
Floods in a changing climate: a review

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This paper begins with an analysis of flooding as a natural disaster for which the solutions to the environmental, social and economic problems are essentially those of identifying and overcoming hazards and vulnerability, reducing risk and damaging consequences. Long-term solutions to flooding problems, especially in a changing climate, should be sought in the wider context of developing more sustainable social organization, economics and technology. Then, developments are described of how scientific understanding, supported by practical modelling, is leading to predictions of how human-induced changes to climatic and geological conditions are likely to influence flooding over at least the next 300 years, through their influences on evaporation, precipitation, run-off, wind storm and sea-level rise. Some of the outstanding scientific questions raised by these problems are highlighted, such as the statistical and deterministic prediction of extreme events, the understanding and modelling of mechanisms that operate on varying length- and time-scales, and the complex interactions between biological, ecological and physical problems. Some options for reducing the impact of flooding by new technology include both improved prediction and monitoring with computer models, and remote sensing, flexible and focused warning systems, and permanent and temporary flood-reduction systems.

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1. Interdisciplinary aspects

This issue on floods in a changing climate arose from discussions at a previous Royal Society meeting on 'Dealing with Natural Disasters (The Royal Society 2000)', held in October 1999, about the need to focus on this topic. This subject has become extremely topical in the UK, with widespread flooding occurring in the winters of 2000–2001 and 2001–2002, following earlier flooding in 1978. Serious floods have also occurred in other countries, notably in Mozambique in 2000 and 2001.

Recent reports have been written on the administrative, scientific and engineering aspects of the UK floods (ICE 2001), and there have been extensive debates in the UK Parliament (Hansard 2000, 2001) with strong speeches about experiences

One contribution of 18 to a Discussion Meeting 'Flood risk in a changing climate'.

in flooded towns and valleys, and in coastal areas affected by rising sea levels and coastal erosion, and about fears for the future. It is clear that governments in the UK and around the world are taking these developments very seriously, and are developing new policies and action plans. As they do so they are clearly listening to the advice and deliberations of engineers and scientists, both natural and social!

Just before this meeting was held, the inter-governmental panel on climate change (IPCC 2001) issued its third assessment report, reinforcing its earlier conclusion about global warming, changed patterns of precipitation (up and down), and sea-level rise. In June 2001 the US National Academy reported to the US President on these predictions, in terms that were quite consistent with the scientific conclusions of the IPCC. The third IPCC report also included more extensive studies of the likely impact of climate change on human health and society generally, prominent among these being the adverse effects of more frequent flooding.

During the 1990s, the International Decade of Natural Disaster Reduction, objectives emerged for studying and dealing with all aspects of the associated challenging tasks, namely

- (i) understanding and predicting ‘hazards’, both the primary natural events themselves, such as flooding, and the secondary effects such as mudslides, collapse of structures, and coastal erosion;
- (ii) assessment of ‘vulnerability’ of communities to natural disasters; this is generally increasing, firstly because of the increasing population, and secondly because many more people live in areas that are hazardous, notably along rivers, along coastlines subject to flooding and hurricanes, and on hillsides subject to mudslides; and
- (iii) reduction of risks before the occurrence of natural disasters and lessening post-disaster consequences to individuals and societies.

This requires prediction and warning about risks and individual events (Hunt 1994; Lee & Davies 1998) and physical measures to reduce the effects of hazards, for example through permanent or temporary structures, or even means of escape, and to remedy the consequences afterwards, from clearing up to reconstruction. Social, financial and governmental measures are crucial in all aspects of reduction, a point that became more widely recognized during this decade.

It is also relevant here to consider the international ‘sustainability’ framework that emerged following the UN conference on the environment at Rio de Janeiro in 1992 for dealing with global environmental change, increased flooding being one of its major manifestations (WCED 1987). The whole framework firstly depends on reliable assessment, prediction, monitoring and dissemination of information about climate change, which is the responsibility of scientific, governmental and international agencies. Next, there are the first two action phases (both of which could take decades of effort), the first being mitigation of environmental change by reducing the human effects on the global environment and on the climate through reducing greenhouse-gas emissions and many other measures. This task could, and perhaps should, involve all the citizens of the world. To an even greater extent they can all contribute to the second action phase, although the world has hardly begun to

address it. This involves adapting societies to the likely changes in the environment. In the UK, measures to reduce the effect of flooding and sea-level rise are considered to be some of the most immediate actions. In other countries, the measures will be quite different, for example conserving water, combating desertification and dealing with melting permafrost.

Increasingly, these two apparently separate areas of action, namely mitigation and adaptation, are being brought together simultaneously and more strategically in the framework of the overall development concept of 'sustainability'. This more holistic approach has the merit of ensuring that economic activities are directed so as to complement the specific technical and organizational measures needed for natural-disaster reduction, as well as for mitigation of and adaptation for climate change.

These themes are reflected in the papers in this issue, with new approaches being studied and being put into practice by governments and communities. Speakers emphasized the need to explain to communities at risk from flooding that there can be no absolute guarantee of safety and prevention of any possible damage (e.g. Battjes & Gerritsen 2002). In other words, such communities need to be taught how to 'learn to live with hazards', while minimizing unnecessary risks such as placing particularly vulnerable institutions on flood plains (Penning-Rowsell *et al.* 2002) or building houses on slopes subject to mudslides. Such public involvement implies, on the one hand, some acceptance of risk, but, on the other, provision by responsible agencies of greatly improved information about the risk. The public should also expect, as science and technology develop, progressively more accurate predictions (see §§ 2 and 3). It was argued that communities are likely to become more effectively engaged when the measures are taken as part of making the whole economy and other activities more sustainable over the long term. For example, measures to reduce flooding should be integrated with land-use planning and management, and potentially with broader issues of catchment management such as pollution control. In tropical areas, the denudation of forests and the occurrence of floods are intimately linked, and urban development will lead to enhanced flood risk unless appropriate mitigation measures are implemented.

2. Changing environmental conditions

(a) Methodology

The Discussion Meeting from which this issue arose provided a useful window into the current research work of those aspects of environmental change, i.e. atmospheric, oceanic, geological and to some extent biological, that affect flooding in river and coastal regions. Research work, allied to greatly improved monitoring, is leading to better understanding and more extensive and detailed predictions of those changes. When tested against past data, the predictive models are also becoming more accurate.

There continues to be a range of deterministic and statistical methods, or a combination of both, for analysing past data, and predicting long-term climatic and environmental changes and their connection to trends in river flows and floods generally (Senior 2002; Young 2002). Ever since the 19th-century pioneers, such as Tyndall and Arrhenius, began considering the chemistry and radiation balance of global climate change, the generally accepted method has been deterministic. They began with simple calculations for global temperature. Nowadays, reductionist models are

based on aggregate computation of physical processes in a very large number (many millions) of elemental volumes ('grid boxes') (typically 150 km wide for global coupled atmospheric–ocean computations), starting the calculation of the ocean and atmosphere by approximating the initial state to that currently observed (or not very far from this condition, thus excluding, for example, the possibility that the Earth is covered with ice!). These incorporate the changes forced on the climate belt by human activities (mainly increasing greenhouse-gas emission and particulates by industrial emission, transportation, agriculture and forest fires), and by variations in solar and other extraterrestrial perturbations (a recent innovation in this modelling work to meet a commonly voiced criticism by scientists and even politicians). The current numerical models used for climate prediction calculated satisfactorily mean temporal and spatial features of the past climate variations, not only over the past 150 years, but also, though with less precision, earlier geological epochs. This comparison has only been possible using detailed analyses of 'proxy' data derived from the biological and classical observations of fossils, tree rings, trapped gas bubbles, etc.

Because of the variety and amount of data, drawing conclusions about long-term trends on different time-scales requires statistical time-series analyses. For example, these help discriminate which aspects of the climate record are not so much trends as natural or forced fluctuations of the atmosphere–ocean and extraterrestrial climate (for example, associated with El Niño or North Atlantic or planetary oscillations). A further complication arises because these global calculations run on a coarse spatial scale. Therefore, they need to be refined to analyse and predict the particular features of climate change that affect rivers and coastal flooding.

This 'downscaling' of climate models is performed by using regional models with fine resolution (e.g. 50 km), but applied only over a limited area (e.g. over Europe). The outer 'boundary' conditions on these numerical models are determined by general circulation models (GCMs). Although all types of computational models have intrinsic errors caused by the neglect of sub-grid-scale processes, the prediction averaged over these kind of scales is being progressively improved through theoretical work and computations on these meso and micro processes in the atmosphere and ocean. Because such local-scale deterministic climate models have many approximations and statistical parametrizations, there is an argument that predictions of local-scale climatic changes should be primarily statistical. These could be based either exclusively on past observational data, or a hybrid statistical-modelling approach, for example, using observed statistical correlations between regional (e.g. river flows) and synoptic scale data, where the latter are derived from GCM prediction.

(b) Predictions

The conclusion of recent studies of the most important environmental changes by IPCC (2001) were accepted by most speakers at the conference as the basis for predicting changes in floods or factors determining flooding. Thus there would be a rise in the yearly average near-surface temperature over the next 100 years; depending on the model calculation the range of predictions would lie between $1\frac{1}{2}$ °C and 6 °C. All models agree that there would be much greater increases in the desert areas of Central Asia, Middle East and Africa, than in maritime areas like the UK. Furthermore, the upper figure could be higher by a further 1–2 °C if the permafrost melts

and a large release of methane hydrates trapped in the ground occurs. These rising temperatures affect land processes, especially through increased evaporation, desertification, and retreat of glaciers. However, a warmer climate, especially in maritime areas such as northwest Europe, causes increased flooding risk. Rainfall data support this tendency for UK winter seasons (Osborn & Hulme 2002; Robson 2002). Rising sea temperatures (by *ca.* 1 °C) might be expected on physical grounds to increase the occurrence and strength of tropical cyclones, which cause most of the precipitation in some subtropical regions. However, these phenomena are on too small a scale to be included at present in numerical models, and observational data do not indicate any firm trend. Although the financial costs of recent cyclones have been increasing, perhaps because of greater 'vulnerability' of coastal communities, this important question is still open.

By contrast, model predictions are unequivocal that temperature and mean sea level will rise inexorably over the next 100 or 200 years (Pugh *et al.* 2002). Whatever is done in the near future to limit greenhouse-gas emissions, current data support this predicted trend, which might lead to sea levels rising by *ca.* 0.8 m over the next 100 years around the UK; its effect on the coast of England is exacerbated by a few centimetres by geological processes that cause land sinking as it slightly tilts.

This projected rise will produce significant coastal floods and damage to coastal defences even if the climate variability remains as it is with the same probability distribution of large storms and ocean waves. However, in future if these effects become more frequent, the coastal areas could be even more threatened. But, at present, although there are physical grounds for expecting this change because of larger temperature differences between the temperate and polar regions, neither the numerical models nor observational data give a clear indication of a trend of greater storminess, though there is some evidence that North Atlantic wave energy has been increasing slightly over the past few years.

Thus, to summarize the current predictions, there will be substantial changes to global and regional climates over the next 100–300 years. These will be mitigated sooner if the human emissions of greenhouse gases are deliberately reduced below current levels (e.g. in accordance with the Kyoto Protocol), or later over a longer period of 200–300 years, when, as is predicted, the world population begins to fall. River and coastal flooding will be affected in a variety of ways by these large-scale changes, but also by regional and subregional scale changes to the Earth's surface. For example albedo, evaporation, precipitation, and run-off will be influenced by deforestation, changes to agriculture, air pollution, and massive urbanization; winds, waves, and flooding in coastal areas will be affected by changes in coastal morphology and changes to vegetation and coastal land use. Models and predictions for these local effects are only just beginning to be reliable enough for planning purposes. It is widely appreciated that these predictions are not only of scientific interest, but now provide the basis for many decisions by government, commercial organizations and even individual householders. But equally, it is realized that they have to be regularly adjusted as scientific understanding improves and more data become available. Therefore, just as members of the public assess quite sensitively the accuracy and usefulness of weather forecasts according to their own particular needs, organizations and the public similarly need regular updates of information about the

changing environment and future predications (especially of precipitation level and sea-level rise).

3. New technology for reducing flooding risk and prevention

(a) *Risk prediction and warning systems*

The first essentials in reducing the risk and consequential damage of any type of natural disaster are to assess, predict, and warn about the natural hazards and the vulnerability of the communities to them. There have been some advances in the practical evaluation of statistical risks of flooding, though there may well be more major progress in the next few years (see §4). However, there have been major improvements in real-time forecasting and warning systems of flooding throughout the world in the past 10 years; these are predicted to continue, provided there is a steady application, at least at current levels, of scientific and engineering research, and technological resources to these problems (Met Office 2001).

Data are available about improvements in weather and precipitation forecasts from national meteorological services (e.g. Met Office 2001), and the World Meteorological Organization, for both short-term (i.e. less than 5 days) and seasonal forecasts (i.e. for several months ahead). For example, a three-day weather forecast for precipitation is about as accurate as a one-day forecast was 15 years ago. Of particular importance for flood forecasting is the error in the location of a moving pressure system, which is *ca.* 120 km for 24 h (and increasing linearly for larger periods), whereas it was *ca.* 200 km only 10 years ago (Cullen 2002). These and other recent developments in longer-period forecasting, were reviewed by Hunt (1999).

There are little systematic data from any countries in the world about the accuracy and improvement of real-time flood forecasts along rivers. For example, if the maximum level of a flood is observed at Shrewsbury, UK, at a certain time, when will the maximum reach Tewkesbury, 100 km downstream, and what is the error in this prediction? Since such forecasts are beginning to be issued with more precision, it will be possible to assess systematically how they improve year by year. Around the coast, statistics are regularly collected at high water levels at tidal stations, to calculate trends and make forward predictions about extreme events. But these also provide a critique of the accuracy of forecasting, especially of maximum events (where typical errors are of the order of 0.1–0.2 m) (Huthnance 2000).

These advances have been based on a number of statistical and technological developments described at this conference. Five main factors have been better measurement, better techniques of analysis and interpretation, greatly expanded computing capacity, improved computing and numerical methods, including post-processing of data, and finally, advances in scientific understanding and numerical models, which are discussed in more detail in §4.

Huge investments in remote sensing technology have provided data on physical quantities that were never measured before, as well as data of greater frequency, spatial resolution and accuracy (Collier 2002). The UK spends (directly and with European collaboration) about £50 million per year on remote sensing data relevant to weather forecasts, precipitation, flooding, land processes, ocean, and river and coastal data. These are obtained from satellite systems, weather radar, aircraft measurement, and detection of atmospheric electrical disturbances. The USA, with a much greater land mass, spends about 30 times as much. The new qualitative

satellite measurements have been of water vapour and wave properties, and the sea surface winds. There has been greatly improved accuracy and spatial resolution of temperature. All of these have greatly improved calculations of evolving weather systems, and precipitation (Bates *et al.* 2002).

In the early 1990s there was a concern that the investment in satellites was not leading to significant improvement in numerical weather prediction (NWP) (e.g. Hunt 1994). But now, as a result of a substantial effort, particularly by the European Centre for Medium Range Weather Forecasting (Hollingsworth 2002), to incorporate the signals from the satellite instruments directly into the NWP codes without any intervening assumption (e.g. about the mean temperature profile), these data are contributing at least as much to forecasts as those provided by meteorological balloons. This explains why three-day forecasts in the Southern Hemisphere, e.g. of precipitation over Mozambique, are now, unlike 10 years ago, as accurate as those in the Northern Hemisphere, where there are many more observations from balloons. (The reason for greater accuracy in the Southern Hemisphere, relative to the number of observations, is probably that it is mainly covered with ocean, whereas in the Northern Hemisphere the land surface is more complex.)

Until five years ago, radar and other local systems were only used as aids by forecasters to supplement other observations and NWP. But now computer-based precipitation and wind forecasts are available for short periods (less than 30 min) and at local scale resolution of 15 km or less.

Data from these systems are used in hybrid calculations that are partly data-extrapolated and partly based on NWP methods (at the mesoscale) (Pierce 2002). Indeed such is the practical and economic benefit from the current radar systems that, as Harrison & Gould (2002) argued, three more such systems should be installed in England. Developments in remote sensing technology have also now provided direct data of river and coastal flooding and associated phenomena through more accurate measurement of water level (to ± 5 cm), ocean waves (to ± 10 cm), and surface winds (within 1 m s^{-1}), e.g. using the ERS and TOPEX/Poseidon satellites. These will be continued in the next generation of environmental satellites being launched by the USA, Europe and Japan.

The increasing speed of large computing facilities, by a factor of 10 about every five years (Moore's law), to the present level of 10^{12} Flops (a teraFlop), has been fully utilized by meteorological services, mainly in providing more accurate and detailed forecasting, rather than to speed up delivery. Forecasts have continued to be delivered about four hours after the data have been received for short-range forecasts, and *ca.* 18 h for 3–10-day forecasts. A major feature of the latter medium-range forecasts is that they now include a range of possibilities, so that it is possible to know if there is a small chance of an extreme event (Palmer & Räisänen 2002). Another use of the full computational capability of national meteorological services is to combine weather and coastal flooding forecasting by coupling the wind stress derived from numerical weather prediction models to coastal oceanographic models (COM), which include the effects of tidal forcing by the deep ocean (Huthnance 2000; Battjes & Gerritsen 2002). However, as regards river flooding, the maximum computer capability is only used for computing the complex land surface processes that generate river flows and the detail of in-bank and out-of-bank river levels for design and research studies, rather than for operational purposes. Currently, physics-based hydrological models are constrained by a lack of capability to observe heterogeneous subsurface processes,

and river models by the need for detailed local information on river channel and flood plain geometry, control structures, and hydraulic roughness. Hence the *operational* computational prediction for river flooding is based on simple and efficient empirical models for each river basin, which predict average channel cross-section quantities (e.g. water height and flow speed). These are developed from studying the data of river flows and precipitation inputs, and can be readily updated in real time to assimilate new observations of river flows or levels. The form and operation of these models varies greatly within countries (including the UK) (cf. Wheater 2002; Young 2002; Fleming 2002; Gupta *et al.* 2002). All the models in practical use require computation at the level of a workstation (*ca.* 10^8 Flops) or less.

With the establishment of the single national environment agency, responsible for river floods in England and Wales, it is likely that there will be greater uniformity in the future. Will this extend to Scotland and Northern Ireland?

In countries where very large rivers cross national frontiers (those in South Asia, North East America, South America, Southern Africa and Continental Europe for example), accurate prediction of flooding requires measurement and communication of timely data of river flows and levels from other countries upstream. Although there are only very limited international agreements about the exchange of hydrological data (WMO 1999), unlike the case for meteorological data, there are local arrangements in certain river basin areas (e.g. for the Danube and Rhine in Central Europe). It is to be hoped that these initial steps will lead to greater improvements in international data exchange, but this will require governments to mandate their national delegation to international conferences to take this issue more seriously than they do at present (WMO 2002).

However, at the other end of the scale, communication about flooding risk and warning to individuals and small communities has changed much more substantially, especially in developed countries. For example, flood risk measures are available on the Internet in the UK, and flood warnings based on model predictions, as well as the general precipitation forecast, are now provided by the media.

(b) *Practical flood reduction measures*

Once the risk of flooding has been estimated, there are four main factors that determine which measures are taken to reduce flooding, namely

- (i) level of risk reduction, with elimination being impractical or uneconomic for risk prone areas (e.g. Battjes & Gerritsen 2002);
- (ii) timelines, so that temporary structures may be the only practical solution before the next flood arrives;
- (iii) cost in prevention, or past disaster, or insurance; and
- (iv) wider environmental, economic and sustainability concerns (Poff 2002; Verworn 2002)

Better risk prediction and more accurate real-time flood forecasts, combined with engineering research and development and greater investment, is leading to improved design and operation of flood reduction systems. Despite the success of some measures, where the risk prediction, planning, and engineering systems work well (e.g.

Thames Barrier), it is well documented that in many areas in the UK and other countries, when there has been insufficient investment, and sometimes wrong planning or technical decisions, significant flooding damage to those communities has occurred. Determining the appropriate next steps in these situations is as much a social, financial and political question as a technical one (Penning-Rowsell *et al.* 2002). The relative financial responsibility of the individual is greater in the UK than in some other countries where the central government takes most of the decisions. This should mean that the individual and local communities are provided all the more with relevant information to enable them to make appropriate decisions, including community planning decisions, and to take technical decisions about remedial measures (e.g. the use of temporary structures). Assuming such devolution of responsibility is associated with devolution of power to communities (which is not clear in the UK, with some planning powers possibly about to be removed from local communities), it is also inevitable that those communities will consider the wider sustainability issues, for example, in relation to agriculture and forestry in valleys subject to flash floods, and in relation to different types of coastal defence, or new types of economic activity in coastal areas at risk from sea-level rise (e.g. Kelman *et al.* 2002). It is interesting that East Anglian communities in the 17th century objected to draining the Fens because of a loss of jobs (Darby 1956). Perhaps there will be more jobs in future associated with partly flooded coastal areas?

4. Possible contributions by mathematical science and engineering research

(a) *Extreme events*

The most difficult and important aspects of flooding are the extreme events, which tend to occur at a given location only quite rarely. The statisticians collect as much of these fragmentary data as possible and develop concepts about their likely frequency. Recent mathematical research has suggested new approaches focusing only on the extremes and not the whole ‘population’, which leads to frequency distributions more in accordance with the observed, but unexpected, repetition of extreme events (e.g. Smith & Goodman 2000). Because these extremes occur at *different* places, statisticians now collect and study spatio-temporal statistics.

This approach brings them closer to determinists whose models include representation of the small scale of recurring features (e.g. clouds) and also of the larger-scale features of these particular weather events, and river floods (using the unit hydrograph and its modern extensions; Fleming 2002). A striking example of a successful forecasting model of a particular extreme event is that of tropical cyclones which is used for real-time forecasting over periods of 1–5 days. But the same concept could be applied to local storms by combining deterministic modelling and some observed statistics (Pierce 2002).

The challenge mentioned in several papers is to predict extremes in a changing climate (Dale 2002). It is likely that the only plausible predictions are those derived by combining numerical model output, perhaps with different input ‘scenarios’ and different assumptions about dynamical processes, together with statistical data for the present state of the climate. The former ‘ensemble’ predictions should help decision makers and the general public understand the possible ranges of climatic scenarios. However, the deterministic models used for climatic calculations are still not

detailed enough in space or time to describe and predict extreme local flooding events. This deficiency may be reduced by use of improved local spatio-temporal precipitation/flood statistics (preferably conditioned on the larger-scale climate) or by computing with improved modelling of river/coastal flows of local meteorology on scales of 10 km or less that are being applied to short-range forecasting (Cox *et al.* 2002; Chandler & Wheeler 2002; Bingham *et al.* 2002).

(b) *Local-scale phenomena and short-range forecasts*

Atmospheric, land surface and ocean phenomena occur on all scales, but there are surprisingly strong interactions between characteristic phenomena over differing scales. This affects how deterministic models are constituted and interpolated as the resolution of computations improves. In these models phenomena are represented explicitly above the grid-scale of the computations, and only in an average or statistical way where they are of smaller scale. However, this method has an intrinsic error, caused by interactions between explicit and sub-grid-scale processes. These interactions tend to be either neglected or greatly simplified. Although this error generally decreases as the grid-scale is reduced, its magnitude is uncertain. Thus, since the sub-grid-scale parametrizations have to be continually readjusted as the grid length-scales are reduced (because larger-scale features are progressively omitted), this is another reason why the accuracy and interpretation of numerical models have to be reassessed when the resolution is changed. For example, in the atmosphere, as has only recently been established theoretically and observationally, the high winds that force coastal flooding typically vary in strength quite rapidly with distance from the shore, reaching their maximum value within 1–2 km out to sea (Hunt *et al.* 2001; Gadian & Thielen 2002). This local phenomenon determines coastline erosion and larger-scale ocean currents.

There are other critical processes, on much finer scales, that can also be determined statistically because they could not possibly be computed explicitly, such as the effects of aerosol and cloud turbulence for motions of 10 mm diameter rain droplets from the much smaller droplets (*ca.* 10 μm) that result from condensation. This is an example of how improvements in the statistical modelling of these sub-grid-scale processes result from basic research.

Similar limitations apply to the modelling of fluid flows at the surface, over and under the land, and in rivers and along coasts. The report of the Institution of Civil Engineers on behalf of DEFRA (ICE 2001; Fleming 2002) emphasized how explicit ‘bottom-up’ or deterministic computational modelling of river channel and flood plain flows using two- or three-dimensional grid-based numerical models is now feasible for predicting flooding both for real-time and statistical prediction (given appropriate data of precipitation). However, the report also emphasizes that the modelling depends crucially on accurate information about the flood plains, and inputs from hydrological models of run-off from fields and urban areas. Modelling the subsurface flow processes which transmit rainfall to the river faces the limitations of scale discussed above, and in addition the need to represent flow through highly variable subsurface materials. To this can be added the challenge of understanding effects at the catchment-scale of land use and land management change. Research needs to address these are defined by Wheeler (2002), and while international model comparisons have been published, these have not addressed the accuracy of forecast predictions of flooding along rivers.

Another reason for errors in prediction of estuaries and coastal flows is the uncertainty about the changes in the bathymetry or elevation of the river or ocean bottom, caused by the movement of sediment. For the prediction of long-term change in bathymetry over decades, it is reasonable to estimate that fluxes of sediment are affected by changing currents associated with rising sea level and perhaps coastal winds.

However for predicting particular river and coastal flooding it is only necessary to know the bathymetry at that time, especially the variation associated with sediment waves. New technologies are available for these measurements, for example using microwave satellite measurements of centimetre waves that vary in amplitude over the water surface as tidal flows accelerate and decelerate over depth changes. New technology and scientific interpretation is needed to refine these methods to necessary depths greater than 20 m.

Coastal flooding occurs in extreme conditions of high winds and high tides, when strong waves move in quite shallow seas. The latter may be absorbed by 'soft' vegetated shorelines or reflected by 'hard' shore defences. In some models, calculations for the maximum surge height and for wave amplitudes are simply superposed, but in others they use ad hoc statistical projections from past data. There is not much confidence about these predictions and there are some indications in the Netherlands that previous estimations of overtopping waves need revision.

Finally, it needs to be emphasized that just as much research is needed on the changing geological and ecological properties of flood-prone areas as on the physical properties of the floods themselves (e.g. Townend & Pethick 2002). A better understanding of how these areas will change is essential to ensure the success of sustainable development projects, for example, allowing the coasts to adjust naturally while developing new economic activities, such as ecotourism, fishing, saline agriculture, forestry, etc. As well as informing the public about short-term flooding changes, such as with forecasts and warnings, it is equally important to explain that the optimum sustainable development solutions vary greatly from one area to another because of intrinsic natural factors, which might be as subtle as the type of sand/clay particulates in a particular coastal area, which it turns out, greatly affect whether beach replenishment is, or is not, a practical solution to rising sea level.

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