Geo Factsheet

www.curriculum-press.co.uk Number 224

STORM SURGES - a growing hazard?

Introduction

Flooding of low-lying coastal areas can occur for a host of reasons, such as tsunamis, intense local precipitation, high river flows, and storm surges.

Some of these flood mechanisms may interact with each other, as well as with other hazards such as human induced subsidence. Coastal areas are characterised by growing concentrations of human population and socioeconomic activity, which means such floods can have severe impacts, including significant loss of life in certain situations. Widespread efforts to mitigate coastal flood hazards are already apparent, and this need is likely to intensify throughout the 21st century due to the above trends, as well as to a general increase in risks due to climate change.

Storm surges are generated by tropical and extra-tropical storms. The low barometric pressure and wind set-up combine to produce large temporary rises in sea level that have the capacity to cause extensive flooding of coastal lowlands. They are usually associated with strong winds and large onshore waves, which increase the damage potential relative to the potential damage caused by surge-induced high water levels alone. The largest surges are produced by hurricane landfalls, but extra-tropical storms can also produce large surges in appropriate settings.

What is a storm surge?

Surges are changes in sea level resulting from variations in atmospheric pressure and associated winds. They occur on top of normal tides, and when positive surges are added to high tides they can cause extreme water levels and flooding (flooding is most severe when a surge coincides with spring tides). Surges are most commonly produced by the passage of [atmospheric] tropical or extra-tropical depressions.

The magnitude of the surge is controlled partly by the storm track and intensity, and partly by the configuration of the coastline and seabed:

- Onshore winds serve to pile water against the coast and to generate surface currents and waves, which add to the maximum sea surface.
- A depression also reduces the atmospheric pressure, resulting in a rise in sea level (a fall of 1mb in pressure results in a sea level rise of 1cm).
- Coastlines fronted by a wide, shallow continental shelf experience larger surges than do coastal areas with steeper slopes and greater water depths.
- Coastal configuration is also important.

The southern North Sea, for example, is open to the north and nearly closed to the south, thus amplifying the potential for surges. Given appropriate conditions, surges due to extra-tropical storms can reach 2 to 3m in the southern North Sea, as happened in the storm surge of January 31–February 1, 1953. In 1953, over 300 people lost their lives in the United Kingdom, and nearly 2,000 people were killed in the Netherlands. In the 1971 cyclone in Bangladesh, the maximum surge reached 3.8m (12.5 feet) above the predicted high tide, resulting in water depths exceeding 4.9m.

The strong winds that contribute to surge events also produce large storm waves. The offshore wave height is dependent upon the fetch, the wind strength, and the length of time the wind has been acting upon the sea surface. Waves increase sea levels and have significant potential to cause damage and exacerbate flooding. In particular, wave action can cause considerable erosion to protective backshore landforms (for example, barrier islands, dune ridges), and damage coastal defences.

Storm surge damage

In "natural" situations with little or no coastal defenses apart from natural dunes, such as those found on the U.S. east coast, a storm surge typically diminishes 0.2 to 0.4m per km inland. Therefore, an extreme 6-m storm surge might reach 11 to 16km inland if elevations are low (only 1 to 2m), as is often the case. However, steeper slopes will curb inland penetration. In the Netherlands, over half the country is threatened by flooding from surges and rivers, but the flood defenses are built to a high standard (nominally up to a 1 in 10,000 year event.

Human-induced subsidence has also increased the number of people potentially exposed to flooding by storm surges. *Table 1* lists some major coastal cities that have experienced significant human-induced flooding due to groundwater withdrawal, and, hence, flooding due to surges has potentially been exacerbated. In Japan, 2 million people live below the normal high water level due to subsidence and depend on flood defenses every day to stop floods, with a much larger population threatened by flooding due to surges (and other flood hazards, such as tsunamis).

Table 1 Some major coastal cities and human-induced subsidence during the 20th Century.

Megacity	Subsidence (m Maximum)	Date Human -Induced Subsidence Commenced	Surge Potential
Shanghai	2.80	1921	Tropical Storms
Tokyo	5.00	1930s	Tropical Storms and Extra-Tropical Storms
Osaka	2.80	1935	Tropical Storms and Extra-Tropical Storms
Bangkok	1.60	1950s	Tropical Storms
Tianjin	2.63	1959	Tropical Storms and Extra-Tropical Storms
Jakarta	0.90	1978	Limited
Metro Manila	0.40	1960	Tropical Storms

Flooding due to surges has a range of impacts, including property damage and destruction, human distress and health effects, and, in the worst case, fatalities. Even under relatively mild surge regimes (< 1m), significant property damage can occur, as happens in the flooding of the historic city of Venice. However, deep surges and fast-moving water can lead to death by drowning.

Millions of people have drowned due to storm surges around the world, with regular recurrence in some notable hotspots around the North Sea, the Bay of Bengal, and East Asia. Areas of the world's coasts that are affected by tropical cyclones are prone to significant surges. These areas include the Caribbean and North America; parts of East Africa; much of south, Southeast, and East Asia; and much of the Pacific, including Papua New Guinea and Australia. Extra-tropical storms affect mid- and high-latitude coastal areas, with noteworthy surge potential in the North Sea, the Baltic Sea, and in the Rio de la Plata (between Argentina and Uruguay).

It is important to note that extra-tropical and tropical storms can produce a range of hazards in addition to surges and waves, particularly intense precipitation, wind damage, and even tornadoes and water spouts. Hurricane Andrew produced a 4m surge in Biscayne Bay, southern Florida, although the major damage in Florida was due to the hurricane-force winds.

Responding to storm surges

Choosing change means accepting the hazard and changing land use, or even relocating exposed populations. Reducing losses includes trying to reduce the occurrence of the hazardous event or, more commonly, reducing the impacts of a hazardous event when it occurs. Both flood-protection and flood-warning systems are approaches to reduce losses. Accepting losses includes bearing the loss, possibly by exploiting reserves, or sharing the loss through mechanisms such as insurance. Hence the ability to recover from the disaster is of the utmost importance if losses are accepted.

Table 2 Generic approaches to hazard reduction based on purposeful adjustment.

Purposeful adjustment	Option
Choose change	Change location Change use
Reduce losses	Prevent effects Modify event
Accept losses	Share loss Bear loss

Over time, technology is increasing the options that are available for hazard risk reduction, particularly those strategies that reduce losses. Examples of these approaches include warning systems, defence works, and resistant infrastructure. This approach is most developed in urban areas around the North Sea, other parts of Europe, China, and Japan, where flooding by surges claimed many lives up to the middle of the 20th century.

Climate change and sea-level rise represent an additional challenge around the world's coastal zones.

Regional Exposure to Storm Surges: 1990 to the 2080s

Considering the base year (1990), it is estimated that, globally, a total of about 200 million people were living in areas vulnerable to flooding caused by storm surges. Further, it is estimated that about 10 million people potentially experience flooding from storm surge each year, which is about 5% of the exposed population. There are also important regional differences. Collectively, the south, east, and south-east regions of Asia contained about 60% of the exposed population and nearly 90% of the people who experience flooding. Other regions, such as North America and north and western Europe, contain a large exposed population (13 million and 19 million people, respectively), but due to higher defence standards vis-a-vis Asia, the incidence of floods due to surges is small. However, despite the protection, the residual risk of flooding due to surges still needs to be considered. Note that, in practice, there are important differences between Europe and North America that the methods used do not explicitly address. In Europe, floods are mainly managed using hard defenses such as dikes and sea walls, with beach nourishment increasingly being utilised in conjunction with the hard defenses. In contrast, the United States follows an approach based on accommodation of the surge hazard - all new buildings are raised designs above the 1-in-100 year surge elevation.

The frequency, magnitude, and impacts of storm surges will change through the 21st Century due to a combination of:

- sea-level rise associated with global warming,
- increasing direct human modifications to coastal areas (for example, further building around estuaries), and
- socioeconomic changes which have led to increased numbers of people living near the coast. World population is rising, but coastal populations are rising even more rapidly.

The Bay of Bengal, and especially Bangladesh, is the number-one surge "hotspot" at the present time. The high incidence of death due to surges around the Bay of Bengal is not unique in human history. There was similar loss of life due to storm surges around the North Sea in the late Middle Ages. More recently, improved defenses have greatly reduced the death toll, but these areas remain threatened.

Case Study 1: Shanghai, China

Shanghai is a good example of a sinking coastal city. It is built on geologically young deposits of the Yangtze delta, and it subsided as much as 2.8m during the 20th century due to shallow, unregulated groundwater withdrawal. The groundwater withdrawals were triggered by the growing city and economy in the 1920s, and subsidence continued until the 1960s when groundwater withdrawal was regulated and subsidence rates were reduced to 3 to 4mm per year - rates of subsidence one would expect in a deltaic setting. Therefore, while human action triggered the subsidence problem, this also made it possible to greatly reduce the subsidence by managing the groundwater withdrawal.

Shanghai was always flood prone due to both high river flows and typhoons. Over 100,000 deaths were due to flooding during a typhoon in 1694. However, the subsidence promoted a substantial increase in the incidence of flooding, the actual flood depths, and the area affected. A range of new flood protection measures was implemented, including a lot of small-scale measures such as flood barriers and sand bags for individual buildings. This culminated in large new flood walls, built in the early 1990s, that protect the main city to a 1-in-1,000 year standard. However, future subsidence problems remain possible. Anecdotal reports suggest that illegal groundwater withdrawal has increased in Shanghai over the last 10 years, and the rate of subsidence has increased again. This illustrates the ongoing nature of managing surge-induced flooding, as is apparent in all the case studies. This experience will have commonalities with many other large subsiding cities. There are several other cities that might start to experience subsidence as they develop and, hence, become more exposed to surges. Hanoi and Ho Chi Minh City (Saigon) in Vietnam, and Yangon in Myanmar are potential examples, with Hanoi known to be actively subsiding.

Case Study 2: Southern North Sea

This region experiences significant surges due to extratropical storms, and the locations susceptible to flooding feature large populations and substantial investments. As technology improved, so did defenses. Major floods continued up to the middle of 20th Century:

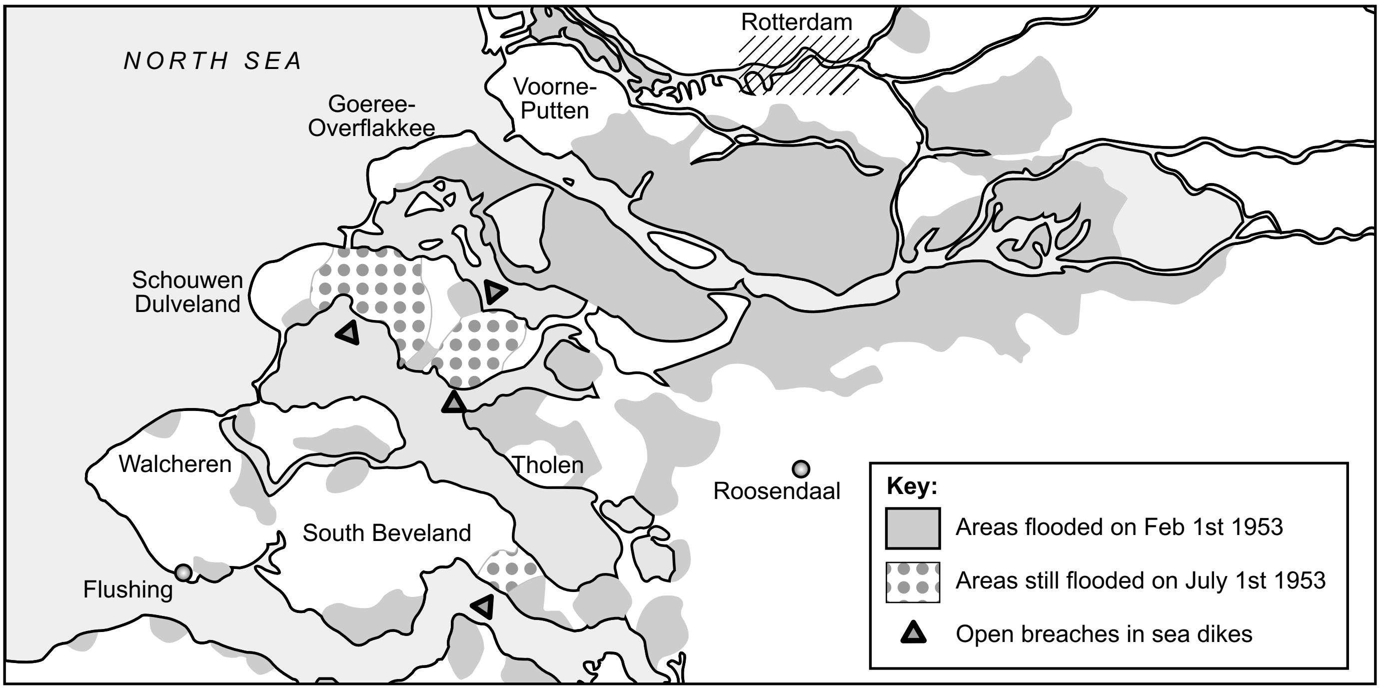
- *The East Coast (United Kingdom) and the delta region of the Netherlands were last flooded in 1953 (Fig. 1).*
- *Germany, including Hamburg, was last flooded in 1962.*

The response to these events was further massive investment in flood-defence infrastructure, as illustrated by the mobile storm surge barriers on the Thames in Greenwich, London, and across the Western Scheldt in the Netherlands. Many of these defenses are built to a 1-in-1,000 year standard or higher, and up to a 1-in-10,000 year standard for some defenses in the Netherlands.

Equally important, an effective storm tide warning service has been developed that provides up to 36 hours warning of a potential flood event. Collectively, these new measures have been effective for the last 20 years, and there has been no flooding around the southern North Sea, even though the extreme water levels of the 1953 event have been repeated and even exceeded in some locations.

The new defenses for London became fully operational when the Barrier was completed in 1983 - that is, 30 years after the decision to build was made. The design life of the Barrier extends to 2030, when rising flood levels due to a combination of global sea-level rise and more local changes will reduce the residual flood risk to below a 1-in-1,000-year standard. Given the long lead-time to upgrade the defenses, planning of the upgrade of the flood defenses to the end of the 21st century is already in its early stages.

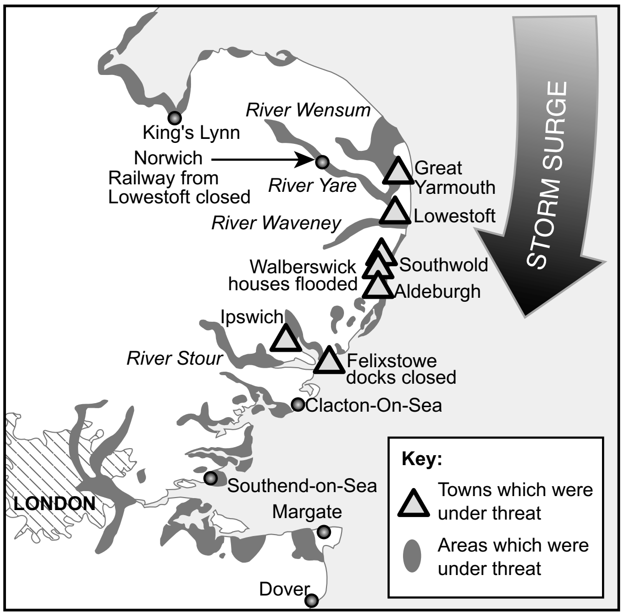
Fig. 1 Areas in the south-west Netherlands flooded by the 1953 storm surge, 1st February 1953.



East Anglia storm surge 2007

In November 2007 East Anglia was expecting the highest seas for more than 50 years. Sandbags had been filled, makeshift barricades erected and thousands of homes were evacuated as the tidal surge approached. But the peak of the conditions caused by a combination of gale-force winds in the North Sea (Fig. 2) and a high tide which battered the coasts of Norfolk and Suffolk left only minor damage. In Norfolk hundreds spent the night in temporary accommodation in schools and leisure centres, while others moved further inland to stay with family and friends. In parts of the region, waters rose above 3m - the highest mark since the 1953 floods, which killed more than 300 people. There was localised flooding in Norfolk and Suffolk but no major defences were breached. One of the worst hit coastal villages was Walcott in Norfolk, where 4m waves breached the sea wall, smashed conservatories and holiday accommodation, and blew caravans and boats across the coast road. In Great Yarmouth there was only localised flooding. Fire crews used dinghies to rescue 30 people from sheltered accommodation in Lowestoft, Suffolk and 700 people were evacuated. Lincolnshire, the Humber, the north-east of England and Kent escaped trouble. In London the Thames barrier and the Queensborough and Dartford Creek barriers were operated. Experts feared that tidal waves would rise by 3m, breaching sea defences and flooding thousands of homes. In the event, levels peaked at around 20cm lower.

Fig. 2 Flood alert areas in East Anglia, 2007.



Case Study 3: Bangladesh, Bay of Bengal

In terms of fatalities, Bangladesh is presently the dominant storm surge hotspot globally. This concentration of fatalities reflects several interacting factors including:

- *a high and rapidly growing coastal population, with little alternative land,*
- *extensive coastal lowland areas that are close to sea level. Many people actually live on chars or islands.*
- *significant and frequent landfall of tropical cyclones, and*
- *shallow coastal areas that exacerbate the surge potential of the cyclones.*

Table 3 Storm surges in Bangladesh, 1970-2007 .

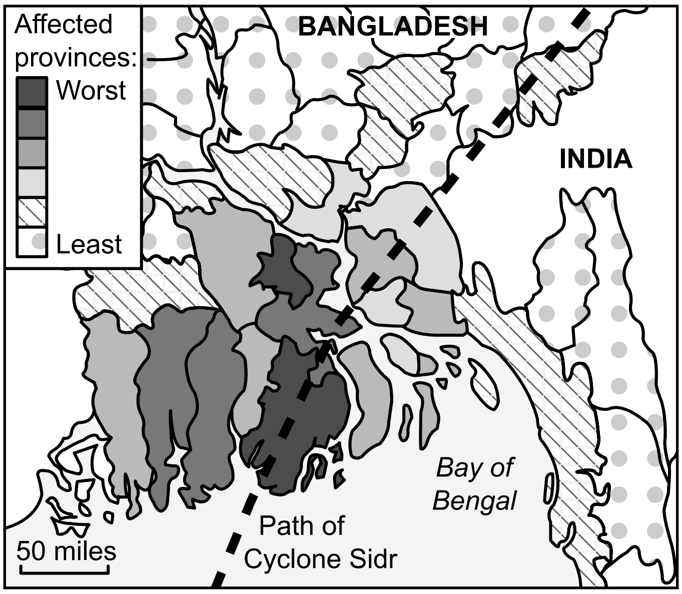
Date	Event
November 1970	A cyclone with 222km winds causes a 20ft tidal surge and kills 500,000 people.
July 1974	Severe flood devastates the grain crop, leading to an estimated 28,000 deaths.
1988	Floods cover three-quarters of the country, killing more than 5,000 and leaving millions homeless.
April 1991	A cyclonic 15ft tidal wave kills up to 138,000.
1998	Flooding from July 12 to September 14 covers 67% of the country, killing 1,200 and causing damage worth $14.5bn.
November 15th 2007	Cyclone Sidr hits Bangladesh, killing at least 3,200 and leaving more than two million struggling for necessities such as food, water, shelter and medicines.

The death toll during cyclones from the years 1800 to 2000 shows a rising trend in deaths due to surges. The 1970 event stands out as the most significant event in terms of fatalities. The loss of life in the 1991 event was again significant, but was substantially lower than in 1970, despite the event being comparable in terms of the surge characteristics. Efforts to improve warnings have continued through the 1990s, and it is suggested rather that they are becoming more effective.

Hurricane Sidr

At around the same time as the Norfolk storm surge, Cyclone Sidr hit Bangladesh (Fig. 3). Early warning systems and shelters saved an estimated 100,000 lives but Oxfam warned that without a massive international response the country would face its worst humanitarian crisis in decades. The early warning systems, introduced over the last 15 years, new cyclone shelters and better planning has meant that more than 100,000 people were saved from the immediate impacts of the cyclone - compared to the loss of life in a similar cyclone in 1991. But with the country's agriculture in ruins vast numbers of people are now threatened with food shortages. More than 3 million people were affected by the cyclone, with around 3,000 people dead, and a similar number missing, 273,000 homes have been destroyed and more than 900,000 damaged, while 855,000 acres of crops have been damaged and nearly 30,000 acres completely destroyed according to government figures. Cyclone Sidr crashed into the southwestern coast at speeds of up to 150mph and triggered a five-metre high tidal wave that washed away three coastal towns. The cyclone levelled villages, destroyed crops and sent telephone poles into the sky across a dozen districts abutting the sea. Electricity and telephone lines were cut across the country. The lack of power made it difficult for officials to uncover the true extent of the disaster. Many towns in the countryside, where homes are shacks made of bamboo and tin, were simply blown away by the cyclone's winds, and about 60% to 80% of the trees have been uprooted.

Fig. 3 Provinces affected by Hurricane Sidr.



Conclusions

A number of important conclusions can be drawn that are of relevance to the "hotspot" analysis:

- Surges are a major issue in only a few global regions, with the Bay of Bengal being the most affected region, and Bangladesh being the main "hotspot" for surge impacts.
- While surges are only one aspect of the impacts of a storm, they are the main killer, and surges have led to several million deaths over the last two centuries, mainly in Asia and particularly in Bangladesh.
- High death rates due to surges appear to be linked to land claim and substantial coastal modification, which have encouraged growth in vulnerable coastal populations without appropriate consideration of the potential for surges (for example, southern North Sea and Bangladesh).
- The death toll in surge events appears to have fallen substantially around the world as protection measures and forecasts/warnings are improved, including most recently in Bangladesh (Hurricane Sidr).
- However, there is no room for complacency, and the surge hazard will continue to evolve throughout the 21st Century due to changing socioeconomic conditions, coastal land use, and climatic risks.
- Damages and disruptions due to surges are more difficult to define as they are one aspect of the storm and as these impacts are often aggregated with other damages, such as damages caused by tornados and other types of wind storms.

Therefore, while it is useful to analyse surge by itself, it is also important to analyse the integrated impacts of coastal storms, as these are what coastal communities experience. In the future, a mixture of analyses is required - one that considers each storm hazard, as well as the integrated impacts.

Acknowledgements
This Factsheet was researched by Garrett Nagle, a well-known author.
Curriculum Press, Bank House, 105 King Street, Wellington, TF1 1NU. Tel. 01952 271318.
 ISSN 1351-5136