05 - Effective flood forecasting: lessons learned from international research and experience

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Abstract

Effective flood forecasting has the potential to save significant numbers of human lives, as well as saving disruption to many times that figure, and has the ability to save enormous sums of money. In the first half of the twentieth century, hundreds of thousands of people lost their lives to flood disasters; on the other hand, in the latter half of the period, hundreds of millions of people were affected. This would imply that whilst the situation has improved in terms of reducing the numbers of people killed through flood disasters, there is still an enormous role for effective flood forecasting and warning to reduce the wider impacts of flood disasters. This paper summarises the findings of research into the effectiveness of a wide range of flood forecasting and warning systems around the world. The research analysed historical flood events to put the problem into context, and investigated the concept of the 'effectiveness' of flood forecasting and warning. It examined the general anatomy of a flood event, and its main components, before summarising the types of flood forecasting service provided around the world. An extensive literature search and international stakeholder engagement activity was carried out, to examine the range of flood forecasting systems in use for a range of applications, and to find evidence of their level of effectiveness. The gathered information was assimilated in order to distil out the key messages to understand the reasons for weaknesses in flood forecasting systems, and hence the way forward to develop more effective systems. The lessons were grouped into seven main areas, and illustrated with examples from the research.

From the beginning of the development of a flood forecasting and warning system, the approach should ensure that all relevant components are captured at an early stage in the planning process; this means that the team should have a range of multi-disciplinary skills, aiming for a fit-for-purpose solution. The level and quality of available data will provide limitations to forecast accuracy which should be recognised from the start; this can be improved with provision of reliable telemetry networks, sensible use of available meteorological products, a drive towards international standards for data exchange and storage, and the use of river basin commissions for international river basins, to provide a mechanism for sharing data across boundaries. The modelling strategy should investigate a range of modelling options to come up with the most suitable choice for the problem, ensuring that the model can easily cope with changes to the catchment over time. Hydraulic model resolution and coverage should be focused on key flood risk zones only. A model management system should be put in place at the start, to include an audit trail to enable quality control, a calibration schedule to maintain accurate model parameters, and regular reviews of system effectiveness (by the full range of stakeholders). The availability of skills should be improved, with consultant engineering staff as well as within end client organisations, through regular training and on-going support. The forecasting and warning strategy, including raising awareness of flood risk, and appropriate communication strategies, has a range of features that can be enhanced by effective system development. Realistic

forecast lead times should be recognised and publicised from the start. Finally, efforts towards the sustainability of the system should involve the end client throughout the system development process to encourage ownership.

1. INTRODUCTION

Effective flood forecasting has the potential to save significant numbers of human lives, as well as saving disruption to many times that figure, and has the ability to save enormous sums of money. In the first half of the twentieth century, hundreds of thousands of people lost their lives to flood disasters; on the other hand, in the latter half of the period, hundreds of millions of people were affected. This would imply that whilst the situation has improved in terms of reducing the numbers of people killed through flood disasters, there is still an enormous role for effective flood forecasting and warning to reduce the wider impacts of flood disasters.

This paper summarises the findings of research into the effectiveness of a wide range of flood forecasting and warning systems around the world. An extensive literature search and international stakeholder engagement activity was carried out, to examine the range of flood forecasting systems in use for a range of applications, and to find evidence of their level of effectiveness. The concept of the 'effectiveness' of flood forecasting and warning is discussed here in order to set the scene, along with some background information on the potential economic benefits involved in getting it right. The information gathered through the research and from wider experience was assimilated in order to distil out the key messages to understand the reasons for weaknesses in flood forecasting systems. The lessons were grouped into key areas which form the core of this paper. A short discussion of the important points is presented.

1.1 What is effective flood forecasting and warning?

A global survey of early warning systems carried out by the UN and the International Strategy for Disaster Reduction, (UN/ISDR, 2006), resulting from the assessment of progress towards Millennium Achievement Goals, concluded that to be effective, early warning systems must be people-centred and must integrate four elements, illustrated in Figure 1. It notes the following: "A weakness or failure in any one part could result in failure of the whole system."

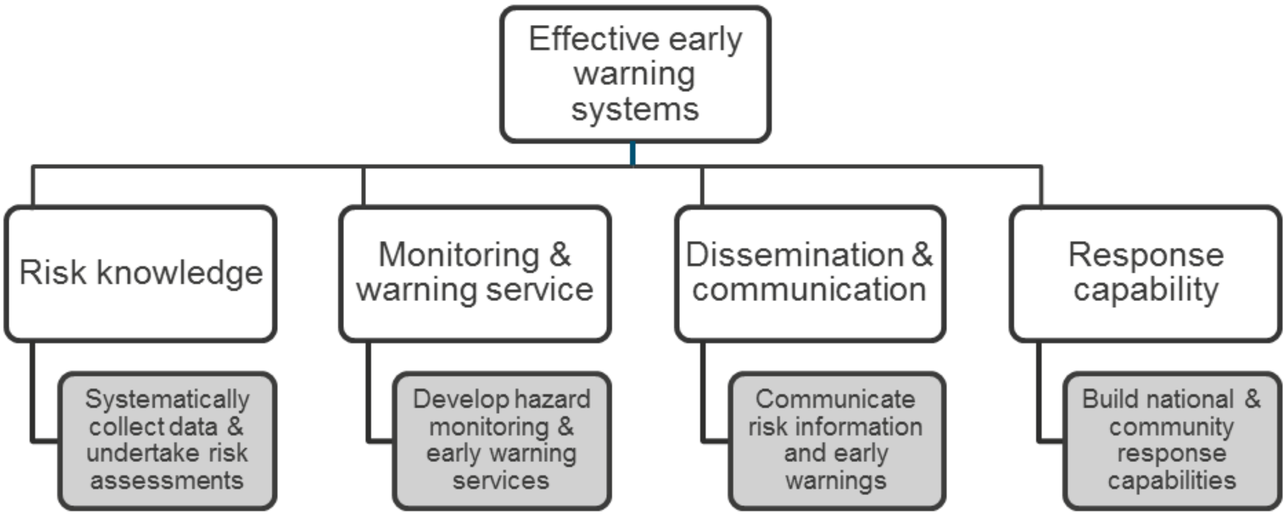


Figure 1: *The four elements of effective early warning systems (after UN/ISDR (2006))*

Furthermore, to be successful, such a system requires sufficient integration of components and collaboration and coordination between multiple institutions. Flood forecasting and warning systems sit at the complex interface of meteorology, hydrology, hydraulics, information technology, and social science. Therefore, each component must be able to perform its role, and the links between them, their integration, must be working effectively, too.

1.2 The economic drivers for effective flood forecasting

In addition to the direct impacts of effective flood forecasts on human lives, economic aspects also offer a persuasive argument for getting it right. Healy and Malhotra (2009) examined the relative benefits of US investment in disaster preparedness versus disaster relief, and found that spending approximately US$1 on preparedness corresponds to spending around US$15 on relief in the long term. When looked at on an annual average basis, EWC II (2003) cites the UNDP World Development Report of 2000/2001 and notes that the average annual losses from flooding in Asia alone amount to about US $15,000 million. Therefore, 'even a small percentage reduction in losses through better early warning will translate into very significant savings, not to mention the benefits of avoiding disruptions of households and businesses and most importantly the saving of lives'. An Australian study stated that the cost-benefit ratio for urban flood warning systems is 'extremely favourable', and that investment in urban flood warning systems is likely to be the most cost-effective flood mitigation strategy - 'a benefit to cost ratio of six was noted' (EWC II, 2003).

Early warning systems tend to have high benefit to cost ratios compared with other flood management options, such as infrastructure development and the rebuilding of natural ecosystems, as well as having relatively high robustness to uncertainties about future climate, such as drainage systems and flood defences, where the choice of measure (and the resulting benefits) is more dependent on assumptions today about the future climate (Ranger and Garbett-Shiels, 2011). However, Jha et al (2012) point out that 'evaluation of the costs and benefits of each measure, or combination of measures, must be integral to a wider strategy which sets future targets for investment in measures and prioritizes spending on the most urgent and effective of these activities'.

2. LESSONS LEARNED FROM INTERNATIONAL EXPERIENCE

A literature search examined the range of flood forecasting systems in use for a range of applications, to find evidence of their level of effectiveness. A subsequent stakeholder interview process made initial contact with more than 45 people involved in a range of aspects of flood forecasting and warning, in around 34 different countries, regions and organisations. The information was assimilated in order to distil out the key messages to understand the reasons for weaknesses in flood forecasting systems, and hence the way forward to develop more effective systems. The lessons were grouped into seven main areas; these are described below.

2.1 Prepare the right approach

A first step in flood forecasting should be consideration of the end-to-end system requirements, to ensure that all relevant components are captured at an early stage in the planning process. The Third International Conference on Early Warning (EWC III) held in Bonn, Germany in 2006 provided the opportunity to present new and innovative early warning projects and to discuss natural hazards and risks around the world and how their impacts can be minimised through the implementation of people-centred early warning. Under the four headings shown in Figure 1, a useful checklist of actions and initiatives to consider when developing early warning systems was produced (EWC III, 2006).

System development should integrate a range of multi-disciplinary skills (including meteorologists, hydrologists, hydraulic engineers, IT experts, and project managers), and should engage with the client and stakeholders to ensure relevance and ownership. The WMO Flood Forecasting Initiative held a series of eight regional workshops to pinpoint the weaknesses in current flood forecasting systems (WMO, 2006c); of these, the Valencia Declaration (WMO, 2004) and the Zaragoza Declaration (WMO, 2006a) both pointed out that in recent years, meteorological products have improved but there is a need for a close collaboration between meteorologists and hydrologists to ensure that the information is optimally used. The UN/ISDR assessment survey (2006) also noted a widespread need for closer collaboration among the meteorological and hydrological agencies and communities at the national and regional levels to ensure enhancement of flood forecasting, modelling and warnings.

Research to review and categorise forecasting approaches used for fluvial flooding in England and Wales identified the main issues and problems associated with forecasting, and produced guidelines on the selection of appropriate methods for real time models (after Zaidman et al., 2005). The project advocated a ‘horses for courses’ approach, whereby the most appropriate modelling solution should be used for the forecasting problem, the catchment characteristics and the project requirements. Forecasting of flash flooding is problematic; this has implications for developing nations which are more exposed to such risks, due to the prevalence of monsoon-type flooding. It is necessary to consider such local factors, at the inception stage of a project, so that a fit-for-purpose approach is taken.

2.2 Recognise the limitations of the data

To a large extent, the amount of relevant available data in the catchment will determine the nature of the forecasts that can be provided, their frequency and reliability. Consideration should be given to the type of forecast required, the size of catchment, and the nature of the flood processes (e.g. flash flooding) as these will dictate the resolution and frequency of the desired data inputs, in order to provide relevant forecasts. Small, urban catchments require measurements and forecasts of precipitation with high spatial and temporal resolutions (e.g. 1 km and 5 minutes). Weather radars are able to provide such measurements, but unfortunately radar rainfall estimations are affected by different sources of error. These errors are often ignored when producing radar-based precipitation forecasts for urban flood forecasting (Centre for Ecology and Hydrology, 2012). The RainGain project obtained high spatial and temporal resolution rainfall observations at urban scales (100 metres; 1 minute intervals), and used them to analyse and predict urban pluvial floods (Ten Veldhuis et al., 2014); such data are necessary to provide urban water managers with detailed peak rainfall information at temporal and spatial scales appropriate to the rapid urban runoff processes.

The quality and availability of telemetry data varies widely. Under the WMO’s Flood Forecasting Initiative, regional consultations found that in many countries of south east Asia, Europe and Africa, there is an urgent need to expand the terrestrial observation hydrological and meteorological networks as well as the need to upgrade and improve the existing networks (WMO, 2003, 2005a, 2005b, &

2006b). Network densities can be too sparse to accurately represent the spatial variability of rainfall events. A study of the Environment Agency's topographic representation of the gauge networks revealed problems at higher elevations, whereby the tipping bucket gauge network was under-represented at elevations exceeding 350 m: "This has particular significance for flood forecasting applications, since the main flood generating areas in a catchment are often in the highest parts of the catchment" (Tilford et al., 2003). A common further problem with some telemetry networks relates to the time lag in the reception of hydrological data "under these circumstances, it is not possible for an operational flood prediction and warning system to be established" (WMO, 2006b). Manually-read gauges are still used in some regions, but these often incur problems through errors in recording readings, and delays in transmission.

The WMO (2003) noted that fragmented data holdings, non-standardized data archiving, data formats and transmission protocols severely limit timely access to data and information. The organic and bespoke manner in which many data systems have been developed mean that there are now many different telemetry file formats, SCADA systems, and database formats. Recent developments towards standards in data file formats and exchange protocols may help make systems more robust. Flood forecasting systems work most effectively with centralised data holdings and regular archiving. The use of recognised data file formats makes communication between SCADA systems and flood forecasting servers more straightforward.

Weather forecast technology and available products are developing fast. Forecasts of the future state of the atmosphere or rivers are often based upon estimating how the current state evolves in time using a numerical predictive computer model. However, as the atmospheric system is chaotic, very small errors in the initial state can amplify as numerical integration proceeds leading to large errors in the forecasts, which limit how far ahead the forecast detail can be specified with any certainty (Centre for Ecology and Hydrology, 2012). Convective rainfall causes some of the greatest challenges to rainfall forecasting, and consequently the ability of the weather forecast system to detect and predict such events is a major issue (Henonin et al., 2010). Nowcasting involves the extrapolation of radar or satellite precipitation patterns, and so can capture the initial information almost perfectly, but as they do not include physics, the skill will decrease rapidly with lead time (Schuurmans, 2008). An alternative is to use Numerical Weather Prediction model outputs (NWPs), whereby the forecast data consist of a number of model outcomes that are all equally likely to occur. These so called "ensemble members" provide insight into the reliability of the model outcomes. These NWPs (by comparison with nowcasts) capture the physics of large systems very well, but lack local detail because of their limited spatial resolution and have imperfect assimilation algorithms. Therefore their skill is not so high for small lead times but decreases only gradually with increasing lead time (Schuurmans, 2008). Ensemble members form part of Ensemble Prediction Systems (EPS) and they are increasingly being used instead of single (deterministic) forecasts for longer flood warning times (Thielen et al., 2009). EPS are designed to give a measure of the uncertainty in the model solution. They need to be generated by very powerful computer models (such as those run by national meteorological agencies). The fact that they can offer a measure of uncertainty in the results is good in theory, but in practice, it can complicate the communication of results to end users. Cloke and Pappenberger (2009) present the key challenges of the use of EPS for flood forecasting, which include the need for higher resolution NWPs and more ensemble members and consequently greater computer power; however, they note that communicating uncertainty and probabilistic forecasts is difficult.

Many examples exist of the problems caused when trying to forecast across international river basins, such as for Bangladesh, sitting at the downstream end of the Ganges-Brahmaputra-Meghna river system, or for the Juba and Shabelle Rivers of southern Somalia, where 90% of their waters originate in Ethiopia, but there is now no trans-boundary hydro-meteorological data sharing between the two countries (Guleid et al., 2007)

2.3 Use an appropriate modelling strategy

The employed modelling strategy needs to recognise the limitations of the available data and the feasibility of providing a useful forecast. Flash flood forecasting offers particular challenges in this area; adoption of a simple threshold procedure for formulating watches and warnings on a national scale is necessitated by the very short lead times allowed by flash flood events for forecast and response activities (Ntelekos et al., 2005). In arid zones, where flash floods are predominant, emphasis should be given to early detection of rainfall.

The nature of flood forecasting based upon a modelling approach is such that the models must be able to run quickly, to produce accurate, reliable forecasts in the minimum amount of time, to support decision making as a flood event develops. The traditional off-line, event-based modelling approach does not necessarily work well when expected to run inside a flood forecasting system; as Hopson and Webster (2009) state "some models are better equipped in certain forecast circumstances than others and that the combined performance of the multimodel generally outperforms any one model". All flood forecasting systems need to offer accurate representation of the initial conditions of the catchment, since this offers the ability to shorten run times by 'hot starting' from realistic catchment conditions at the start of the run, hence doing away with the need for long model warm-up times. This effectively results in a 'continuous' simulation, which offers more accurate results.

Some of the main sources of uncertainty in the models can be grouped into these categories: catchment averaging procedures, choice of model type and structure, model calibration, operational simulation, real time updating procedures (Sene et al., 2007). These sources of uncertainty could be used as a checklist for analysing each of the main system components, during both the system development stage, as well as the operational stage. The system owners should be prepared to have a regular model re-calibration regime, to ensure that the systems function as intended (Henonin et al., 2010; Commonwealth of Australia, 2009). This regular review should be part of a wider assessment of system effectiveness: "System review should occur at different levels and, where possible, performance indicators should be devised so system effectiveness can be assessed objectively." (Commonwealth of Australia, 2009).

2.4 Ensure the availability of skills

The WMO's Flood Forecasting Initiative (WMO, 2010) identified skills as a limitation to the effectiveness of its flood forecasting services, with the Nile Basin Initiative as an example of the challenges of institutional and professional capacity building in flood forecasting and the use of hydrological models including correct interpretation of model results. the WMO study of the efficiency of forecasting services worldwide resulted in a set of bench-marking criteria for institutional aspects. It includes:

- Skill level adequate to operate flood forecasting models:

- Staff motivation (recognition of services, career development, promotions);
- Capacity building activities (opportunities for capacity building regular upgrade of skills, introduction to new technologies);
- Internal training programs;
- External training programs;
- Certification of achieved skills after training.

Availability of appropriate skills at all stages of flood forecasting system development and operation can be problematic. In a study of problems relating to modelling in flood forecasting systems at the UK Environment Agency, Zaidman et al. (2005) noted lack of skills and expertise in the client and in the consultant staff working on flood forecasting projects "This means that the Agency is sometimes unable to offer a suitable level of technical guidance to consultants, which in turn can lead to difficulty in agreeing on and attaining an appropriate type, resolution or scale of model, and a number of other technical problems. There can also be problems procuring models and agreeing a project brief for the same reasons."

2.5 Consider the warning dissemination strategy

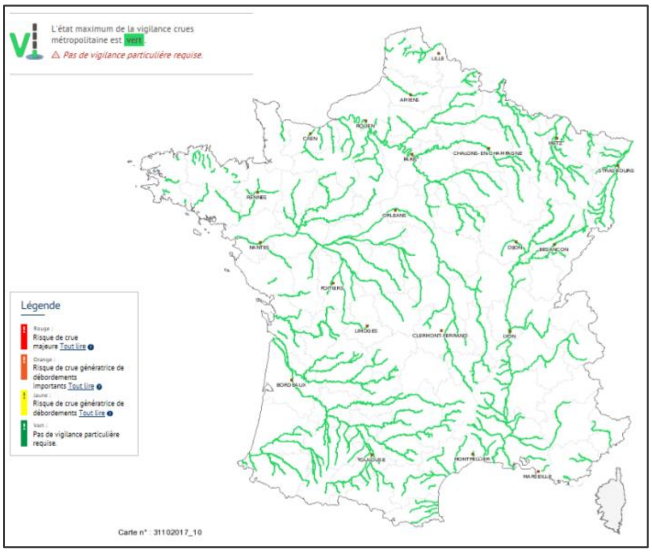
Failures in early warning systems typically occur in the communication and preparedness elements (UN, 2006; JICA, 2007; Jacks et al., 2010; WMO, 2005b). Forecasters need reliable information upon which to issue forecasts. "The balance between failure to warn adequately in advance and the corrosive effects of too many false alarms must be carefully managed" (Jha et al., 2012).

Inaccurate forecasts may lead to populations ignoring warnings issued subsequently. The lack of clear warning and instruction may have resulted in the deaths of people escaping the Big Thompson Canyon flood in the US in the 1970s. Without clear instructions many people were killed trying to drive out of the canyon rather than taking the safer option of abandoning cars and climbing to higher ground. The case of Hurricane Katrina demonstrated the scenario where clear advanced warnings failed to protect the population because the evacuation planning was inadequate.

Early warning systems need to have not only a sound scientific and technical basis, but also a strong focus on the people exposed to risk (Basher, 2006). In his review of the 2007 UK floods (Pitt, 2008), Sir Michael Pitt identified several aspects of the flood forecasting and warning service that needed improvement, including: long lead time warnings for infrastructure operators; low probability warnings to increase preparation times for emergency responders; and personalization of public warnings. A review of flood forecasting and warning systems in Africa indicated that, in most countries, they are not perceived by stakeholders to be effective (Lumbroso et al., 2016).

For catchments offering longer lead times of a week or more, a sequence of information actions can successfully be used to activate different end users in a range of ways as the flood event approaches, moving from awareness raising and mobilisation, through to active evacuation (Golding, 2009).

In the late 1990s in France, devastating floods highlighted the weaknesses in their national warning system; there were too many warnings, which lessened their impact, the information for the general public was not well expressed, the impacts of meteorological events (such as wind speeds) were not explained, and even if the event was well explained, the general public would not necessarily know how to react to the warning (EWC II, 2003). After this analysis, Météo-France and its partners developed a new system in order to overcome all these difficulties: the "Carte de Vigilance", or weather watch map system. It is a colour-coded map for France, with each department assigned a colour according to the seriousness of the predicted meteorological risk. Each colour is accompanied by a brief explanation of how unusual the predicted conditions are and what sort of response the public should take. The map is updated at least twice a day, and is valid for 24 hours. An example of the flood version of the map (“Vigicrues”) is given in Figure 2.



Assessment and then communication of the errors and uncertainties (and thus the accuracy of a forecast) can be used to increase public confidence in the warnings and their willingness to respond (Jha et al., 2012). The Mekong River Commission publishes on its website information about the mean absolute error of its forecasts, but notes that “for the actual flood forecast these values are further adjusted by the Forecaster-In-Charge using knowledge of bias and system behaviour, and of weather patterns and specifics of the input data. This usually improves the forecast significantly”.

Figure 2: *Vigicrues: Information on the risk of flooding (http://www.vigicrues.gouv.fr/)*

2.6 Recognise the available forecast lead time

Longer lead time warnings are better for emergency responders and infrastructure operators. Desired longer lead times are best achieved with the use of new forecasting technologies, such as EPS, providing that the forecasts are presented in probabilistic terms and interpreted appropriately. (Golding 2009). During system design, it is possible to estimate the duration of the flood warning process, and the probable lead time. The Environment Agency (2002) note the following sources of time delays in the whole flood warning process:

- The time taken for the telemetry system to poll all outstations in the catchment;
- The time taken to process and quality control incoming data;
- The time interval at which Met Office rainfall actuals/forecasts are received;
- The time taken for a forecasting model to run and the time interval between each run;
- The lead time provided by the forecasting model(s);
- The appropriateness of any trigger levels or alarms which are set including contingencies;
- The time taken to run additional ‘what if’ scenarios and interpret the results;
- The time taken for flood warning staff to interpret forecasts and decide whether to issue a warning;
- The time taken for warnings to be issued, flood wardens etc. to all properties at risk”.

2.7 Consider the sustainability of the system

Flood forecasting systems are expensive to develop and install. It makes sense to consider the longer term sustainability of the system to support the initial investment. However, for many developing and least developed countries the sustainability of warning systems is a major challenge (UN/ISDR, 2006). Reasons for the lack of success of such systems noted by Uran (2003) were:

- Users find the system too detailed, time consuming and costly to use;
- The general complexity of the system;
- The uncertainty of the model output and the appropriateness for solving the decision question;
- Limited involvement of users in the development phase;
- No training is given to the users.

The WMO (2003) found that there is a pronounced "communication gap" between meteorological and hydrological services with regard to forecasting concepts, methods, products and services, outreach to end-users and even the technical language used. Figure 3 shows that, of the 86 reporting countries, fewer than half of the national flood forecasting and warning services could be considered 'well established'.

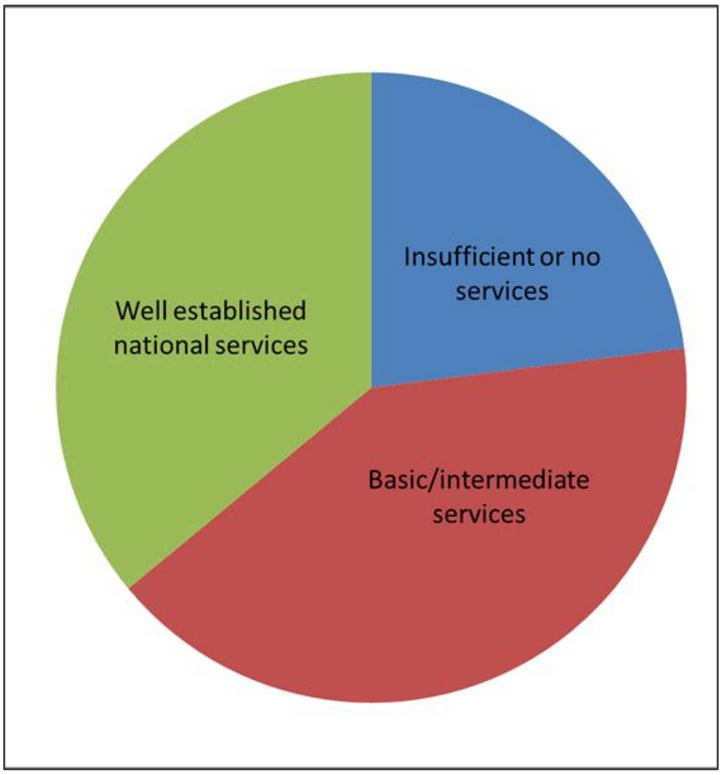


Figure 3: *Overall status of national flood forecasting and warning services. Source: WMO (2006c)*

The major reasons for a lack of national flood forecasting capability in those 86 reporting countries were examined, and the findings are reproduced in Figure 4.

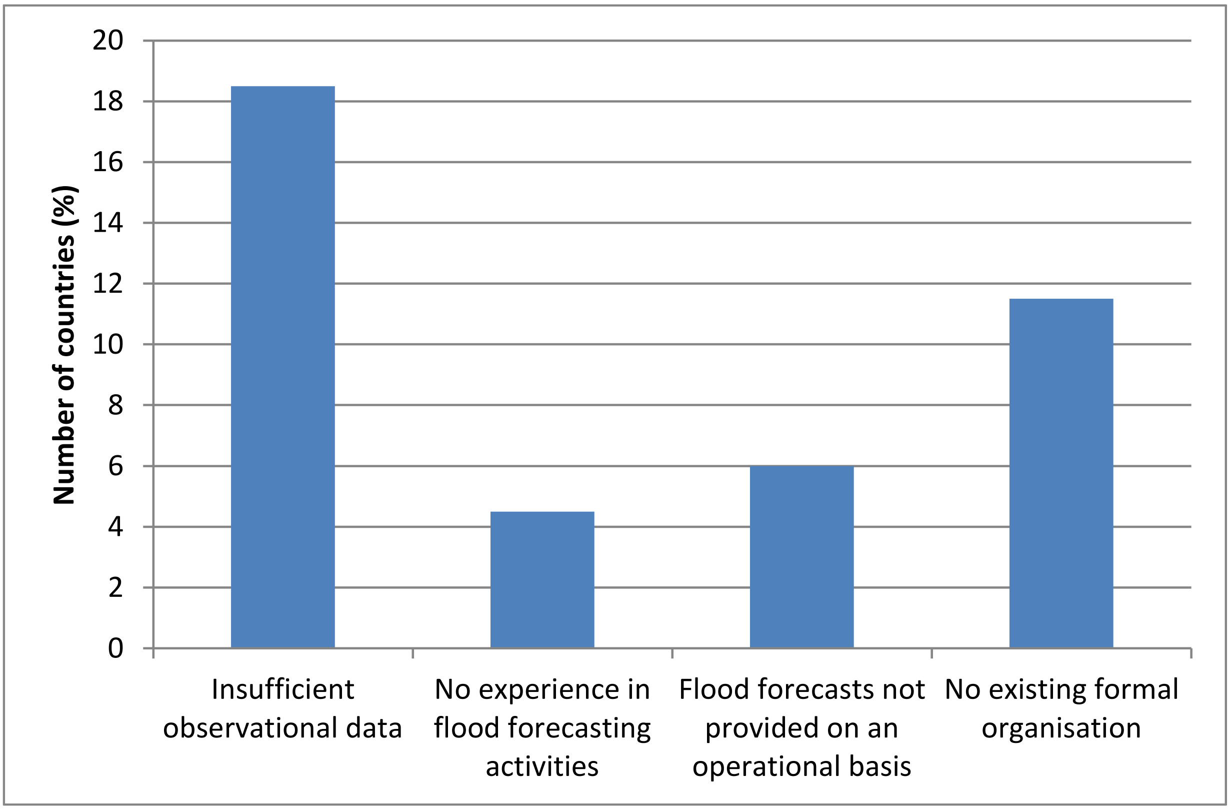


Figure 4: *Main symptoms of insufficient or non-existent national flood forecasting capability. Source: WMO (2006c)*

It is important to recognise that any flood forecasting system has a cost associated to each phase of its life, from design and development, deployment, through usage and long-term maintenance. In order to ensure sustainability, the cost of each of these phases has to be realistically assessed and considered when investigating the installation of a flood forecasting system; the cost range from very simple systems to advanced systems can be significant.

3. DISCUSSION

The main perceived weaknesses of flood forecasting systems have been classified into seven areas, from which lessons can be learned for improving system effectiveness. From the research it was clear that these weaknesses are common to many of the existing systems and procedures around the world. Similar problems and challenges are faced relating to data availability, skills shortages, lack of funding, and inadequate planning for sustainability. Recognising these challenges at the start of system development means that their impacts can be mitigated and sensible, holistic, sustainable solutions can be developed.

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