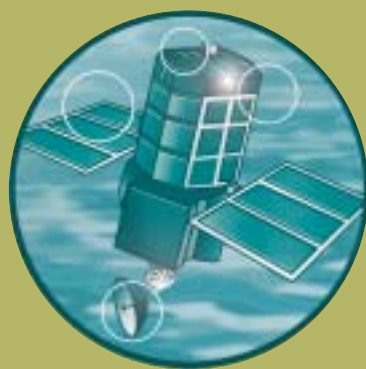# Risk assessment for flood incident management:

risks and onsequences of failure of reactive mitigation measures

R&D Technical Report SC050028/SR4

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Environment Agency

defra
Department for Environment
Food and Rural Affairs

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

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Science at the Environment Agency

Science underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us and helps us to develop monitoring tools and techniques to manage our environment as efficiently and effectively as possible.

The work of the Environment Agency's Science Group is a key ingredient in the partnership between research, policy and operations that enables the Environment Agency to protect and restore our environment.

The science programme focuses on five main areas of activity:

- **Setting the agenda,** by identifying where strategic science can inform our evidence-based policies, advisory and regulatory roles;
- **Funding science,** by supporting programmes, projects and people in response to long-term strategic needs, medium-term policy priorities and shorter-term operational requirements;
- **Managing science,** by ensuring that our programmes and projects are fit for purpose and executed according to international scientific standards**;**
- **Carrying out science**, by undertaking research – either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques,** by making appropriate products available to our policy and operations staff.

Steve Killeen

Head of Science

Executive Summary

In the process of flood incident management (FIM), the mitigation measures are subjected to risks of failure of flood defences and supporting infrastructures and to risks to personnel who manage the flood events.

This particular work package investigates the risks in terms of probability and consequences of failure of the supporting infrastructure (that is, assets other than flood defence assets) and personnel who manage the flood events (workforce). The objective was to develop a framework to estimate the aggregative risk from failure of the supporting infrastructure and workforce.

The approach is based on experiences during the FIM process and related studies in the water sector. In the framework that was developed, objects represent supporting infrastructures and workforce and attributes are assigned to objects. This object-oriented approach enables us to represent the particular FIM process in the form of a multi-stage hierarchical structure. This is necessary, as it has been observed that there are interdependencies among the different objects and each object is threatened either by the flood (primary threat) or through the failure of other objects (secondary or tertiary threats). As there are a number of objects and threats to these objects, an aggregative risk analysis is performed by estimating the probability and consequences of failures of different objects from different threats. The attributes of different objects help to extract information from experts to assign the probability and consequences of failure of each object. In the procedure the product of the likelihood of a failure event and its consequences defines each risk item. Both the likelihood and the consequences of a failure event are defined with 'fuzzy numbers' to capture the vagueness in the qualitative linguistic definitions. This is because the available field data are both quantitative and qualitative and, when available, they are often uncertain and vague. The detailed methodology and the questionnaires required to extract the information from the experts are discussed. The utility of the developed approach is demonstrated with an example.

The report concludes that the proposed methodology would enable the Environmental Agency and other concerned organisations to estimate the risks to mitigation measures and accordingly prioritise their activities and improve the FIM process. A full study is recommended to develop software and apply the method for a real case-study area. This will include the collection of data and responses from experts on the likelihood of failure of each object and its consequences for mitigation measures.

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1. Introduction

The flood incident management (FIM) process is complex and, in addition, there is a risk to different mitigation measures undertaken during FIM. These risks result from failure of flood defences and supporting infrastructures and from risks to personnel who manage the flood events. The flood defences include active flood defences (such as barriers, pumps, gates and demountables) and passive flood defences (such as embankments and walls). Supporting infrastructure includes assets other than flood defences, such as communication networks, power supplies, water, sewerage, health and transport, etc. Personnel who manage the flood events or workforce include personnel from the Environment Agency, emergency services (police, fire brigade, etc.), relief volunteers and the community. This particular work package (Working Package 4, WP4) investigates the probability and consequences of failure of the reactive mitigation measures in relation to the supporting infrastructure (that is, assets other than flood defence assets) and personnel who manage the flood events or workforce.

A conceptual framework has been developed to assess the risks to FIM processes. The developed framework is novel in the sense that it uses:

- **the object-oriented approach** to represent the FIM process;
- **an aggregative risk analysis approach** to estimate the risk to FIM that arises from failure of the supporting infrastructure and the workforce (hereinafter referred to as 'objects' or 'agents' in WP4);
- **fuzzy set theory** to incorporate uncertainties in the estimation of risk factors (probability and consequences of the failure of objects) and to represent the linguistic variables;
- **analytical hierarchical process** (AHP) to obtain information on the relative importance of failure of one object over that of another.

1.1 Object-oriented approach

An object-oriented approach is based on the concept that systems comprise collections of interacting objects that have different attributes. For example, an object has identity or class (that is, it can be distinguished from other objects by a unique identifier of some kind), state (data associated with it) and behaviour (things other objects can do to the object or that it can do to other objects). Decision problems can naturally be modelled by a collection of objects. Some research has been conducted on the application of object orientation in decision analysis. This approach has been successfully used in automobile (Crossland *et al*. 2003), hydrology (Edwards *et al*. 2002, Wang *et al*. 2005), meteorological hazard assessment (Watson and Johnson 2002) and aviation (Wyss *et al*. 2004) applications. However, its application is limited in the water-related decision problems.

The object-oriented approach in this study is motivated by a need to:

- simplify the way we view the FIM process in real world situations;
- provide decision makers and/or the Environment Agency with tools to deal with a complex FIM process that is dynamic in nature.

The major objective to assess the risk to mitigation measures from failure of the supporting infrastructure and workforce is to identify efficiently scenarios for different mitigation measures that can cause undesired effects and to estimate the likelihood and consequences

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associated with those scenarios. As the FIM process is complex and dynamic in nature, an ideal risk assessment tool should enable examination of a wide variety of scenarios quickly, systematically, and probabilistically. Previously, fault-tree analysis, event-tree analysis, hazards and operability, and failure modes and effects analysis have been used in different applications, including in the water sector.

Event-tree analysis enables probabilistic exploration of the 'universe' of possible scenarios that might arise as a result of a set of initial conditions (for example, for specific initial states of different objects in FIM process). However, the complex and dynamic nature of FIM means the risk assessment tool should support the development of event scenarios with variable event sequences (unlike traditional event-tree analyses). In addition to this, the above-mentioned methods need analysis of the Monte Carlo type. In event simulation based on Monte Carlo methods, it is difficult to detect low-frequency failure combinations (very large numbers of scenarios must be generated and assessed) – a single dominating scenario is selected and analysed many times, which thus wastes significant computational effort (Wyss *et al*. 2004). Instead, an ideal tool should determine the likelihood of each possible scenario based on a single computation and should be based directly on a behavioural model of the system so that a wide variety of analyses could be performed without having to manually construct and validate many different models. The object-oriented model has the ability to perform these requirements.

Objects are used to represent real-world entities that can 'communicate' with each other by exchanging messages between them. Messages are in the form of the transfer of information, materials, or energy. When an object receives a message, it responds by:

- modifying its internal state (that is, its underlying behaviour changes in a fundamental way);
- modifying its important characteristics (or 'attributes');
- generating outbound messages to communicate its conditions to the other objects in the model.

The way in which the object responds to messages depends on its internal processes and on its internal state. Objects in the world are categorised as a hierarchy. According to the object-oriented approach, the system comprises independent yet interactive physical or non-physical objects that can be arranged hierarchically. Once object-based models have been formulated, the system is organised into classes, objects and their attributes and functions are identified, and relationships among the objects and interfaces are established.

The specific advantages of the object-oriented approach are (Liu and Stewart 2004):

- reusability and extensibility – reusability indicates that the system classes can be reused for the implementation of similar systems, whereas extensibility means that a system can be extended easily by adding classes as basic building components to the system;
- well-identified reusable classes that have been tested in the field on earlier projects in object-oriented analysis and design are the basis for the analysis and design of the systems to be assembled, which leads to high productivity and higher quality;
- object-oriented approach can deal with the complex system because of the aggregation (scaling up from small to large subsystems) and representation in the hierarchical form;
- object orientation offers a philosophy to model naturally the real world – object-oriented analysis permits the system to be described in the concepts of the real world.

During FIM, for each type of supporting infrastructure both floods (primary) and the failure of other infrastructure (secondary or tertiary) can introduce threats. The secondary and tertiary threats often result from the interdependence between the supporting infrastructures. For example, in January 2005 during the floods in Carlisle power cuts caused by the flooding also affected telephone landlines and subsequently many mobile phone connections. This meant that some people were unable to receive warnings from television, mains powered radio or mobile and landline telephone networks.

Thus, in the process of FIM, the types of threats (primary, secondary, etc.), their hierarchical nature and their interdependencies mean that the object-oriented approach is perceived to be appropriate to analyse the risk to FIM processes from failure of the supporting infrastructure and workforce. The object-oriented approach also expresses the interrelationships among the various supporting infrastructures and workforce with a hierarchical structure that is required for the aggregative risk analysis (explained in Section 1.2).

1.2 Aggregative risk analysis approach

The risk to mitigation measures from failure of the supporting infrastructure and workforce arises through several factors that are interdependent, so it is necessary to quantify the risk and know the contribution of these factors to the risk for the different mitigation measures. Thus, this is a decision-making problem that involves the assessment of risk to different mitigation measures caused by the failure of the supporting infrastructure and workforce. The different methods widely used in decision making in the literature are:

1. Statistical techniques.
2. Multi-attribute utility analysis.
3. Compromise/composite programming.
4. Analytic hierarchy process.
5. Outranking techniques.
6. Mathematical theory of choice.
7. Expert judgement.

The risk of failure of different mitigation measures is the probability by which the specified mitigation measure cannot be implemented successfully with the available resources because of failure of the supporting infrastructure and workforce. Thus, this refers to the joint probabilities of an occurrence of an event of flood and its consequences. However, as stated above, FIM is a complex system that involves various contributory risk items with uncertain sources and magnitudes and cannot be treated with the above-mentioned statistical or mathematical and ranking techniques. To assess the risk caused by failure of different objects that are interdependent on each other, it is necessary to consider the following aspects:

- interrelationships of the different objects;
- ratings of the attributes under each alternative;
- weights of each rating;
- aggregation of each rating, together with its weights.

Hence, the aggregative risk analysis approach is considered for this study. Based on the aggregation, a decision can be made to choose the desired alternative or to know the contribution of the failure of different objects on the aggregative risk. The aggregative risk analysis has been performed in many sectors. These include risk software development (Chen 2001, Lee *et al*. 2003), air pollution monitoring (Khan and Sadiq 2005), oil and gas facilities (Khan *et al*. 2004), e-commerce development (Ngai and Wat 2003), drilling waste (Sadiq and Husain 2005) and water quality failure in distribution network (Sadiq *et al*. 2004).

As stated in Section 1.1, in the object-oriented approach various infrastructures and workforces are identified as objects and then their hierarchical structure constructed according to the types of threats to these objects. As there are a number of objects and threats to these objects and each object can have different properties to their attributes, an aggregative risk analysis needs to be performed by estimating the probability and consequences of failures of different objects through different threats. For this purpose, a multi-stage hierarchical conceptual model of aggregative risk for these failures needs to be developed. Hence, a conceptual framework is presented to analyse the aggregative risk associated with the supporting infrastructure and workforce in the FIM system. In the procedure the product of the likelihood of a failure event and its consequences define each risk item.

1.3 Fuzzy set theory

The main concern in this risk assessment study is that both the likelihood and the consequences of a failure event are uncertain in nature and linguistic form. In addition to this, in actual FIM these risk factors cannot be assessed precisely because of unquantifiable, incomplete and non-obtainable information and also through partial ignorance or personal biases and viewpoints. For example, the probability of the failure of a road network because of a flood is 'very low', 'low' or 'high'. Hence, this subjectivity should be accounted for in a rational approach to risk assessment.

Many techniques are available to evaluate and estimate risk. These are either qualitative or quantitative, depending on the information available and the level of detail required. Quantitative techniques rely heavily on statistical approaches. These include Monte Carlo simulation, fault- and event-tree analysis, sensitivity analysis, etc. (White 1995, Bennett *et al*. 1996, Ngai and Wat 2005). Qualitative techniques rely more on judgement than on statistical calculations, such as scenario analysis (Rainer *et al*. 1991) and fuzzy set theory (Zadeh 1965), etc.

Fuzzy set theory was introduced by Zadeh (1965) to deal with problems in which vagueness and uncertainty were present and linguistic values have been widely used to approximate reasoning. A fuzzy set is different to the classic set in that in classic set theory, the individual is either a member of the set or a non-member of the set (in stochastic cases, the individual is a member or non-member of the set with a certain probability). A fuzzy set can be defined mathematically by assigning to each possible individual a value that represents its grade of membership in the fuzzy set. This grade represents the degree to which that individual is similar or compatible with the concept represented by the fuzzy set. Thus, an individual may belong in the fuzzy set to a greater or lesser degree, as indicated by a larger or smaller membership grade. These membership grades are very often represented by real-number values that range in the closed interval between 0 and 1. The fuzzy set, therefore, introduces vagueness (with the aim to reduce complexity) by eliminating the sharp boundary that divides members of the class from non-members since the transition to member from non-member is gradual rather than abrupt (Klir and Folger 1988).

This approach has proved very useful in medical diagnosis (Lascio *et al*. 2002), information technology (Lee 1996), reliability analysis (Sadiq *et al*. 2004) and in many other applications (Lawry 2001), where reported data are either qualitative or decision making is based on expert opinions. Fuzzy set theory has been effective in such a variety of areas because it can handle inexact yet useful information. Thus, among all these techniques, the application of fuzzy set theory to assess the risk to mitigation measures through failure of the supporting infrastructure and workforce seems appropriate, as this analysis is highly subjective and related to inexact and vague information.

1.4 Analytical hierarchical process

In the developed framework, it is necessary that the decision makers assign weights to indicate their preferences to the relative importance of the objects in a particular group. In the literature three methods are normally found to assign the weights:

- 'Equal weights' method assigns an equal weight to all the objects of a particular group. The weights are assigned such that their sum equals one.
- 'Variable weights' method gives the user flexibility to assign different weights to different objects of a particular group. The different weights are based on the decision maker's perception of the relative importance of one object over another. Again, the sum of the weights assigned must be equal to one.
- The analytical hierarchy process (AHP), which is a mathematical technique for multi-criteria decision making (Saaty 1977, 1980, 1994), allows the policy analyst to do this by structuring the problem hierarchically and guiding him or her through a sequence of pair-wise comparison judgements.

AHP is perhaps the most widely used method for weight assignment. This method is chosen in this study because it:

- is a structured decision process;
- is applicable to decision situations that involve multi-criteria;
- is applicable to decision situations that involve subjective judgement;
- uses both qualitative and quantitative data;
- provides measures of consistency of preference;
- is suitable for group decision-making.

Hence it is proposed here to use AHP to obtain the probability and consequences of a failure event that results from primary, secondary and/or tertiary threats.

The major objective of this study is to develop and evaluate a hierarchical model to assess the aggregative risk of flood incidents on the flood mitigation measures caused by the failure of different supporting infrastructures and workforce. Based on the analysis of aggregated risk, the range of mitigation measures and methods to manage the supporting infrastructure and personnel will be made. The proposed framework is based on research that has been carried out to look at aggregative risk analysis in water supply distribution systems. The outputs from WP3 are to:

- identify the interdependence between the supporting infrastructure that has an affect on FIM;
- assess the causes and consequences of the failure of the supporting infrastructure;
- produce a conceptual framework to analyse and assess the aggregate risk as a result of failure of the supporting infrastructure.

2. Methods

As stated in Chapter 1, this particular work package (WP3) investigates the probability and consequences of the failure of reactive mitigation measures in relation to the supporting infrastructure (that is, assets other than flood defence assets) and personnel who manage the flood events. The supporting infrastructures covered include transport, utilities (for example, gas water, and electricity), communication networks, emergency services and health services. The personnel include Environment Agency personnel, emergency workers, relief volunteers and community members. Based on the review, a conceptual framework was developed based on the object-oriented approach, shown in *Figure 2.1*, that assesses the risks to both supporting infrastructure and social personnel. This object-oriented approach is based on the concept that systems comprise collections of interacting objects and classes.

The developed approach shown in *Figure 2.1* requires information and knowledge on mitigation measures to a flood incident, consequences of failure of the supporting infrastructure, risks to successful FIM practices and ability of socio-economic groups to cope and respond to FIM. This chapter presents the background on which the proposed method was built.
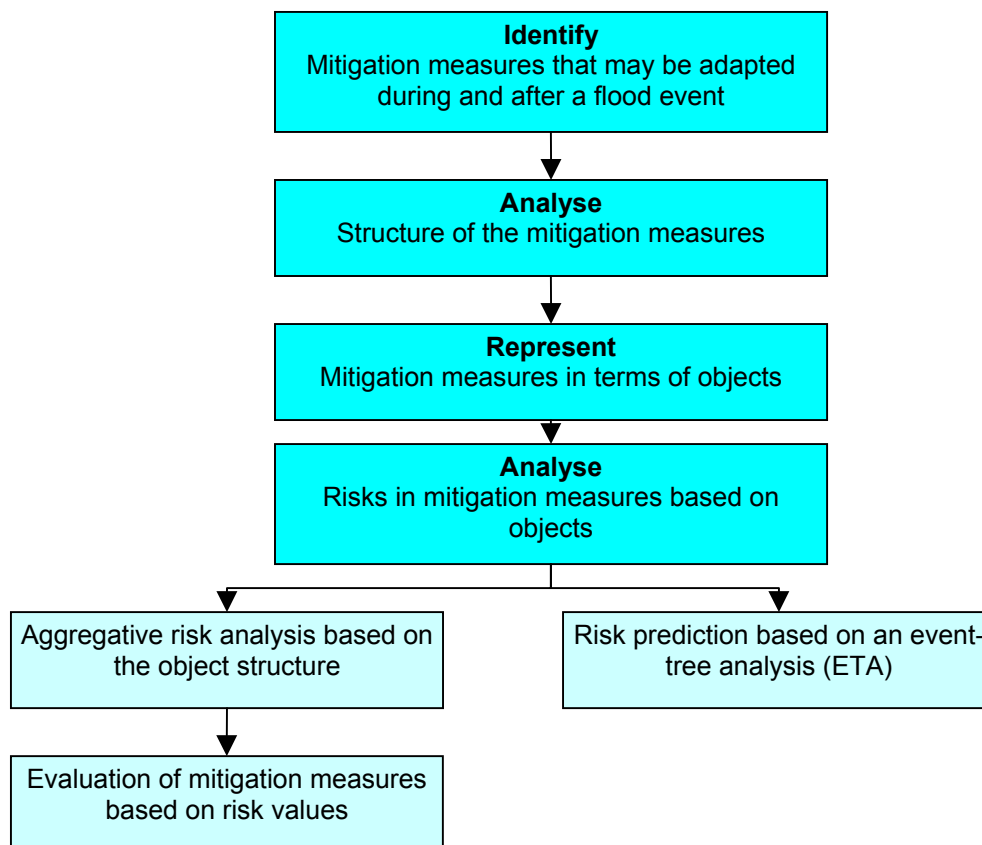
Figure 2.1 Object-oriented approach to assess risk to mitigation measures from failure of the supporting infrastructure and workforce.

2.1 Different reactive mitigation measures that have been adopted during and after floods

Flood hazard management has shifted away from the traditional focus solely on land drainage and flood defence towards a more strategic, multi-method and integrated approach of risk-based FIM. In this risk management approach to floods, decision makers are required to account for changes and trends, in both the short and long terms, across catchments, functions and institutional boundaries. It involves process to:

- perform hazard analysis;
- perform vulnerability analysis;
- identify potential measures to minimise losses;
- select and implement the mitigation measures.

Mitigation is the core of FIM. It's the ongoing effort to lessen the impact of disasters on people and property. The reactive mitigation measures adopted in FIM can be classified broadly into structural and non-structural measures.

2.1.1 Structural measures

Structural measures are an important reactive mitigation measure to reinforce flood defence structures with the aim to protect human health and safety, and valuable goods and property. Structural measures may present in many different ways, such as flood defence structures (dams, reservoirs), channel and catchment modification (floodway and flood plain), and flood proofing (embankment). Flood protection, though, is never absolute and may generate a false sense of security. The concept of residual risk, which includes potential failure or breach, should therefore be considered.

2.1.2 Non-structural measures

Non-structural measures are an anticipatory response for flood hazard management. The review showed that many different methods have been adopted for the non-structural measures. Based on the experiences of these mitigation measures during and after the flood events, the concerned agencies, organisations and departments developed recommendations to improve the mitigation measures. These measures can be categorised as:

- flood warning and forecasting, and institutional arrangements to disseminate the information;
- planning, including flood emergency planning, catchment management and land-use planning, flood relief, etc.;
- control, including flood fighting, evacuation, emergency assistance and relief, and flood-relief measures;
- public education (awareness raising).

2.1.2.1 Flood warning and forecasting, and institutional arrangements to disseminate the information

These include:

- Prediction of an imminent flood and warnings given to those in the risk area.
- Issuing the results of a forecast to the public or public authorities. Advance notice that a flood may occur in the near future at a certain station or in a certain river basin.

- The planned public announcements to those in exposed areas concerning incipient and expected floods. In this a designated, responsible civil authority, having analysed the hydrological and meteorological conditions and determined the potential for and level of imminent flooding, issues warnings to local authorities and to the public according to the expected severity of the flood.
- Set up of flood early warning system – a real-time event system that consists of remote gauging sites that transmit information to a base station. The overall system is used to collect, transport and analyse data, and to make a flood forecast, to maximise the warning time to occupants in the flood plain.

2.1.2.2 Planning, including flood emergency planning, catchment management and land-use planning, flood relief, etc.

These include:

- Emergency action plan – a set of pre-planned and integrated steps taken by a community or group of communities before and during flooding.
- Emergency flood-proofing – protection of property (for example, with sandbags) after receipt of a warning; it may be planned or spontaneous.
- Emergency planning – preparation by public authorities of plans to be implemented upon receipt of a warning.
- Emergency preparation – providing the physical and organisational infrastructure to react to flood events.
- Floodplain land-use planning – the study and planning for appropriate land use in the floodplain (zoning, regulations, acquisition, relocation).
- Floodplain management – the control and supervision by public authorities of the development and construction on identified flood plains, the maintenance of those water storage or flood-flow capacities vital to the passage of floods and/or on which flood damage risks are unacceptably high from the public viewpoint.
- Floodplain regulations – laws to define acceptable uses of land in defined areas by means of zoning. The adoption and use by communities of legal tools with which to control the extent and type of future development to be permitted in the river valleys. Regulations may include a requirement for flood proofing, minimum floor levels, etc.
- Floodplain zoning, flood zoning, zoning – definition of areas within flood plains appropriate for different land uses. These may include recreational open space, agricultural, open industrial and similar uses. Zones are often based on flood risk, and critical facilities are kept out of high-risk areas. The total designation of flood plain areas into zones of differing exposure to flooding to control land use and development thereon.
- Flood proofing – the modification of buildings and structures and their immediate surroundings to reduce damage in flooding.

2.1.2.3 Control, including flood fighting, evacuation, emergency assistance and relief, and flood-relief measures

- Flood fighting – actions undertaken during floods to prevent loss of life, damages and failure of flood-control structures, as well as to divert floods from sensitive areas.
- Evacuation – removal of people and property at risk, following a warning.
- Co-ordination – between different organisations involved in flood fighting.
- Communication.

2.1.2.4 Public education (awareness raising)

- Flood adaptation – to convince people in flood-prone areas to learn to live with floods. Flood adaptation means developing an attitude in the people to accept flooding as a way of life when it occurs and to learn to live with it by taking individual and/or collective measures to reduce the damage from such periodical floods.
- Flood-response planning – preparing the community for the event that floods occur and then, by implementing certain organisational measures (like evacuation), ensure that disruption and damage caused by the floods is kept to a minimum.

2.2 Examples of mitigation measures

To identify the risks associated with these mitigation measures and their impact, hazard and vulnerability analyses need to be performed. The risk estimation based on hazard and vulnerability is very useful to develop strategies to reduce that risk and the creation of policies and programmes to put these strategies into effect. This section explains briefly the reactive mitigation measures undertaken during and after some selected flood events.

2.2.1 Floods of North Wales and North of England, 2005

Some 28,000 residential properties were flooded across many locations in North Wales and the north of England in 2005. Most flooding occurred in Cumbria, where there was substantial flooding at ten locations that together accounted for more than 90 per cent of all properties flooded. Carlisle was particularly badly affected, with more than 1900 properties flooded in the city. Elsewhere in Cumbria more than 100 properties were flooded in each of Keswick, Cockermouth and Kendal, with more than 50 flooded in Appleby. Mitigation measures, among others, involved issuing warnings to those registered, disseminating warnings through the media, internet and by other means, such as loudhailers and direct door knocking. Operational staff were sent to erect temporary defences, clear grids and observe flood levels (without this deployment, flooding would have been more extensive). Special measures were put in place to reduce the risk to staff safety. Staff operated in pairs and all field staff were required to report in hourly. These reports also contributed to understanding the situation as it developed. The media coverage through North West BBC Radio Cumbria helped inform the public about the seriousness of the event, and measures they could take to help themselves.

2.2.2 Hurricane Katrina on New Orleans, USA, 2005

Hurricane Katrina and the subsequent flooding in August 2005 devastated the city. The official death toll now stands at 1302 and the damage from $70 to $130 billion, the most expensive natural disaster in US history. Over a million people were displaced. Several sections of the levee system in New Orleans collapsed. The hurricane left an estimated five million people without power. Over 150,000 properties in New Orleans were damaged or destroyed by wind, water and fire in the wake of Hurricane Katrina. Mitigation measures included forcibly evacuating people (mostly by bus to neighbouring states), and relief efforts (food, water, medical and other supplies) by trucks that can travel in 4 foot of water, helicopters and ships.

2.2.3 Boscastle flood 2004

During the floods of 2004 in Boscastle, 60 properties were flooded from the Rivers Valency, Jordan and Paradise or from surface water that flowed down the hillsides and roads. Three buildings were demolished by the floodwater and a further eight partially destroyed. A footbridge was swept away and the parapets of both road bridges were demolished. Approximately 80 cars and vans were swept away, and several caused damage to buildings as they careered through the village. The culvert became blocked and the river flooded through the houses. A hundred people were evacuated from the hotel lobby.

The auxiliary coastguard in Boscastle recognised the severity of the event and called the coastguard for assistance. The emergency services and rescue helicopters were on the scene within an hour. Up to 150 people were airlifted to safety and a further 34 rescued by

the Fire Brigade. The Environment Agency exercised emergency plans with Local Authorities in Cornwall and the value of this exercise was demonstrated by the effective way the Environment Agency, Local Authority and emergency services, among others, worked together during this event. There was no loss of life.

Those evacuated were not allowed back to the properties until all the buildings had been checked for safety, and then only to retrieve possessions.

After the event the Environment Agency's response continued with an emergency workforce and area operations team assisting North Cornwall District Council to clear tress, large boulders and other debris, recreate the river bed profiles and dispose of wastes. After the event the Environment Agency set up a drop-in centre to find out the experiences of those involved, which provided a valuable source of information.

The Environment Agency's Customer Charter states that 'we will provide flood warnings at least two hours before flooding happens in an areas where a service can be provided'. It is considered that where deep flooding can occur very quickly there is significantly more risk to life than in locations where flooding occurs more slowly or remains shallow. Research from USA on dam safety shows that up to an hour's warning can reduce fatalities caused by sudden flooding from 15 per cent to 2 per cent. After the Boscastle flood of 2004, the Environment Agency developed recommendations for the national compilation of catchments in which the speed, depth and velocity of flooding could cause risk to life. It also set a different standard and targets for those catchments in which a 2-hour lead time cannot be achieved, but a shorter lead time could potentially save life. The Environment Agency recommended several other mitigation measures based on forecasting improvements and operation during the flood.

2.2.4 The 2004 hurricane of Jamaica

The 2004 hurricane season posed a major challenge to Jamaica. On 10 August 2004 Hurricane Charley, a category 1 storm, passed along the island's south coast. It caused extensive flooding in sections of southern parishes. Four weeks later, Hurricane Ivan followed a similar path, though with far more devastating results. The mitigating measures included, among others:

- public education and awareness (to maintain interest and participation in disaster management at all levels of the nation, and to ensure that the public has the necessary information to protect lives and property);
- building community teams (communities with the skills systematically respond better to events, and are able to assist themselves and response agencies with evacuation, shelter, assessments and management of supplies);
- cleaning of drains and gullies;
- evacuation.

2.2.5 Flood event in North Dakota, USA, 1997

These floods affected Grand Forks, sited on the left bank of the Red River, North Dakota (population 50,000), and East Grand Forks, sited on the right bank of the Red River, Minnesota (population 80,00). Predicted was a peak flood level of 49 feet, but agencies and the communities prepared for 52 feet; the Red River eventually crested at 54 feet. Everyone in the two towns was evacuated – damage amounted to approximately $1 billion, but fortunately no lives were lost. Over 9000 residential properties and over 750 commercial properties suffered flood damage, some so seriously that they had to be demolished. The mitigation measures included:

- demolishing of properties;
- moving of property — not only did this reduce the amount of damage that another flood could cause, but it also eased future flood-fighting efforts, since the city will no longer need to allocate valuable resources to protect these difficult areas in the event of a flood;
- changes made to existing structures to make them more flood proof (City Hall, Information Service Department, water treatment plants, schools, etc.);
- improved protection system.

In addition to limiting the damage that another flood could cause, the city has also taken steps to improve its protection systems and reduce the possibility of another flood inundating the community. Three main areas of flood mitigation are being pursued:

- an interim plan to improve the existing flood defence system;
- a permanent long-term flood defence project;
- long-term, basin-wide water management.

2.2.6 The Missouri floods, USA, 1993

The Missouri floods of 1993 ruined more cropland, destroyed more residences and businesses, and cost taxpayers more money than any other flood in the state's long history of flooding. The most important mitigation measures taken were to 'retire' the most vulnerable riverside properties. Local towns have been able to purchase and demolish the most frequently flooded properties, and turn them into parks or recreation land. Some homes were elevated and new properties were built on elevation (FIMA 2002).

2.3   Risks to successful flood incident management practices

FIM is a complex system that includes several sub-systems for forecasting, warning, emergency planning, emergency operation, use of technologies and assets, and behaviour of institutions and individuals. Each of these sub-systems can fail in many different ways, with the risk that the failure propagates through the system and affects it interactively and eventually risks the FIM practice. For example, during the 2005 floods of Carlisle, the public utility infrastructure and public service response arrangements proved vulnerable to floods. During the 2005 Hurricane Katrina on New Orleans, USA, all the metropolitan New Orleans television news services that were supposed to take part in FIM had evacuated their studios in the city and were broadcasting from remote locations. Several hundred school buses were not deployed because the City was unable to find drivers. Therefore, there is an evident need to assess the risk for each sub-system and then aggregate these risks to appraise the FIM practice.

As stated in Section 1.2, the aggregative risk analysis approach is suitable because of the interdependencies of several supporting infrastructures and workforces on each other in the event of flood. The aggregative risk analysis needs the entire process to be represented in a hierarchical manner, with proper representation of the supporting infrastructure and workforce at each level. The object-oriented approach described in Section 1.1 offers the appropriate platform for such a type of aggregative risk analysis, as this approach enables each supporting infrastructure and workforce to be represented as an object. Once these supporting infrastructures and workforces are represented as objects, the developed framework allows a model of generic structure to be built for a particular mitigation measure. This approach also makes it feasible for large and complex FIM systems that incorporate uncertainty to be built collaboratively by teams of experts, rather than by an individual. In

addition to this, new classes of object and relationships can be defined by adding new attributes if necessary.

An object-oriented approach is therefore identified as a promising technique to assess the risk associated with flood risk-mitigation measures in WP3. The sub-systems are viewed as objects of FIM (*Figure 2.2*). The risk for each sub-system is assessed using their respective objects. The risk for FIM is obtained by aggregating the risk for each sub-system using multi-criteria decision-making methods.
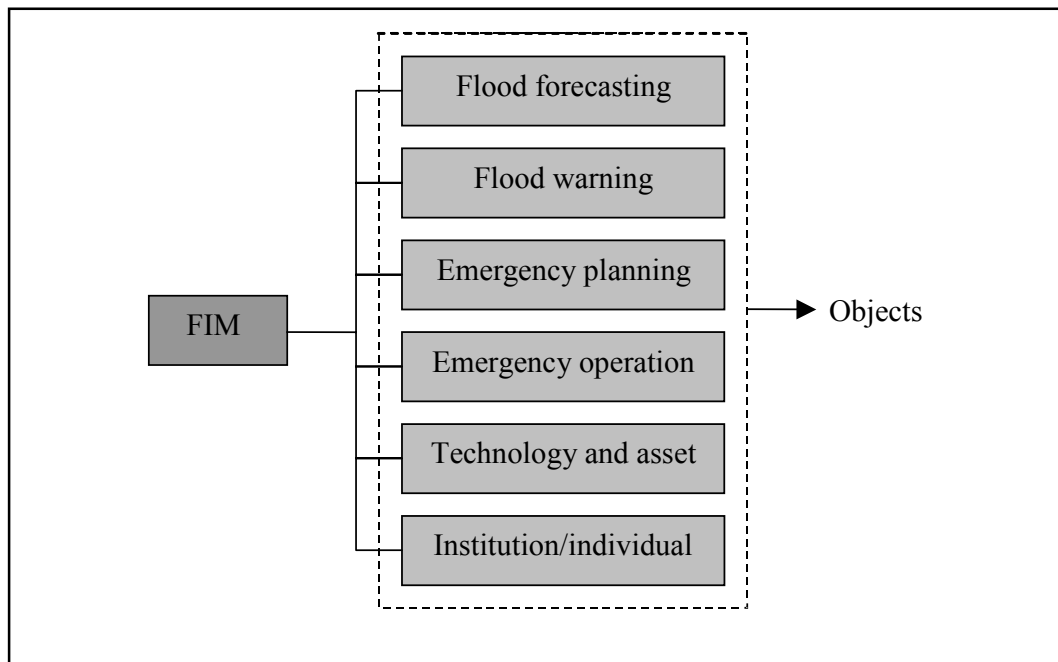
Figure 2.2 Risk assessment for flood incident management.

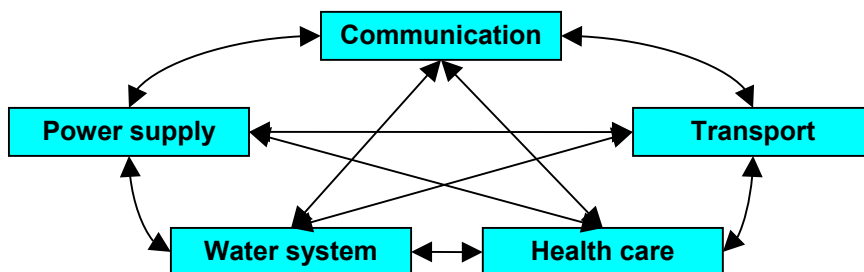## 2.4 Consequences of failure of supporting infrastructure

The object-oriented approach encompasses identifying various social and infrastructure-related objects and then classifying the risks to them. This is shown in Figure 2.3.
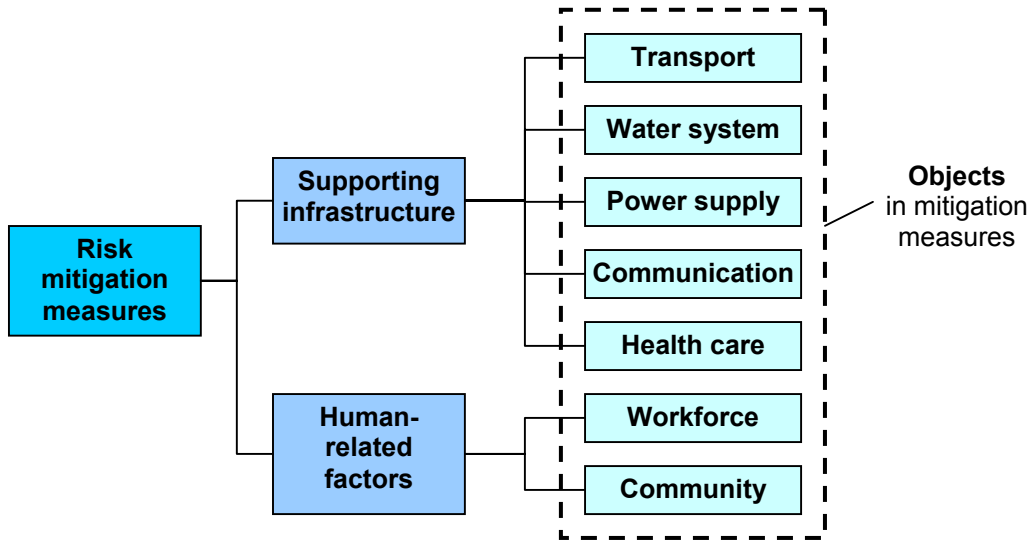
Figure 2.3 Definition of the objects.

In *Figure 2.3*, transport, water system, power supply, community, etc., are all viewed as objects that have attributes and functions. For example, community is viewed as an object that has attributes (like economic status, living pattern, previous experience in flooding event, etc.) and functions (like coping and responding to mitigation measures). During the flood event of 2004 at Boscastle, with the speed, depth and velocity of the flooding it was remarkable that there was no loss of life. This was a result of the swift action of some local residents. A local resident had seen that the Jordan was rising rapidly and cleared the hotel only minutes earlier. Communication is another object that has attributes (like service areas) and functions (like providing communication in flood mitigation). With respect to successful FIM practices, it is identified that detailed works need be performed on supporting infrastructure and human-related factors specifically, as discussed in this section and Section 2.5.

Responses to floods are becoming more complex as more interdependent systems are affected, which requires a more integrated approach (Vlachos 1995). Interdependencies of this kind are shown in *Figure 2.4*.

Figure 2.4 Interdependence between supporting infrastructures.

These interdependencies mean the consequences of failure of a supporting infrastructure become more complicated. For example, during the Missouri floods of 1993, the power and water supplies had been put out of action by the flood. A fire started in the Grand Forks city centre during the flood and, ironically, as there were no power and water supplies, there was

no means of fighting the fire, which then raged unchecked and destroyed 11 major buildings, including 60 apartments. The fire and damage to apartments and buildings posed a threat to the health and safety of personnel involved in the rescue operation.

In January 2005 during the floods in Carlisle substantial damage occurred to the infrastructure, including to the police and fire stations, council offices, landline and mobile telephone networks, power supplies, sewerage treatment works, railways and local bus fleet. Carlisle Civic Centre, which had been designated as the headquarters for emergency responses, was among the buildings damaged, and Gold Control had to be relocated to police headquarters in Penrith. Power cuts caused by the flooding also affected telephone landlines and subsequently many mobile phone connections. This means that some people were unable to receive warning information from television, mains powered radio and mobile and landline telephone networks. During the 2005 flood of Cumbria, gale force winds and intense rainfall made conditions dangerous for the workforce and staff involved in emergency operations.

During the Central European floods of 2005 several thousands of tourists were stranded, and the only way out was by helicopter or by crossing one of the high Alpine passes. The main phone line between Vorarlberg and the rest of Austria was destroyed and had to be replaced by a radio communication. This caused much obstruction to the flood relief efforts.

During the 2005 Hurricane Katrina on New Orleans, USA, there was no clean water or electricity in the city, and some hotels and hospitals reported diesel fuel shortages. A breach in the levee at the 17th Street Canal caused further trouble – the pumps designed to pump water out of the city redirected it into Lake Pontchartrain, which then circulated back through the breach. Some pumps overheated, which caused valve damage and also negated their effectiveness during the flooding. Coordination of rescue efforts on 29 August and 30 August were frustrated by the inability to communicate. Many telephones, including most cell phones, were not working because of line breaks, the destruction of base stations or power failures, even though some base stations had their own back-up generators. A number of brick facades collapsed into the street. At least three fires were reported in the New Orleans area, which destroyed several buildings. The extensive flooding caused by levee breaches meant a number of residents were stranded, unable to leave their homes, long after Hurricane Katrina had passed. With the attention of the military police focused on rescue efforts, the security in New Orleans degraded quickly. By 30 August looting had spread throughout the city, often in broad daylight and in the presence of police officers. There were incidences of rape and shootings. The New Orleans Convention Centre was not a city refuge, but people who gathered there broke in and opened the doors. By Thursday 1 September the facility, like the Superdome, was overwhelmed and declared unsafe and unsanitary. Reports from the Methodist Hospital highlighted the suffering in the city, with people dying of dehydration and exhaustion while the staff worked unendingly in horrendous conditions. The first floor of the hospital flooded and the dead were stacked in a second-floor operating room. Patients who required ventilators were kept alive with hand-powered resuscitation bags. On September 6, *Escherichia coli* was detected in the water supply. Five people died from bacterial infections caused by the toxic waters. The deaths appear to have been caused by the *Vibrio vulnificus* bacteria, of the cholera family.

These facts strengthen the approach undertaken using an object-oriented model that considers the influences from both flood and other infrastructure. A conceptual assessment framework is proposed in *Figure 2.5*.
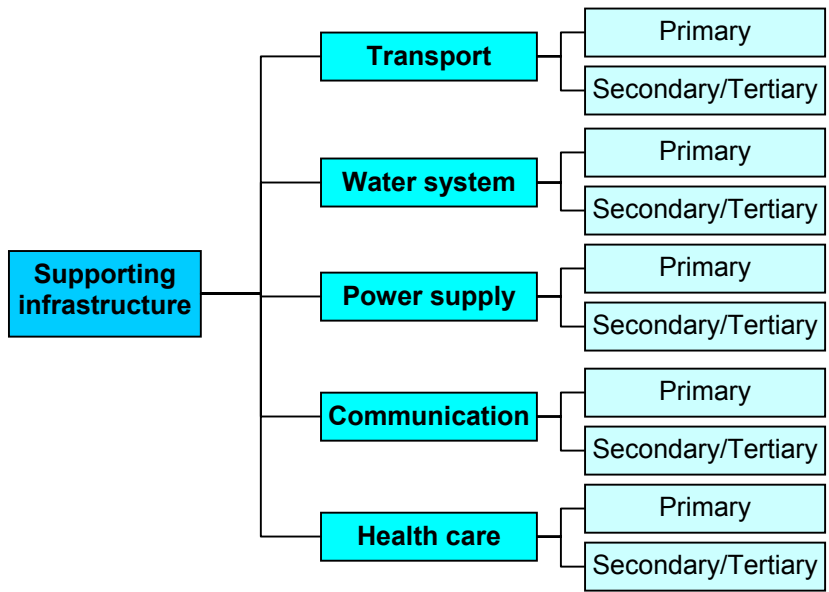
Figure 2.5 Object-based threat analysis for supporting infrastructure.

In *Figure 2.5*, for each type of supporting infrastructure the threats are classified as floods (primary) and the failure of other infrastructure (secondary or tertiary). This also indirectly reflects the consequences introduced by the infrastructure in FIM. During the flood event, the operation status of supporting infrastructure plays an important role in effective FIM. For example, during the 2004 floods of Boscastle, the Environment Agency's Area Environmental Manager had to agree to allow stockpiling of waste at an unlicensed site local to Boscastle, prior to proper licensed disposal (the nearest licensed site was a two-and-a-half hour round journey). This was an interim arrangement during the early post-event emergency phases because of the need for rapid excavation and the risk of further floods.

Therefore, reliability assessment of each of these elements (objects) to floods (primary) should be performed to provide information of its normal operation and probability of failure under some abnormal conditions. For the secondary and tertiary threats, risk information needs to be obtained by working on the matrix shown in *Table 2.1*. By combining the influences from other infrastructure, the risk introduced by secondary and/or tertiary threats can be obtained. Then aggregative risk analysis methods can be used to perform the risk assessment of the structure in *Figure 2.5*.

Table 2.1 Interactions of supporting infrastructure.

	Transport	Water system	Power supply	Communication	Health care
Transport					
Water system					
Power supply					
Communication					
Health care					

2.5 Ability of socio-economic groups to cope and respond to flood incident management

The long history of co-existence between human beings and flood events means that FIM is, in some circumstances, viewed as a 'socio-economic' phenomenon that is not only a hydrological process, but also closely related to socio-economic status of human beings. Especially in the process of coping and responding to flooding failures, economic status and previous experience with flooding events are believed to be major factors that affect human behaviour during disasters (like individual risk perception, disaster recognition, acceptance of the mitigation measure, etc.; Hansson *et al.* 1982, Simonovic and Ahmad 2005). At the time of the 2005 Carlisle floods, less than 50 per cent of those who were at risk had registered to receive direct flood warnings from the Environment Agency (the vast majority of those registered for the flood warning service were sent warnings before they were affected by flooding).

Basically, socio-economic characteristics of human beings mainly have two functions in FIM. On one hand, a higher socio-economic level usually introduces more complexity and high vulnerability to floods because along with it are higher urbanisation, increasing densities and/or higher industrialisation. This indicates that communities with higher socio-economic levels are areas in which the consequences to flood events are greater. On the other hand, higher socio-economic level means better mobilisation of institutions and higher perceptions in communities. As effective responses in FIM require broader mobilisation of institutions and higher perceptions and/or awareness of the people, socio-economic status should be viewed as an important positive factor for successful FIM. As it is considered the role of the task package WP3, the second function of socio-economic characteristics is given much consideration in this study. Based on the above analysis and the structure in *Figure 2.3*, an object-based assessment framework for human-related factors is proposed in *Figure 2.6*.
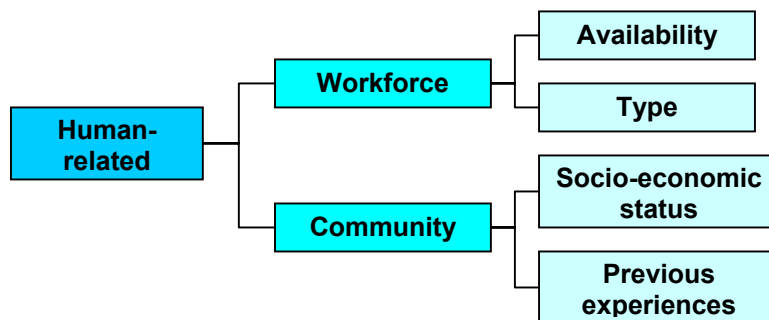
Figure 2.6 Object-based threat analysis for human-related factors.

The type of personnel, together with availability, determines the probability and associated consequences of failure of the workforce. Here the workforce can be viewed as an object, and availability and type are two key attributes of this object. The type of personnel can comprise Environment Agency personnel, emergency workers, relief volunteers, engineering technicians, etc. The ability of the members in the workforce group largely determines the efficiency of FIM. Therefore, assessment of the workforce group is required for the FIM practices. Factors such as health status, whether out or not, etc., can be used to assess the availability of the workforce.

With respect to the response of the community, socio-economic status and previous experiences of the community members determine the probability and associated

consequences of failure of their emergency response. To assess the socio-economic status of community members, lots of factors have to be considered (such as proposed by Laska 1990, Simonovic and Ahmad 2005). These factors can be summarised as in *Table 2.2*.

Table 2.2 Factors related to socio-economic status (based on Simonovic and Ahmad 2005).

Initial factors	Awareness of risk
	Knowledge of flood disaster
	Knowledge of mitigation measures
	Education level
Social factors	Present address
	Age
	Children
	Living standard
	Behaviour of others
	Coherence of community
External factors	Flood incident information
	Rain
	Inundation conditions
	Upstream conditions
	Warnings
	Orders

By considering the stages in FIM practices together with factors (in *Table 2.2*) of the community under study, the socio-economic status and previous experiences can be assessed. Then combining this with the analysis given above, an aggregative risk analysis on human-related factors in mitigation measures can be obtained.

3. Results

The concept introduced in Chapter 2 has resulted in the development of a methodology that assesses risk to flood mitigation measures based on the probability of failure of the supporting infrastructure and personnel and their consequences. The methodology involves following three major steps, which are described in detail in this chapter:

- identify the interdependencies between the supporting infrastructures for building a hierarchical framework based on an object-oriented approach;
- assess the probability and consequences of the failure of the supporting infrastructures;
- assess the aggregate risk as a result of failure of the supporting infrastructure with the help of the aggregative risk analysis approach, incorporating fuzzy set theory to represent uncertainties and linguistic variables.

Thus, this study attempts to identify infrastructure interdependencies, their effect on the FIM process and the consequences of their failure on FIM process.

3.1. Interdependencies

This section focuses on 'identifying the interdependence between the supporting infrastructures that have an effect on FIM' and examines the complexity of the infrastructure interdependency from the view of FIM.

As stated by the President's Commission on Critical Infrastructure Protection, USA, infrastructure has been defined as '*a network of independent, mostly privately owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services*' (Rinaldi *et al.*, 2001). Thus infrastructures are a complex set of interconnected, interdependent, adaptive systems on which individuals and normal and emergency services depend. Any natural disaster, including floods, disrupts the normal operations of these infrastructures and also of emergency operations. The complexity of the infrastructures and their interactions and interdependence pose new challenges for their reliable management and operation, and prevent us from knowing *a priori* how these interactions will influence individuals, states or the nation and normal and emergency operations in the event of floods.

Normally, the infrastructure service providers have vast experience in responding to (and mitigating) day-to-day minor disruptions, but there is considerable concern about how they respond to and recover from severe disruptions, such as a natural disaster (floods, earthquakes) or a catastrophic terrorist attack. This is because these infrastructures are interdependent and have cascading effects of failure. According to Rinaldi (2004), '*an interdependency is a bi-directional relationship between infrastructures through which the state of each infrastructure is influenced by or correlated to the state of the other*'. He has provided a simple example that is given here in *Box 3.1*.

Box 3.1

The national electric power grid and natural gas network are interdependent – natural gas fuels many electrical generators, and elements of the natural gas infrastructure (e.g., gas conditioning plants, compressors, and computerized controls) require electricity to operate. A disturbance in the electrical system can cascade into the natural gas system, and loss of natural gas pressure can curtail the generation of electricity. Consequently, the states of these systems are mutually correlated. (Rinaldi 2004)

This example highlights the importance of understanding the interdependencies and their effects in the event of natural or man-made disasters.

3.1.1. Interdependencies in flood incident management

A flood incident influences the infrastructures, and what happens to one infrastructure can directly and indirectly affect other infrastructures and in turn influence FIM processes. The infrastructures have a key role in FIM. Responses to floods are becoming more complex as more interdependent systems are affected and thus there is a need for a more integrated approach (Vlachos 1995). This kind of interdependency is shown in *Figure 3.1*. These interdependencies mean the consequences of failure of the supporting infrastructure become more complicated, as discussed in Section 2.4 with the example of fire during the Missouri floods of 1993.
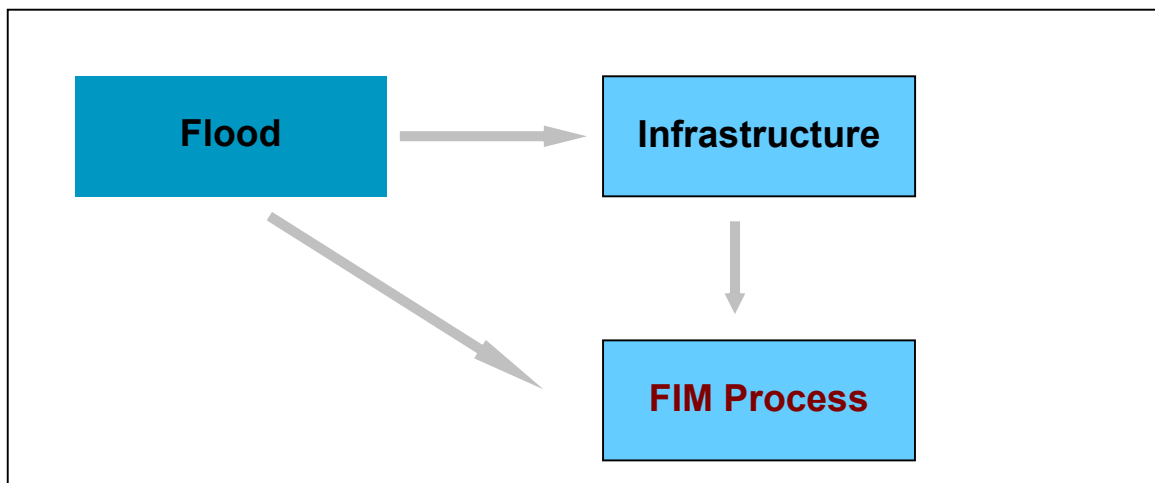
Figure 3.1 The FIM process affected by flood and failure of infrastructure.

To identify, understand and analyse interdependencies among the infrastructure are significant challenges. These challenges are greatly magnified by the complexity of flood events. The infrastructures and services that affect FIM processes include power (electric supply and natural gas), telecommunications, transportation, water supply, health and other emergency services, such as fire protection, etc. The FIM processes have a duel impact – direct from flood and as a result of failure of the infrastructure because of the flood, as shown in *Figure 3.2*.
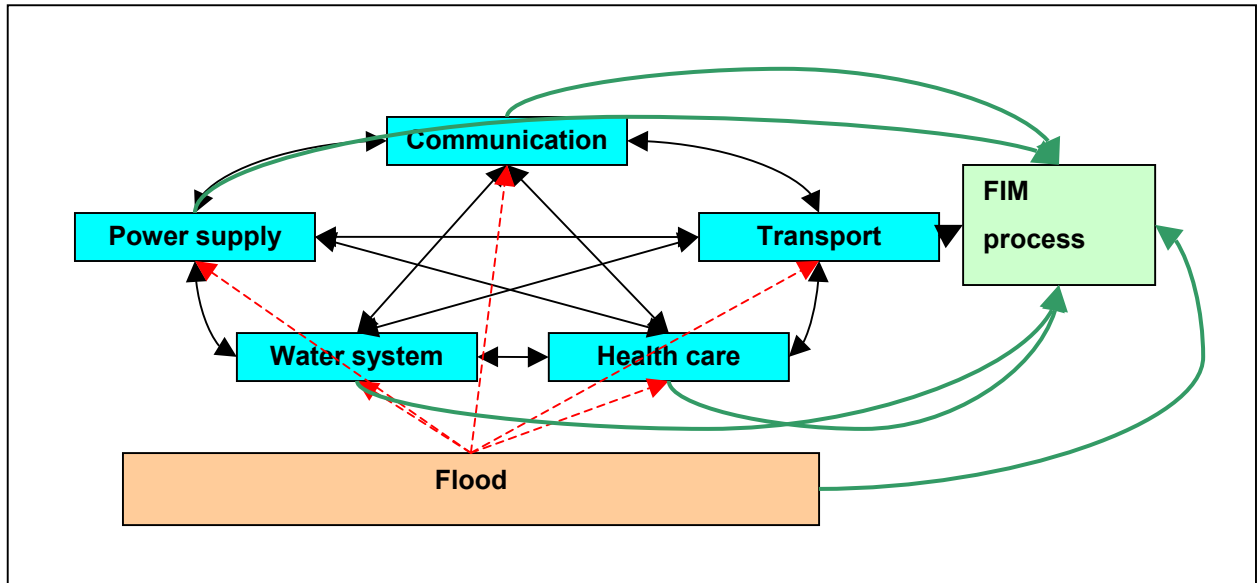
Figure 3.2 Interdependencies among the different supporting infrastructures, the failures of which through flood affect the FIM process.

3.1.2. Object-oriented approach

The interdependencies among the infrastructures create an additional complexity for the FIM process. Therefore, a basic understanding is required of each supporting infrastructure in respect of their failure in the event of flood and their impacts on other infrastructures and the FIM process. This study proposes to view each supporting infrastructure as a set of objects (see *Figure 3.3*). In WP4, this is referred to as an 'agent'. In *Figure 3.3*, transport, water system, power supply, community, etc., are all viewed as objects that have attribute and functions. Communication is another object that has attribute (like service areas) and functions (like providing communication in flood mitigation).

In addition to this, the workforce or the personnel involved in FIM process and the local people are also viewed as a set of objects. The literature shows that the people play their role in the FIM process, and Section 2.4 above includes an example of prompt action by a local resident during the flood incident in 2004 in Boscastle.
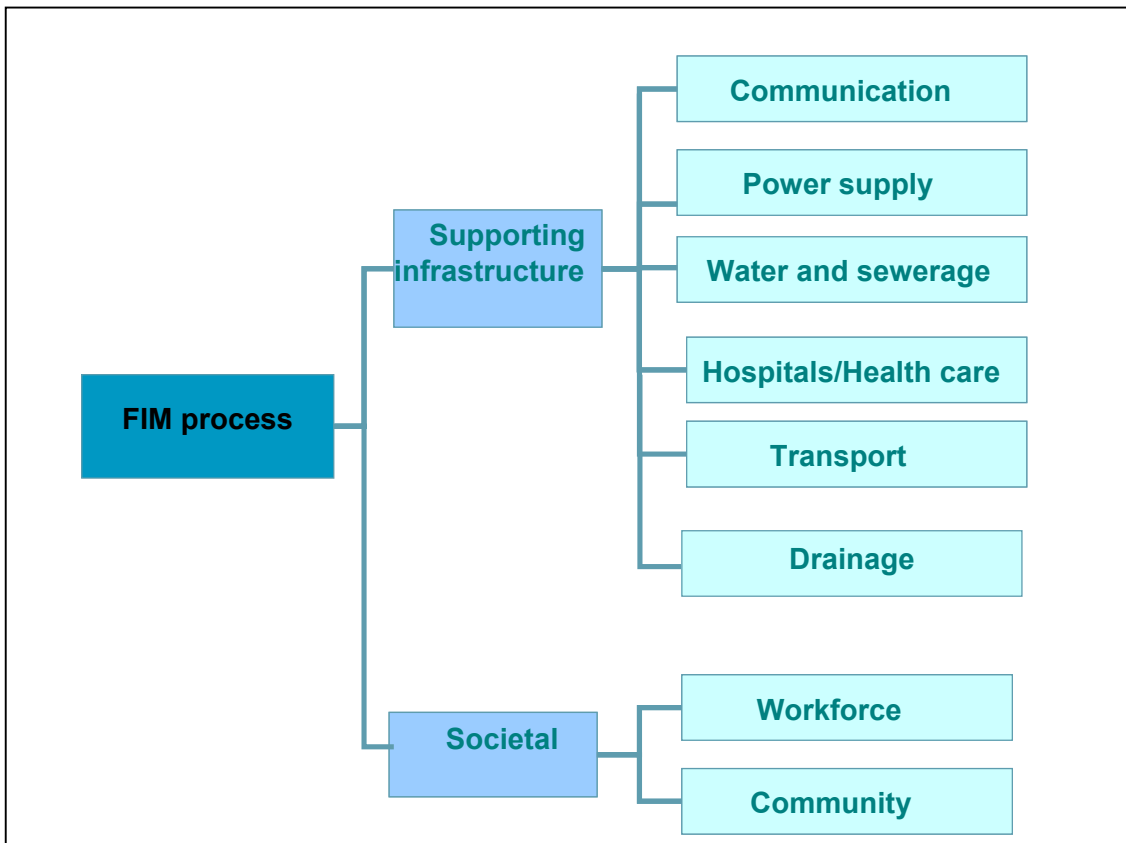
Figure 3.3 Representation of the FIM process as objects.

Each of these objects has different components. For example, as shown in *Figure 3.4*, the object 'drainage' constitutes several components and the object 'the workforce' may constitute the Environment Agency, fire services, police, local authorities, etc. In the event of flood, these may fail together or individually.
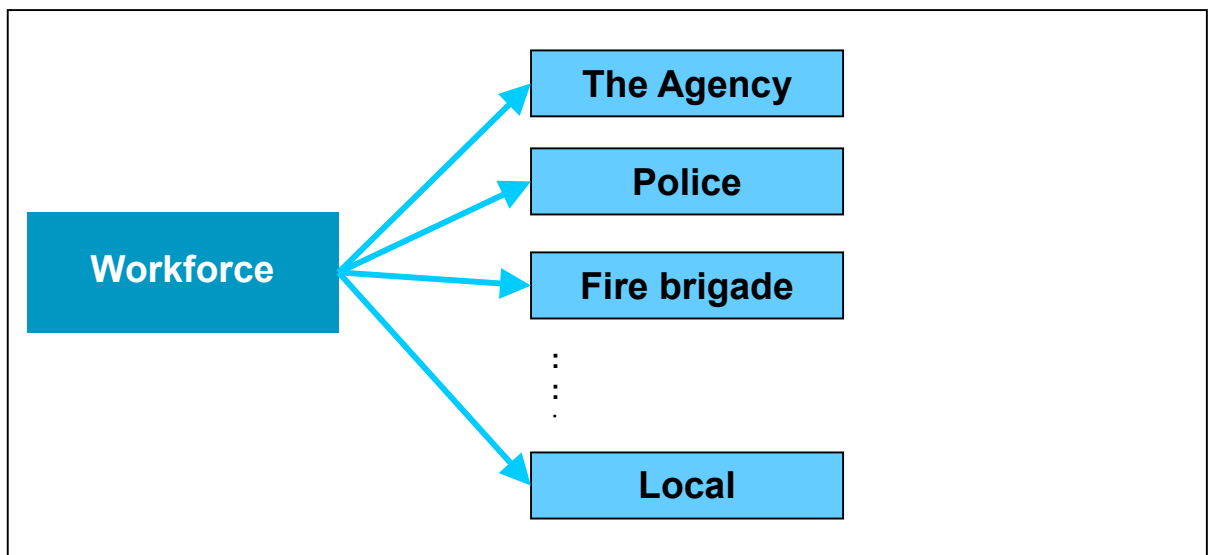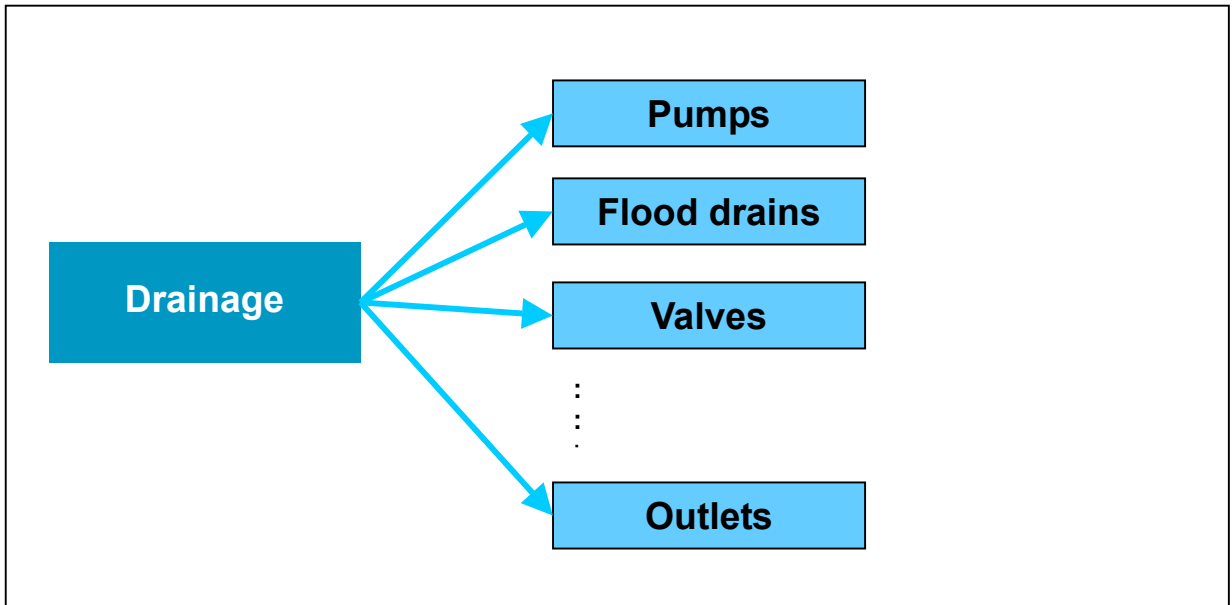
Figure 3.4 Examples of components of objects.

## 3.2. Consequences of failure of objects

With respect to successful FIM practices, it is identified that a detailed study needs to be made specifically of the supporting infrastructure and human-related factors, which are discussed in this section and Section 3.3.

Sections 2.4 and 2.5 provide examples of complexity and interdependency from Missouri, Carlisle, Central Europe and New Orleans, with major impacts from the failure of supporting infrastructure and human-related factors. More interdependent systems call for a more integrated approach (Vlachos 1995).

3.2.1. Conceptual framework

The complexity and interdependencies strengthen the value of an object-oriented model that considers the influences from both flood and other infrastructure. A conceptual framework required for to assess the FIM processes is proposed in *Figure 3.5*.

In *Figure 3.5*, for each type of supporting infrastructure, threats are classified as floods (primary) and the failure of other infrastructure (secondary or tertiary). This also indirectly reflects the consequences introduced by infrastructure in FIM. During the flood event, the operational status of the supporting infrastructure plays an important role in effective FIM, as shown by examples in Sections 2.4 and 2.5 above.
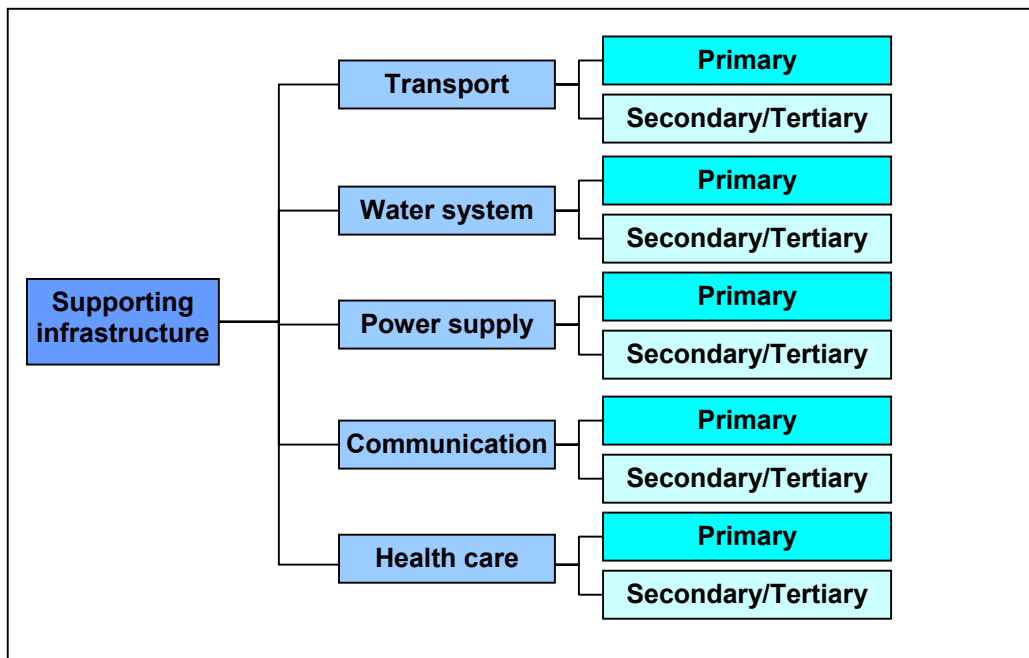
Figure 3.5 Proposed conceptual framework to assess the FIM processes.

The information on the risk of failure of objects through a primary threat (for example, caused by floods) needs to be obtained under normal operation and some abnormal conditions. For the secondary and tertiary threats, risk information needs to be obtained by working on a matrix similar to that shown in *Table 2.1*. Then the aggregative risk analysis methods can be used to perform a risk assessment of the structure shown in *Figure 3.5* (explained in Section 3.2).

3.2.2. Types of threats and attributes of objects used to analyse threats

As stated above these objects can fail through direct threats from the flood. This is called a 'primary threat'. For example, the inundation of a pumping station by flooding. An object can fail because of the failure of another object through flood. This is called a 'secondary threat'. For example, the pump may fail to operate because of the failure of the electricity supply through flooding. Similarly, there is tertiary threat. For example, the coal required to generate the electricity could not be transported because of the flooding (though normally there is enough storage of coal at a power station).

An object is considered as an entity with attributes. These attributes may be location, capabilities and capacities, state, threat from (for failure) and threat to (for failure) – see *Figure 3.6*.

For example, the pump used to lift water from an affected area has some geographical 'location', a certain 'capability and capacity' (that is, what it can do from its location – for example, the pump can lift water at '*x*' rate continuously for '*t*' hours, etc.) and 'state' (for example, the age of the pump, how long it can operate without overheating, etc.). The pump has the 'primary threat from' flood (because of inundation of the pumping station) and a 'secondary threat from' the failure of electricity because of flood. Similarly, failure of the pump can threaten the water level. Here, the 'state' and 'threat from' are important as they decide the probability that the pump will fail during the FIM. Similarly, 'location', 'threat to' and 'capability and capacity' decide the consequences of failure of the pump.

The state of the object needs to be obtained from the history and the other data required to estimate the probability of its failure and consequences from the historical evidence and experts. In this study, 'supporting infrastructure' (SI) and 'workforce' or 'societal' (S) are considered as objects that have attributes as stated in *Figure 3.6*. Probability and consequence of failure are obtained from the experts based on the attribute data for each of these objects.
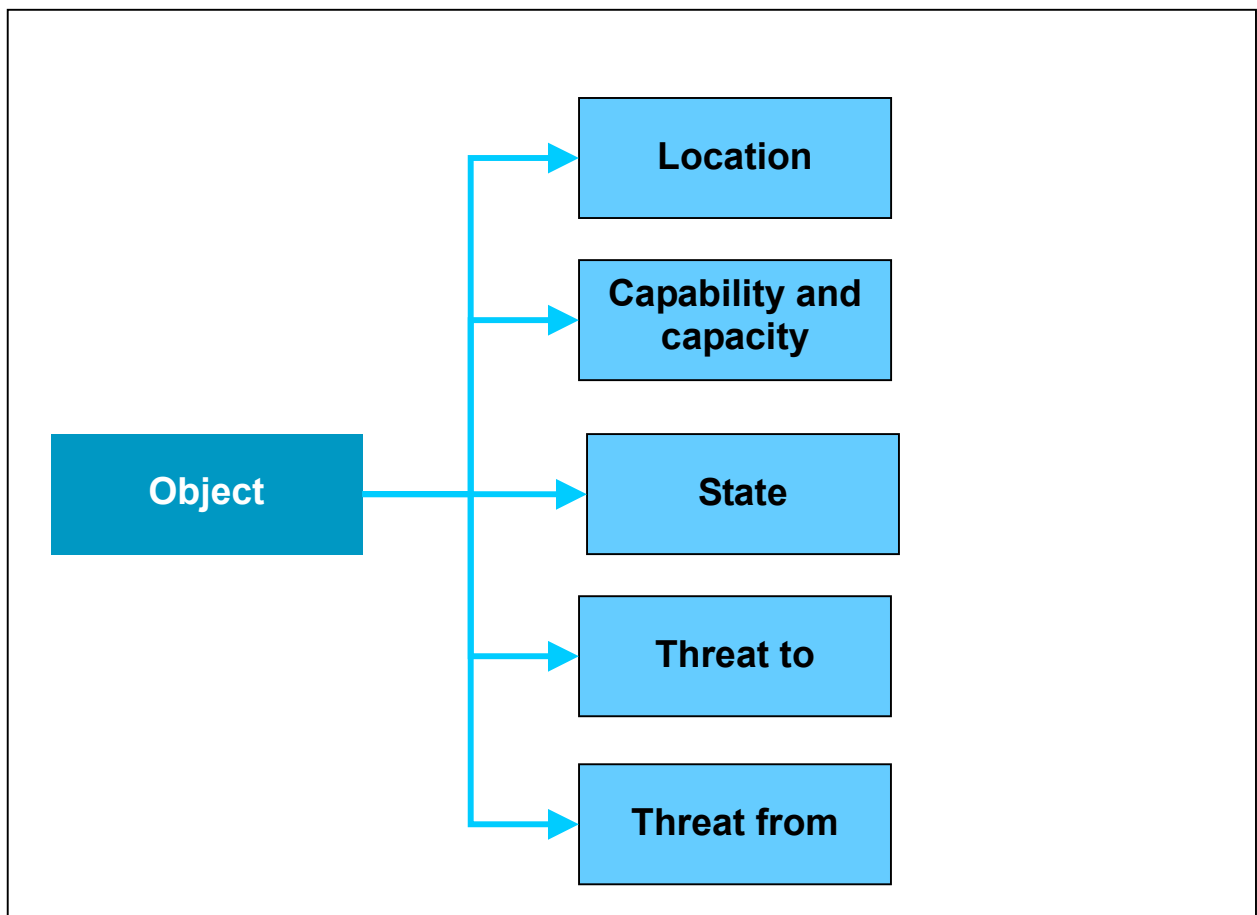
Figure 3.6 The attributes of the object.

3.3. Probability and consequences of the failure of the objects

One of the objectives of this study is to assess the risk to mitigation measures in FIM caused by the failure of different objects (supporting infrastructure and workforce). Risk is defined as a chance of the failure of objects (happening) that will have an impact on the mitigation measure. It is measured in terms of probability of happening (failure of objects) and consequences of happening.

To assess the probability and consequences of the failure of the objects (supporting infrastructure and workforce and/or societal) is a complex process. This complexity results from different characteristics of the flood – catchments, flood-affected areas and also interdependencies among the different objects that affect the FIM process. To some extent the probability and consequences of the failure of the objects can be obtained from the historical data in numerical or quantifiable form.

In a complex system like FIM that involves various contributory risk items with uncertain sources and magnitudes, the probability and consequences are not always numerically quantifiable. For example, what is the probability of failure of 'telecommunication' because of failure of 'power supply' through the effects of flood, and what are the consequences of its failure? There are not enough data available to be able to present the 'probability' and 'consequence' in numerical form. In addition to this, there are always particular uncertainties associated with these data. However, the 'probability' and 'consequence' can be very well represented in the linguistic form by using expert knowledge in this field, such as the probability of failure of 'telecommunication' through failure of 'power supply' is 'extremely low', but its consequences are 'important'. The representation in the linguistic form is always qualitative and uncertain.

Qualitative data cannot be dealt with using traditional numerical techniques. Zadeh (1996) introduced the fuzzy set theory that involves computing with qualitative or linguistic data. Fuzzy set theory has the ability to analyse the qualitative data and consider the uncertainties by representing judgements in linguistic form – 'extremely low' or 'important' – in a certain range of numerical values that have a membership function (fuzzy numbers). This approach has been used in many applications, such as information technology, medical sciences and the water industry. Hence, in this study the use of 'fuzzy set theory' is proposed to analyse the probability and consequences of failure of objects on FIM processes. As the complex nature of the FIM process involves interdependencies, it is necessary to analyse the probability and consequences by preparing a hierarchical structure of the objects that influence the FIM process. This involves four major steps:

- list the different supporting infrastructural and workforce (and/or societal) objects that affect the mitigation measures;
- prepare the hierarchical structure;
- obtain the ranks for probability and consequences of failure of objects;
- obtain the weights for each object at the appropriate level of hierarchy to show the relative importance of failure of one object over another.

3.3.1. Different supporting infrastructural and workforce (and/or societal) objects that affect the mitigation measures

This involves obtaining information on the objects that influence a specified FIM process, on each attribute of all the objects and on their components from a data base and past experience of FIM. The databases of all the objects need to be prepared.

For example, one of the mitigation measures in the FIM process is 'to evacuate the people from the flood affected area to shelter'. The list of different objects that may affect this mitigation measure is given in *Box 3.2*. This is used only as an example and the objects in the list may vary from location to location.

Objects that have a primary threat from flood and influence the FIM process of 'evacuation'

1. Transport network
Roads
Rail links
Waterway
Air

2. Transport means
Road vehicles
Trains
Boats
Helicopters

3. Communication system
Landline
Mobile
Radio
Television

4. Information system
Warning system
Evacuation information system
      evacuation route map
      evacuation plan

Objects that have a secondary threat from flood and influence the FIM process of 'evacuation'

1. Power supply
Electricity – to operate trains and communication systems
Fuel – to operate road vehicles
Warning systems – to inform the communication system

**Objects that have tertiary threat from flood and influence the FIM process of 'evacuation'**

Electrical power supply – to operate fuel stations

3.3.2.   Hierarchical structure

The hierarchical structure proposed for 'evacuation' is presented in *Figures 3.7(a)* to *3.7(d)*. While preparing the hierarchical structure for secondary and tertiary threats, it is important to consider at lower level only those objects that are dependant on a higher level. For example, if vehicles at location A are not dependent on fuel source B, then for the hierarchical tree of source B, vehicles at location A need not to be considered.
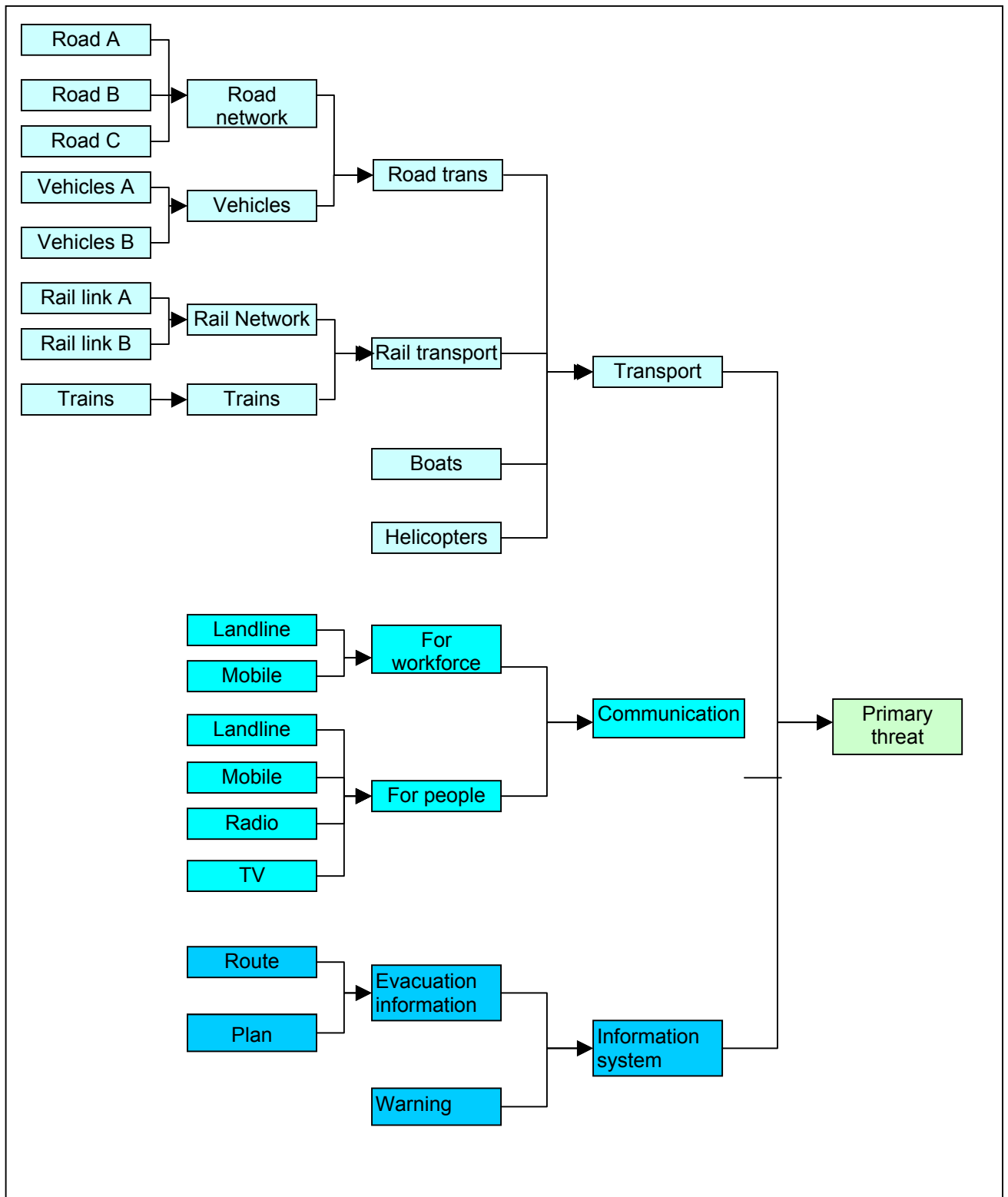
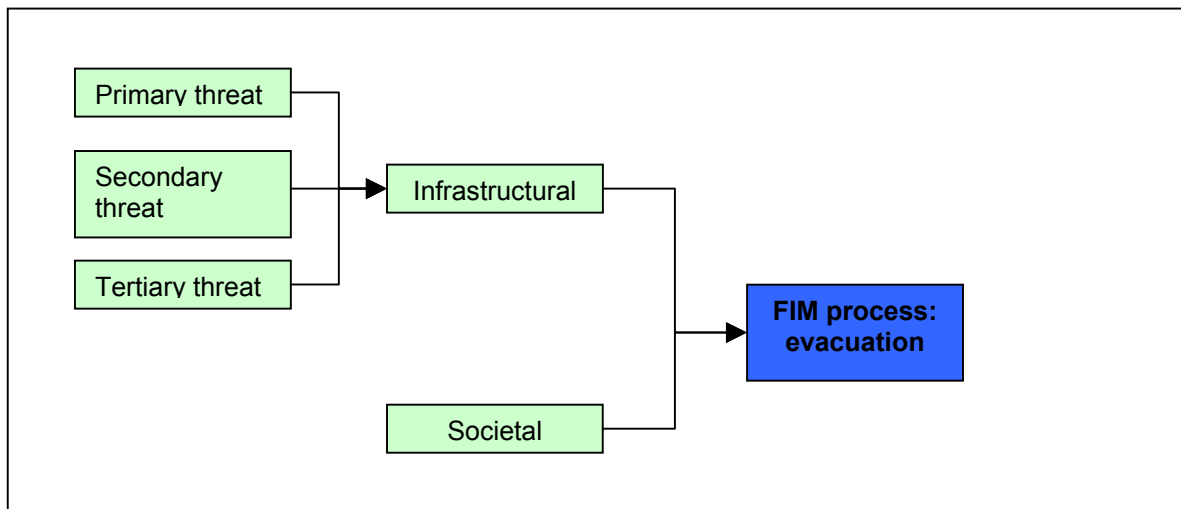**Figure 3.7(a)** Hierarchical structure to assess the risk to mitigation measures of 'evacuation' (infrastructural primary threat).
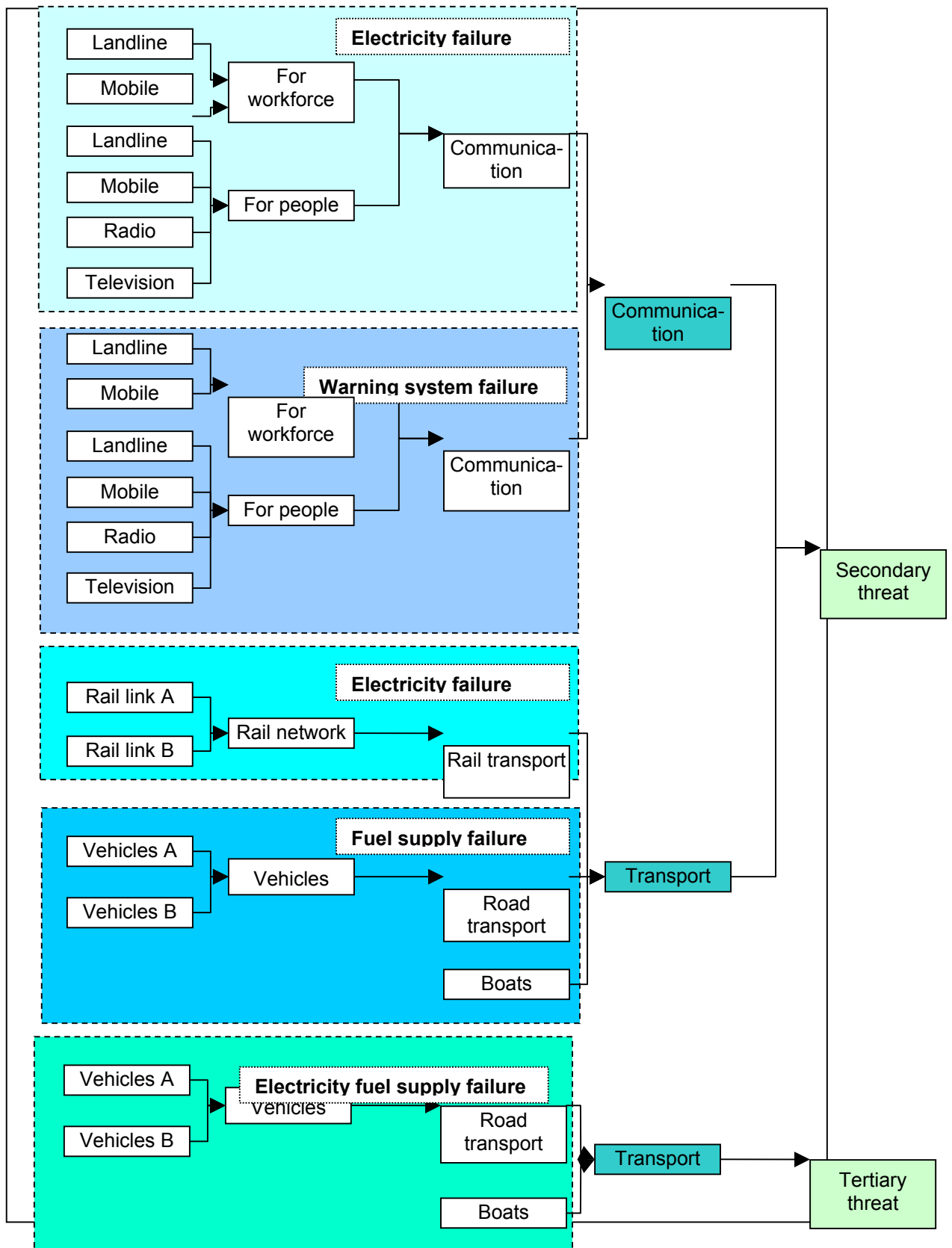
Figure 3.7(b) Hierarchical structure to assess the risk to mitigation measures of 'evacuation' (infrastructural secondary and tertiary threats).
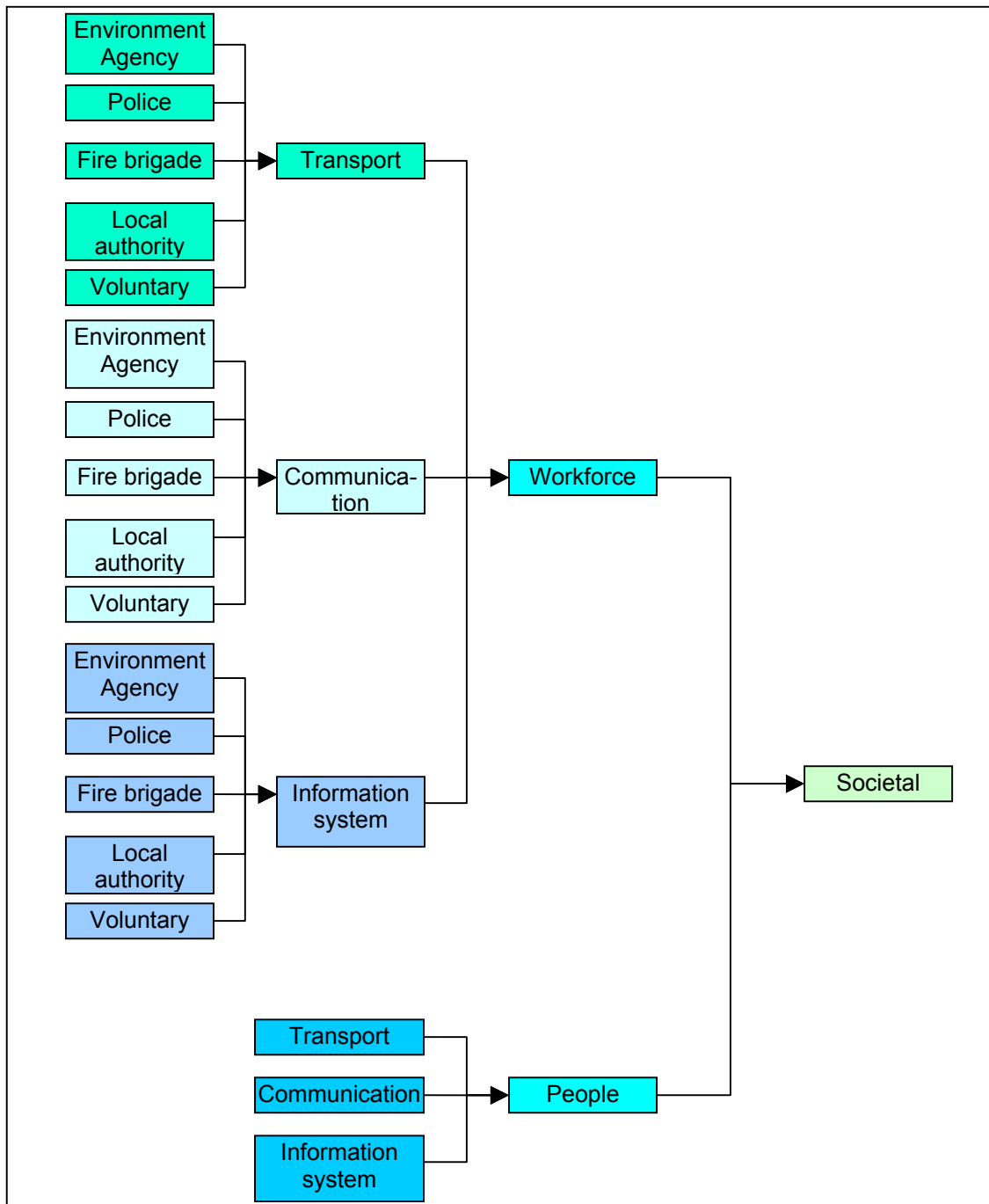
Figure 3.7(c) Hierarchical structure to assess the risk to mitigation measures of 'evacuation' (workforce and/or societal).

Figure 3.7(d) Hierarchical structure to assess the risk to mitigation measures of 'evacuation' (overall).

3.3.3.   Determination of ranks for probability and consequences

As stated at the beginning of this section, the approach suggested in the proposed method depends on obtaining qualitative information from the experts. The qualitative information is in the linguistic form, such as 'probability is extremely low', 'the consequences are extremely important', etc. In this case the important task is to determine the number of ranks for qualitative explanation and the associated fuzzy numbers that describe the imprecision and vagueness in the data.

One example of a qualitative information rank system and the proposed equivalent fuzzy numbers is given in *Table 3.1*, in which there are 11 ranks. The ranks for the probability and consequences of failure of a particular object are obtained from the experts, who often may not be comfortable with a large number of ranks and may provide ambiguous answers. In this case a smaller number of ranks is advisable. An example with three ranks is presented in *Table 3.2*. However, this shows that three ranks are too few to extract all the relevant information from the experts and do not provide them with many options. Examples of intermediate numbers of ranks (five, seven and nine) are presented in *Tables 3.3*, *3.4* and *3.5*. It is very important to choose the appropriate rank system. In this study, based on discussions with experts and other team members of the project, it is proposed to use systems with seven ranks. The fuzzy number representation could be changed or modified, based on expert panel recommendations.

The membership functions of the triangular fuzzy numbers for the seven-rank qualitative scales, according to the fuzzy number description in *Table 3.4*, are:

$$\mu_i(x) = \begin{cases} 1-6x & 0 \le x < 0.177 \\ 0 & 0.17 \le x \le 1 \end{cases}$$
$$i = 1$$

$$\mu_i(x) = \begin{cases} 6x-(i-2), & \dfrac{i-2}{6} \le x < \dfrac{i-1}{6} \\ i-6x & \dfrac{i-1}{6} \le x < \dfrac{i}{6} \\ 0 & \dfrac{i}{6} \le x \le 1 \end{cases}$$
$$for \quad i = 2,6 \quad and$$

$$\mu_i(x) = \begin{cases} 0 & 0 \le x \le \dfrac{5}{6} \\ 6x-5 & \dfrac{5}{6} \le x \le 1 \end{cases}$$
$$i = 7$$

(3.1)

where:

i = rank number (see *Table 3.4*)

μ = fuzzy number

$\mu_i(x)$ = membership function of fuzzy number, x, for ith rank.

Table 3.1 Example of ranks and their proposed qualitative equivalent (11 rank case).

Rank	Probability – qualitative explanation	Fuzzy number (triangular/trap)	Consequence – qualitative explanation	Fuzzy number (triangular/trap)
1	Absolutely low	(0.0, 0.0, 0.1)	Absolutely unimportant	(0.0, 0.0, 0.1)
2	Extremely low	(0.0, 0.1, 0.2)	Extremely unimportant	(0.0, 0.1, 0.2)
3	Quite low	(0.1, 0.2, 0.3)	Quite unimportant	(0.1, 0.2, 0.3)
4	Low	(0.2, 0.3, 0.4)	Unimportant	(0.2, 0.3, 0.4)
5	Mildly low	(0.3, 0.4, 0.5)	Mildly unimportant	(0.3, 0.4, 0.5)
6	OK	(0.4, 0.5, 0.6)	OK	(0.4, 0.5, 0.6)
7	Mildly high	(0.5, 0.6, 0.7)	Mildly important	(0.5, 0.6, 0.7)
8	High	(0.6, 0.7, 0.8)	Important	(0.6, 0.7, 0.8)
9	Quite high	(0.7, 0.8, 0.9)	Quite important	(0.7, 0.8, 0.9)
10	Extremely high	(0.8, 0.9, 1.0)	Extremely important	(0.8, 0.9, 1.0)
11	Absolutely high	(0.9, 1.0, 1.0)	Absolutely important	(0.9, 1.0, 1.0)

Table 3.2 Example of ranks and their proposed qualitative equivalent (three-rank case).

Rank	Probability – qualitative explanation	Fuzzy number (triangular/trap)	Consequences – qualitative explanation	Fuzzy number (triangular/trap)
1	Low	(0.0, 0.0, 0.5)	Unimportant	(0.0, 0.0, 0.5)
2	OK	(0.0, 0.5, 1.0)	OK	(0.0, 0.5, 1.0)
3	High	(0.5, 1.0, 1.0)	Important	(0.5, 1.0, 1.0)

Table 3.3 Example of ranks and their proposed qualitative equivalent (five-rank case),

Rank	Probability – qualitative explanation	Fuzzy number (triangular/trap)	Consequences – qualitative explanation	Fuzzy number (triangular/trap)
1	Extremely low	(0.0, 0.0, 0.25)	Extremely unimportant	(0.0, 0.0, 0.25)
2	Low	(0.0, 0.25, 0.5)	Unimportant	(0.0, 0.25, 0.5)
3	OK	(0.25, 0.5, 0.75)	OK	(0.25, 0.5, 0.75)
4	High	(0.5, 0.75, 1.0)	Important	(0.5, 0.75, 1.0)
5	Extremely high	(0.75, 1.0, 1.0)	Extremely important	(0.75, 1.0, 1.0)

Table 3.4 Example of ranks and their proposed qualitative equivalent (seven-rank case).

Rank	Probability – qualitative explanation	Fuzzy number (triangular/trap)	Consequences – qualitative explanation	Fuzzy number (triangular/trap)
1	Extremely low	(0.0, 0.0, 0.7)	Extremely unimportant	(0.0, 0.0, 0.7)
2	Quite low	(0.0, 0.17, 0.33)	Quite unimportant	(0.0, 0.17, 0.33)
3	Low	(0.17, 0.33, 0.50)	Unimportant	(0.17, 0.33, 0.50)
4	OK	(0.33, 0.50, 0.67)	OK	(0.33, 0.50, 0.67)
5	High	(0.50, 0.67, 0.83)	Important	(0.50, 0.67, 0.83)
6	Quite high	(0.67, 0.83, 1.0)	Quite important	(0.67, 0.83, 1.0)
7	Extremely high	(0.83, 0.1.0, 1.0)	Extremely important	(0.83, 0.1.0, 1.0)

Table 3.5 Example of ranks and their proposed qualitative equivalent (nine-rank case).

Rank	Probability – qualitative explanation	Fuzzy number (triangular/trap)	Consequences – qualitative explanation	Fuzzy number (triangular/trap)
1	Absolutely low	(0.0, 0.0, 0.125)	Absolutely unimportant	(0.0, 0.0, 0.125)
2	Very low	(0.0, 0.125, 0.25)	Very unimportant	(0.0, 0.125, 0.25)
3	Low	(0.125, 0.25, 0.375)	Unimportant	(0.125, 0.25, 0.375)
4	Mildly low	(0.25, 0.375, 0.5)	Mildly unimportant	(0.25, 0.375, 0.5)
5	OK	(0.375, 0.5, 0.625)	OK	(0.375, 0.5, 0.625)
6	Mildly high	(0.5, 0.625, 0.75)	Mildly important	(0.5, 0.625, 0.75)
7	High	(0.625, 0.75, 0.875)	Important	(0.625, 0.75, 0.875)
8	Very high	(0.75, 0.875, 1.0)	Very important	(0.75, 0.875, 1.0)
9	Absolutely high	(0.875, 1.0, 1.0)	Absolutely important	(0.875, 1.0, 1.0)

3.3.4. Obtaining the information from the experts

Two kinds of information are required from the experts:

- ranks for the probability of the failure of different objects in the above hierarchical structure and for the consequences on mitigation measures;
- weights for each object (having different 'capability' attributes).

It is important to prepare proper questionnaires for this purpose to obtain the appropriate information from the experts. An example of a questionnaire for assigning the ranks for probability and consequences of the failure of different objects is given in Appendix A.

The weights to each object that show the relative importance of one object over another in a group of objects are also obtained from the experts. The weights are necessary only when the 'capability' attributes of the objects of a particular group of the hierarchical structure are different. Normally, at the first level the objects have the same capability attributes and hence there is no necessity to obtain the weights at this level. For example, in *Figure 3.7(a)*, the group 'Road network' has three objects – Road A, Road B and Road C. All these objects have the same capability, that is to provide the surface on which road vehicles transport in the process of evacuation.

It is proposed to use AHP to obtain the weights. The details of AHP are given Appendix C. As in the case of obtaining the ranks for probability and consequences, here also it is important to prepare proper questionnaires to obtain the appropriate information from the experts. An example of a questionnaire is given in Appendix D.

It is suggested that the Delphi method be used to obtain the information from experts. The Delphi method is described in Appendix B.

3.4. Assess the aggregate risk as a result of failure of the supporting infrastructure

The quantification of aggregative risk involves two major steps, described in detail in this section. As stated earlier, experience from the assessment of risk in the water sector (Lee et al, 2004, Sadiq *et al.* 2004, Sadiq and Husain 2005) has been used for this purpose:

- qualitative evaluation of risk;
- computation of aggregative risk.

3.4.1. Qualitative evaluation of risk

Qualitative evaluation of risk consists of determining the ranks for the risk, computing the risk as the fuzzy product of probability and consequences, and then representing the risk as the fuzzy number.

3.4.1.1. Determination of ranks for the risk

Risk is the product of probability of failure of the object and its consequences on the mitigation measures. As stated in Section 3.3, probability and consequences are treated in qualitative terms in this study. This qualitative representation may induce imprecision and bias into the decision-making process, but provides useful insights into the process, especially where quantitative information is limited or variables involve subjectivity. *Tables 3.1* to *3.5* describe these qualitative scaling systems for probability and consequences. As for probability and consequences, as stated in Section 3.2.3, a seven-rank system is proposed for risk in this study.

The criteria ratings of risk are described in terms of linguistic variables. For the seven ranks of risk (1, 2, 3, 4, 5, 6 and 7), the corresponding qualitative description is *extremely low, quite low, low, OK, high, quite high and extremely high*, respectively. The triangular fuzzy numbers shown in *Table 3.6* are then used to represent these qualitative descriptions.

Table 3.6 Example of ranks and their proposed qualitative equivalent for risk(seven-rank case).

Rank	Risk – qualitative explanation	Fuzzy number (triangular/trap)
1	Extremely low	(0.0, 0.0, 0.17)
2	Quite low	(0.0, 0.17, 0.33)
3	Low	(0.17, 0.33, 0.50)
4	OK	(0.3, 0.50, 0.67)
5	High	(0.50, 0.67, 0.83)
6	Quite high	(0.67, 0.83, 1.00)
7	Extremely high	(0.83, 1.00, 1.00)

3.4.1.2. Computation of risk

Fuzzy mathematics is used to determine the product of probability and consequences (Klir and Yuan 1995). The probability and consequences are fuzzy numbers and the product of these two triangular fuzzy numbers is also a fuzzy number.

A fuzzy number can be defuzzified by various methods. The most commonly used methods are the Chen (1985) ranking and the Yager (1980) centroidal methods (Yager 1996). In this study, for simplicity Yager's centroidal method (1980; Equation 3.2) is proposed for defuzzification.

$$R(p,c) \quad = \quad \frac{\int_{xl}^{xu} x\left(\mu_p(x)\mu_c(x)\right)dx}{\int_{xl}^{xu} \left(\mu_p(x)\mu_c(x)\right)dx}$$

(3.2)

where:

$R(p,c)$ = defuzzified risk value for the probability of pth rank and consequence of cth rank
  $\mu_p(x)$ = membership values of probability of pth rank
  $\mu_c(x)$ = membership values of consequence of cth rank
    xu = upper limit of integral
    xl = lower limit of integral

The example of computation of risk as a fuzzy number that results from the product of two fuzzy numbers (probability and consequences) and its defuzzified values is shown below.

Refer to the questionnaire in Appendix A. Let us consider that the expert has answered 'Low' to a question 'what is the probability that road 'A' will fail to operate for 'evacuation' in the event of flood?', and 'Quite important' to a question 'How do you consider the consequence of failure of road 'A' on the mitigation measure of 'evacuation' by road transport network?' In this case the rank for probability p is 3 and the rank for consequence c is 6.

The triangular fuzzy number for p = 3 is (0.17, 0.33, 0.50) and the triangular fuzzy number for c = 6 is (0.67, 0.83, 1.00) – see *Table 3.4*. Their defuzzified product according to Equation (3.2) is 0.29.

The defuzzified values of risk for different ranks of probability and consequences in a seven-rank system are presented in *Table 3.7* and *Figure 3.8* for quick reference.

Table 3.7. Defuzzified value of risk for different ranks of probability and consequences.

		Rank for probability						
		1	2	3	4	5	6	7
Rank for consequence	1	0.007	0.014	0.021	0.028	0.035	0.043	0.049
	2	0.014	0.042	0.069	0.098	0.125	0.153	0.168
	3	0.021	0.069	0.124	0.180	0.236	0.290	0.325
	4	0.028	0.098	0.180	0.264	0.348	0.430	0.486
	5	0.035	0.125	0.236	0.348	0.459	0.569	0.646
	6	0.043	0.153	0.290	0.430	0.569	0.707	0.804
	7	0.049	0.168	0.325	0.486	0.646	0.804	0.922

The risk contours that represent the defuzzified or crisp values of risk are shown in *Figure 3.8*. On the figure the risk values increase from left to right and bottom to top with an increase in probability and consequence of the risk alone or together.
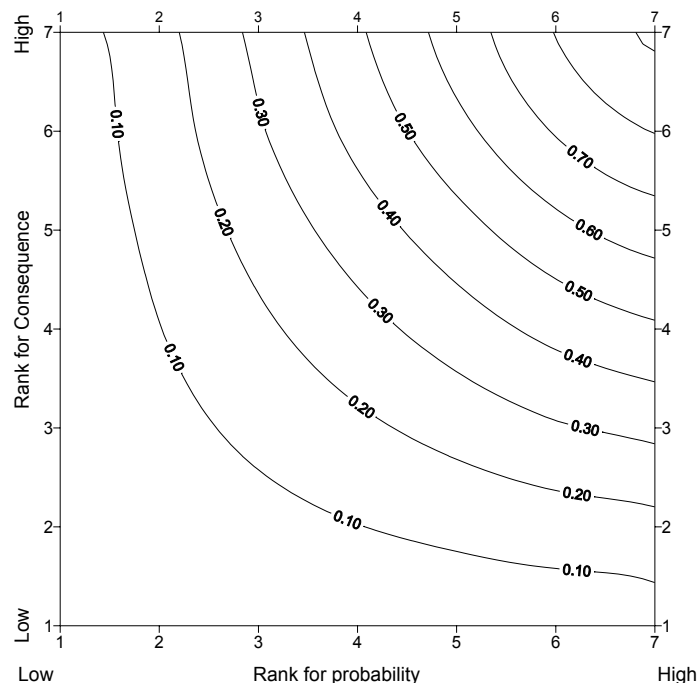

Figure 3.8 Risk values for different probabilities and consequences.

3.4.1.3. Fuzzy representation of risk

After finding the defuzzified risk value from the ranks for probability and consequence for each object, as discussed in previous two sections, this defuzzified risk value needs to be represented as a fuzzy number. The procedure for this is explained below.

Construct the triangular fuzzy number for different classes or ranks of risk as shown in *Figure 3.9*. Then, for the defuzzified risk value find out the values of the contribution of risk for each of the criteria ratings (in this case seven), as shown in *Figure 3.9*.

For example, in a seven-point scale for probability and consequences, if the probability of the failure of particular object is 'quite high' and the consequences of failure are 'quite unimportant', then the corresponding rank for probability is '6' and for consequences is '2' (*Table 3.2*). From *Table 3.7* or *Figure 3.8*, for probability rank of 6 and consequences rank of 2, the defuzzified value of risk is 0.153. Then, as shown in *Figure 3.9*, the contribution of risk from risk class 1 (extremely low) is 0.25 and from risk class 2 (quite low) is 0.75. From all other remaining classes, the contribution is zero. Thus, the fuzzy representation of '0.153' in the seven-rank system is (0.25, 0.75, 0, 0, 0, 0, 0).
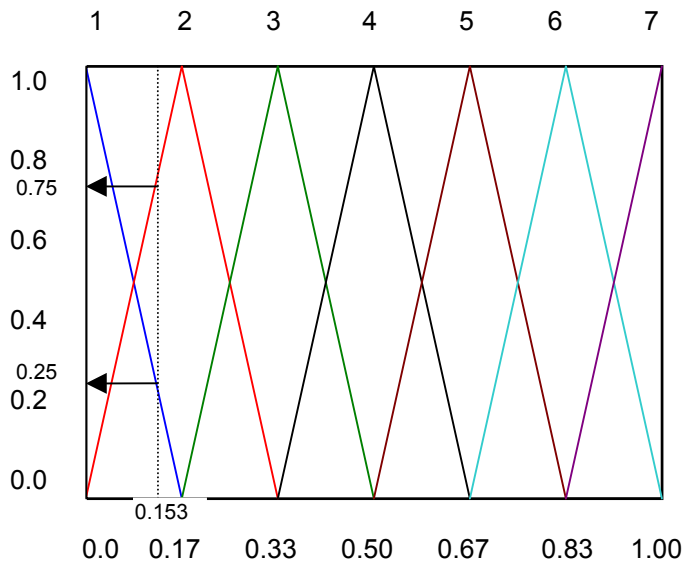
Figure 3.9 Triangular fuzzy numbers for different classes of risk.

3.4.2. Computation of aggregative risk

3.4.2.1. Hierarchical structure

It is necessary to represent the specified FIM process using the hierarchical structure model, as discussed in Section 3.7.1. To explain the related terms clearly, the FIM process is represented by a simple hierarchical structure, as shown in *Figure 3.10*.
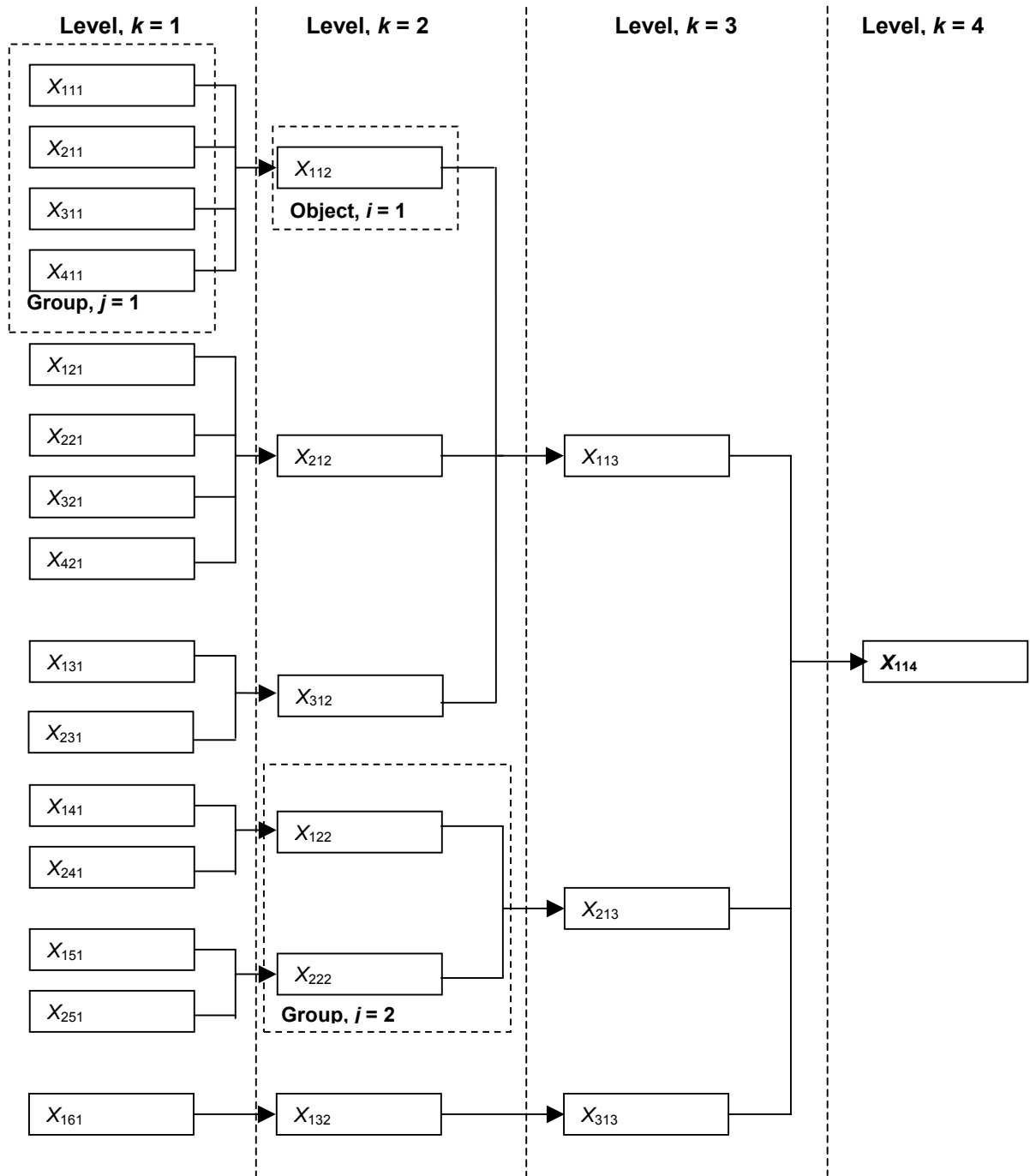
Figure 3.10. The simple hierarchical structure.

In *Figure 3.10*, 'X' represents the object, for example 'Road', and the notation 'k' represents the level number. The hierarchical structure shown in *Figure 3.10* has four levels ($K = 4$, where 'K' is the total number of levels). The notation 'j' represents the group number at the specified level and 'J_k'' represents the total number of groups at the jth level. For example, for $k = 2$, $J_k = 3$. The notation 'i' represents the object number and 'I_{jk}' is the total number of objects in the jth group at the kth level. For example, for $j = 1$, $k = 1$ and $I_{jk} = 4$.

Also, the notations 'P', 'C' and 'R' represent the probability, consequence and risk, respectively. The notations 'p', 'c' and 'r' represent the rank numbers for probability, consequence and risk, respectively.

3.4.2.2.   Compute the aggregative risk

The following procedure is proposed to compute the aggregative risk.

Start with level 1, k = 1

1. Fuzzy representation of risk

For each object of each group at level 1, find out the fuzzy representation of risk as shown below.

If p_{ijk} and c_{ijk} are the ranks for the probability and consequences for the ith object in the jth group at the kth level, then the defuzzified value of risk for the ith object in the jth group at the kth level, R_{ijk} (see Section 3.7.1 and Equation 3.2). This defuzzified value is represented as fuzzy number (see Section 3.7.1):

f_{rijk} for r = 1, T or

$[f_{1ijk}, f_{2ijk},   f_{Tijk}]$

where:

f = contribution of risk from the specified class or rank
r = notation for the class or rank
T = total number of ranks (in this study, T = 7).

2. The fuzzy representation matrix

The fuzzy representation matrix is found out for each group of objects as:

$$\begin{bmatrix} f_{11jk,} & f_{21jk} & f_{31jk,} & ...f_{T1jk} \\ f_{12jk,} & f_{22jk} & f_{32jk,} & ...f_{T2jk} \\ \vdots & & & \\ f_{1Ijk,} & f_{2Ijk} & f_{3Ijk,} & ...f_{TIjk} \end{bmatrix}$$

3. Weight assignment

As discussed in Section 1.4, it is necessary that the decision makers assign weights to indicate their preferences to the relative importance of the objects in a particular group. The weights for each object are obtained as discussed in Section 3.6.3. At the first level, there is no need to compute weights or the weights are equal, as the 'capability' attributes of the objects of the groups at level 1 are same. However, the weights need to be considered from the second stage onward and hence the procedure to include weights is explained.

Let W_{ijk} represent the weights assigned to the ith object in the jth group at the kth level. In matrix form weights can be represented as:

$[W_{ijk}, W_{ijk},   W_{ijk}]$ for i = 1, I, j = 1, J_k and k = 1, K

4. Risk matrix

The risk matrix for the *j*th group at the *k*th level is computed as the product of the weight matrix and fuzzy representation matrix:

$$[A_{1ijk}, A_{2ijk}, \quad A_{Tijk}]_{(1 \times T)} = [W_{ijk}, W_{ijk}, \quad W_{ijk}]_{(1 \times I)} \times \begin{bmatrix} f_{11jk,} & f_{21jk} & f_{31jk,} & \cdots f_{T1jk} \\ f_{12jk,} & f_{22jk} & f_{32jk,} & \cdots f_{T2jk} \\ \vdots \\ f_{1Ijk,} & f_{2Ijk} & f_{3Ijk,} & \cdots f_{TIjk} \end{bmatrix}_{(IxT)}$$

where:

A = risk for each class

$$A_{lijk} \quad = \quad \sum_{i=1}^{I_{jk}i} W_{ijk} f_{lijk}$$

This risk matrix is the fuzzy representation matrix for the next stage, which means:

$[A_{1ijk}, A_{2ijk}, \quad A_{Tijk}] = [f_{1i(j+1)k}, f_{2i(j+1)k}, \quad f_{Ti(+1)jk}]$

The procedure is repeated from Step 2 to 4 until the last level is reached (from second level onward, there are no values for probability and consequence, but there are weights for each object of the group.). At the last level (that is, *k = K*), the risk representation matrix is:

$[A_{111K}, A_{211K}, \quad A_{T11K}]$

The *final aggregative risk* is obtained by multiplying the final stage risk matrix with the defuzzified values of the triangular fuzzy number of risk for each class (*Table 3.6*):

Aggregative risk = $A_{111K} * d_1 + A_{211K} * d_2 + \ldots + A_{T11K} * d_T$

where:

d = the defuzzified value of triangular fuzzy number of the risk (*Table 3.6*).

For a seven-rank system:

d_1 = 0:056
d_2 = 0:167
d_3 = 0:333
d_4 = 0:500
d_5 = 0:667
d_6 = 0:834
d_7 = 0:944

4. Analysis and discussion

The scope of this study was limited to investigate the possibility of developing a framework and methodology to estimate the aggregative risk to mitigation measures from the failure of the supporting infrastructure and workforce. The methods in use in the water sector were reviewed and, together with authors' experience, the methodology outlined in the Chapter 3 is proposed.

At this stage, it is not possible to demonstrate the strength of the developed methodology by developing a case study. For this catchment data are required, as are interviews with experts. This was not possible given the limited time to complete this phase of the project. However, the methodology is demonstrated with the help of one example in this chapter.

4.1 Example

Section 3.2.2 presents the hierarchical structure required for the mitigation measure of 'evacuation'. To demonstrate the methodology developed to estimate aggregative risk (described in Section 3.3), this structure was simplified by omitting the objects at level 1 and the objects related to workforce. The simplified hierarchical structure used for the example is shown in *Figure 4.1*.

In this example, how to estimate the risk to the mitigation measure of evacuation through the failure of the supporting infrastructures because of primary threats from flood and secondary and tertiary threats from the failure of other infrastructures is demonstrated.

4.1.1 Probability and consequences

As described in Section 3.2.3, the probability and consequences of the failure of different objects (infrastructure) are obtained by developing the questionnaire. The questionnaire with the sample response is presented in Appendix E. The probability and consequences of failure are obtained only at first level here (k = 1).

The ranks of the probability and consequences of failure of different objects at the first level in a seven-rank system, as obtained after the analysis of questionnaire, is given in *Table 4.1*.

4.1.2 Weight assignment

As stated in Section 3.2.4, the weights assigned to each object to show the relative importance of one object over another in the group of objects need to be obtained from the experts. The weights are necessary only when the 'capability' attributes of the objects of a particular group of the hierarchical structure are different (that is, for the objects at level 2 onwards). The AHP method was used to obtain the weights. The questionnaire designed for this purpose, with a sample response, is presented in Appendix D. The weights assigned to each object of the different groups at the different levels obtained after the analysis are given in *Table 4.2* (see the procedure presented in Appendix C for the analysis and in Appendix G for a detailed analysis for group 1 at levels 2 and 3).

Table 4.1 Probability and consequences of failure of different objects at level 1.

Sr. No.	Object	Rank for probability (*p*)	Rank for consequence (*c*)
1	X_{111}	6	5
2	X_{211}	2	3
3	X_{311}	3	7
4	X_{411}	5	4
5	X_{121}	2	6
6	X_{221}	2	3
7	X_{321}	1	5
8	X_{421}	2	3
9	X_{131}	1	7
10	X_{231}	2	6
11	X_{141}	3	4
12	X_{241}	1	4
13	X_{151}	1	6
14	X_{251}	2	6
15	X_{161}	1	6

Table 4.2 Estimated weights obtained by using AHP for different objects (the objects of a specified group at level 1 have equal weights).

Level	Group	Object	Notation for object	Weight
2	1	1	X_{112}	0.63
		2	X_{212}	0.24
		3	X_{312}	0.13
2	2	1	X_{122}	0.80
		2	X_{222}	0.20
2	3	1	X_{132}	1.0
3	1	1	X_{113}	0.64
		2	X_{213}	0.26
		3	X_{313}	0.10
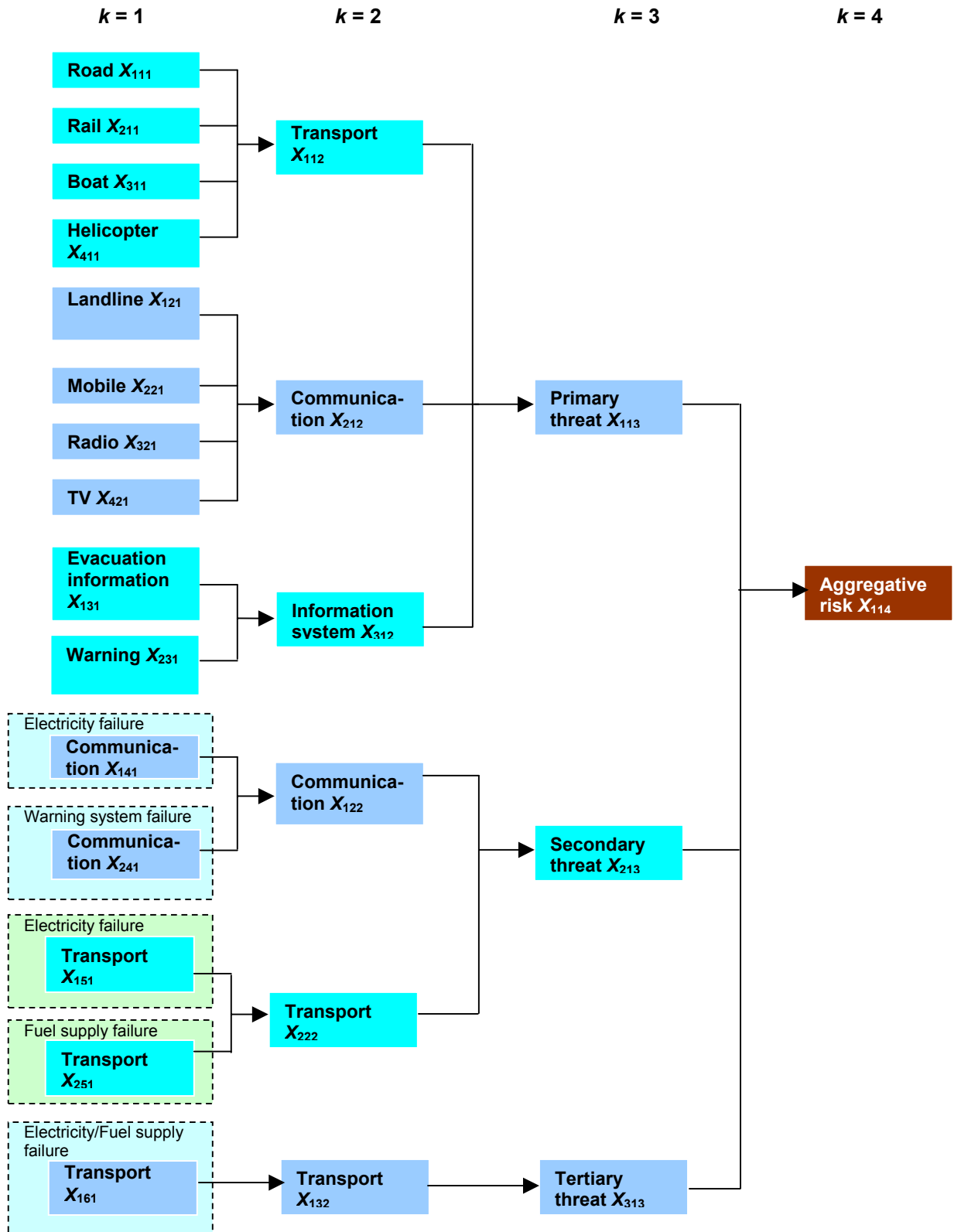
Figure 4.1 Simplified hierarchical structure used for the example.

4.1.3 Computation and fuzzy representation of risk

The risk is the product of probability and consequences of failures. These are fuzzy variables and hence fuzzy arithmetic, as stated in Section 3.3.1, is used for this purpose. *Table 3.7* gives the values of risk as the fuzzy multiplication of probability and consequences for different combinations of their ranks. This table was used to obtain the risk for the specified ranks of probability and consequences. The procedure explained in Section 3.3.1 and *Figure 3.9* was used for the fuzzy representation of the risk. The risk and its fuzzy representation for the different objects at the first level are presented in *Table 4.3*.

Table 4.3 Risk values and their fuzzy representation of objects at level 1.

Sr. No.	Object	Risk	Fuzzy representation of risk
1	X_{111}	0.707	(0.00,0.00,0.00,0.00,0.80,0.20,0.00)
2	X_{211}	0.069	(0.76,0.24,0.00,0.00,0.00,0.00,0.00)
3	X_{311}	0.325	(0.00,0.05,0.95,0.00,0.00,0.00,0.00)
4	X_{411}	0.348	(0.00,0.00,0.94,0.06,0.00,0.00,0.00)
5	X_{121}	0.153	(0.25,0.75,0.00,0.00,0.00,0.00,0.00)
6	X_{221}	0.069	(0.76,0.24,0.00,0.00,0.00,0.00,0.00)
7	X_{321}	0.035	(0.90,0.10, 0.00,0.00,0.00,0.00,0.00)
8	X_{421}	0.069	(0.76,0.24,0.00,0.00,0.00,0.00,0.00)
9	X_{131}	0.043	(0.87,0.13,0.00,0.00,0.00,0.00,0.00)
10	X_{231}	0.153	(0.25,0.75,0.00,0.00,0.00,0.00,0.00)
11	X_{141}	0.180	(0.0,0.92,0.08,0.00,0.00,0.00,0.00)
12	X_{241}	0.028	(0.92,0.08,0.00,0.00,0.00,0.00,0.00)
13	X_{151}	0.043	(0.87,0.13,0.00,0.00,0.00,0.00,0.00)
14	X_{251}	0.153	(0.25,0.75,0.00,0.00,0.00,0.00,0.00)
15	X_{161}	0.043	(0.87,0.13,0.00,0.00,0.00,0.00,0.00)

4.1.4 Computation of aggregative risk

See Section 3.7.2 for the procedure.

Level 1

The *fuzzy representation matrices* for different groups at level 1 are shown in *Table 4.4*.

Table 4.4 Fuzzy representation matrices for different groups at level 1.

Level	Object	Group	Fuzzy representation of risk
1	X_{111}	X_{112}	$\begin{bmatrix} 0.00,0.00,0.00,0.00,0.80,0.20,0.00 \\ 0.76,0.24,0.00,0.00,0.00,0.00,0.00 \\ 0.00,0.05,0.95,0.00,0.00,0.00,0.00 \\ 0.00,0.00,0.94,0.06,0.00,0.00,0.00 \end{bmatrix}$
	X_{211}		
	X_{311}		
	X_{411}		
1	X_{121}	X_{212}	$\begin{bmatrix} 0.25,0.75,0.00,0.00,0.00,0.00,0.00 \\ 0.76,0.24,0.00,0.00,0.00,0.00,0.00 \\ 0.90,0.10,0.00,0.00,0.00,0.00,0.00 \\ 0.76,0.24,0.00,0.00,0.00,0.00,0.00 \end{bmatrix}$
	X_{221}		
	X_{321}		
	X_{421}		
1	X_{131}	X_{312}	$\begin{bmatrix} 0.87,0.13,0.00,0.00,0.00,0.00,0.00 \\ 0.25,0.75,0.00,0.00,0.00,0.00,0.00 \end{bmatrix}$
	X_{231}		
1	X_{141}	X_{122}	$\begin{bmatrix} 0.0,0.92,0.08,0.00,0.00,0.00,0.00 \\ 0.92,0.08,0.00,0.00,0.00,0.00,0.00 \end{bmatrix}$
	X_{241}		
1	X_{151}	X_{222}	$\begin{bmatrix} 0.87,0.13,0.00,0.00,0.00,0.00,0.00 \\ 0.25,0.75,0.00,0.00,0.00,0.00,0.00 \end{bmatrix}$
	X_{251}		
1	X_{161}	X_{132}	$\begin{bmatrix} 0.87,0.13,0.00,0.00,0.00,0.00,0.00 \end{bmatrix}$

Risk matrices for different groups at level 1 are computed next.

Group 1
(The objects of a specified group at level 1 have equal weights.)

$$[0.25, 0.25, 0.25, 0.25]_{(1x4)} \quad \times \quad \begin{bmatrix} 0.00,0.00,0.00,0.00,0.80,0.20,0.00 \\ 0.76,0.24,0.00,0.00,0.00,0.00,0.00 \\ 0.00,0.05,0.95,0.00,0.00,0.00,0.00 \\ 0.00,0.00,0.94,0.06,0.00,0.00,0.00 \end{bmatrix}_{(4x7)}$$

$$= \quad [0.19, 0.0725, 0.4725, 0.015, 0.2, 0.05, 0.0]_{(1x7)}$$

{(weight matrix) × (fuzzy representation matrix) = risk matrix}

Group 2
(Note that the objects of specified group at level 1 have the equal weights)

$$[0.25, 0.25, 0.25, 0.25]_{(1x4)} \quad \times \quad \begin{bmatrix} 0.25,0.75,0.00,0.00,0.00,0.00,0.00 \\ 0.76,0.24,0.00,0.00,0.00,0.00,0.00 \\ 0.90,0.10,0.00,0.00,0.00,0.00,0.00 \\ 0.76,0.24,0.00,0.00,0.00,0.00,0.00 \end{bmatrix}_{(4x7)}$$

$$= \quad [0.6675, 0.3325, 0.0,0.0, 0.0, 0.0, 0.0]_{(1x7)}$$

Group 3

$$[0.50, 0.50]_{(1x2)} \quad \times \quad \begin{bmatrix} 0.87, 0.13, 0.00, 0.00, 0.00, 0.00, 0.00 \\ 0.25, 0.75, 0.00, 0.00, 0.00, 0.00, 0.00 \end{bmatrix}_{(2x7)}$$

$$= \quad [0.56, 0.44, 0.0, 0.0, 0.0, 0.0, 0.0]_{(1x7)}$$

Group 4

$$[0.50, 0.50]_{(1x2)} \quad \times \quad \begin{bmatrix} 0.0, 0.92, 0.08, 0.00, 0.00, 0.00, 0.00 \\ 0.92, 0.08, 0.00, 0.00, 0.00, 0.00, 0.00 \end{bmatrix}_{(2x7)}$$

$$= \quad [0.46, 0.50, 0.04, 0.0, 0.0, 0.0, 0.0]_{(1x7)}$$

Group 5

$$[0.50, 0.50]_{(1x2)} \quad \times \quad \begin{bmatrix} 0.87, 0.13, 0.00, 0.00, 0.00, 0.00, 0.00 \\ 0.25, 0.75, 0.00, 0.00, 0.00, 0.00, 0.00 \end{bmatrix}_{(2x7)}$$

$$= \quad [0.56, 0.44, 0.0, 0.0, 0.0, 0.0, 0.0]_{(1x7)}$$

Group 6

$$[1.00]_{(1x1)} \quad \times \quad [0.87, 0.13, 0.00, 0.00, 0.00, 0.00, 0.00]_{(1x7)}$$

$$= \quad [0.87, 0.13, 0.00, 0.00, 0.00, 0.00, 0.00]_{(1x7)}$$

Level 2

The groups of level 1 are the objects of level 2 and hence risk matrices of groups at level 1 become the fuzzy representation of objects at level 2. These fuzzy representations are presented in *Table 4.5*.

Table 4.5 Fuzzy representation of risk of the objects at level 2.

Sr. No.	Object	Fuzzy representation of risk
1	X_{112}	$(0.19, 0.0725, 0.4725, 0.015, 0.2, 0.05, 0.0)$
2	X_{212}	$(0.6675, 0.3325, 0.0, 0.0, 0.0, 0.0, 0.0)$
3	X_{312}	$(0.56, 0.44, 0.0, 0.0, 0.0, 0.0, 0.0)$
4	X_{122}	$(0.46, 0.50, 0.04, 0.0, 0.0, 0.0, 0.0)$
5	X_{222}	$(0.56, 0.44, 0.0, 0.0, 0.0, 0.0, 0.0)$
6	X_{132}	$(0.87, 0.13, 0.00, 0.00, 0.00, 0.00, 0.00)$

The fuzzy representation matrices for different groups at level 2 are shown in *Table 4.6*.

Table 4.6 Fuzzy representation matrices for different groups at level 2.

Level	Object	Group	Fuzzy representation of risk
	X_{112}	X_{113}	$\begin{bmatrix} 0.1900, 0.0725, 0.4725, 0.015, 0.2000, 0.0500, 0.0 \\ 0.6675, 0.3325, 0.0000, 0.000, 0.0000, 0.0000, 0.0 \\ 0.5600, 0.4400, 0.0000, 0.000, 0.0000, 0.0000, 0.0 \end{bmatrix}$
	X_{212}		
	X_{312}		
	X_{122}	X_{213}	$\begin{bmatrix} 0.46, 0.50, 0.04, 0.0, 0.0, 0.0, 0.0 \\ 0.56, 0.44, 0.00, 0.0, 0.0, 0.0, 0.0 \end{bmatrix}$
	X_{222}		
	X_{132}	X_{313}	$\begin{bmatrix} 0.87, 0.13, 0.0, 0.0, 0.0, 0.0 \end{bmatrix}$

Risk matrices for different groups at level 2 are computed next.

Group 1

$$[0.63, 0.24, 0.13]_{(1x3)} \quad \times \quad \begin{bmatrix} 0.1900, 0.0725, 0.4725, 0.015, 0.2000, 0.0500, 0.0 \\ 0.6675, 0.3325, 0.0000, 0.000, 0.0000, 0.0000, 0.0 \\ 0.5600, 0.4400, 0.0000, 0.000, 0.0000, 0.0000, 0.0 \end{bmatrix}_{(3x7)}$$

$$= \quad [0.3527, 1827, 0.2977, 0.009, 126, 0.0315, 0.0]_{(1x7)}$$

Group 2

$$[0.80, 0.20]_{(1x2)} \quad \times \quad \begin{bmatrix} 0.46, 0.50, 0.04, 0.0, 0.0, 0.0, 0.0 \\ 0.56, 0.44, 0.00, 0.0, 0.0, 0.0, 0.0 \end{bmatrix}_{(2x7)}$$

$$= \quad [0.480, 0.488, 0.032, 0.0, 0.0, 0.0]_{(1x7)}$$

Group 3

$$[1.00]_{(1x1)} \quad \times \quad [0.87, 0.13, 0.00, 0.00, 0.00, 0.00, 0.00]_{(1x7)}$$
$$= \quad [0.87, 0.13, 0.00, 0.00, 0.00, 0.00, 0.00]_{(1x7)}$$

Level 3

The groups of level 2 are objects of level 3 and hence risk matrices of groups at level 2 become the fuzzy representation of objects at level 3. These fuzzy representations are presented in *Table 4.7*.

Table 4.7 Fuzzy representation of risk of the objects at level 3.

Sr. No.	Object	Fuzzy representation of risk
1	X_{113}	(0.3527, 0.182675, 0.297675, 0.00945, 0.126, 0.0315, 0.0)
2	X_{213}	(0.48, 0.488, 0.032, 0,00, 0.00, 0, 00, 0.00)

| | 3 | X_{313} | (0.87, 0.13, 0.00, 0.00, 0.00, 0.00, 0.00) |

The fuzzy representation matrix for level 3 is shown in *Table 4.8*.

Table 4.8 Fuzzy representation matrices for different groups at level 3.

Level	Object	Group	Fuzzy representation of risk
	X_{113}	X_{114}	$\begin{bmatrix} 0.3527, 0.1827, 0.2977, 0.0094, 0.126, 0.0315, 0.0 \\ 0.4800, 0.4880, 0.0320, 0.0000, 0.000, 0.0000, 0.0 \\ 0.8700, 0.1300, 0.0000, 0.0000, 0.000, 0.0000, 0.0 \end{bmatrix}$
	X_{213}		
	X_{313}		

The final stage risk matrix is computed as:

$$[0.64, 0.26, 0.10]_{(1x3)} \times \begin{bmatrix} 0.3527, 0.1827, 0.2977, 0.0094, 0.126, 0.0315, 0.0 \\ 0.4800, 0.4880, 0.0320, 0.0000, 0.000, 0.0000, 0.0 \\ 0.8700, 0.1300, 0.0000, 0.0000, 0.000, 0.0000, 0.0 \end{bmatrix}$$

$$= [0.43, 0.25, 0.19, 0.007, 0.1, 0.025, 0.0]_{(1x7)}$$

4.1.5 Final aggregative risk

The final aggregative risk is obtained by multiplying the final stage risk matrix with the defuzzified values of the triangular fuzzy number of risk for each class (*Table 3.6*):

Final aggregative risk = [(0.43*0.056)+(0.25*0.167)+(0.19*0.333)+(0.007*0.50)+
(0.1*0.667)+(0.025*0.834)+(0.0*0.944)]

= **0.22**

4.2 Discussion

The methodology to estimate the aggregative risk to mitigation measures is demonstrated in Section 4.1. The aggregative risk was 0.22. Risk varies in the range 0 to 1. It is necessary to perform a sensitivity analysis to see whether the risk can be reduced. The sensitivity analysis can be performed in the following ways:

1. To change the 'state' attributes of the objects and obtain a modified value of the probability of failure. For example, in the case of 'road', if the current state of 'road' is changed from 'Bad' to 'OK', the response for the probability of failure may change from 'Quite high' to 'OK'. This will subsequently reduce the value of aggregative risk, which means that the risk to the mitigation measure of evacuation will be reduced if the condition of the road is improved.
2. To add a new object that is complimentary to the existing objects of similar attributes of 'capability'. For example, if a new road is added to improve transport, the consequences through failure of the existing road may change from 'Quite important' to 'Unimportant'. This leads to reduced values of aggregative risk, which means that if the road network is upgraded, there will be less risk to the mitigation measure of evacuation.

Comparison of the aggregative risk values of different mitigation measures would enable the Environment Agency to guide different infrastructure owners to improve or upgrade their utilities so that the risk is reduced during FIM.

The proposed methodology heavily relies on obtaining information from experts in FIM. It is felt that this approach is more suitable than to rely on unreliable data or no data. The fuzzy approach is hence adopted to represent and deal with the qualitative information obtained from experts.

It is emphasised here that the panel of experts should be chosen carefully. For example, if the proposed methodology is used to estimate the aggregative risk for certain mitigation measures through the failure of the supporting infrastructure and workforce in a particular catchment, the panel of experts should consist of people from the relevant sectors who have experience of this particular catchment or a similar catchment.

5. Conclusions

This particular work package investigated the risks in terms of probability and consequences of failure of the supporting infrastructure (that is, assets other than flood defence assets) and personnel who manage the flood events (workforce). The framework proposed involves three steps.

- identify the interdependencies between the supporting infrastructures;
- assess the probability and consequences of the failure of the supporting infrastructures;
- assess the aggregate risk as a result of failure of the supporting infrastructures.

The procedure involves defining each risk item by the product of the likelihood of a failure event and its consequences. Both the likelihood and the consequences of a failure event are defined using 'fuzzy numbers' to capture the vagueness in the qualitative linguistic definitions. This is because the available field data are both quantitative and qualitative, and when available, they are often uncertain and vague. Hence the developed methodology should enable the decision makers to assess qualitatively the risks in the process of FIM.

It is anticipated that the proposed methodology will enable the Environment Agency and other concerned organisations to estimate the risks to mitigation measures and accordingly prioritise their activities and improve the FIM process.

6. Recommendations

A methodology is proposed in this work package to estimate the aggregative risk to mitigation measures through the failure of the infrastructure and workforce during FIM. The proposed methodology will enable the Environment Agency and other concerned organisations to estimate the risks to mitigation measures and, accordingly, prioritise their activities and improve the FIM process. The utility of the developed approach is demonstrated with an example. The objective of this phase of the study (Phase 1) was to develop the framework and demonstrate it with an example. However, it is strongly recommended that the required data be collected and the responses on assessing the probability and consequences for the example catchment be obtained. Considering the potential application of the methodology to FIM, it is recommended:

1. To undertake a full study (Phase 2) that will involve the further refinement of the methodology, development of the spatial decision-support system and computer software for this methodology and the application of this methodology to case study catchments.
2. To undertake an actual test of this methodology in representative catchments of the UK as the next phase (Phase 3) of the study.

References and Bibliography

Bennett J C, Bohoris G A, Aspinwall E M and Hall, R C, 1996 *Risk analysis techniques and their application to software development.* European Journal of Operational Research, **95**, 467-475.

Carby B E, 2005 *Jamaica's experience with Hurricane Ivan: the case for mitigation and preparedness programmes*. The Caribbean Disaster Emergency Response Agency. (http://www.cdera.org/cunews/news/jamaica/article_1073.php).

Chen S H, 1985 *Ranking fuzzy numbers with maximising set and minimising set*. Fuzzy Set Systems, **17**, No.2, 113-129.

Chen S, 2001 *Fuzzy group decision making for evaluating the rate of aggregative risk in software development*. Fuzzy Sets and Systems **118**, 75-88.

Crossland R, Williams J and McMahon C A, 2003 *An object-oriented modelling framework for representing uncertainty in early variant design*. Research in Engineering Design, **14**, 173-183.

Curtin J, 2004 *The Boscastle and North Cornwall Flooding – 16th August 2004*. Bristol: Environment Agency.

Edwards M, Barreteau O, Cernesson F and Hill D, 2002. *An object oriented model linking hydrological and social processes at an aggregate level*. 3rd Workshop on Agent-Based Simulation, 7-9 April 2002, Passau, Germany.

Environment Agency, 2005 *Managing flood risk – Dealing with flooding: a review of the floods in northern England and North Wales*. Bristol: Environment Agency.

FIMA, 2002 *Success Stories from the Missouri Buyout Program* (http://www.FIMa.gov/pdf/reg-vii/mo_buyoutreport.pdf).

Green C H, Parker D J and Tunstall S M, 2000 *Assessment of Flood Control and Management Options*. Thematic Review IV.4 prepared as an input to the World Commission on Dams, Cape Town.

Hansson R O, Noulles D and Bellovich S, 1982 *Knowledge, warning, and stress: a study of comparative roles in an urban floodplain*. Environmental Behaviour, **14**, No. 2, 171-185.

Khan F I and Sadiq R, 2005 *Risk-based prioritization of air pollution monitoring using fuzzy synthetic evaluation technique*. Environmental Monitoring and Assessment, **105**, 261-283.

Khan F I, Sadiq R and Haddara M M, 2004 *Risk-based inspection and maintenance (RBIM): multi-attribute decision-making with aggregative risk analysis*. Process Safety and Environmental Protection, **82**, No. B6, 398-411.

Klir G J and Folger T A, 1988 *Fuzzy Sets, Uncertainty and Information*. Englewood Cliffs: Prentice-Hall.

Klir G J and Yuan B, 1995 *Fuzzy Sets and Fuzzy Logic-Theory and Applications*. Englewood Cliffs: Prentice-Hall.

Lascio L D, Gisolfi A, Albunia A, Galardi G and Moschi F, 2002 *A fuzzy-based methodology for the analysis of diabetic neuropathy*. Fuzzy Sets and Systems, **129**, 203-228.

Laska S B, 1990 *Homeowner adaptation to flooding: an application of the general hazards coping theory*. Environmental Behaviour, **22**, No. 3, 320-357.

Lawry J, 2001 *A methodology for computing with words.* International Journal of Approximate Reasoning, **28**, 51-89.

Lee H, 1996 *Applying fuzzy set theory to evaluate the rate of aggregative risk in software development*. Fuzzy Sets and Systems, **79**, 323-336.

Lee H, Lee S, Lee T and Chen J, 2003 *A new algorithm for applying fuzzy set theory to evaluate the rate of aggregative risk in software development*. Information Sciences, **153**, 177-197.

Lee H, Lee T, Lee S and Chen J, 2004 *A fuzzy group assessment model for evaluating the rate of aggregative risk in software development*. International Journal of Reliability Engineering, Quality and Safety, **11**, No. 1, 17-33.

Liu D and Stewart T J, 2004. *Integrated object-oriented framework for MCDM and DSS modelling*. Decision Support Systems, **38**, 421-434.

Ngai E W T and Wat F K T, 2005 *Fuzzy decision support system for risk analysis in e-commerce development*. Decision Support Systems, **40**, 235-255.

Pepper A C, Stonecipher C and Vein K A, 2002 *Flood management: lessons from a US city*. Proceedings of the Institution of Civil Engineers (Municipal Engineer), 1**51**, No. 4, 295-304.

Rainer R K J R, Snyder C A and Carr H H, 1991 *Risk analysis for information technology.* Journal of Management Information Systems, **8**, No. 1, 129-147.

Rinaldi S M, 2004 *Modelling and simulating critical infrastructures and their Interdependencies*. Proceedings of the 37th Hawaii International Conference on System Sciences, 1-8. Washington DC: IEEE Computer Society.

Rinaldi S M, Peerenboom J P and Kelly T K, 2001. *Identifying, understanding, and analyzing critical infrastructure interdependencies*. IEEE Control Systems Magazine, No. 6, 11-25.

Saaty T L, 1977 *A scaling method for priorities in hierarchical structures*. Journal of Mathematical Psychology, **15**, 57-68.

Saaty T L, 1980 *The analytic hierarchy process*. New York: McGraw-Hill International.

Saaty T L, 1994 *Fundamentals of decision making and priority theory with the AHP*. Pittsburgh: RWS Publications.

Sadiq R and Husain T, 2005 *A fuzzy-based methodology for an aggregative environmental risk assessment: a case study of drilling waste*. Environmental and Modelling Software, **20**, 33-46.

Sadiq R, Kleiner Y and Rajani B, 2004 *Aggregative risk analysis for water quality failure in distribution network*. Journal of Water Supply: Research and Technology, **53**, No. 4, 243-261.

Simonovic S P and Ahmad S, 2005 *Computer-based model for flood evacuation emergency planning*. Natural Hazards*, **34**, 25-51.

Vlachos E, 1995 *Socio-economic impacts and consequences of extreme floods*. US–Italy Research Workshop on the Hydrometeorology, Impacts, and Management of Extreme Floods, Perugia, Italy.

Wang J, Hassett J M and Endreny T A, 2005 *An object oriented approach to the description and simulation of watershed scale hydrologic processes*. Computers and Geosciences, **31**, 425-435.

Watson C C and Johnson M E, 2002 *A Modular, Object Oriented Model for Meteorological Hazard Assessment.* (http://hurricane.methaz.org/papers/ams_taos_det_00.pdf).

White D, 1995 *Application of systems thinking to risk management: a review of the literature*. Management Decision, **3**, No. 9, 35-45.

WIKIPEDIA, 2005a *Effect of Hurricane Katrina on New Orleans* (http://en.wikipedia.org/wiki/Effect_of_Hurricane_Katrina_on_New_Orleans).

WIKIPEDIA, 2005b *2005 European Floods*. (http://en.wikipedia.org/wiki/2005_European_floods).

Wyss G D, Durán F A and Dandini V J, 2004 *An object-oriented approach to risk and reliability analysis: methodology and aviation safety applications*. Simulation, **80**, No. 1, 33-43.

Yager R R, 1980 *A general class of fuzzy connectives*. Fuzzy Sets and Systems, **4**, 235-242.

Yager R R, 1996 *Fuzzy logic computing with words*. IEEE Transactions, Fuzzy Systems, **4**, No. 2, 103-111.

Zadeh L A, 1965 *Fuzzy sets*. Information and Control, **8**, 338-353.

Zadeh L A, 1996 *Fuzzy logic = computing with words*. IEEE Transactions, Fuzzy Systems, **4**, No. 2, 103-111.

Appendix A

Example questionnaire to assess probability and consequences

Guidelines: provide here information on each attribute of all objects

Notes: The following is an example to assess the probability of failure of road A for the mitigation measure of evacuation and the consequences of failure of road A on the evacuation by road transport (refer to *Figure 3.7(a)*).

What is the probability that road 'A' will fail to operate for 'evacuation' in the event of flood?		
❑ Extremely low ❑ Quite low ❑ Low	❑ OK	❑ High ❑ Quite High ❑ Extremely high

How do you consider the consequences of failure of road 'A' on the mitigation measure of 'evacuation' by road transport network?		
❑ Extremely unimportant ❑ Quite unimportant ❑ Unimportant	❑ OK	❑ Important ❑ Quite important ❑ Extremely important

Appendix B

Delphi method to obtain responses from experts

The purpose of the Delphi method is to obtain responses from a group of experts for a particular situation. For example, in the framework developed to assess the risk from failure of the supporting infrastructures and workforce, it is necessary to assess the probability and consequences of failure of different supporting infrastructures and workforce on the mitigation measures. Experts who work in flood incident management (FIM) can assess these appropriately.

The Delphi method is based on a structured process to collect and distil knowledge from a group of experts by means of a series of questionnaires interspersed with controlled opinion feedback (Adler and Ziglio 1996). The object of this method is the reliable and creative exploration of ideas or the production of suitable information for decision making. According to Helmer (1977), the Delphi method represents a useful communication device among a group of experts and thus facilitates the formation of a group judgement. This method makes discussion between experts possible without permitting social interactive behaviour, as happens during normal group discussion and hampers opinion forming. This method has been used widely to generate forecasts in technology, education and other fields (Cornish 1977).

The major steps that need to be performed for the Delphi method (Fowles 1978) are:

1. Formation of a team to undertake and monitor the process on a given subject.
2. Selection of one or more panels to participate in the exercise. Customarily, the panellists are experts in the area to be investigated.
3. Development of the first round of questionnaire.
4. Testing the questionnaire for proper wording (for example, ambiguities, vagueness, etc.).
5. Circulation of first questionnaire to the members of the panel.
6. Analysis of the first round of responses.
7. Preparation of second round of the questionnaires and possible testing.
8. Circulation of second questionnaire to the members of the panel.
9. Analysis of the second round of responses (Steps 7 to 9 are performed as long as desired or until stability in the results is obtained).
10. Preparation of a report by the analysis team.

Appendix C

Analytic hierarchy process

The analytical hierarchy process (AHP) is a mathematical technique for multi-criteria decision making (Saaty 1977, 1980, 1994) and allows the policy analyst to do this by structuring the problem hierarchically and guiding him or her through a sequence of pair-wise comparison judgements. At the core of AHP) lies a method of converting subjective assessments of relative importance into a set of overall scores or weights.

The fundamental input to AHP is the decision-maker's answers to a series of questions of the general form, 'How important is criterion A relative to criterion B?' These are termed as pair-wise comparisons. Questions of this type may be used to establish, within AHP, both weights for criteria and performance scores for options on the different criteria.

AHP is conducted in the following steps:

1.   Set up the hierarchy (factors or options and alternatives)
2.   Perform pair-wise comparisons for factors
3.   Prepare a matrix (judgement matrix) for factors
4.   Compute the priority vector for factors
5.   Compare alternatives
6.   Compute the priority vector for alternatives
7.   Assess consistency of pair-wise judgements
8.   Compute the relative weights and/or ranks

When the relative influence of different factors on only one alternative needs to be assessed (as in this study), Steps 5 and 6 are skipped. The procedure used to obtain the relative weights for each factor is described below and in the flowchart in *Figure C.1*.
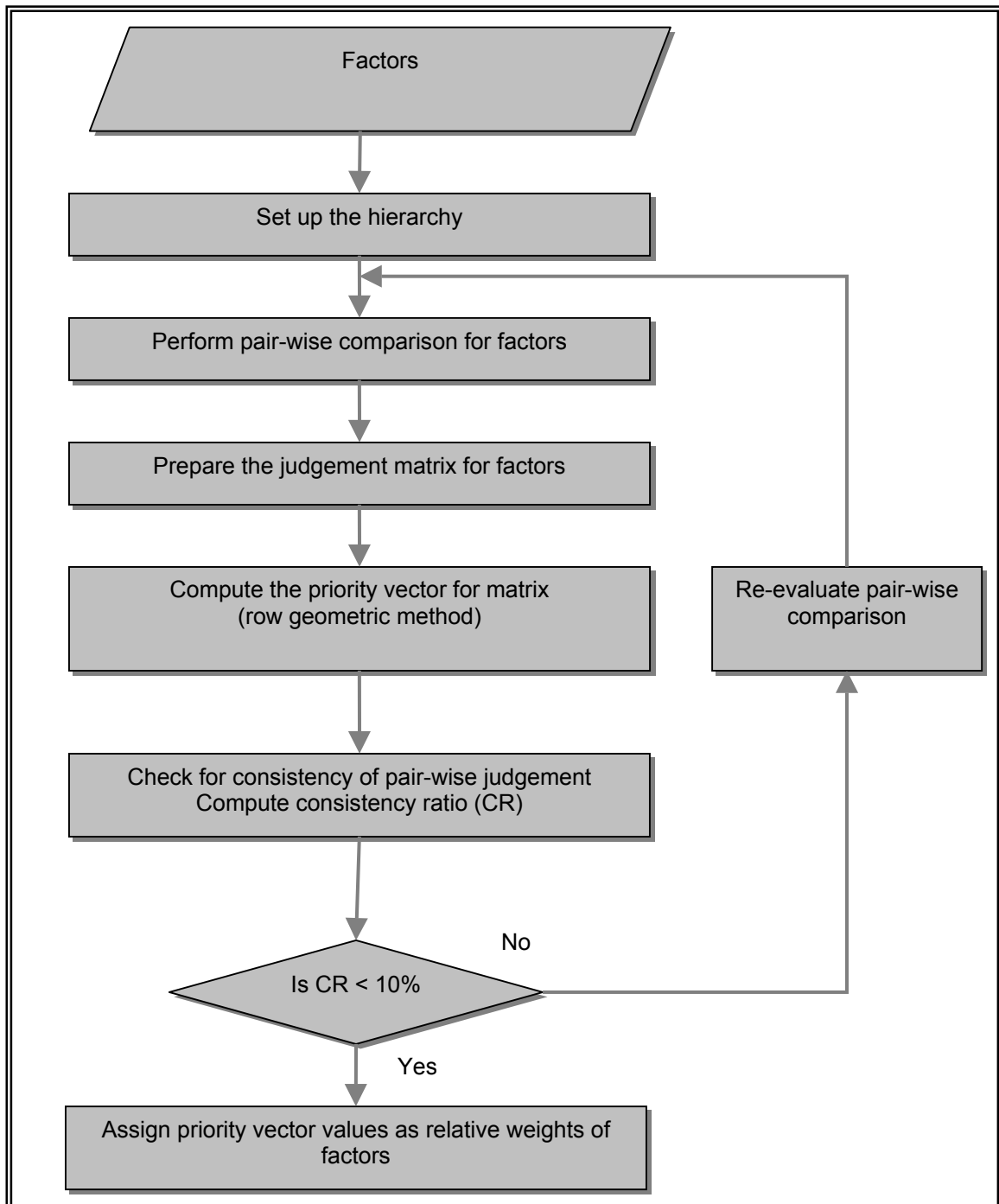
Figure C.1 Procedure to obtain the relative weights for each factor.

1. Setting up the hierarchy

The problem needs to be structured into a hierarchy (see *Figures 3.7* and *C.2*). At one level the relative importance of different types of transportation means needs to be established to evaluate the risk from the failure of different objects (supporting infrastructural and workforce/societal) to the mitigation measure 'evacuation'. In this case five means (factors)

are under consideration – road, rail, boat, helicopter and walk. The number of factors involved can vary from case to case.
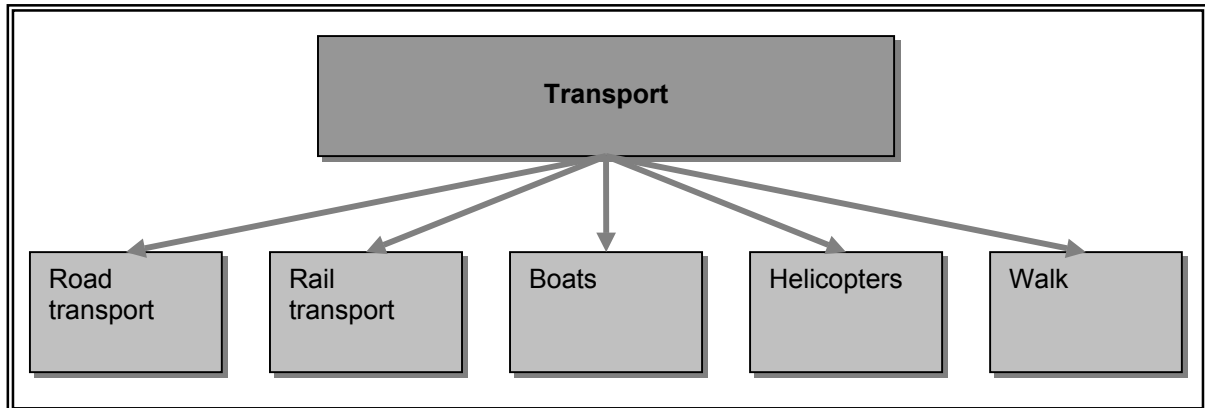
Figure C.2 Establishing the hierarchy of the problem.

2. Pair-wise comparisons

The AHP method does not require a decision maker to quantify precisely the level of importance. However, the decision maker is required to carry out pair-wise comparisons among factors to give the relative importance of each pair according to established nine-point intensity scale systems as shown in *Table C.1*. Thus in this step, the factors are compared with each other to determine the relative importance of each factor to accomplish the overall goal. The structure of the questionnaire to aid the decision maker to determine the relative importance of each factor over another according to this scale system is presented in Appendix D.

Table C.1 Scales for pair-wise comparisons.

Comparative Importance	Definition	Explanation
1	Equally important	Two decision elements (road and rail) equally influence the parent decision element
3	Moderately more important	One decision element is moderately more influential than the other
5	Strongly more important	One decision element has a stronger influence than the other
7	Very strongly more important	One decision element has significantly more influence over the other
9	Extremely more important	The difference between the influences of the two decision elements is extremely significant
2, 4, 6, 8	Intermediate judgement values	Judgement values between equally, moderately, strongly, very strongly and extremely
Reciprocals		If v is the judgement value when i is compared with j, then $1/v$ is the judgement value when j is compared with i

3. Matrix for factors

A matrix with the factors (in our example road, rail, boat, helicopter and walk) listed at the top and on the left is prepared. Based on individually surveyed information and the resultant informed judgement of the decision maker (Step 2), the matrix is filled in with numerical values that denote the importance of the factor on the left relative to the importance of the factor on the top. A high value means that the factor on the left is relatively more important than the factor at the top. In *Table C.2,* for example, road is considered to be three times as important as rail, whereas boat is only one-third as important as walk. When a factor is compared with itself the ratio of importance is obviously one, which results in a diagonal line across the matrix. The resulting matrix is known as the judgement matrix.

Table C.2 Judgement matrix for the factors.

	Road	Rail	Boat	Helicopter	Walk
Road	1	3	4	2	2
Rail	1/3	1	2	2	2
Boat	1/4	½	1	1/3	1/3
Helicopter	1/2	½	3	1	1
Walk	1/2	½	3	1	1

In this example the priorities are clear. Road is considered the factor that influences transport most (transport in turn influences the evacuation), followed by helicopter and walk. Rail is considered more important than boat.

4. Priority vector for factors

In this step the decision maker uses the matrix (*Table C.2*) to obtain an overall priority value for each factor. AHP computes an overall priority value or weight for each decision element based on the pair-wise comparisons using mathematical techniques, such as:

- eigenvalue;
- mean transformation;
- row geometric mean.

Below, the 'row geometric mean' technique to compute the weights under AHP is described.

Row geometric mean: In this method, the geometric mean of each row is calculated (that is, the elements in each row are multiplied with each other and then the nth root is taken, where n is the number of elements in the row). This forms the vector of the geometric mean. The elements of this vector are normalised by dividing them by the sum. The resultant normalised vector is an approximated maximum eigenvector, herein named a priority vector. The calculations for the example are:

Vector of geometric mean

Road $\qquad (1*3*4*2*2)^{\frac{1}{5}} \qquad = 2.17$

Rail $\qquad (0.333*1*2*2*2)^{\frac{1}{5}} \qquad = 1.21$

Boat $\qquad (0.25*0.50*1*0.333*0.333)^{\frac{1}{5}} \qquad = 0.42$

		Helicopter	Walk

Helicopter $(0.50 * 0.50 + 3.0 + 1 + 1)^{\frac{1}{5}}$ = 0.94

Walk $(0.50 * 0.50 * 3.0 * 1 * 1)^{\frac{1}{5}}$ = 0.94

Total = 5.70

Priority vector

Road 2.17/5.70 = 0.38
Rail 1.21/5.70 = 0.21
Boat 0.42/5.70 = 0.07
Helicopter 0.94/5.70 = 0.17
Walk 0.94/5.70 = 0.17
Total = 1.00

5. Consistency of pair-wise judgements

One of the most practical issues in AHP is non-consistency in pair-wise comparisons. If all the comparisons are perfectly consistent, the following expression should hold true for any combination of comparisons of the judgement matrix.

$$a_{ij} = a_{ik} \times a_{kj} \tag{C.1}$$

where:

a_{ij} = relative importance factor (tabulated values in *Table C.2*) of decision criteria i to j.

Table C.2 is reproduced as *Table C.3* with values of *i* and *j*.

Table C.3 Judgement matrix for the factors.

		Road	**Rail**	**Boat**	**Helicopter**	**Walk**
		1	2	3	4	5
	i *j*					
Road	1	1	3	4	2	2
		a_{11}	a_{12}	a_{13}	a_{14}	a_{15}
Rail	2	1/3	1	2	2	2
		a_{21}	a_{22}	a_{23}	a_{24}	a_{25}
Boat	3	¼	½	1	1/3	1/3
		a_{31}	a_{32}	a_{33}	a_{34}	a_{35}
Helicopter	4	½	½	3	1	1
		a_{41}	a_{41}	a_{41}	a_{41}	a_{41}
Walk	5	½	½	3	1	1
		a_{51}	a_{51}	a_{51}	a_{51}	a_{51}

If $i = 1$; $j = 2$; $k = 3$
$a_{12} = 3$
$a_{13} = 4$
$a_{32} = ½$

According to Equation (C.1), a_{12} should be equal to $a_{13} \times a_{32}$.

However, perfect consistency rarely occurs in practice. The consistency ratio (CR) is commonly used to reflect the degree of consistency of a judgement matrix. The CR is calculated as:

$$CI = \frac{\lambda_{max} - n}{(n-1)} \qquad (C.2)$$

$$CR = \frac{CI}{RCI} \qquad (C.3)$$

where:

CI	= consistency index
λ_{max}	= maximum eigenvalue of judgement matrix
RCI	= random consistency index as given in *Table C.4*
N	= number of factors.

Table C.4 RCI values for different values of *n*.

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The maximum eigenvalue (λ_{max}) is obtained by adding the columns in the judgement matrix and multiplying the resultant vector by the vector of priorities (that is, the approximated eigenvector) obtained earlier. The procedure is explained below.

Adding the columns in the judgement matrix

Road	Rail	Boat	Helicopter	Walk
2.58	5.50	13.00	6.33	6.33

Vector of priorities

Road	0.38
Rail	0.21
Boat	0.07
Helicopter	0.17
Walk	0.17

Multiplication and addition

Road	2.58 x 0.38	0.98
Rail	5.50 x 0.21	1.15
Boat	13.0 x 0.07	0.91
Helicopter	6.33 x 0.17	1.07
Walk	6.33 x 0.17	1.07
Total	λ_{max}	5.18

$$CI = \frac{5.18 - 5}{(5-1)} = 0.045$$

$$CR = \frac{0.045}{1.12} = 0.04$$

The pair-wise comparisons in a judgement matrix in AHP are considered to be adequately consistent if its CR is less than 10 per cent (Saaty 1980). If CR is greater than 10 per cent, further evaluation of the pair-wise comparison in the judgement matrix is needed. In the example above, CR is 4 per cent, which indicates that the pair-wise comparison is consistent.

6. Computing the relative weights

If the CR of the judgement matrix is satisfactory (less than 10 per cent, for example), the priority vector values are assigned as relative weights of factors. Thus, in this example the relative weights for each factor are:

Road	0.38
Rail	0.21
Boat	0.07
Helicopter	0.17
Walk	0.17

Appendix D

Example questionnaire for AHP

Guidelines

The questionnaire consists of two columns for each comparison. The respondents are required to tick the choice of preference in *column 1* and tick the degree of preference in *column 2* of each comparison.

For example, to compare the two factors *road* and *rail*, if a respondent feels road is the more contributory factor for evacuation compared to rail, the respondent should tick 'road' in column 1 of the table and then go to column 2. If the respondent thinks that 'road' is 'strongly contributory' compared to 'rail' evacuation, then 'strongly preferred' should be ticked in column 2 of the table. In this way the respondent is required to complete all the pair-wise comparisons for each group. Notes might be given at the beginning of the questionnaire to describe how each factor contributes to the final output.

Criteria

```
Notes:

Road

Rail

Boat

Helicopter

Walk
```

1. Road–Rail

Column 1	Column 2	
❑ Road ❑ Rail	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

2 Road–Boat

Column 1	Column 2	
❑ Road ❑ Boat	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

3 Road–Helicopter

Column 1	Column 2	
❑ Road ❑ Helicopter	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

4 Road–Walk

Column-	Column-	
❑ Road ❑ Walk	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

5 Rail–Boat

Column 1	Column 2	
❑ Rail ❑ Boat	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

6 Rail–Helicopter

Column-1	Column-2	
❑ Rail ❑ Helicopter	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

7 Rail–Walk

Column1	Column2	
❑ Rail ❑ Walk	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

8 Boat–Helicopter

Column 1	Column 2	
❑ Boat ❑ Helicopter	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

9 Boat–Walk

Column 1	Column 2	
❑ Boat ❑ Walk	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

10 Helicopter–Walk

Column 1	Column 2	
❑ Helicopter ❑ Walk	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

Appendix E

Questionnaire to assess the probability and consequences for example in Section 4.1

Group 1 (transport)

Road (X_{111})

What is the probability that 'road' will fail to operate for 'evacuation' in the event of flood?		
❏ Extremely low	❏ OK	❏ High
❏ Quite low		❏ Quite high √
❏ Low		❏ Extremely high

How do you consider the consequences of failure of 'road' on the mitigation measure of 'evacuation' by transport network?		
❏ Extremely unimportant	❏ OK	❏ Important
❏ Quite unimportant		❏ Quite important √
❏ Unimportant		❏ Extremely important

Rail (X_{211})

What is the probability that 'rail' will fail to operate for 'evacuation' in the event of flood?		
❏ Extremely low	❏ OK	❏ High
❏ Quite low √		❏ Quite high
❏ Low		❏ Extremely high

How do you consider the consequences of failure of 'rail' on the mitigation measure of 'evacuation' by transport network?		
❏ Extremely unimportant	❏ OK	❏ Important
❏ Quite unimportant		❏ Quite important
❏ Unimportant √		❏ Extremely important

Boat (X_{311})

What is the probability that 'boat' will fail to operate for 'evacuation' in the event of flood?		
❑ Extremely low ❑ Quite low ❑ Low √	❑ OK	❑ High ❑ Quite high ❑ Extremely high

How do you consider the consequences of failure of 'boat' on the mitigation measure of 'evacuation' by transport network?		
❑ Extremely unimportant ❑ Quite unimportant ❑ Unimportant	❑ OK	❑ Important ❑ Quite important ❑ Extremely important √

Helicopter (X_{411})

What is the probability that 'helicopter' will fail to operate for 'evacuation' in the event of flood?		
❑ Extremely low ❑ Quite low ❑ Low	❑ OK	❑ High ❑ Quite high √ ❑ Extremely high

How do you consider the consequences of failure of 'helicopter' on the mitigation measure of 'evacuation' by transport network?		
❑ Extremely unimportant ❑ Quite unimportant ❑ Unimportant	❑ OK	❑ Important √ ❑ Quite important ❑ Extremely important

Group 2 (communication)

Landline (X_{121})

What is the probability that 'landline' will fail to operate for 'evacuation' in the event of flood?		
❑ Extremely low ❑ Quite low √ ❑ Low	❑ OK	❑ High ❑ Quite high ❑ Extremely high

How do you consider the consequences of failure of 'landline' on the mitigation measure of 'evacuation' by communication network?		
❏ Extremely unimportant	❏ OK	❏ Important
❏ Quite unimportant		❏ Quite important √
❏ Unimportant		❏ Extremely important

Mobile (X_{221})

What is the probability that 'mobile' will fail to operate for 'evacuation' in the event of flood?		
❏ Extremely low	❏ OK	❏ High
❏ Quite low √		❏ Quite high
❏ Low		❏ Extremely high

How do you consider the consequences of failure of 'mobile' on the mitigation measure of 'evacuation' by communication network?		
❏ Extremely unimportant	❏ OK	❏ Important
❏ Quite unimportant		❏ Quite important
❏ Unimportant √		❏ Extremely important

Radio (X_{321})

What is the probability that 'radio' will fail to operate for 'evacuation' in the event of flood?		
❏ Extremely low √	❏ OK	❏ High
❏ Quite low		❏ Quite high
❏ Low		❏ Extremely high

How do you consider the consequences of failure of 'radio' on the mitigation measure of 'evacuation' by communication network?		
❏ Extremely unimportant	❏ OK	❏ Important √
❏ Quite unimportant		❏ Quite important
❏ Unimportant		❏ Extremely important

Television (X_{421})

What is the probability that 'television' will fail to operate for 'evacuation' in the event of flood?		
❑ Extremely low ❑ Quite low √ ❑ Low	❑ OK	❑ High ❑ Quite high ❑ Extremely high

How do you consider the consequences of failure of 'television' on the mitigation measure of 'evacuation' by communication network?		
❑ Extremely unimportant ❑ Quite unimportant ❑ Unimportant √	❑ OK	❑ Important ❑ Quite important ❑ Extremely important

Group 3 (information system)

Evacuation information (X_{131})

What is the probability that 'evacuation information' will not be obtained for the purpose of 'evacuation' in the event of flood?		
❑ Extremely low √ ❑ Quite low ❑ Low	❑ OK	❑ High ❑ Quite high ❑ Extremely high

How do you consider the consequences of failure of obtaining 'evacuation information' on the mitigation measure of 'evacuation' by information system?		
❑ Extremely unimportant ❑ Quite unimportant ❑ Unimportant	❑ OK	❑ Important ❑ Quite important ❑ Extremely important √

Warning (X_{231})

What is the probability that 'warning' will not be delivered for the purpose of 'evacuation' in the event of flood?		
❑ Extremely low ❑ Quite low √ ❑ Low	❑ OK	❑ High ❑ Quite high ❑ Extremely high

How do you consider the consequences of failure of 'warning' on the mitigation measure of 'evacuation' by information system?		
❑ Extremely unimportant ❑ Quite unimportant ❑ Unimportant	❑ OK	❑ Important ❑ Quite important √ ❑ Extremely important

Group 4 (communication – secondary threat)

Communication – electricity failure (X_{141})

What is the probability that 'communication' will fail through failure of electricity in the event of flood?		
❑ Extremely low ❑ Quite low ❑ Low √	❑ OK	❑ High ❑ Quite high ❑ Extremely high

How do you consider the consequences of failure of 'communication' through electricity failure on the mitigation measure of 'evacuation'?		
❑ Extremely unimportant ❑ Quite unimportant ❑ Unimportant	❑ OK	❑ Important √ ❑ Quite important ❑ Extremely important

Communication – warning system failure (X_{241})

What is the probability that 'communication' will fail through failure of the warning system in the event of flood?		
❑ Extremely low √ ❑ Quite low ❑ Low	❑ OK	❑ High ❑ Quite high ❑ Extremely high

How do you consider the consequences of failure of 'communication' through warning system failure on the mitigation measure of 'evacuation'?		
❑ Extremely unimportant ❑ Quite unimportant ❑ Unimportant	❑ OK	❑ Important √ ❑ Quite important ❑ Extremely important

Group 4 (transport – secondary threat)

Transport – electricity failure (X_{151})

What is the probability that 'transport' will fail through failure of electricity in the event of flood?		
❏ Extremely low √	❏ OK	❏ High
❏ Quite low		❏ Quite high
❏ Low		❏ Extremely high

How do you consider the consequences of failure of 'transport' through electricity failure on the mitigation measure of 'evacuation'?		
❏ Extremely unimportant	❏ OK	❏ Important
❏ Quite unimportant		❏ Quite important √
❏ Unimportant		❏ Extremely important

Transport – fuel supply failure (X_{251})

What is the probability that 'transport' will fail through failure of fuel supply in the event of flood?		
❏ Extremely low	❏ OK	❏ High
❏ Quite low √		❏ Quite high
❏ Low		❏ Extremely high

How do you consider the consequences of failure of 'transport' through fuel supply failure on the mitigation measure of 'evacuation'?		
❏ Extremely unimportant	❏ OK	❏ Important
❏ Quite unimportant		❏ Quite important √
❏ Unimportant		❏ Extremely important

Group 5 (transport – tertiary threat)

Transport – electricity failure – fuel supply failure (X_{161})

What is the probability that 'transport' will fail through failure of electricity caused by failure of fuel supply in the event of flood?		
❏ Extremely low √	❏ OK	❏ High
❏ Quite low		❏ Quite high
❏ Low		❏ Extremely high

How do you consider the consequences of failure of 'transport' through electricity failure that is caused by failure of fuel supply on the mitigation measure of 'evacuation'?		
❑ Extremely unimportant ❑ Quite unimportant ❑ Unimportant	❑ OK	❑ Important ❑ Quite important √ ❑ Extremely important

Appendix F

Questionnaire to obtain the weights of different objects of different groups (for level 2 and onward) for the example in Section 4.1

Level 2, Group 1 (primary threat)

1 Transport – communication

Column 1	Column 2	
❑ Transport ✓ ❑ Communication	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred √	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

2 Transport – information system

Column 1	Column 2	
❑ Transport ✓ ❑ Information system	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred √ ❑ Extremely preferred
Reasons for preference if any		

3 Communication – information system

Column-	Column 2	
❑ Communication✓ ❑ Information system	❑ Equally preferred ❑ Moderately preferred √ ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

Level 2, Group 2 (secondary threat)

1 Transport – communication

Column 1	Column 2	
❑ Transport ✓ ❑ Communication	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred √ ❑ Extremely preferred
Reasons for preference if any		

Level 3, Group 1 (aggregative risk)

1   Primary threat – secondary threat

Column 1	Column 2	
❑ Primary threat ✓ ❑ Secondary threat	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred √	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

2   Primary threat – tertiary threat

Column 1	Column 2	
❑ Primary threat ✓ ❑ Tertiary threat	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred	❑ Very strongly preferred ❑ Extremely preferred √
Reasons for preference if any		

3   Secondary threat – tertiary threat

Column 1	Column 2	
❑ Secondary threat ✓ ❑ Tertiary threat	❑ Equally preferred ❑ Moderately preferred ❑ Strongly preferred √	❑ Very strongly preferred ❑ Extremely preferred
Reasons for preference if any		

Appendix G

Level 2   Group 1

	Transport	Communication	Information system	Geometric mean	Priority vector (weights)	Eigenvalue
Transport	1	**3**	**4**	2.29	**0.63**	0.99
Communication	0.333	1	**2**	0.87	**0.24**	1.07
Information system	0.25	0.500	1	0.50	**0.14**	0.96
Add columns	1.583	4.500	7	3.66	1.00	3.02
					Consistency index	0.009
					Consistency ratio	**0.016**

Pair-wise comparison is consistent

Level 3   Group 1

	Primary threat	Secondary threat	Tertiary threat	Geometric mean	Priority vector (weights)	Eigenvalue
Primary threat	1	3	5	2.47	**0.64**	0.98
Secondary threat	0.333	1	3	1.00	**0.26**	1.12
Tertiary threat	0.2	0.333	1	0.41	**0.10**	0.94
Add columns	1.533	4.333	9	3.87	1.00	3.04
Consistency index						0.019
Consistency ratio						**0.033**

Pair-wise comparison is consistent

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