Flood and the energy industry
how to quantify the true risk of flooding?

Oliver Peterken and Matthew Foote, Willis Consulting Limited

Oil, Petrochemicals & Energy Risk Association (OPERA)
Natural Perils relevant to Energy Insurance Risks seminar

25 September 2001, London

Willis

Flood and the energy industry – how to quantify the true risk of flooding?

Introduction

"The only asset was oil, ready to flow. There was no refinery and no means of getting the oil to the refinery site - ten kilometres away, across swamps and flood-plains and through the dense, intractable, ever-growing jungle. A path had been hacked through the jungle and a sort of tramway put in place, along which (so the idea went) barrels of oil could be carted. But floods had washed away parts of the line. Kessler [the second president of Royal Dutch] *threw out the idea and instead began laying a pipeline, working alongside the hired Chinese labourers waist-deep in water and in the pouring rain."*

The above extract, from a history of the then Royal Dutch oil company (Shell, 2001), highlights the importance of flood risk throughout the history of the energy production industry. The need for large amounts of water for cooling and as a raw material as well as the obvious advantages to petrochemical and energy producers of siting on coastal and riverine floodplains makes the energy industry susceptible to flood risk on a global scale.

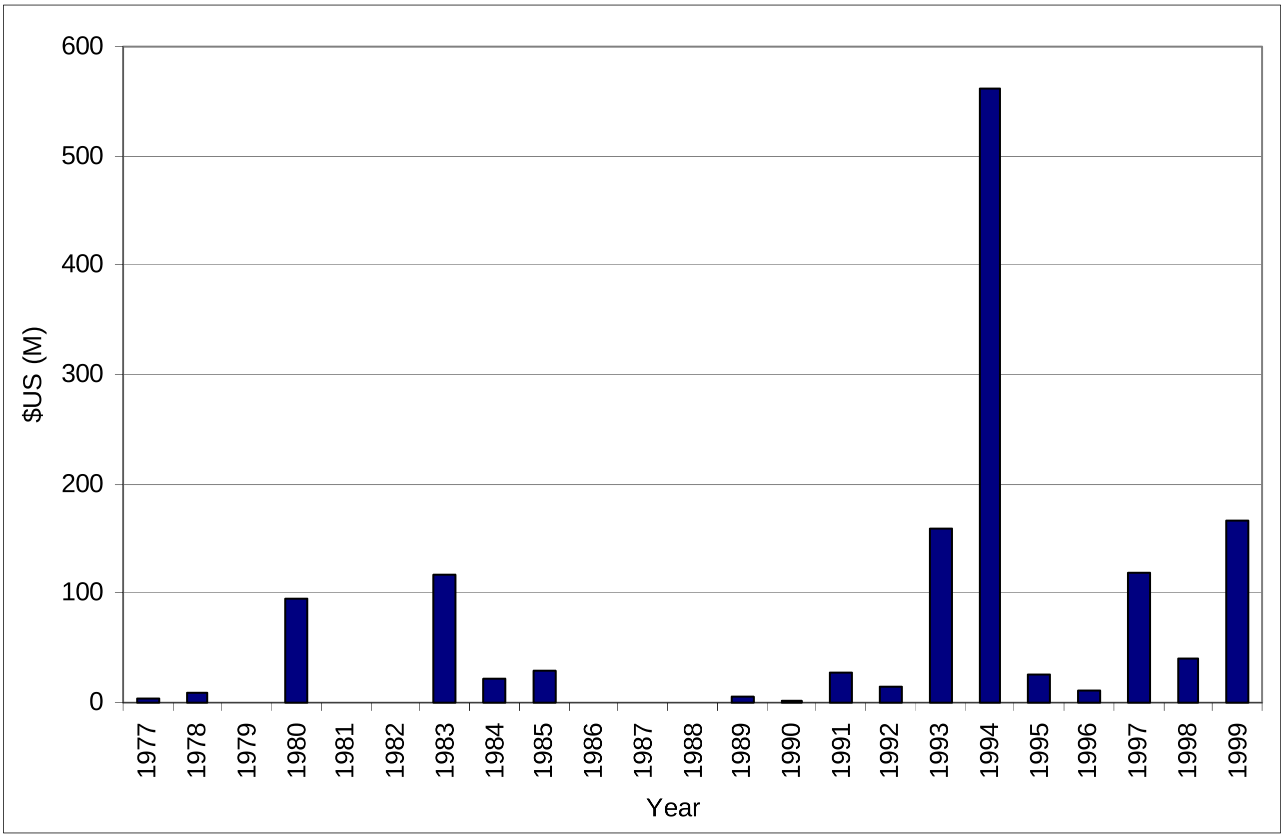
In comparison to other hazards such as vapour cloud explosion, flood is not considered a 'maximum' loss hazard for most energy installations. In many cases, sensitive production or distribution sites, when considered to be at risk from flooding, are protected by engineering structures such as dikes or drains which may act to reduce the perceived risk to the assessor.

However, recent events, as described in this paper, make it clear that flooding can be a serious risk to the industry across all sectors, particularly in locations where large aggregates of exposure exist and even where engineered defences and risk assessments have been implemented. The future potential for significant changes to the magnitude and frequency of flood events due to forcing factors such as climate change may also increase the relative risk to energy insureds and it is in this light that a re-assessment of the risk from flooding should be made.

Global flood risk and energy industry exposure

Flood losses have increased globally across all sectors, contributing up to a third of all world natural disaster losses, whilst energy sector flood losses (greater than $US 1 million) have also increased significantly (figure 1).

Figure 1 - Annual energy sector losses (greater than $US 1million) reported to be caused by flood



Source: Willis Energy Loss Database

This apparent increase can be attributed to many factors, including the potential issues arising from climatic change, an increased development of energy infrastructure on flood-prone areas and an increase in risk transfer from governments to insurers. Each factor is difficult to isolate. This is due to the inter-dependence of each to the other and the uncertainties underlying the assumptions made about each.

It is therefore important that the risk of flood to an insured property can be quantified to an acceptable level of accuracy. In order to do this, engineers and risk analysts use numerous techniques, including statistical flood frequency analysis and geographic flood risk modelling.

Flood definition

As with all natural perils, the key to accurate quantification of flood risk is a sound understanding of the causes of flood events. The term ‘flood’ encompasses a large number of physical processes not all of which can be viewed as a risk. A general definition of a flood is:

> ‘ A body of water which rises to overflow land not normally submerged’ (Ward 1978).

However, this does not differentiate between sources of floodwaters nor the effects that such processes may have on the affected land and property. This involves not only the hydrological processes but also the character of the land over which the floodwaters travel and which combine with other controls to define the floodplain. In order to adequately assess the true risk of flood to an insured property, whether that property is an individual household or a large petrochemicals complex, it is essential that the risk assessor is aware of the factors as well as the methods used to define and quantify that risk.

Historical data for flood risk assessment

Historical records of flood events are perhaps the simplest means of determining the magnitude and location of flood events. Many countries will have archives of flood maps and other historical accounts, which may be used to identify risk areas. Historic flow gauge records or in some cases headwater and tailwater levels at locks and other engineering structures can be supplemented with less quantitative accounts to produce records of use for some of the more major rivers and coastal areas. Past claims information and engineering data are also of value for historical flood risk analysis.

However, the use of historical datasets as a primary source of flood risk information is problematic in as much that past events cannot necessarily be used in a reverse of James Hutton’s famous geological postulation[1], to provide the exact key to the future. This is especially true of the relatively short time scales of human flood observation and recording and of the average defence design lifetime of around 50 to 75 years. It is important to recognise that many historical records of flood extent reflect the complex nature of the flood plain at the time of the flood event. Changes in land use, flood defences and bridges within the floodplain can significantly influence the extent and magnitude of flooding in a particular area. In many cases, it is also difficult to accurately define the frequency of occurrence of a historical event due to the complex interdependence of climatic, geomorphological and human factors which can significantly vary the response of a catchment to flood. The patchy and variable nature of historical records also makes them a secondary rather than a primary data source.

Computational and geographical modelling techniques for risk assessment

Hydrologic and geographic modelling techniques have been used to provide a quantitative means of assessing flood risk. Models are available with varying degrees of complexity and as a general rule of thumb, the more complex the computation, the more input data required and the greater the computational resource necessary to produce the result. It must be pointed out that there is no ‘correct’ flood risk zone. All models include errors and assumptions and these errors are introduced at each stage of the flood modelling process. It is essential that the risk assessor or surveyor responsible for the flood risk assessment is aware of the limitations surrounding each modelling methodology and that these errors and their aggregate impact can be reported to the user in a way that allows a rational assessment to be made. In many cases this can be difficult due to the sheer number of uncertainties and in many cases, unknowns of the modelling process.

---

[1] Hutton’s statement that ‘the present is the key to the past’ underpinned the theory of uniformitarianism, which states that geological processes operating now are identical to those which have shaped the earth during its history and can therefore be used to explain relict landforms and other geological features.

Geographical modelling

Flood is an inherently spatial problem and all of the input data sets are spatial. Geographical Information Systems (GIS) are valuable tools for producing the required spatial data, visualising the impact of a flood over a floodplain and also provide a means of analysing the effect of the flood on the assets at risk through spatial co-location and geographic analysis. They may also be used as a modelling tool in their own right through use of the same spatial component. Some research has been done to develop dynamic flood models using GIS (see for example, Conseguera et al 1995), although the data structure and standard algorithms may be regarded as non-optimal for detailed flood modelling problems.

'Static' flood modelling, where the water level is raised to a height above the terrain based on a computed water height within the river channel, calculates water height without the movement of water across the floodplain. This has been used successfully to define coarse flood risk zones for a number of locations (see for example, Morris and Flavin 1996, Sanders and Tabuchi, 2000). Static flood models have the advantage that they provide flood risk zonation over large areas relatively quickly, as long as the relevant input data are available and are of acceptable quality. They do not, however, take account of detailed flood flows or of any flow barriers or changes in flow retardation across the floodplain and can therefore result in an over-estimate or misplacing of the flood risk extent where such factors could retard flow and channel it in specific directions. As with other, computational models, the GIS approach requires detailed data to make any assessment of flood risk useful.

Computational hydraulic modelling

Computational hydraulic models are used to predict both water flow (measured as a velocity) and water level (depth) over a range of scales and applications and parameterise the hydrodynamic character of the flood to varying degrees of sophistication. Their use is not confined to site-specific projects but are also used in the provision of regional flood risk assessments where applicable.

Within the choice of steady or unsteady flow, the flood hydrograph is modelled using a variety of means, which provide varying levels of complexity to the solution of the open channel equations (Dingman 1993, Bates and Anderson 2001). Recently models have included GIS to visualise the resulting flood envelopes in plan.

The dimensionality of a computational model also determines its complexity and hence the level of computational power and system resource required to operate them. In all cases, the calculated numerical solution to the flow is linked to information describing the surface such as a digital elevation model.

There is, as with all models, a trade-off between process complexity and the resolution of the result.

- 1-dimensional models have traditionally been employed for flood modelling at the medium scale (for instance to model medium sized urban and rural catchments). They utilise the 1-dimensional open channel flow continuity equations to varying levels of complexity to determine both channel water levels. Cross-sections across the flood plain are used to define water levels and flood envelopes at defined intervals along the streamline. They average flood water flow by area and through the water column.
- 2-dimensional models have traditionally been used to predict flow velocity and other hydraulic parameters for large-scale (small area) problems and projects such as the design of new flood structures. They employ depth-averaging velocity calculations to determine the discharge rate between 'cells' or nodes across a model surface. They describe flow in x and y components and therefore do not average aerially.

- 3-dimensional models are the most computationally intensive and are often used to predict velocities around structures and as inputs to other models such as sediment budget calculators, engineering systems models and other programmes. They include parameterisations for advected turbulence and other hydrodynamic factors.

With all models, the quality and applicability of the result is defined by the quality of the data used within it. All flood risk analysis models require data describing the following factors to some extent.

Hydrological inputs

Dependent on the form of the model being developed, the hydrological input can be records of precipitation, sea levels and tidal predictions, river flow information (either headwater / tailwater stages or stream discharges) or a combination of these. As mentioned previously, in many cases, these will be empirically based records of observed phenomena, such as stream or rainfall gauge records. As such, they may also be subject to the same problems of availability, system interdependence and record length of any other historical records. In many cases, records will be collected for a small number of river reaches or coastal locations. In order to apply the often short records and sparse observations, many techniques can be employed. For coastal data, storm surge models may be developed which calculate maximum likely flood elevations from tidal and wave data, ocean basin models and meteorological predictions. For river data, ‘regional’ models such as the UK Flood Estimation Handbook (Reed et al, 1999) or the US Geological Survey (USGS) (Dingman, 1994) can provide estimates of water peak for a given frequency of occurrence based on empirical relationships developed by regression analysis between catchment characteristics and measured water heights. Such regional relationships can then be applied to catchments where gauge data are unavailable. Other techniques, such as continuous simulation, attempt to make up for the lack of extreme event, low frequency flood data (Calver et al 1999, Cameron et al 2001) through synthesis of rainfall records using generalised linear models (GLMs). Some work has been undertaken to apply a similar technique to UK flood risk in an attempt to create ‘event specific’ flood risk maps based on stochastic rainfall models. However, the lack of available calibration information (particularly radar) and the unavailability of detailed flood defence data makes use of such techniques difficult at the present time (Lamb and Calver 2001, Chandler et al 2001).

Catchment and floodplain characteristics (the physical environment)

Of equal importance to computational and geographic models are data that describe the characteristics of the catchment and which influence the form of the flood hydrograph as it travels through the drainage system, as well as the extent and depth of the resulting flood. The choice of modelling methodology will also determine the amount of catchment and floodplain data required to calculate flood risk. For instance most 1-d and 2-d computational models require data on channel and flood plain cross-sectional areas, defence height and position, drainage and pumps as well as a general assessment of terrain elevation in order to carry out the flood routing and depth assessment.

Of particular importance is the terrain model used to define the topography of both the catchment and the floodplain. Propagation of the resulting flood wave is controlled by the shape of the earth surface and therefore the terrain data used should fit the purpose intended and be described in terms of its accuracy. Digital terrain and elevation models (DTMs and DEMs) provide a computer-readable definition of the land surface as a mesh of discrete elevation measurements above a datum. Until recently, most terrain information was derived from national mapping sources or from specially conducted surveys of localised areas.

Difficulties with consistency, data accuracy and the costs of producing the data meant that most hydraulic models were produced using relatively poor quality terrain information, with vertical errors of around +/- 2.5m to +/- 5m. Recent advances in airborne data collection techniques, most particularly laser scanning (LIDAR) and interferometric synthetic aperture radar (IfSAR) have provided terrain data with consistent, high vertical and horizontal accuracy (table 1) over relatively large spatial areas.

In the past these data would be captured from ground survey or aerial photogrammetry at large cost and lower vertical and horizontal resolution. For the energy industry, it is important that the terrain data collected is of applicable accuracy and coverage for the problem at hand. In many cases, a detailed ground survey of the insured property and associated risks and defences is essential to ensure that the local risk is properly identified. However, it is also important that an accurate regional risk assessment is conducted in order to gauge the risk around the site, which may have a significant impact on the overall risk analysis. This is especially true of areas where there may be a large aggregate risk or risk to structures which are not protected by the main insured site defences.

Table 1 – comparison of terrain data collection systems

Data collection technique	Relative cost	Vertical resolution	Horizontal resolution	Comments
Ground survey	High	Medium – high	Medium – low	Requires significant personnel resource / inconsistent over large areas
Aerial photogrammetry	High	Medium – low	Medium – low	Expensive data collection and processing
Airborne laser scanning by LIDAR	Medium	Medium – High	Medium – high	High resolution, relatively difficult to process
Airborne inteferometric synthetic aperture radar (IfSAR)	Medium – low	Medium (improving)	Medium – high	Consistent resolution – poor data collection in high rise urban canyons

As with all data, terrain models, however they are collected, contain errors which must be quantified in order to allow a valid risk assessment to be made. These errors are the result of a number of factors, most notably sensor or operator error, post-processing errors such as conversion to a local map projection and geoid, as well as errors due to signal noise and sampling area. Most digital terrain models will report the range of uncertainty by means of a ‘root mean square’ error (RMS error). This provides a single value of the expected error range calculated as the square root of the difference of values compared to a validation dataset. RMS error is also used in many cases to describe the quality of other digital map data, such as bridge and building positions. It can also be used to provide a ‘fuzzy’ estimate of flood risk through the calculation of three different depth or waterline values, based on the reported value and values at the two RMS error ranges about that value (figure 2). Uncertainty may also be reported through similar error bands for the flood depths calculated by the hydrological model or historical dataset. It should therefore be possible to produce bands of uncertainty around the reported flood envelopes, which take into account all major sources of model error (table 2). The error bands will vary in size and location dependent on a number of factors, including local terrain slope, as the shallower the slope angle, the wider the potential error band for a given vertical uncertainty.

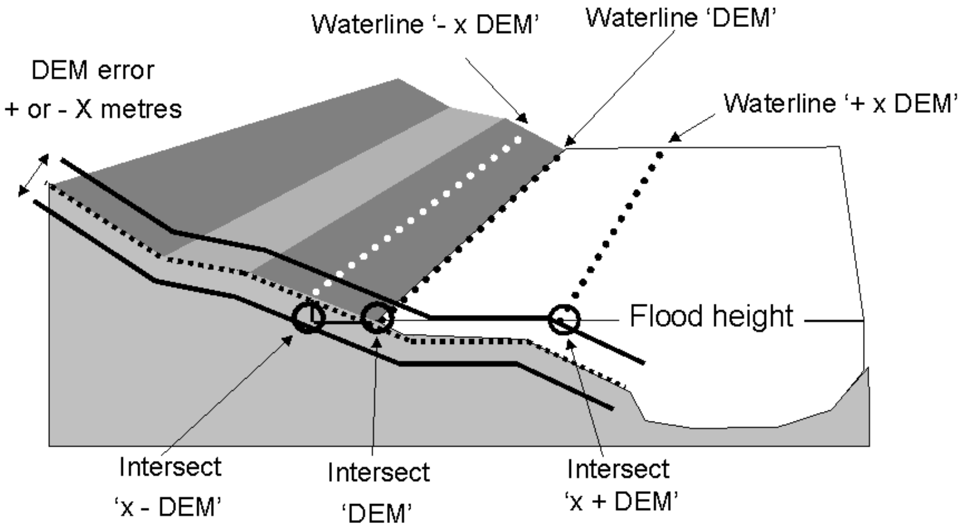


Figure 2 – DEM error and its effect on flood risk delineation. Three flood/surface intersections are possible using the mean and extreme terrain error bands around it as separate surfaces. The two extreme values define the planimetric band of uncertainty of the terrain model. A similar uncertainty band exists for the flood height data.

Other errors may be introduced into the modelling process through more elementary, human means, including the wrong choice of model for the study area or available data (table 2). Whilst it is not essential for the risk assessor to be a trained hydrologist or geomorphologist, it is recommended that they are fully aware of the source of any flood risk assessment, including the type of model used, the source and currency of data used and the boundary conditions chosen. One other, less publicised difficulty in flood risk assessment is the tendency for engineering studies to concentrate on the freeboard design of defences but to ignore the potential impact of flood in areas around the defended site, including additional infrastructure such as pipelines or other transportation / delivery networks.

Table2 – major error sources within flood risk mapping

Error source	**Examples**	**Impact and mitigation**
Data		
Hydrological input data	Short gauge records, wrong statistical distribution function used, lack of extreme events within observed records, sparse geographical coverage of gauges, lack of calibration data for gauged/ungauged catchment analysis.	Potentially high, may be mitigated by generation of synthetic records or regional flood frequency analysis. Errors may be quantified and reported as error bands around extreme values.
Meteorological input data	Short time series, poor spatial resolution, inapplicable to local sites, lack of calibration, validation data for stochastic models.	Potentially high if used as a core input data set (e.g. for non-riverine overland flow floods).
Terrain data	Horizontal re-sampling too large for stated vertical accuracy, geodetic correction errors, systematic and random sensor errors, inconsistent scale and quality, lack of coverage, poor 'bare earth classification', urban canyoning effects.	Medium to high – if uncertainties are catalogued can be used to generate error bands around risk zones. Error likely to be higher in low gradient areas such as floodplains. Urban canyoning can severely reduce the accuracy of airborne DTMs in built up areas. Requires independent validation datasets and should be properly recorded.

Error source	Examples	Impact and mitigation
Data		
Flow modification structures	Inconsistent coverage, lack of detailed hydraulic information, spurious flow retarding structures from DTM	Lack of hydraulic structure information can affect the resulting flood flow model. DTM information from airborne sensors may be mis-classified as retarding structures. Some models will not operate without adequate structural information.
Flood defence data	Poor spatial resolution, unavailability, out-of-date surveys, lack of accurate failure data	Flood risk maps using defence data provide a different ‘100 year’ risk to maps not using defence data. This should be made clear to the risk assessor.
Exposure data	Poor resolution, lack of detail, different scale to model results, out-of-date data, wrongly located data, damage and loss curve availability and applicability.	Essential to the model results – the resolution of available exposure data will determine the type of model most applicable.

Error source	Examples	Impact and mitigation
Modelling		
Flood frequency analysis	Invalid statistical relationship used, regional frequency model not valid for un-gauged catchments, lack of calibration / validation data, short historical datasets skewing extreme values.	Potentially very high – ranges of water heights should be used to delimit uncertainty bands around flood height estimates.
Flood event definition	Stated return period of hydrological flood height may not be the return period of the loss or the flood extent. ‘Defence included’ vs ‘defence omitted’ modelling results in different flood footprints. Return periods are sensitive to length of the historical record, outlier flood heights and changes in forcing factors, e.g. climate change, land use, river defences.	Very high impact. The stated frequency of event occurrence will be specific to the type of event being referred to. Most hydrological models, for example storm surge models or river flood stage frequency models, are highly sensitive to either record length or the parameters chosen to determine the flow characteristics. Validation data is essential.
Parameterisation error	Over-parameterisation or complete removal of key hydrodynamic processes e.g. depth and area averaging, routing models, static geographic flood models.	Potentially high – dependent on required use, available data – essential for risk analyst to be aware of model type used for risk assessment and parameterisations included. For instance, if flood scour is an important risk, velocity is an important hazard factor and the model chosen should be a 2-d or 3-d.
Equation error	Inaccurate coding of the model equations.	Less important if recognised and validated modelling systems used, more important if the flood modelling is bespoke.

Error source	Examples	Impact and mitigation
Modelling		
Conceptual error in system description	Incorrect assignment of floodplain routing model, inaccurate description of flood flow system e.g. structure definition, water retention systems, etc. Incorrect selection of input parameters and boundary conditions.	Potentially high impact. Incorrect selection of input and boundary conditions may render model results invalid.
Calibration error	Lack of available data for independent calibration, validation. Validation datasets may not be applicable to the task, e.g. 1947 Thames flood maps are not ‘100-year’ event maps.	High – can invalidate the whole model.
Inconsistent coverage and model result mosaicing	Amalgamation of results from different models, lack of model availability across whole floodplain, temporal variation in models.	Potentially high – can result in spurious assessments, lack of data in important areas, especially if developed after models have been produced.

Definition of risk and the assessment of extreme event frequency

One area which can commonly confuse in a flood risk assessment is the definition of event frequency. In many cases, a 'return period' flood event is used to define flood risk frequency. The technique provides a probability of a river or coastal water level to be reached or exceeded, on average, on an annual basis. A '100-year' return period event is therefore the event which has a one percent chance of being equalled or exceeded in a given year and is therefore not an 'average' value.

It is important to note that the 'return period' is calculated from the best available estimates of peak flow at a particular point along a water course or coastline and can be highly influenced by the length of the record being analysed and the events that it records.

It is also important to distinguish between event and loss return periods. Event return periods refer to the probabilities of the natural hazard occurring at different levels of severity. This is not the same as loss return periods which are the exceedance probability for a given monetary amount of loss. Loss return periods are calculated by simulating losses to property profiles across a large number of hazard scenarios to create a loss exceedance curve. A loss return period is therefore the result of a large number of hazard events, each with their own probability.

Whilst an assessment of flood modelling methodologies such as this is of use to the risk analyst when interpreting the results of models, it is also important to realise that errors or omissions may be the result of inadequate knowledge or to the inadequacy of structural design codes in the risk area. Structures may be constructed to the required standards, but may still be at risk from unforeseen flood-related events such as scour from high-velocity flood waters.

A number of events can be chosen to illustrate where an inadequate assessment of risk has resulted in a significant loss to the energy industry. Case studies of the San Jacinto flood in 1994 and the Blayais nuclear power station in December 1999, provide examples of where a lack of detailed information, inadequate records and an aggregation of exposure not considered at risk in a confined area have contributed to a significant flood related damage.

Case study 1 – the San Jacinto flood, October 1994

The San Jacinto catchment in Texas drains an area of approximately 14,500 square kilometres. The catchment is located within the Texas Gulf Coast area and drains into Galveston Bay. Much of the coastal area is low-lying marshland or floodplain. There are two major lakes, Lake Houston and Lake Conroe, both of which act as flood water reservoirs along the main stream. The area is subjected to frequent flooding, due mainly to tropical weather systems over the summer and autumn period (table 3). The river itself is heavily managed, including channelisation of meanders and the thinning of the river due to bridges and other river structures. The geomorphology of the floodplain had also been significantly modified by sand and gravel extraction before the 1994 event.

Table 3 – reported floods between 1907 and 1978, San Jacinto basin

1907	1929	1932	1935	1940	1941	1942	1943	1945
1946	1949	1950	1959	1960	1961	1972	1978	

Source: NTSB special investigation report PB96-917004

The catchment includes much of the city of Houston, as well as the industrial-economic infrastructure of the Houston area (figure 3). Up to 400 exploration firms and 30 pipeline operators are concentrated into the basin with a number of major pipeline distribution hubs. 69 pipelines, carrying petroleum, chemicals and LPG crossed the river floodplain at the time of the 1994 flood event. Whilst the main production and distribution sites were protected to varying levels by flood defence works, the pipelines were, in many cases, not designed to withstand flood-related scour and undermining. Indeed, of the 69 pipelines in the floodplain, 31 were installed before 1980, with 8 still in place from the 1930's and 1940's (table 4 - NTSB 1996).

Table 4 – year of pipeline installation in San Jacinto area

Year	1930's	1940's	1950's	1960's	1970's	1980's	1990's
Number of pipelines	2	6	19	4	19	9	6

Source: NTSB special investigation report PB96-917004

The flooding between 14 and 20 October 1994 was the result of heavy thunderstorm activity around a frontal system based on the remnants of Hurricane Rosa. Gauged rainfall measurements of between 170mm and 500mm were recorded over the storm period (NOAA 2001). This rainfall fell over much of the San Jacinto catchment and the resulting flood wave caused the San Jacinto river to rise up to 5.7m above the average stage with peak discharges of 10,200 m^3/s at the basin mouth (TWRI 1995).

The effect of this flood when out-of-bank was to cause extensive scouring and later deposition of large amounts of sediment, and the cutting off of large meanders which had pipelines crossing them. 29 of the 68 pipelines were undermined by scouring, with 8 failures reported (NTSB 1996). These failures caused large losses of gasoline and LPG. 3,000 residential fire damage claims resulted after the spills travelled into residential areas across the river. Total reported loss was over $US 370 million (table 5) and according to the Willis Energy Loss Database, accounted for around 10 percent of all large energy industry losses reported globally for 1994.

Table 5 – reported energy industry losses in San Jacinto area, October 1994

Date	Insured	PD loss ($US M)	BI loss ($US M)	total loss ($US M)
16-Oct-1994	Pipeline	22.0	0.0	22.0
17-Oct-1994	Petrochemical plant	25.0	85.0	110.0
17-Oct-1994	Petrochemical plant	3.6	0.0	3.6
20-Oct-1994	Pipeline	45.0	0.0	45.0
20-Oct-1994	Petrochemical plant	35.0	57.0	92.0
20-Oct-1994	Pipeline	97.0	0.0	97.0

Source: Willis Energy Loss Database

The post-event investigation reported that the pipeline owners, whilst ensuring their construction met Federal regulations, did not in 3 of the 4 failures across the largest meander cut-off, provide any evidence of flood plain scouring studies being performed on their design (NTSB 1996). Geomorphological changes to the floodplain since the installation of many of the pipelines, including land subsidence from groundwater abstraction and commercial sand removal around the meanders resulted in increased sediment erosion and may have contributed to the damage magnitude. A recommendation of the NTSB report was to ensure that the petroleum industry performs periodic flood risk assessments of all infrastructure which cross or follow known floodplains.

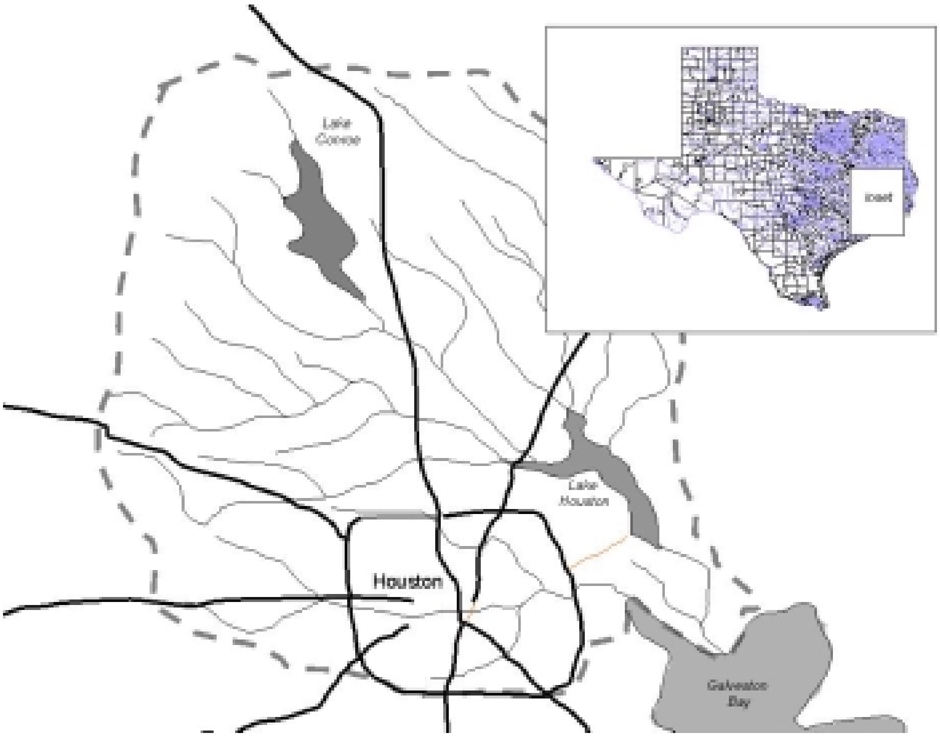


Figure 3 – Sketch map of the San Jacinto catchment area

Case study 2 – Blayais Pressurised Water Reactor, France December 1999

The Blayais nuclear power station is located approximately 15km to the north of the city of Blaye on the Gironde estuary, western France. The area is relatively sparsely populated and is mainly reclaimed marshland or other low-lying coastal plain. Run by the state energy company, Electricité de France (EDF), the power station provided 417 TWh in 2000. The four pressurised water reactors (PWR) require large volumes of sea water. This is pumped into the reactor system via two large pumping stations, at the coastal edge of the site. Construction of the site began in 1976 and the station went on-line in 1983. The site is designed to continue operation until 2023.

The main reactor and sea water pumping stations are protected by an enclosing dyke, designed to protect up to the 1000-year event storm surge height. The design run up heights of the dykes were calculated from wave records collected over a time period of 'several decades' at a measurement station 2.5km downstream of the power station (IPSN 2000). It is likely that extreme value analysis would have been used to provide an extrapolated statistical assessment of the 1000-year water height from the available record. As a result, the dykes were constructed to a height of 5.2m above datum along the coastal edge, with 4.75m above datum defences along the other perimeter sides. Within the site, much of the main infrastructure, including the pumping machinery and electricity transformers, were buried by as much as 10m below datum (figure 4). Consequently, a large proportion of the site is at risk to flood from a breach of the dykes. Further analysis recommended in 1998 that the defences be raised to 5.7m above datum. This work was scheduled for 2000, but was postponed until 2002.

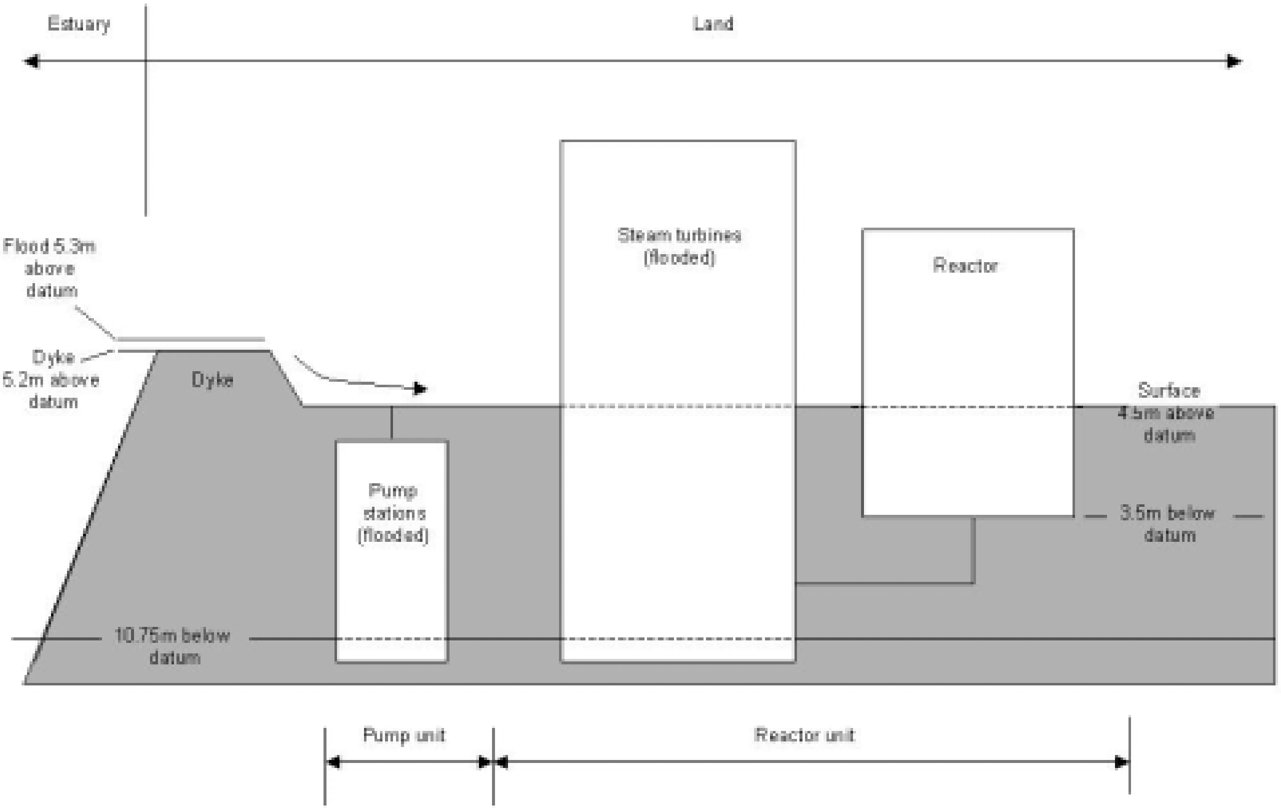


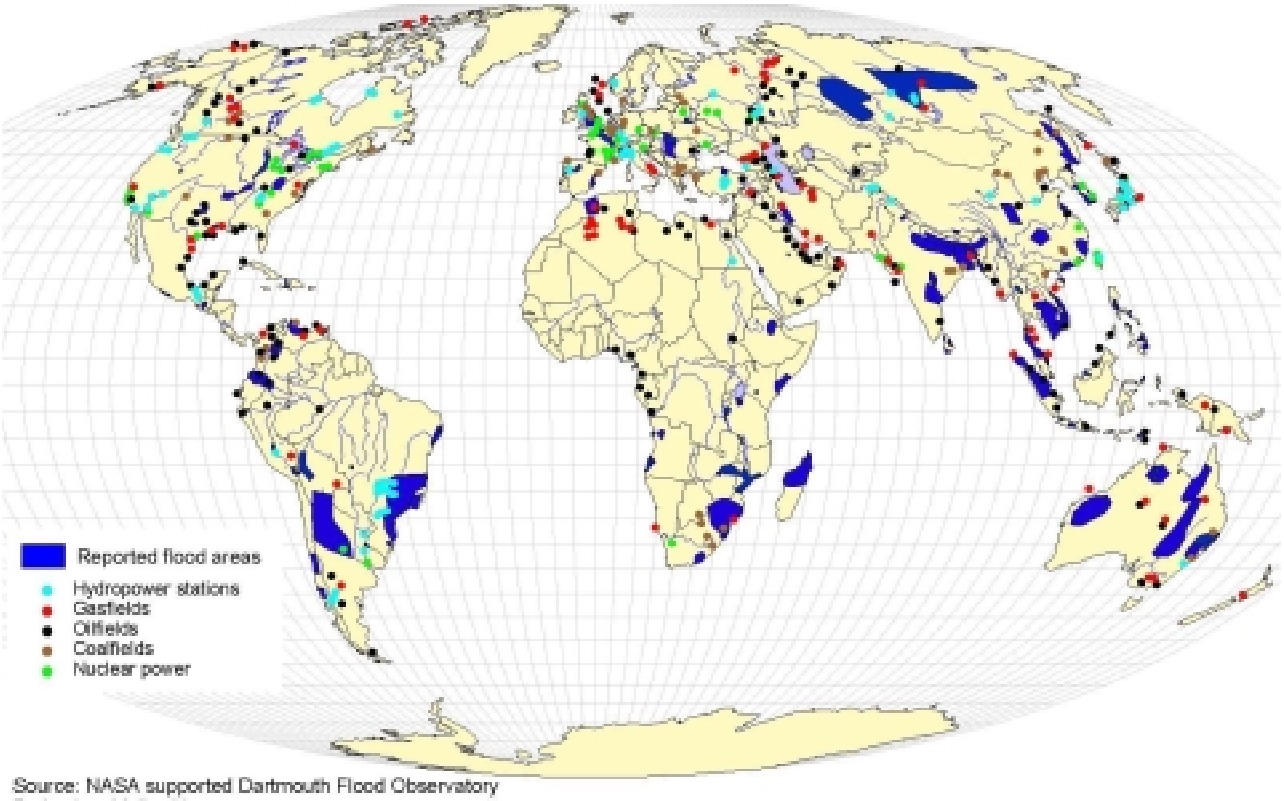
Figure 4 – cross-section of Blayais power station – diagrammatic explanation of flood defences and impact of the 27 December 1999 storm surge breach. Measurements are not to scale.

Over the period of December 26 to December 28 1999, much of central and western France was affected by two unusually strong windstorms, named Lothar and Martin. In both cases, the winds were produced by extremely deep North Atlantic depressions which tracked across northern and central France, intensifying as they moved inland. As well as the toppling of over 280 high voltage and high tensile transmission pylons, the storm passage caused a storm surge of 2.5m in the Gironde estuary. This resulted in the overtopping of the main 5.2m flood defence by around 0.1m, enough to force up to 40,000 m^3/h of water into the main power station site. The result was flooding of one of the two subterranean pumping stations, a loss of water intake to the reactor and the emergency shut-down of the plant. The event was later classified as a ‘level 2’ nuclear emergency by the French Government, an incident with significant failures in safety provisions (IAEA 2000). One of the reactors was not re-started until four months after the event.

Post-event analysis has suggested that only 3 out of 19 French PWR stations had adequate flood defences equivalent to the storm surge seen at Blayais. Further analysis has been undertaken to identify the required defence upgrading.

Flood and the energy industry – how to quantify the true risk of flooding?

Global floods 2000/2001



Source: NASA supported Dartmouth Flood Observatory
Projection: Mollweide

Figure 5– reported global floods 2000 – 2001 and energy Industry exposure.

It is clear from these two case studies that all operational aspects of the energy industry are at significant risk to flood-related losses in many locations around the globe. Other recent events reinforce this position. These include the ice-dam flooding in Siberia in 2001 where a refinery flooded and released pollutants in to the local water supply, as well as the June 2001 flooding, again in the Houston area of Texas which resulted in a loss of production to at least 6 refining operations (DFO, 2001). The Dartmouth Flood Observatory reports around 100 large river flood events across the world per year. Many of these events are in areas where there are large energy industry aggregate exposures (figure 5).

Climate change

The potential impact of climate change on the risk to installations globally cannot yet be clearly quantified. However, there is increasing evidence that the regional impacts of global warming will include changes to the severity and frequency of flood events across the globe. The most widely reported of these has been the potential rise in sea level over the next 80 years. Most general circulation models (GCMs) suggest that global sea levels will rise by up to 1.2m by 2100. Increased storminess, narrowing of coastal buffers such as beaches due to increased erosion and an increase in rainfall intensity and frequency will all have potential impacts on the extreme flood extents and depths expected in many regions of the world, but particularly northern hemisphere mid to high latitude land masses (IPCC 2001). A rise of more than 10m above present day levels has also been postulated if the West Antarctic ice sheet, much of which grounds below present sea level, were to break up. Such a rise would cause significant flooding of many low-lying coastal regions, including the Niger Delta, the US eastern and southern seaboards (including the area around Houston) and many areas in Western Europe, including much of Holland and the Eastern United Kingdom.

However, the levels of uncertainty currently reported by GCMs make precise quantification difficult. Instead, it is important that the likely impacts are properly accounted for during flood risk estimation. As most sea and river defences are designed to either the 100 or 1000-year event, it is likely that many existing defences will need to be strengthened or enhanced in other ways to combat any exaggerated rise in sea level. In many cases this will not be possible, as the complex impacts of climate change on the flood process and resulting morphological effects will be hard to model at the scale of individual operator sites.

Conclusions

The examples cited here suggest that flood can be a significant hazard to the energy industry. Extreme events, whether from river or coastal flooding, have caused large individual damage as well as aggregate losses to the industry. Currently flood risk may be underestimated for many locations and this situation may worsen due to the impact of climate change on extreme flooding events. It is not likely that engineering solutions will be applied to all ‘at-risk’ sites in time to mitigate the effects of such changes. It is important, therefore that analysts and risk assessors responsible for quantifying the risk to energy operations are able to accurately identify the potential impact of flooding.

The increased availability of detailed modelling packages and high resolution data to include in them, such as airborne terrain data has revolutionised the way in which flood risk may be assessed. The use of powerful visualisation tools such as GIS to report the result of modelling can also help in the assessment process. It is important, however that the limitations of the methods and data used are fully understood as the results may be applicable to only a small range of situations.

On a general note, it is also suggested that an increased understanding of the geomorphological processes operating within large flood events would aid the risk manager in identifying risks not generally highlighted by standard modelling and risk assessment procedures, particularly in relation to physical processes such as scour around fixed structures such as pipelines.

References

Bates P.D, Anderson, M.G 2001. *Validation of hydraulic models*. Chapter 13 in Model Validation: Perspectives in Hydrological Science. Anderson M.G, Bates P.D (eds) John Wiley and Sons Ltd, Chichester. pp 325-356.

Calver, A., Lamb R., Morris S.E., 1999. *River flood frequency estimation using continuous runoff modelling*. Proceedings of the Institution of Civil Engineers, Water, Maritime and Energy. Vol. 136 pp 225-234

Cameron D., Beven K., Tawn, J., Naden P., 2001. *Flood frequency estimation by continuous simulation (with uncertainty)*. Proceedings, National Meeting of the British Hydrological Society, Centre for Ecology and Hydrology, Wallingford, 5th July 2001

Chandler R.E., Wheater, H.S., Isham V.S., Onof C., Bate S., Northrop P.J., Cox D.R., Koutsoyiannis D., 2001. *Generation of spatially consistent rainfall data.* Proceedings, National Meeting of the British Hydrological Society, Centre for Ecology and Hydrology, Wallingford, 5th July 2001

Conseguera D, Joerin F, Vitalini, F 1995. *Flood delineation and impact assessment in agricultural land using GIS technology*. Chapter 9 in Geographical Information Systems in Assessing Natural Hazards. Carrara A, Guzzetti F (eds). Kluwer Academic Publishers, Dordrecht. pp 177-198

Dartmouth Flood Observatory 2001. *Flood Archives*. http://www.dartmouth.edu/artsci/geog/floods/

Dingman S.L. 1994. *Physical Hydrology*. Prentice Hall, New Jersey. p 575.

Institut de Protection et de Surete Nucleaire 2000. *Rapport sur l'inondation du site du Blayais, survenue le 27 Decembre 1999*. http://www.ipsn.fr/Blayais/Blayais.htm

International Atomic Energy Authority 2000. *The International Nuclear Event Scale*. http://www.iaea.or.at/worldatom/inforesource/factsheets/ines.html

Intergovernmental Panel on Climate Change 2001. *Technical Summary. Climate Change 2001: Impacts, adaptation and vulnerability*. Report, Working Group II IPCC, Geneva, Switzerland.

Lamb R., Calver, A 2001. *Continuous simulation as a basis for national flood frequency estimation.* Proceedings, National Meeting of the British Hydrological Society, Centre for Ecology and Hydrology, Wallingford, 5th July 2001

Morris D.G., Flavin R.W., 1996. Flood risk map for England and Wales. Report number 130, Institute of Hydrology 88p

National Oceanic and Atmospheric Administration, 2001. *Tropical/Middle Latitude Rain Event with an October Cold Front*. http://www.srh.noaa.gov/EWX/html/attach/oct/oct94wx.htm

National Transportation Safety Board 1994. *Pipeline special investigation report. Evaluation of pipeline failures during flooding and of spill response actions, San Jacinto River near Houston, Texas, October 1994.* National Transportation Safety Board Report PB96-917004, NTCB/SIR-96/04

Reed, D.W., Houghton-Carr, H.A., Richardson B.D 1999. *Introducing the Flood Estimation Handbook.* Proceedings, 34th Conference of River and Coastal Engineers, Ministry of Agriculture, Fisheries and Foods. pp 2.1.1-2.1.7

Sanders R., Tabuchi S., 2000. *Decision support system for flood risk analysis for the River Thames, United Kingdom*. Photogrammetric Engineering and Remote Sensing. Vol. 66, No. 10 October 2000 pp 1185-1193

Shell, 2001. *Kessler's activities in the Far East*. http://www.shell.com/royal-en/content/0,5028,25444-50924,00.html

Texas Waterways Research Institute 1995. *UH researchers evaluate how, why San Jacinto River changed course after massive 1994 floods.* NewWaves Volume 8 Number 1: March 1995

Ward 1978. *Floods: a geographical perspective*. Macmillan, London. 382p