Retail	600	0.3	2	0.15
	600			0.3
Industrial	1000	0.3	2	0.3
	1000			0.45
Emergency Services	450	0.3	4	0.15
	600			0.3
General Infrastructure	600	0.3	2	0.3
	600			0.3

NOTE: The above figures are indicative and reflect conditions in which, given the presence of adequate warnings and preparation, appropriately equipped personnel could undertake emergency activities. However they are not definitive. Each site must therefore be considered individually and a judgement taken in the context of the particular circumstances which could prevail at that site.

2.1.3 Development Lifetime

Flood risk must be considered over the anticipated lifetime of each development. Current EAW policy has been to accept a development lifetime of 50 years. However, for residential developments, the EAW consider this to be too short a period and as best practice they now advise that we consider up to 100 years development life for residential, developments. This report, therefore, considers both a 50 year and 100 year time horizons in assessing the areas of Haverfordwest against the acceptability criteria given in Appendix 1.15 of Tan15.

3 Objectives of this study

In the context of the existing planning policy guidance described in the previous Section, the objectives of the study are:

- Determine the flood depths and velocities in areas of the town and compare with the indicative guidance defined in TAN15.
- Identify the extent and severity of flood risk in the area of Haverfordwest town centre with regard to the acceptance criteria given within TAN15.
- Comment on the areas of the town which cannot be developed without further work to mitigate the flood risk.
- Comment on areas which, if developed, might affect flood risk elsewhere.
- Identify areas to which flood risk may affect safe access and egress routes
- Identify potential emergency response issues
- Suggest a range of mitigation options which may be appropriate for different areas of the town and which may be explored in further studies.
- Inform the sustainability appraisal so that flood risk is taken account of when considering options and in the preparation of strategic land use policies
- Identify the level of detail required for site-specific FCAs in particular locations, and
- Enable the determination of the acceptability of flood risk in relation to emergency planning capability.

This SFCA will not assess the economic benefit of development, or if the council was to implement any works, suggest a prioritisation based on social benefit or similar.

No assessment will be made with regard to council's response requirements under the terms of the Civil Contingencies Act, although it is possible that the results of this study could be used to assist in such a purpose if required.

3.1.1 The Elements of the Study

The elements of the study which have been undertaken to achieve the study objectives comprise:

1. Liaison with Pembrokeshire's Forward Planning officers to define area of interest
2. A review of the existing hydrological and hydraulic modelling available
3. Reference to previous reports on flood risk in the area
4. Identify the main sources of flooding
5. Develop hydraulic river models to identify
 - i. routes of overland flow
 - ii. flow velocities and water depths at key locations
6. Scope out a list of potential options to mitigate flood risk.

4 Flood Risks

4.1 Flood History

Haverfordwest has flooded from both the Western Cleddau and the Cartlett Brook on a number of occasions in recent times, notably, August 1986, October 1987 and October 2005.

Areas adjacent to Old Bridge on the Western Cleddau flooded in October 1987. At this time overland flow paths formed around the Mart Ground (now the site of Wilkinson's car park) and through the town. However, these flow paths have been reported³ in earlier work by WS Atkins to have been affected by construction works for the Haverfordwest by-pass.

In addition, redevelopment of the town centre has seen river defences raised between the new A467 and New Bridge to reduce the risk of flooding. The flow paths from the 1987 event cannot, therefore, be used for corroborative evidence for the results of the current river modelling, described in Section 6, below.

The 2005 flood event was reported in the local newspaper to cause flooding to the basement of the Council Offices. However, discussion with the PCC's land drainage officer suggests that this arose from high groundwater levels rather than from overland flow paths from either watercourse. Enquiries with the Environment Agency and PCC Land Drainage team have yielded no additional information on any flooding in October 2005.

The flood event on the Cartlett Brook in 1986 resulted in flooding to the caravan park at Southwell Park, upstream of the study area, previously estimated to be approximately 8.0mAOD. No estimates of flow are available, although the event is reported to have been more severe than the 1987 event.

Enquiries have been made with both the Environment Agency and Pembrokeshire County Council Land Drainage Team with regard to reported surface water flooding. There is little information available on flooding from direct surface water flooding.

It is known that the brook draining Union Hill has a history of overtopping. Anecdotal evidence also suggests that surface water run off from Hermon's Hill has affected properties on Quay Street on the right bank of the Western Cleddau.

The Dwr Cymru Welsh Water register of properties affected by sewer flooding (DG5 record) has also been consulted. Only a single incidence lies within the study area and cannot be considered indicative of any area wide problem.

4.2 Topographical Information

Existing topographical survey of the river channels and culverted sections of the Western Cleddau and Cartlett Brook, including the top of defences has been obtained from the Environment Agency Wales. This survey was undertaken for the EAW Section 105 flood risk mapping of the Western Cleddau in early 1996 by Messrs Longdin & Browning.

We have supplemented this survey with additional river cross Sections and defence heights undertaken in January 2008 by Contract Surveys Limited. This was undertaken to better define the channel and defences between Old Mart Bridge and New Bridge at the

³ WS Atkins August 1996, Report on Mike 11 Model of Western Cleddau

northern end of the town centre, and to assist in determining potential overtopping lengths along this reach. Survey drawings are included in Appendix A.

The EAW has also supplied the following LiDAR survey data,

- Western Cleddau catchment – grid size 2m x 2m.
- Haverfordwest town centre – grid size 0.5m x 0.5m

4.3 Sources of flooding

This study has considered the following sources of flooding in Haverfordwest town centre.

4.3.1 Fluvial

The Western Cleddau River and Cartlett Brook.

Within the study area, the Western Cleddau River runs approximately north to south through the centre of Haverfordwest town centre. At the north end of the town centre, it is crossed by the A487 road bridge, and proceeding south from this point, by a further three bridges. Immediately upstream of the confluence with the Cartlett Brook is Town Weir which is the normal tidal limit (NTL) on the Western Cleddau.

The Cartlett Brook flows through two culverted Sections between its inlet at Cartlett Road, west of the rail station, and its confluence with the Western Cleddau. The first of these Sections runs from the Cartlett Road inlet to a short open channel Section in the middle of the roundabout on the A40 opposite the County Hall. The second Section runs from the roundabout under the County Hall to discharge into the Western Cleddau, immediately downstream of Town Weir.

4.3.2 Tidal

The town is considered to be at risk from extreme tide levels in the Milford Haven. The impact of tide locking of fluvial flood flows has also been investigated as part of this study.

The crest level of Town Weir opposite the Council Offices is 3.06mAOD. Significant areas of the town centre lie at ground levels of between 5.0 and 6.0mAOD. Riverbank defence levels along the Western Cleddau average some 6.3mAOD. The Quay areas on the right bank downstream of New Bridge are essentially undefended with ground levels at the riverside of generally of 4.9mAOD around Town weir. Ground levels rise west towards Quay Street to a general minimum of 5.3mAOD.

This compares to current 0.5% and 0.1% annual chance tide levels of 5.44 and 5.66 mAOD, respectively. These are estimated to rise to 6.41 & 6.64mAOD by 2107, based on current DEFRA guidance on sea level rise (see Section 5.2.2).

4.3.3 Other sources

Groundwater is not known to be a significant contributing factor in flood risk in Haverfordwest. Localised flooding of basements is possible due to changes in the underlying water table, especially adjacent to the river.

Surface water drainage, we have been made aware of only a two sources that might impact the study area – Union Hill and Hermon's Hill.

Combined sewers – Although not identified as a particular area problem, we would expect consultation with Dwr Cymru Welsh Water as part of any site specific design of foul water disposal provision. There are no works planned for the AMP works in Haverfordwest Town centre in connection with sewer flooding.

Dwr Cymru – Welsh Water do not consider that combined sewer floods is a problem within the Haverfordwest Town Centre. There are no works planned for the Asset Management plan (AMP) work in Haverfordwest Town Centre with respect to combined sewer flooding.

Future developments outside the study area, such as 1000 new properties proposed for Slade Valley would have potential surface water runoff issues. We would expect this to be controlled by the planning process to ensure that Sustainable Urban drainage systems are made a condition of a planning approval.

4.4 Flood Defences

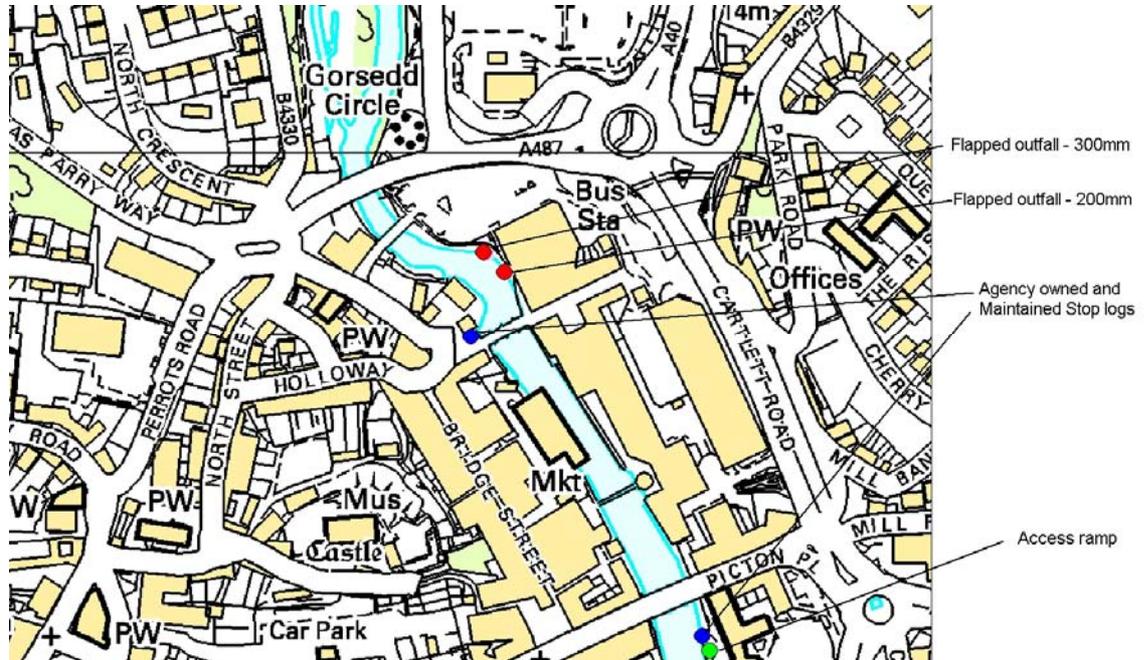
A detailed inspection of the flood defence assets in the town centre is outside the scope of this study. However, where appropriate we have made comment on the nature and visual condition of the defences.

The ongoing integrity of structures serving a flood defence function, albeit informal will impact the flood risk and flood consequences into the future.

There are Environment Agency maintained defences on the Cartlett Brook upstream of the culverted Sections.

On the Western Cleddau, through the town centre there is a range of walls and shop fronts providing a flood defence function. Environment Agency assets on the Western Cleddau are restricted to those shown in Figure 4.1. The majority of defences in the centre of the town are assumed to be in private riparian ownership.

Figure 4.1 Environment Agency Assets on the Western Cleddau



Defence levels on the Western Cleddau have been raised since 1986 as part of the development of the town centre. Some of these defences are formed by shop frontage bounding the river, and by walls of varying design in other places. An example of a Section of wall is shown in Plate 4-1, below. The ability of the wall to fulfil a flood defence function into the future is questionable.

Plate 4-1 Riverside wall right bank downstream of Wilkinsons' Access Bridge



There is no clear maintenance regime in place to ensure the integrity of flood defence along the Western Cleddau in Haverfordwest. This position should be clarified and formalised as part of any proposed development in the flood plain.

5 Hydrology & Tide Level Estimates

This Section of report presents the main results from the hydrological analysis undertaken in this study, as well as detailing the main steps involved in the analysis. The fluvial hydrological analysis involved estimating the flow hydrographs for flood events of different annual probabilities to be used as inputs into the hydraulic model. The tidal analysis involved estimating the sea level at Haverfordwest, across a range of annual probabilities. These sea levels are also used as a downstream boundary condition in the hydraulic model.

5.1 Fluvial Hydrology

Hydrographs are required as inputs to the hydrodynamic hydraulic model. These hydrographs represent estimates of the flow-time relationship for flood events of different probabilities or annual chance of occurrence.

In this study, the required hydrographs represent the 50% (1 in 2 or median flood), 1% (1 in 100) and the 0.1% (1 in 1000) annual chance events. [These are denoted QMED, Q100, and Q1000, respectively.]

5.1.1 Location of estimates

The hydrological estimates are required at two locations within the model reach, to allow for an accurate representation of the upstream flow and any lateral inflows that arise from tributaries.

Table 5.1- Location of hydrological nodes

Node	Easting	Northing	Location
1	195504	215720	Western Cleddau, at New Bridge, upstream of Cartlett Brook confluence
16	195609	215680	Downstream extent of Cartlett Brook

5.1.2 Estimation techniques

Peak flow estimates were provided by the EAW. These were prepared for the Pembrokeshire and Ceredigion Rivers Catchment Flood Management Plan (CFMP), using techniques included within the Flood Estimation Handbook (FEH). The FEH is an industry recognized technique for the estimate of flood flows at various annual probabilities of occurrence.

The Environment Agency has advised that the QMED for each watercourse was estimated using catchment descriptors, and then adjusted using donor catchments (gauged catchments with similar characteristics to the study catchment).

A growth curve was derived from a pooling group to provide sufficient data for assessment of 0.5% (1 in 200) annual chance flood event. This methodology was used to estimate flood flows, up to a 1% (1 in 100) annual chance event.

The latest Environment Agency guidance recommends using a different technique for estimating peak flows for 0.1% (1 in 1000) annual event chance flood events. The recommended technique is to use the Revitalised Flood Hydrograph (ReFH) rainfall-runoff method to estimate the 1% and 0.1% annual chance event flood peaks. The ratio between these values is then applied to the 1% annual chance event flood peak, as calculated from the FEH statistical method to yield a hybrid estimate of the peak flow for a 0.1% (1 in 1000) annual chance flood event.

5.1.3 Impact of climate change

TAN 15 recommends that the potential impacts of climate change should be considered in assessing the consequences of flooding. The latest DEFRA guidance for fluvial flows is to apply a 20% increase in peak river flows. In this study, the 1% annual chance event peak is increased by 20%. Because the 0.1% annual chance event is so uncertain, no additional allowance has been added for climate change.

Table 5.2 – Estimates of peak flows for a range of annual chance events

Node	Location	Peak flows (m ³ /s) for various annual chance events			
		50% (1 in 2)	1% (1 in 100)	1% (1 in 100) + Climate Change	0.1% (1 in 1000)
1	New Bridge, Western Cleddau	56	130	156	212
16	Downstream extent of Cartlett Brook	11	25	30	42

5.1.4 Generation of Hydrographs

The Revitalised Flood Hydrograph (ReFH) software, developed by the Centre of Ecology and Hydrology supersedes the Flood Studies Report Rainfall-Runoff method. This technique allows for a fluvial hydrograph to be generated for a specified location on a river as specified for a range of annual probability of occurrence. The generation of hydrographs requires a storm duration and profile, which can then be scaled to the peak flows discussed in Section 5.1.2. On predominantly rural catchments, such as on the Western Cleddau, flooding normally occurs in the winter season, and the ReFH methodology suggests using a winter storm profile, which is less peaky than a summer storm profile. The ReFH methodology also recommends using a critical storm duration, based on the catchment descriptors. The critical storm durations for the Western Cleddau and the Cartlett Brook are 14 and 9 hours respectively. For this assessment we used the same storm duration of 14 hours at both nodes, as if the same storm were to occur over both sub catchments. This decision does not affect the peak flows at each node, although it affects the timing of the peaks. This decision is conservative, in that it leads to a greater interaction of the flows at the confluence. Hydrographs were generated for events of the four events indicated in Table 5.2 above, and these were then scaled to match the peak flows indicated.

5.2 Sea level estimates

The downstream boundary of the hydraulic model is determined by the sea level at Haverfordwest. Three sea levels are required for the modelling. These are the Mean High Water Spring level, and the extreme sea levels that have an annual chance of 0.5% (1 in 200) and 0.1% (1 in 1000).

5.2.1 Methodology

Mean High Water Springs (MHWS) at Haverfordwest have been taken from the UK Ports Authority Tide Tables.

Extreme tide levels for Milford Haven have been estimated using techniques contained with the POL, Report 112⁵⁴. We have calculated extreme tide levels for Haverfordwest (downstream of Town Weir, adjacent to the Bristol Trader Public House) based on a comparative relationship between Milford Haven and Haverfordwest, provided by EAW.

⁴ Spacial analysis for the UK Coast: Dixon and Town; Proudman Oceanographic Laboratory Internal Document No.112.

5.2.2 Impact of Climate Change

Climate change is taken into account, by applying an allowance for the net rise in sea levels. The current DEFRA guidance (adopted by WAG, July 2007) for Wales is to assume sea level rises of

- 3.5mm/year from 1990-2024,
- 8mm/year from 2025 to 2054,
- 11.5mm/year from 2055 to 2084, and
- 14.5mm/year from 2085 onwards.

These increases predict a 300mm increase in the next 50 years and nearly 1m over the next 100 years.

The estimates of surge tides at Haverfordwest are presented in the table below, including the impact of seal level rise.

Table 5.3 – Sea levels at Haverfordwest

Sea level event	Extreme sea level at Haverfordwest	
	Year	Level (mAOD)
Mean High Water Spring	2007	3.72
	2057	4.05
	2107	4.70
0.5% (200 year)	2007	5.44
	2057	5.76
	2107	6.41
0.1% (1000 year)	2007	5.66
	2057	5.99
	2107	6.64

6 Hydraulic Modelling

6.1 Introduction

To inform our assessment of flood risk to the Haverfordwest town centre we have carried out hydraulic modelling of the Western Cleddau and the Cartlett Brook. Based on our initial assessment of the study area we believe that when the river banks are overtopped there will be an interaction (mixing) between overtopping floodwater from the Western Cleddau and the Cartlett Brook. A conventional one-dimensional hydraulic model cannot simulate such a flow mechanism appropriately. Therefore, a 1D/2D (dimensional) hydrodynamic model of the Western Cleddau and the Cartlett Brook has been developed using the ESTRY and TUFLOW software packages.

The ESTRY and TUFLOW software packages are widely used in the UK (and worldwide) for flood modelling. A combined 1D and 2D dimensional model means that the river channel and flood plain are dynamically linked, such that the exchange of floodwater between the river and its floodplain can be modelled effectively.

6.2 Geographic Extent of the Hydraulic Model

The main aim of the study is to assess flood risk to areas of Haverfordwest town centre, both currently and over the anticipated lifetime of potential developments in these areas.

The extent of the study area and the location of the river cross Sections used in the hydraulic model are presented in Figure 6.1.

Table 6.1 Hydraulic Model extents

River	Model extent	Location	Ordnance Survey National Grid Reference (OSNGR)
Western Cleddau	Upstream	200m upstream of Bridge Meadow Football Ground	195336, 216863
	Downstream	350m downstream of confluence with Merlin's Brook	196330, 214848
Cartlett Brook	Upstream	350m downstream of Shoal's Hook level crossing	196678, 216572
	Downstream	Confluence with the Western Cleddau at County Hall	195544, 215543

6.3 Model Construction

6.3.1 Site Visit

In order to gain a more complete understanding of the river system, a walkover inspection of the study area was undertaken in January 2008. This assessment concentrated on the estimation of hydraulic roughness of the channel, banks and floodplains, inspection of structures, and assessment of probable overland flow paths. The continuity of the natural banks and artificial defences were also noted.

Figure 6.1 Cross Section locations in 1D model of Western Cleddau & Cartlett Brook, Haverfordwest



6.3.2 Model Geometry

The Environment Agency has made its Section 105 HEC-RAS model of the Western Cleddau and Cartlett Brook available for the current study. The geometry of the river channels has been extracted and the in-bank cross-section data of the Western Cleddau and Cartlett Brook has been imported into the 1D ESTRY model of the river channels. The information on hydraulic structures such as bridges, culverts and weirs were also taken from the HEC-RAS model and incorporated within the current model.

The two-dimensional (2D) TUFLOW model is based on a Digital Elevation Model (DEM) of the area. Un-filtered LiDAR data has been used to generate a DEM on a 5m x 5m computational grid of a floodplain. Minor changes to the ground profile may have occurred since the LiDAR survey, however, it is not considered that these changes would make significant difference to the modelling results. Using an un-filtered data ensures that the elevation of man made objects such as buildings, roads etc. are taken into consideration.

6.3.3 Bridges, Culverts and Weirs

The study reach of the Western Cleddau consists in total of 8 bridges and 1 broad crested weir. The Cartlett Brook consists in total of 1 bridge and 4 culverts. The schedule of these structures is given in Table 11.2, Appendix Appendix A: with Section references identified on Figure 6.1

The bridges have been modelled using height varying loss coefficients. Flow constrictions will occur if the bridge opening area is not sufficient to pass the maximum flood discharge. Bridge piers, eccentricity and skewness also restrict the flow. These factors are taken into account using a loss coefficient. A higher value loss coefficient implies higher restriction to the flow through bridges. We have derived the loss coefficients used in the model by reference to the FHA's⁵ *Hydraulics of Bridge Waterways* and the TUFLOW manual⁶. Culverts are modelled using contraction, entry and exit loss coefficients. Standard recommended values are adopted for these coefficients as given in Table 11.1 in Appendix Appendix A: .

The Town Weir is modelled as a broad-crested weir using standard weir flow formula (*Hydraulics of Bridge Water Ways*).

6.3.4 Roughness Coefficient

Manning's coefficient was used to represent roughness along rivers and its floodplain. Along the main channel, a constant Manning's coefficient of 0.045 was used. For the floodplain, the Manning's coefficients used were based on the land use pattern. The different land use patterns were extracted from the OS Master Map data provided by the client. A walkover survey of the site was undertaken to assess the roughness coefficient. The values used were adopted following site visit and by referring to Chow (1959) *hydraulics text book*⁷ and the TUFLOW manual. The values adopted are given in Table 11.3, Appendix Appendix A: .

6.3.5 Ground Model Grid Size and Time Steps

The 2D model of the Western Cleddau and Cartlett Brook is based on a 5m x 5m computation grid. The ground model is based on the unfiltered LiDAR level data provided by the EAW (see Section 4.2, above). Changes were made to the model in locations

⁵ U.S. Department of Transportation, Federal Highway Administration (US FHA 1973) *Hydraulics of Bridge Waterways* Hydraulic Design Series No. 1, Second Edition.

⁶ BMT WBM Pty Ltd (July 2007) TUFLOW User Manual – GIS Based 2D/1D Hydrodynamic Modelling, July 2007

⁷ Chow, V.T. (1959) *Open Channel Hydraulics* McGraw-Hill.

where it was known that flow paths would not be reasonably represented. These changes comprise:

- Footbridge over A40 Cartlett Road – removed to allow flow along road
- Elevated bridge connection between Pembs Council buildings removed to allow flow between buildings
- Modern arch over road connection between Swan Square and Market Hall service area – levels lowered to road level either side of roof
- It is understood that an overland flow path was constructed as part of the County Hall office development to direct out of bank flow from the Cartlett Brook. A flood gate (referred to as stop logs in Figure 4.1 in Section 4.1) exists in the defence wall in front of the Council Offices to allow flood water from the overland flow of the Cartlett Brook to drain into the Western Cleddau. This gate is assumed closed in the model, as it is likely that in a flood event river levels would be elevated in the Western Cleddau. Its function is assumed to be to assist in draining flood water after floods.
- Similarly, details of an overland flow path under the County Hall building, were not available at the time of the study. The model allows overland flow paths to only develop around and not through the building.

As part of the walkover survey for the hydraulic model construction, it was noted that a Section of raised wall adjacent to the Ebenezer Road car sales lot on the right bank downstream of Old Mart Bridge (access bridge to Wilkinson Car Park) was not of a standard considered appropriate for an engineered defence (see Plate 4-1). This was excluded from the geometry used in the hydraulic modelling. The defence level in this area has effectively been reduced for the purposes of the modelling, reducing the levels in the model from some 6.3mAOD to 5.7mAOD, the level of the ground behind the wall.

A time step of 1 second is used for both the 1D and 2D computations. This means that the floodwater depth and velocities are calculated every 1 second for the entire duration of inflow hydrographs. This produces a stable model for which run times are completed within suitable durations and which provides the required level of accuracy for this strategic level study.

6.3.6 Initial and Boundary Conditions

Boundary conditions are applied at both the upstream and downstream end of the model. An “Inflow versus Time” boundary condition is applied at upstream end. A “Head Versus Time” boundary condition is used at downstream end to reflect the fluctuations in tide levels. A water elevation of 3.7mAOD was used as an initial boundary condition.

6.3.7 Design Flood Events (Fluvial and Tidal)

The Western Cleddau is tidally dominated at its downstream extent. Therefore, combinations of fluvial and tidal events have been considered as presented in the table below. The predicted increases in sea level and fluvial flows have been accounted for in the modelling of the scenarios for 50 years’ and 100 years’ time.

Table 6.2 Range of fluvial and tidal flood events tested

Flood Event Scenario	Assessment Year	Fluvial Flow (cumec.)	Tidal Level (mAOD)
		WC - W. Cleddau CB - Cartlett Brook	
1% chance fluvial (Q100) routed against a MHWS tide	2007	W. Cled – 130	3.72 – MHWS
		C Brook - 25	
	2057	W. Cled - 156	4.05 – MHWS
		C Brook -30	
	2107	W. Cled - 156	4.70 – MHWS
		C Brook -30	
Medium flood routed against 0.5% chance tidal (T200)	2007	W. Cled – 56	5.44 - T200
		C Brook – 11	
	2057	W. Cled - 67	5.76 - T200
		C Brook – 13	
	2107	W. Cled – 67	6.41 - T200
		C Brook - 13.	
0.1% chance fluvial (Q1000) routed against a MHWS tide	2007	W. Cled – 212	3.72 – MHWS
		C Brook – 41	
	2057	W. Cled – 212	4.05 – MHWS
		C Brook – 41	
	2107	W. Cled – 212	4.70 – MHWS
		C Brook – 41	
Medium flood routed against 0.1% chance tidal (T1000)	2007	W. Cled – 56	5.66 - T1000
		C Brook – 11	
	2057	W. Cled - 67	5.99 - T200
		C Brook – 13	
	2107	W. Cled – 67	6.64 - T200
		C Brook - 13.	

6.4 Calibration and verification

No level information, such as surveyed trash marks, associated with historic flooding events is known to exist.

The last significant flood for which any significant overland flow information is available is the event of October 1987. Since this time, significant changes in development have taken place along the banks of the Western Cleddau through the town centre, increasing river bank including defence levels. It was not felt that any calibration information could be extracted from this event.

6.4.1 Comparison with previous modelling of the Western Cleddau

Comparison has been made of the river levels predicted using the Environment Agency's existing steady state HEC-RAS model of the Western Cleddau and the ESTRY model used for this study.

The Town Weir is a critical control structure on the Western Cleddau. The assumptions used in modelling this structure will affect the upstream water levels. The Environment Agency's steady state HEC-RAS model appears to use a default weir coefficient and so takes no account of the loss in conveyance over the weir associated with the fish pass structure. As discussed in Section 6.3.3, above, an allowance has been made in the current modelling for the fish pas structure.

7 Results of modelling

7.1 Presentation of Results

The study area of the town centre has been divided up into the sub areas A to H as described in Table 2.1 Section 2.1.

The mechanisms of flooding are described qualitatively in Section 7.2. The quantification of the consequences of flooding are presented in Sections 8.1 and 8.2 as Figures and Tables, the formats of which are described below.

7.1.1 Figures

The combined flood outline for the 1% fluvial and 0.5% tidal flood events are presented in Section 8.1. Three figures are presented which show the outlines in the existing situation, in 50 years' time and 100 years' time (Figure 8.1 to

Figure 8.3).

Two sets of Figures showing respectively, contours of the maximum depth and maximum velocities for the 0.1% annual chance events (maximum of tidal and fluvial events in each case) are presented in Figure 8.4 to Figure 8.9.

The contours are coloured coded to denote failure or pass of the acceptability criteria for either maximum depth or maximum velocity as defined in TAN15. (see Table 2.2 and Table 2.3 in Section 2.1.2 for indicative values).

- BLUE denotes an area passing the criterion displayed for any type of development
- AMBER fails for residential development but passes for non-vulnerable development
- RED fails for all types of development

7.1.2 Tables

Tables are presented in Section 8.2.2. These include the existing situation, in 50 years' time and in 100 years' time. The TAN 15 acceptability criteria for maximum depth and maximum velocity of flow are listed by each sub area. The tables are colour coded such that:

- GREEN indicates that the whole of the area complies with the criterion indicated for that type of development.
- AMBER indicates that part of the area fails and part passes the criteria.
- RED indicates that the area fails the criteria for the type of development indicated

7.2 Mechanisms of flooding

The interaction of the sources of flooding is complex. However, the mechanisms of flooding to each of the sub areas of the town can be simplified and broken down to identify the main mechanisms. This is described below. The magnitude of the consequences of the flooding is detailed in Sections 8.1 and 8.2.

Note that the magnitude of the tidal flooding will be conservative as a fixed tidal level has been assumed over the duration of the tide cycle rather than a varying level. The depths and velocities will be upper bound estimates.

In order of which mechanisms occur first:

7.2.1 1% fluvial event

1. The Cartlett Brook overtops its banks upstream of the inlet to the culvert at Cartlett Road (the more upstream of the two culverted Sections).
2. Overland flow paths are developed in a northerly direction along the A40, in the direction of Areas A & B and west into car park of County Hall.
3. Limited overtopping of the Quay area on right bank of Western Cleddau upstream of the Town Weir

7.2.2 0.5% tidal event

1. Tide level (5.44mAOD) in Western Cleddau surcharges the outlet of the culvert (soffit - 4.37mAOD) of the Cartlett Brook. As a result overtopping occurs of the open channel Section in the centre of the roundabout outside County Hall.
2. Water from the above flows north along A40 in direction of Areas A & B, extending into Wilkinson's Car Park area. This source also affects the car park of County Hall.
3. Tidal flood level overtops the right bank of the Western Cleddau in the area of New Quay upstream and downstream of Town Weir.
4. The Cartlett Brook overtops its banks upstream of the inlet to the culvert at Cartlett Road (the more upstream of the two culverted Sections).

7.2.3 0.1% fluvial event

1. Overland flow path origination from the centre of the A40 roundabout (Cartlett Brook) inundates Areas A, B and C.
2. The Cartlett Brook overtops its banks upstream of the inlet to the culvert at Cartlett Road (the more upstream of the two culverted Sections).
3. Western Cleddau overtops the right bank at New Quay, upstream of Town Weir.
4. Western Cleddau overtops its left bank upstream of Old Mart Bridge into Wilkinson's car park. The overland flow path from the Cartlett Brook along the A40 now reverses such that flow is south from Area A to Area C.
5. Western Cleddau overtops the right bank at the Old Quay area, downstream of Town Weir.

7.2.4 0.1% tidal event

1. Overland flow path origination from the centre of the A40 roundabout (Cartlett Brook) inundates Areas A, B & C.
2. Overtopping right bank of Western Cleddau at New and Old Quay areas, upstream and downstream of Town Weir.
3. The Cartlett Brook overtops its banks upstream of the inlet to the culvert at Cartlett Road (the more upstream of the two culverted Sections).
4. Overtopping of right bank of the Western Cleddau at the Priory.