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CASE STUDY

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Disaster management for urban areas is a growing priority owing to factors such as the relentless migration to cities, unplanned development, changing climate, and increasing operational and maintenance costs. New information and communication technologies offer improved opportunities to address these factors. This paper presents and describes the digital city concept as a means of capturing, analysing and applying (digital) information about the city area, its services, and their design and operation. In particular, the functionality of the digital city can be adapted for managing urban flood disasters. The paper highlights the need to manage the urban stormwater cycle integrated with urban planning. Urban flooding should be mitigated by having a judicious mix of both structural and nonstructural strategies, which are selected with the full participation of all stakeholders. The management of urban flooding is illustrated with application to the tropical island of St Maarten.

Keywords: urban hydroinformatics; digital city; disaster management; forecasting; GIS; monitoring; simulation modelling; urban floods; flood warning systems

1. Introduction

The relentless migration of people from rural areas to cities puts growing pressure on urban services, and especially on the management of emergencies and disasters. Certain sections of society are particularly vulnerable, especially the poor who have to resort to living in areas that are at high risk from natural disasters, such as flooding and landslides, and in shelters that readily collapse during earthquakes. City managers and the directors of the various emergency services are under pressure because of the apparent growing frequency of such disasters, and the difficulties in assessing risk and managing appropriate responses to emergencies. Given the threats of climate change, natural disasters are likely to strengthen this trend in the coming years.

Emergency or disaster management is the preparation, support and reconstruction of society when natural or man-made disasters occur. This is not intended to be an intermittent sequence of events but an ongoing process by which individuals, groups and communities manage hazards in an effort to avoid or ameliorate the impact of disasters resulting from the hazards.

When reviewing reports of natural disasters it is evident that they are evenly spread around the world, but developed countries are much better prepared to manage the consequences of disasters such that 95% of the deaths owing to natural disasters occur in developing countries. Relief agencies report that 2005 was the year for disasters. The UN's emergency relief coordinator has commented, 'We're overstretched and underfunded like never before, around the globe really'. The situation is so severe that the United Nations is seeking to establish a central fund for emergency relief. There are reports that governments too often ignore the risks of natural disasters, and that lives and billions of dollars could be saved with better planning.

The present paper discusses the key elements of disaster management planning and introduces the '*digital city*' concept within the field of study of *urban hydroinformatics*, which attempts to provide the '*central knowledge content*' between domain data and end users in the context of managing natural disasters. The paper reviews recent practical experiences of urban flood management on the Caribbean island of St Maarten.

2. The 'digital city' concept

At the preparation stage for natural disasters, the focus is on preventing hazards from developing into disasters altogether, or reducing the effects of disasters when

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they occur. The reduction and even the elimination of risk are brought about by the introduction of long-term measures.

One way of improving the preparation for natural disasters is by investing in the '*digital city*'. In this respect, the application of hydroinformatics technologies in urban water systems (the domain of *urban hydroinformatics*) plays a vital role (Vojinovic and van Teeffelen 2007). Increasingly, city managers are turning to the collection, archiving and analysis of data for their urban areas, especially through facilities offered by advanced geographic information systems (GIS) and remote sensing. GIS maps of areas at risk are valuable information and communication facilities in their own right (see an example in Figure 1). They can delineate flood plains, zone areas for protection from flooding and identify plans for different types of land use; see Yang and Tsai (2000). Properly presented they become important means of communicating information on potential natural disasters at, say, public meetings or over the internet. Underground cable networks make the collection and presentation of real-time data more feasible through better monitoring of potable water demand, energy consumption of pumps, sewerage water levels and flows, groundwater levels, flows to treatment works, and so on. These measurements, coupled with remote sensing of land use and terrain levels, forecasts of rainfall based on weather radar and ensemble predictions from global circulation of the atmosphere and associated local area models, routine asset inspections and maintenance, and stakeholder and customer reports, can help to provide a digital overview of the risks associated with potential disasters. In order to assess risk however, it is necessary to generate scenarios of the possible initiation of disasters coupled with their consequences in the light

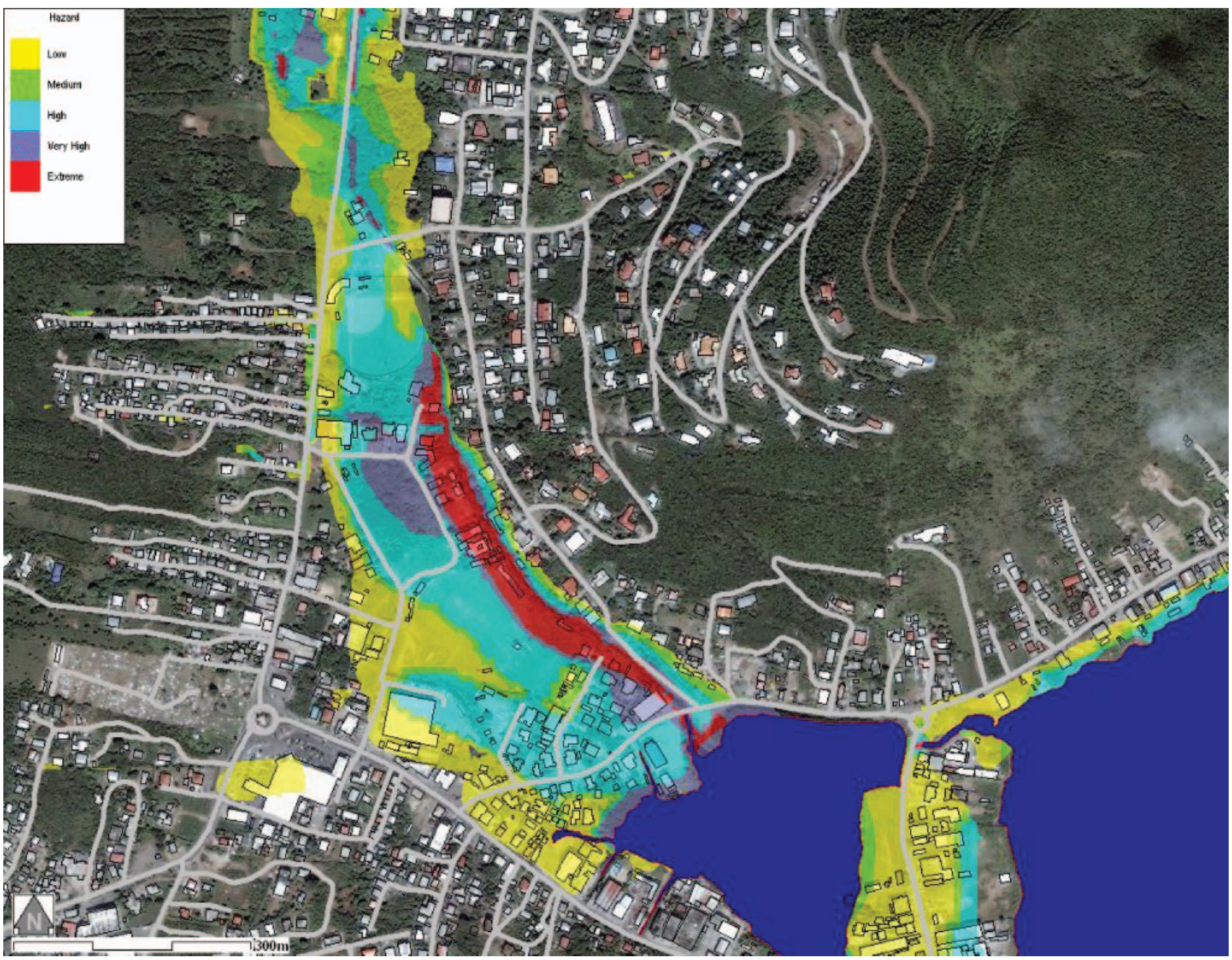

Figure 1. An example of a road network and modelled flood hazard data presented in a GIS environment (UNESCO-IHE 2007).

of different control and mitigation actions. Physically based computational modelling is invaluable for this purpose. With instantiated models, it is possible to explore the generation of disasters and to simulate the consequent effects in response to any control actions. Data-driven modelling augments such physically based modelling for forecasting during disaster events (see, for example, Varoonchotikul *et al.* 2002) or conceptual models can be used for planning and management of risks associated with a potential disaster. An example of how hybrid models (i.e. a combination of data driven and physically based models) can be efficiently applied for modelling urban drainage flows can be found in Vojinovic *et al.* (2003). The generation of new information using these approaches can inform decision making through appropriate decision support systems. These systems can be coupled with data acquisition and modelling systems to provide warnings of impending disasters and advice to various levels of authority, the emergency services, and to the public.

The appropriate level of modelling for the assessment of disaster risk or for forecasting depends crucially on the nature of the physical situation and on the availability of data. Urban topography, drainage network layouts and even detailed geometry of the networks can be readily surveyed using current technology. It is more difficult to measure the temporal dynamics of rainfall and flows, especially in extreme events. There is considerable need to find better ways of monitoring rainfall over urban areas, and water levels and velocities during flood events, not only for forecasting but for planning, which demands where possible the availability of reliable historical data.

Where flood flows are confined to well-defined conduits, a robust one-dimensional (1D) model can usually be instantiated, and used to generate results safe for decision making. However, the flows generated in urban flood disasters are normally highly complex because the morphology of the urban surface is eminently artificial, with its highly irregular geometry, and is often contrary to natural flow paths. Modelling flows in such complex geometrical situations is difficult. Small geometric 'discontinuities' such as road or pavement curbs can play a significant role in diverting the shallow flows that are generated along roads, through fences and around buildings. Head losses owing to flow over or round such structures are difficult to accommodate. Frequently the urban flows are super-critical whereas many of the available modelling products, although they simulate flows that are in reality super-critical, in practice they use modified sub-critical flow algorithms. The use of finite difference methods in conjunction with the reduced momentum equation together with the boundary condition structure inherent to subcritical flow conditions is a standard approach used for numerical simulation of all flow regimes (i.e., subcritical, supercritical and transcritical) in most of the commercial packages. Owing to incomplete equations and inadequate boundary conditions used to model supercritical and transcritical flows, such an approach may introduce unrealistic backwater effects, nonamplifying oscillations and other computational instabilities (see, for example, Djordjevic *et al.* 2004). There is also the issue of treating the transition from channel flows to over-ground shallow depth flows. This necessitates the coupling of simulations using 1D and two-dimensional (2D) modelling systems; see, for example, Hsu *et al.* (2000), Djordjevic *et al.* (2005) Chen *et al.* (2005) and Vojinovic *et al.* (2006a), and also Figure 2.

Geo-referenced results from 1D or even 1D–2D coupled models can readily be used to communicate the risk of flooding and to gain insights into the nature of floods and their impacts on communities. The knowledge gained can then be transformed into a set of effective and acceptable actions to be taken by all who are affected. In this context, spatial visualisation tools play an essential role to facilitate an exchange of information and views. Effective communication of information and knowledge is the key to ensuring that all those concerned have a common understanding and can jointly implement each phase of managing an urban flood disaster. It follows that effective disaster planning depends on a correspondingly effective communication process. For such communication to take place between all stakeholders, it is important that the data and technical information are presented in a form that can be assimilated by everyone. For example, information from a model becomes knowledge generating only in so far as the end user interprets that information correctly. Therefore, the provision of appropriate means to enable such an effective communication process to take place is a challenge that faces all those involved in urban flood disaster management.

The important role of modelling is in complementing the acquisition of data to improve the information and understanding about the performance of a given drainage network, taking into account the associated urban terrain. Considerable attention needs to be given to the acquisition of good geometric and topographical data at adequate resolution in order to describe the primary features of the flow paths through the urban area. Given such instantiated urban flood models it is then possible to begin optimising the performance of the drainage network in terms of rehabilitating the drainage network itself and even introducing necessary modifications to the urban topography that are consistent with the appropriate planning criteria (see, for example, Vojinovic *et al.* 2006b). Obviously, there

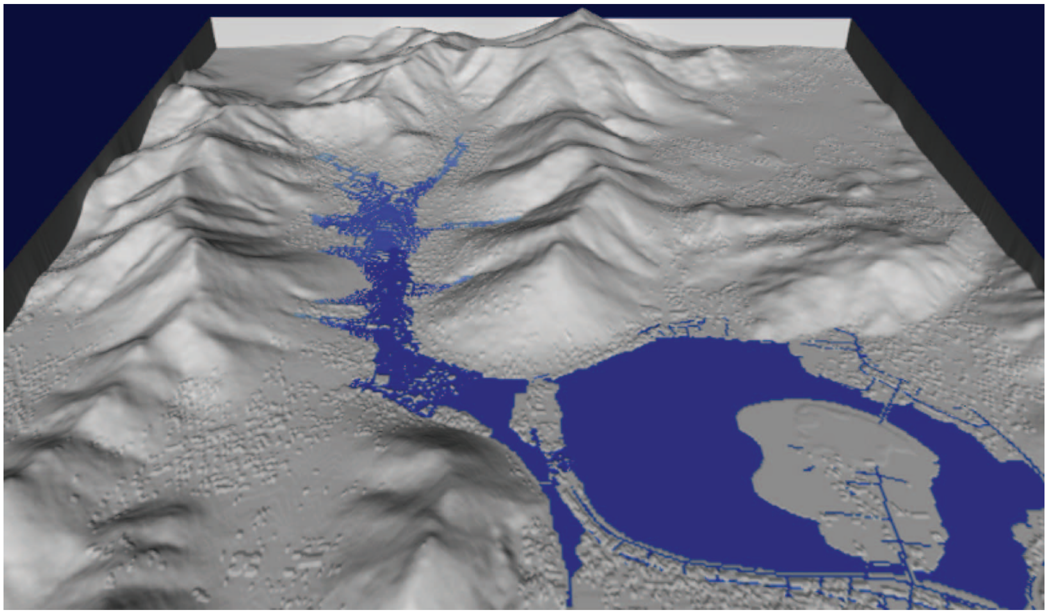

Figure 2. 3-dimensional view of the water surface simulated using a 1D-2D coupled model (St Maarten). The coupling in this example involves channel flows generated by a 1D model superimposed on the flood plain identified by a digital terrain model (DTM) of the 2D ground surface. In the DTM, elevation levels of all buildings are raised by 5m and all roads are lowered by 0.25m in order to represent actual physical conditions.

needs to be close cooperation between the drainage and planning authorities in order to develop an effective and efficient drainage system.

The monitoring system and its associated database, coupled with an effective modelling system can form the basis of a reliable decision support system, which has at least four major functions. First, through scenario building and evaluation it can inform engineers and planners on better ways of determining risks associated with potential disasters, and formulating and implementing appropriate mitigation works, whether structural or nonstructural. Second, the conjunction of data monitoring, historical databases and modelling systems can enable reliable forecasts to be used as the basis of a warning system for the authorities, emergency services and public. Third, both the decision support system for disaster mitigation and warning can involve all the relevant stakeholders in the decision making process, ensuring that all who are potentially affected by a disaster have a say in what is done in response to it. Fourth, the decision support system can also be adapted as an educational tool by raising public awareness of potential disasters through use in educational programmes, games and role-plays. In this respect, GIS and other computer-based information systems enable a wide range of presentational material to be easily generated and tailored for the target audience. Three-dimensional views, zoom and pan, and rotational techniques can be combined with other informational material such as pictures, overheads or slides. Examples of 2D and three-dimensional (3D) GIS flood inundation maps based on results from a hydrodynamic model are given in Figures 1 and 2. Such material is invaluable for demonstrating the probable impact of an impending flood to residents.

There is therefore the need to combine appropriate technological advances and digital data, not only to develop effective disaster management plans but also to communicate accurate and understandable information and knowledge to those concerned. The '*digital city*' concept provides, in effect, the '*central knowledge content*' between domain data, such as generated by point monitoring stations, network systems, weather radars, satellite image processors, models, city policies, regulations and so on, and the stakeholders. What was previously 'the numerical model of a drainage system' now becomes the *knowledge encapsulator*, which incorporates (or even *integrates*) all that is known about the urban water cycle within the wider urban planning context. This encapsulator, referred to here as '*the digital city*' concept, must be capable of using all relevant city data that are available and of processing them in such a manner that an engineer or even a stakeholder can use them efficiently. The encapsulation and integration within the '*digital city*' platform can proceed, of course, in several ways, according to the particular circumstances of a given urban area and the needs of the corresponding end users. The main features of the '*digital city*' system are:

(1) a GIS-based system,
(2) a centre for data storage,
(3) data (not only spatial and temporal data but also city plans, regulations, standards, etc.),
(4) models for each urban water process, which permit the interaction between them,
(5) data and results manipulation tools, communication tools and an interface shell (which could be run on either a web-based or a stand-alone platform), Figure 3.

The main focus of the '*digital city*' concept is on creating an environment in which end users responsible for various aspects of the disaster management plan are empowered to appreciate various flood-related problems, and as a result to make better judgements, improved decisions and efficient action plans through the decision support tools provided. Certainly, the list of end users of the '*digital city*' platform should not be limited to the planners and disaster management agencies only: a wider audience including different stakeholder groups and the public should also have access to such a platform. The purpose of including users other than the disaster management team is to transform the entire process of planning disaster management activities from a *reactive* one (in which users are instructed to *react* according to pre-defined actions) into an *interactive* one (in which each stakeholder *interacts with the other stakeholders* within a community). In this case, the different stakeholders communicate and cooperate in forming and shaping the disaster management plan, making it an essentially *socio-technical* process.

3. Managing urban flood disasters

The evaluation of risk owing to flooding in urban areas requires a detailed assessment of the potential risks that are possible (see Teng *et al*. 2005, Mark and Parkinson 2005). Initially, the flood hazard across the

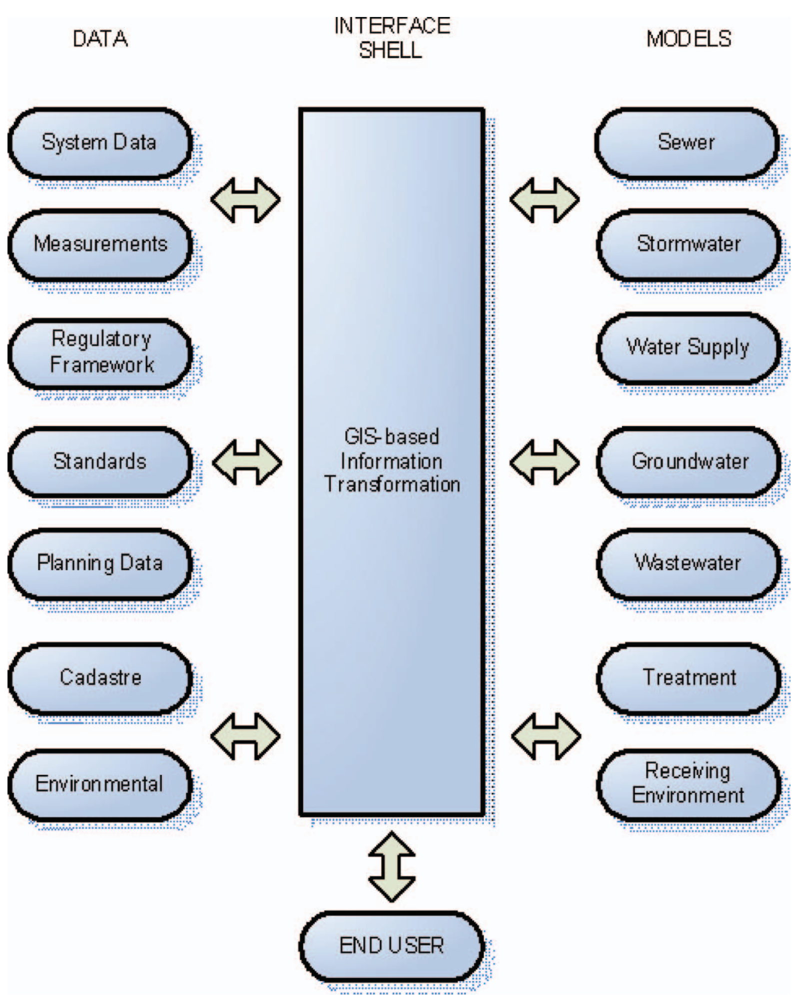

Figure 3. A schematisation of the '*digital city*' concept.

urban area is determined in terms of flow depths and velocities and then transformed into associated tangible and intangible damages; see McConnell (2000). The hazard-specific risk is determined as the product of the probability and the level of impact of the hazard occurring. Inevitably such calculations are data intensive; hence, the need for models to augment the data. Because this analysis identifies property and population at different risk levels, it can be used to identify emergency responses that may be required, including the need for temporary shelters and evacuation strategies.

Typically, several steps are required before we can identify risks and come up with the most appropriate measures for proactive flood management. Figure 4 provides a schematisation of this process.

An important part of the process depicted in Figure 4 is the risk assessment. In order to evaluate the risk to communities, properties and infrastructure effectively, it is important to estimate the distribution of hazards and the magnitudes of flood-related damages.

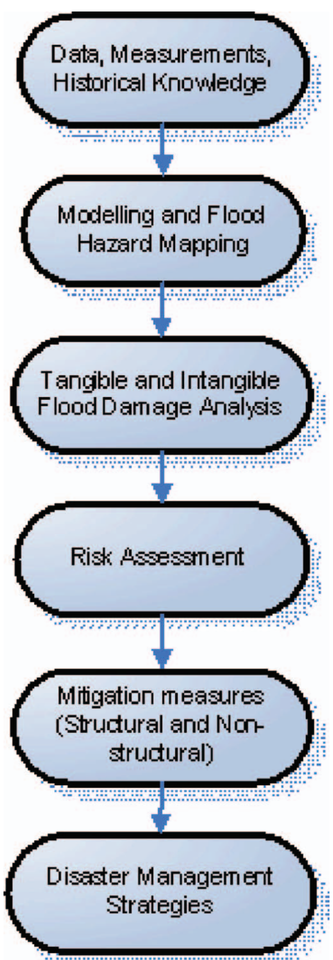

Figure 4. A schematisation of steps associated with proactive flood management.

Generally, such damages are divided into *tangible* and *intangible* damages. Those that can be estimated and expressed directly in monetary terms are referred to as *tangible* damages (e.g., damages to properties, infrastructure, etc.); see Penning-Rowsell and Chatterton (1977), Kanchanarat (1989). Damages that are difficult to identify in monetary terms are referred to as *intangible* damages (e.g., loss of social values, loss of life, anxiety, etc.); see Lekuthai and Vongvisessomjai (2001). Tangible damages may be classified further into *direct* and *indirect* damages. *Direct* damages are those that have occurred from a direct interaction with the flood (e.g., property and infrastructure damages). *Indirect* damages occur because of direct flood impacts. They include reduced economic activity and individual financial hardship, as well as adverse impacts on the social comfort of a community. Indirect damages also take into account disruptive impacts such as loss of trading time and loss of market demand for products. The methodologies for estimating these categories of flood damages may differ from country to country, but essentially, they all tend to address and quantify various aspects of possible damages; see for example Tang *et al.* (1992), Nascimento *et al.* (2007).

Typically, the two variables of interest needed for the estimation of the tangible direct damages are flood depth and duration. These two variables are combined in the following equation

$$DPE = a_0 + a_1 H + a_2 L, \qquad (1)$$

where,

DPE = damage per establishment ($);
H = maximum flood depth (m);
L = flood duration (hour);
a_0, a_1, a_2 = parameters

The parameter values a_0, a_1, a_2 used in equatiom (1) are set to define different land use characteristics (residential, commercial, industrial, agricultural, etc.). A successful application of such a method certainly requires considerable local knowledge and data of market conditions.

Tangible indirect damages are often considered as a fixed percentage of the direct damage. This assumption is accepted by many researchers and practitioners for practical reasons, as the time required for a detailed analysis of indirect analysis is far too great to be justified in an individual flood study.

The assessment of intangible damages is a complicated and difficult task. Nevertheless, some researchers have attempted to quantify such damages as objectively as possible (see, for example, Lekuthai and Vongvisessomjai 2001). Research in quantifying intangible damages has resulted in the development of an 'anxiety–productivity-income' (API) approach (Figure 5). This assumes that 'anxiety' is a function of the flood depth and duration, which is similar to the functional relationship used in the tangible damage assessment. Land-use patterns may also be incorporated in this model. The relationship between flood depth and anxiety is generally assumed to be given by a nonlinear polynomial function. This approach depends on having access to the results of a socioeconomic study of the area under consideration.

The total flood damage values are calculated by combining both types of damages (tangible and intangible) into one. These values, calculated for different scenarios of rehabilitation works, can be compared using the methodology originally developed by Penning-Rowsell and Chatterton (1977); see Figure 6. This methodology combines the following four graphs (see Figure 6):

(a) flood levels and extents: stage-discharge data (graph A);
(b) return period of different flows: probability-discharge data (graph B);
(c) losses caused by various levels of flooding: stage-damage data (graph C);
(d) damage probability to determine the expected annual flood damage (graph D).

The final output from the flood damage analysis can provide invaluable information not only for comparing the effectiveness of different rehabilitation measures but also for the development of disaster management plans and for decision making at local, regional, and national levels.

With knowledge of the attendant risks for the various specific hazards a range of possible mitigation measures are available. The two important categories of measures are *structural* and *nonstructural*. It is important to note that neither the structural nor the nonstructural approach is sufficient on its own: we need an integrated approach that designs and balances different measures. In particular, we should consider social, environmental and economic impacts in the overall assessment of technical measures. Structural measures involve building facilities such as flood embankments, retaining walls or storage ponds or areas (such as parks), or designing interconnected, designated flow paths over the urban surface (usually along roads and between certain structures following the natural ground topography). We can construct such measures to various levels of protection, usually based on: 1) national standards for flood protection; 2) the optimum level of costs and benefits based on a cost-benefit analysis; or 3) meeting established levels of risk acceptable to the affected community. There is a similar range of nonstructural measures, which include

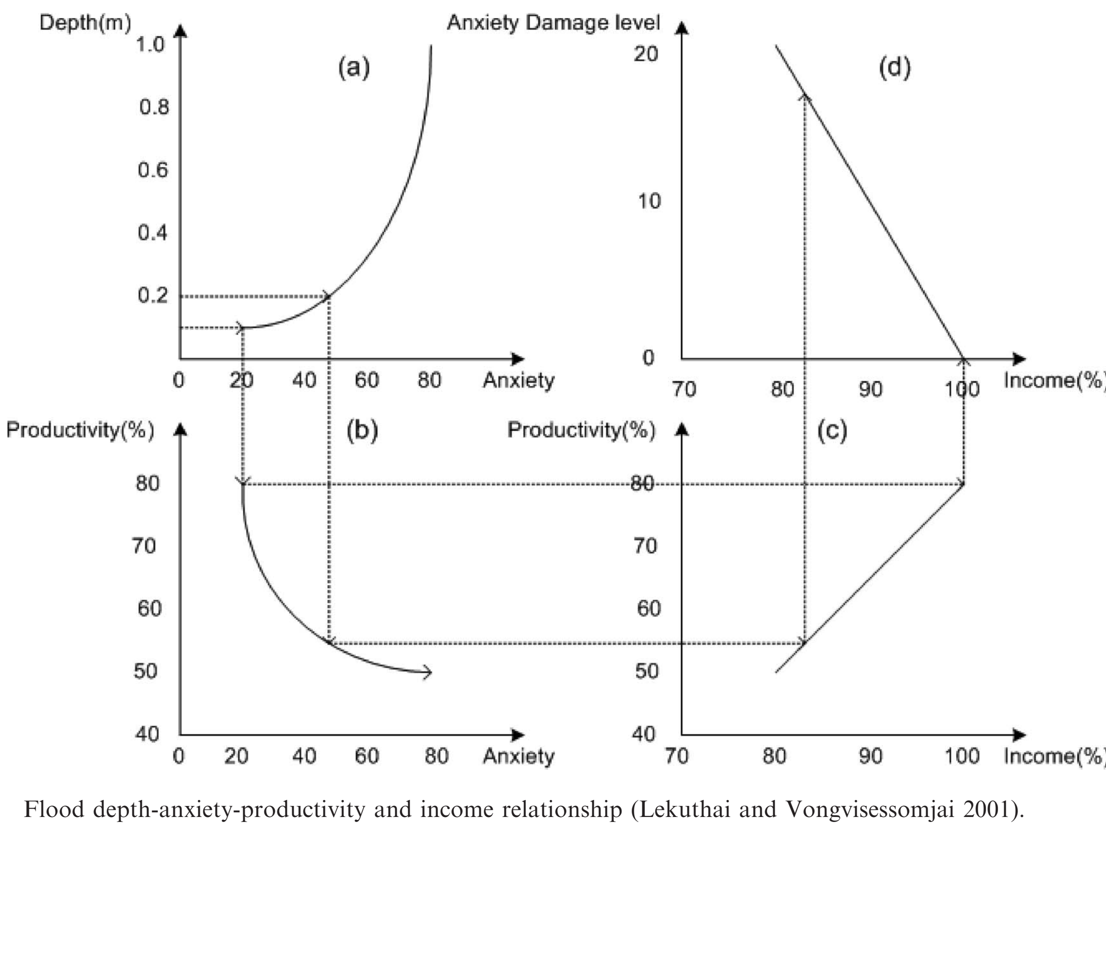

Figure 5. Flood depth-anxiety-productivity and income relationship (Lekuthai and Vongvisessomjai 2001).

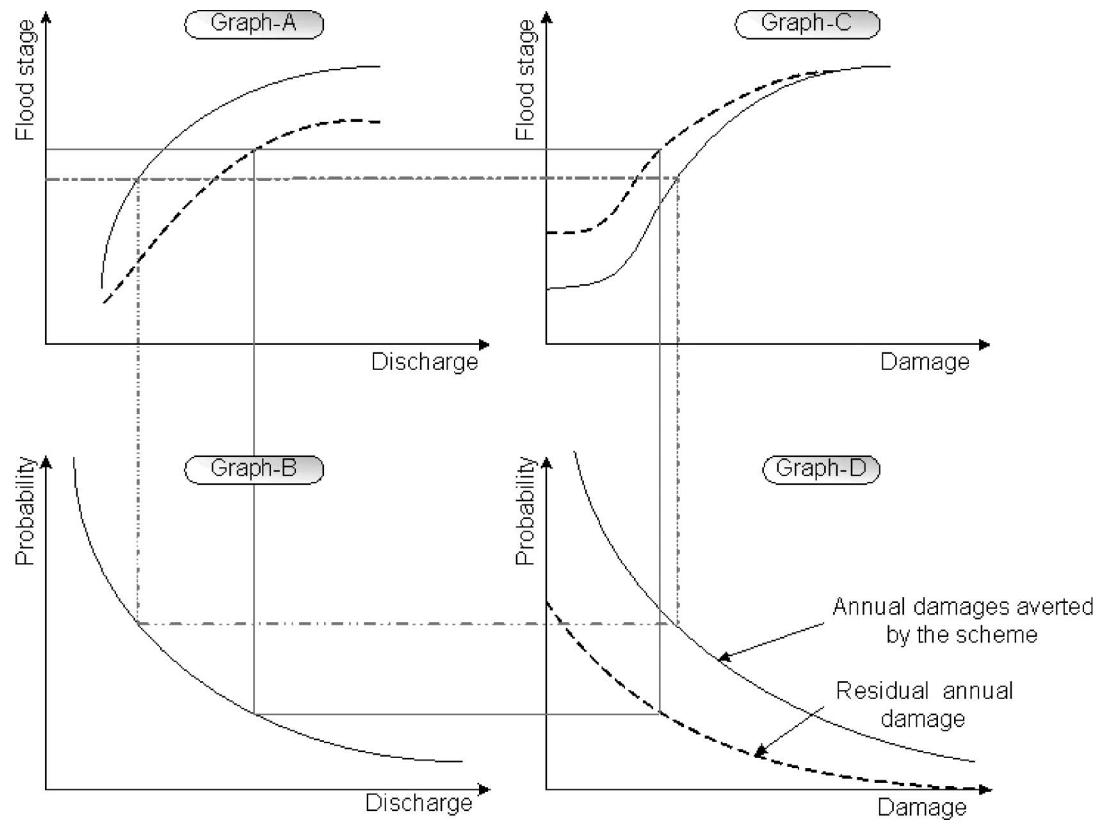

Figure 6. Annual flood damage assessment (Penning-Rowsell and Chatterton 1977). The graphs show damage values before (solid line) and after (dashed line) rehabilitation.

the use of legislation to enforce planning criteria, changing land-use, especially restricting construction on natural flood plains of even normally small streams, introducing flood insurance schemes where the national economy permits, and producing real-time forecasting and warning systems. In the last case, the short response time of urban flooding between peak rainfall and runoff makes the introduction of warning systems in urban areas more difficult. We need to find ways to make such systems viable. This may necessitate the forecasting of rainfall some hours or even days ahead. Developed countries are making increasing use of ensemble rainfall forecasts produced by global circulation of the atmosphere and associated local area models. These can provide forecasts up to 10 days ahead. Remote sensing data or weather radar can supplement such forecasts by generating reliable information up to 3 h ahead. With regular improvements in the technology, the data are becoming more readily available such that the methodology is becoming possible for developing countries also.

Regrettably, the process of disseminating flood warnings to people living in flood-prone areas has often been ineffective, being too slow and imprecise and having only limited value. The challenge now is to utilise nontraditional means for dissemination purposes. For example, the intensive use of cell phones worldwide generates new possibilities for disseminating flood warnings to populations exposed to flooding. Traditionally, web sites, public authorities, television channels, etc are used to disseminate the flood warning information. It is now possible to disseminate important flood warnings through cell broadcasting (GSM and UMTS) to all active cell phones within a given flood-prone area (see for example Mark *et al.* 2002). The next challenge is to transform digital flood GIS maps computed by the numerical models into cell phone messages directed to a specific geographical area. The application of such a nonstructural measure is perhaps even more crucial for the developing world than it is for the so-called 'developed world', bearing in mind the lack of sufficient resources to enable a more effective protection.

We can apply different approaches to selecting appropriate structural and nonstructural measures. These approaches differ according to the selected design event. Typically, we can select a design event based on frequency of occurrence, the maximum probable event or the historical worst case that has occurred in a particular area. The severity of the historical flood experience in a given area is the basis for the final choice of the design event. A logical choice would be an event that leads to the loss of human life through drowning, whereas, in all other cases, either of the remaining two approaches could be applied. Whatever choice is made, a community and its government must decide together on which design event to adopt as a standard for protection works. This should be based on the concept of '*acceptable risk*' rather than on a '*level of protection*', which is normally associated with a specific probability of occurrence.

Given adequate planning and the implementation of appropriate hazard mitigation measures, the next need is for adequate preparation for the occurrence of a disaster. Action plans need to be in place for disaster management. Such plans cover the maintenance and training of emergency services, regular testing and maintenance of flood warning and defence systems, and the preparation of emergency shelters and evacuation plans. There need to be formal agreements about threshold warning levels and the issuance of unambiguous, credible warnings. In addition, there must be regular servicing and maintenance of communication systems. Arrangements must be made for appropriate pre-emptive actions in such matters as diverting floodwater, ordering evacuation of communities and reinforcing flood defences.

The success of any disaster mitigation strategy involves the people who are directly affected, whether in managing or servicing the disaster or as potential victims. The involvement of all stakeholders in preparing for a disaster can benefit the planners in giving them access to local knowledge. Such knowledge can help to identify people and properties at risk, to assess the capability of groups to help themselves, to determine what additional information is needed, to assist in prioritising investment in mitigation measures, and to achieve better understanding and a sense of ownership of disaster mitigation plans. In the last case, the use of techniques such as '*learning alliances*' can greatly help to facilitate a thoroughgoing community involvement. Given ownership by stakeholders of plans made in preparation for a disaster it is then more likely that the whole community affected by a disaster will pull together in terms of helping each other and coming up with the capacity to take appropriate action. There will be better understanding of the warnings issued by the authorities and greater trust in the assistance provided by the emergency services. After the event, stakeholders have important roles in appraising the disaster and its consequences as well as providing valuable information to the authorities and planners. The sense of community that a disaster often strengthens can form the foundation for better ways of reconstructing people's lives and the urban infrastructure. The short-term requirements following a disaster need a sober assessment of damages leading to the provision of appropriate funding to restore basic services, rebuild housing, and safeguard public health. There may also be the need to encourage the reestablishment of the local economy, especially in providing employment. In the longer-term there is the need to rehabilitate the infrastructure with appropriate improvements, and to introduce possibly unpopular mitigation measures as well as revised standards and policies; see Mark and Parkinson (2005). There should be government investment in economic development. Every effort should be made to retain a community memory of the event. In many cases, there will be the need to develop effective policies and programmes to maintain control over new development in flood prone areas combined with measures to reduce damages to existing development. Such concerns are relevant even more in developing countries then in the developed world. This is owing to the large population pressure on the occupation of land at risk of hazards, especially by the poor and dispossessed.

The general wisdom that has emerged from the lessons learned from urban flood disasters across the world is summarised by The Associated Programme on Flood Management (2004):

- manage the urban water cycle as a whole (integrated urban water management), giving attention to the vulnerability of drinking water and sewerage treatment works to flooding, and the consequences for public health;
- integrate urban planning and water management, bringing together city planners and water engineers to craft a more viable and sustainable urban environment;
- adopt a sound mix of structural and nonstructural strategies for mitigating urban flooding, taking into account the uniqueness of the area and analysing the associated problems and opportunities;
- ensure a participatory approach by all stakeholders to ensure ownership of disaster management plans and to capture and retain local knowledge; and
- break the poverty cycle through improved risk management that recognises the vulnerability of the poor.

4. Flood disaster management on St Maarten

The island area of St Maarten (Dutch: Eilandgebied Sint Maarten) is one of five island areas (Eilandgebieden) of the Netherlands Antilles, encompassing the

Figure 7. On 31 July 2005, sudden cloudburst brought deadly flash floods to St Maarten which killed two people and caused enormous property and infrastructure damages.

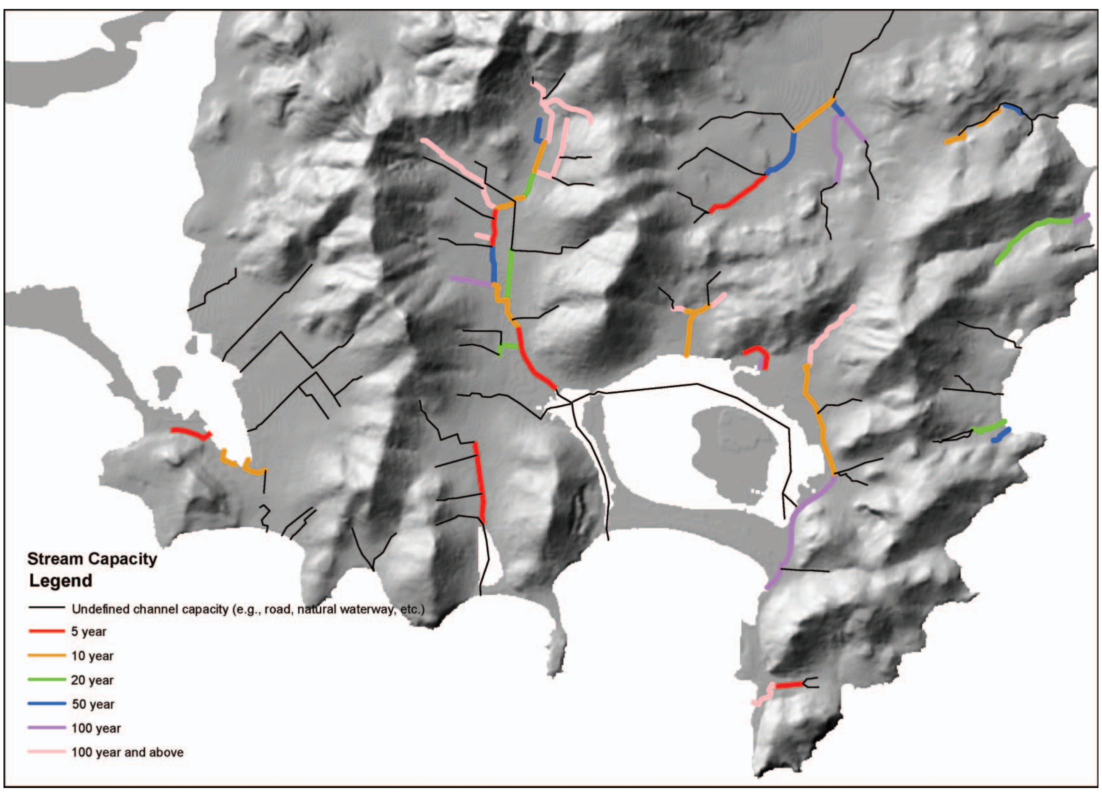

Figure 8. A GIS map of all modelled channels and their corresponding capacities.

southern half of the island of Saint Martin/Sint Maarten. St Maarten borders the French overseas collective of Saint-Martin, which occupies the northern half of the island. With the population growth and degree of development activities experienced over the past decades, flooding has become a growing and serious problem for the Island Territory of St Maarten N.A. It has by far exceeded all other water-related issues (such as, drinking water, sewerage, treatment and impacts on the receiving environment) in such a way that the problems incurred so far by all these aspects together still have much smaller impacts then the problems generated by the inadequate stormwater system alone. This is associated not only with severe infrastructure and property damages but also with the recent loss of two human lives (31 July 2005); see Figure 7. The flood-related evidence to date confirms the vulnerability of the island and highlights the fact that life on St Maarten is at high risk owing to the insufficient capacity of the existing stormwater system.

Through involvement in the urban flood management project on St Maarten, UNESCO-IHE has been developing and applying urban hydroinformatics systems that facilitate a new, integrated approach to storm water management based on the '*digital city*' concept. In this approach, flood mitigation strategies are derived using hydroinformatics technologies, such as numerical models, flood forecasting and real-time warning systems, integrated within a GIS-based framework. Moving away from a traditional, reactive form of disaster management and adopting an integrated, proactive approach provides better hazard mitigation and prevention, improved preparedness and warning systems, and well-organised pre-emptive action and emergency response. In what follows we describe the new approach, which is being developed for the Dutch side of the Island Territory of St Maarten (see also Vojinovic and van Teeffelen 2007).

4.1. Stormwater modelling work

The development of a proactive disaster management plan for St Maarten requires results from the numerical models to be used to identify potential scenarios and a set of measures and actions to minimise the risk of disaster and maximise the effectiveness of actions and measures against a disaster. The modelling system used in the present work is the MIKE 11 package developed by DHI Water and Environment (see http://www.dhigroup.com/Software/WaterResources/MIKE11.aspx). The total modelled stormwater network system containing lined and natural channels, natural waterways and roads, which convey the storm water runoff in the absence of proper channels, has a length of about 49 300 m. The natural waterways and roads (for which the capacities are undefined) have a cumulative length of 31 600 m

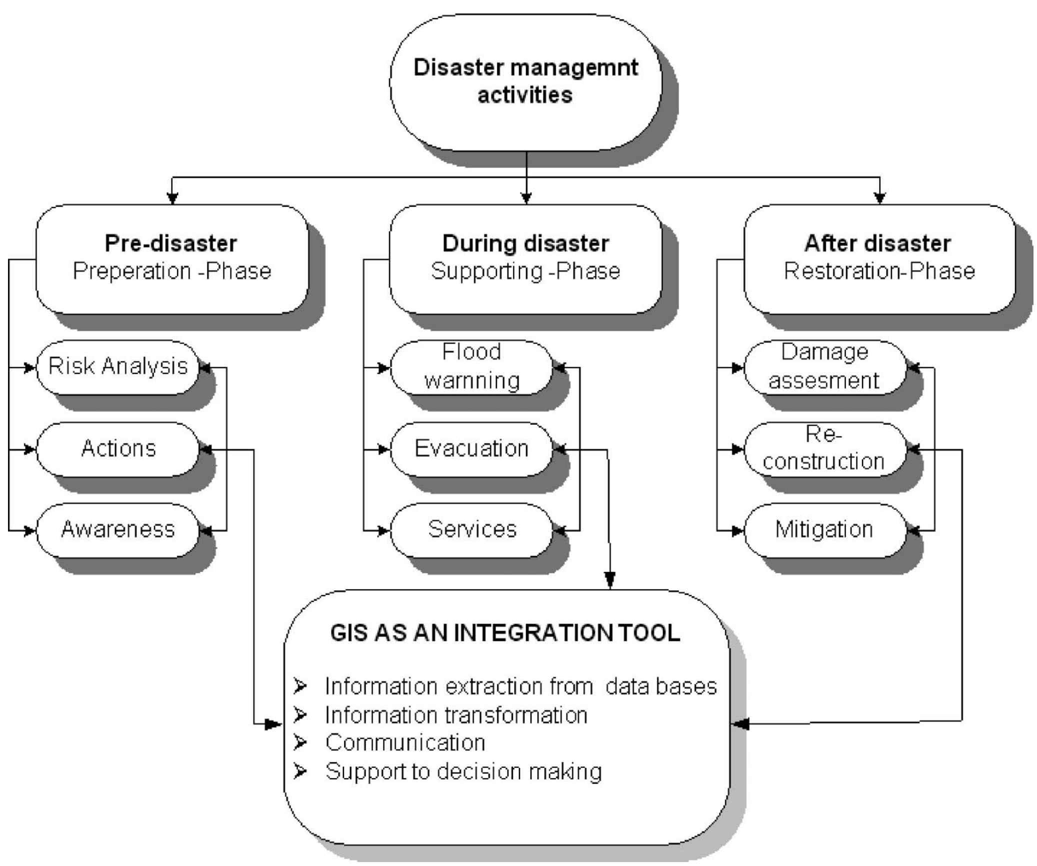

Figure 9. A disaster management framework for St Maarten.

(64%); the remaining length includes channels (or streams) with calculated capacities (36%). See Figure 8 for an illustration of the modelled network and the calculated channel capacities.

Different scenarios were modelled for different rainfall events and the results were analysed to obtain sufficient knowledge about the functioning of the system. The computed water depths and velocities were then combined to produce flood hazard maps, which formed the basis of an assessment of rehabilitation strategies and for the planning of disaster management activities (see, for example, Figure 1). In addition to the delineation of hazards, a vulnerability analysis considering the population and structures at risk within the flood-prone area was carried out. Such an analysis indicates the potential costs of flooding in terms of damages to buildings, roads, bridges and critical infrastructure, such as utilities. The analysis was performed for various probabilities of floods, and elevation damage curves were developed. The results from such analysis were used as a basis to identify the emergency responses that may be required, including the need for temporary shelters and evacuation requirements.

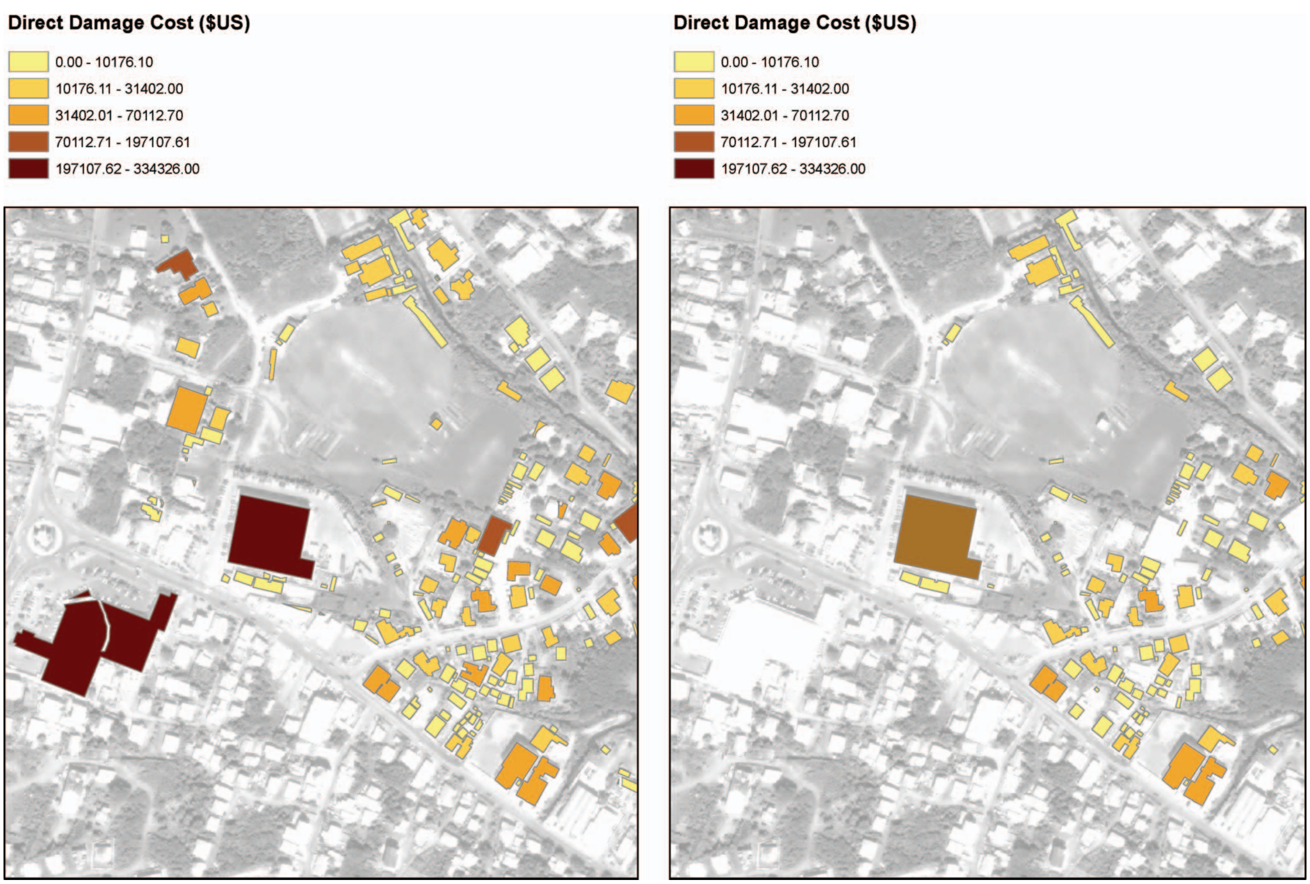

Figure 10. Example of a GIS presentation of flood damages before and after rehabilitation. In this presentation the benefits of a stormwater detention pond were evaluated; UNESCO-IHE Report (2007).

Table 1. The hazard criteria used in the present work.

	Low	Medium	High	Very high	Extreme
Velocity (m s^{-1})	<0.5	<2	<3	<4 and >0.5	>0.5
Depth (m)	<0.4	<0.8	<1.8	>0.2	>0.2
Velocity $\times$ Depth	<0.2	<0.5	<1.5	<2.5	>2.5
Safe for	Cars and able bodied adults	Heavy vehicles and wading for adults	Light constructions	Heavy constructions	Nothing

4.2. *Framework for disaster management*

The most critical element in the suite of activities associated with disaster management is emergency preparedness and response activity. As the response to a natural disaster warning must be immediate, comprehensive, and demonstrate very clear lines of command, the hierarchy in the chain of command was established for all responsible personnel. Further to the specification of roles and responsibilities for those involved in disaster management activities, the main tasks responding to different disaster scenarios were identified. Figure 9 displays a summary of disaster management activities for St Maarten, which were grouped according to the following three major stages:

(1) pre-disaster (preparation phase)
(2) during disaster (supportive phase)
(3) post-disaster (restoration phase)

During the pre-disaster phase detailed response plans need to be prepared and reviewed by all key players. The disaster management team needs to be well-resourced and trained in advance, and individual skills should be continually upgraded. During the disaster phase, activities such as notification and warning, evacuation of residents from affected areas, traffic control, stockpiling of sandbags, distribution of emergency food and water supplies, and the evacuation of high value goods from flood prone areas can be undertaken. Once the event has passed, the emergency response does not end, but continues through cleanup, restoration and resettlement activities. This is marked as the post-disaster phase. As part of the post-disaster phase, it is beneficial to conduct an assessment of the causes and effects of the flood and to make recommendations that would improve preparedness for the next event and reduce future losses.

4.3. *Pre-disaster phase*

One of the first activities of the pre-disaster phase undertaken for St Maarten was to evaluate the hazards and quantify the extent of flood damages. Different Average Recurrence Interval (ARI) flood events were simulated (5 year, 10 year, 20 year, 50 year, 100 year and 200 year) and corresponding hazards and damages were calculated; refer to Figure 10.

The flood damage costs were computed within the GIS platform based on model results and damage curves derived from a local survey. The flood damage calculation was carried out as for the tangible damage estimation described above. The hazards were calculated based on velocities and depths and further divided into five categories namely: *low, medium, high, very high* and *extreme*. Table 1 gives the range of velocity and depth values used to define these categories; refer also to Figure 11, which shows the corresponding graph depicting different hazard categories from Table 1; see McConnell (2000).

Once the hazard areas were identified for each rainfall scenario and the corresponding flood damages computed, the next step was to evaluate the hazards and risks associated with the road infrastructure; see examples given in Figures 12 and 13.

GIS technology has proved to be an invaluable tool in this work for integrating different sources of data with the results from the numerical models, and extracting and displaying various components of information for communication to various groups, which are required to respond to a flood emergency. Furthermore, a GIS platform was used to interpret the basic hydraulic and hydrologic inputs and other spatial data to provide flood intelligence, including:

- flood-affected properties in terms of the degree of damage associated with different rainfall events;
- stream capacities in relation to different rainfall events;
- evacuation and exit routes, including the nearest locations for evacuation and predicted flood depths and relative timing along evacuation routes to and from evacuation zones;
- affected road/bridge crossings in terms of the predicted impact on road crossings and bridges;
- flood damage, using a post flood spatial assessment of the distribution of likely damages.

With the model results processed within the GIS, the most relevant information was then synthesised and displayed to suit the disaster management planning process. A key element in the GIS-based framework

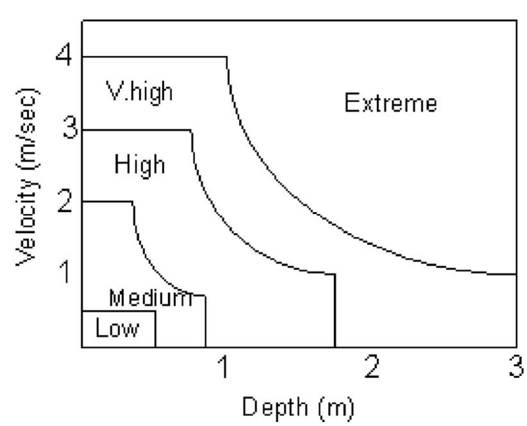

Figure 11. Flood hazard categories with respect to calculated velocities and depths.

developed for St Maarten is its simplicity of use by emergency response personnel while maintaining flexibility in the variety of views available and the integration with any number of GIS layers. Figures 12 and 13 give an example of the information produced for particular rainfall events, including the location and magnitude of hazards for properties and infrastructure. Certainly, it is not only the disaster management team that benefits from such information, but also the planners, design engineers and decision

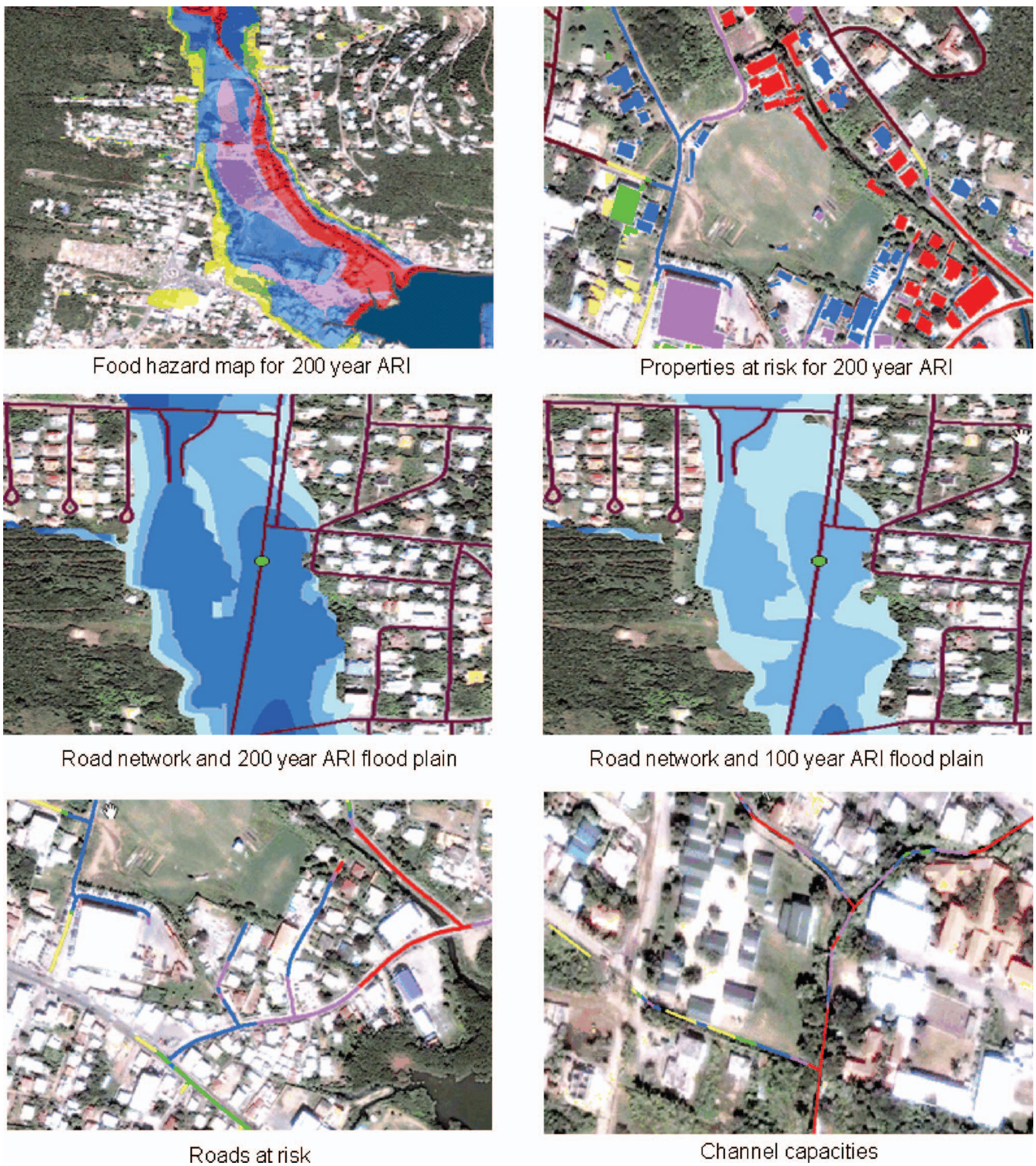

Figure 12. Example of information generated by a model with GIS for the purpose of developing a disaster management plan for St Maarten.

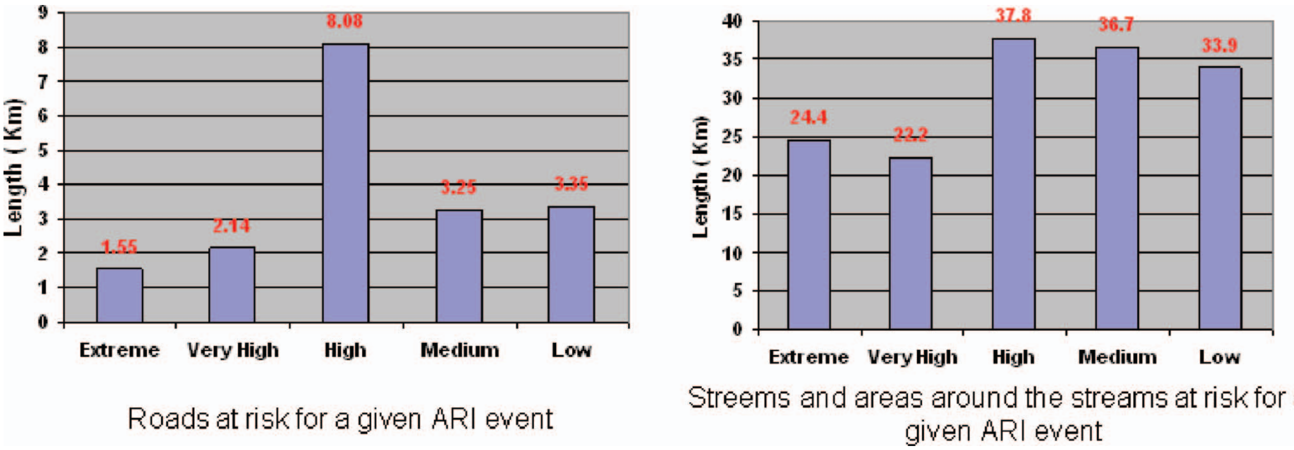

Figure 13. Example of the GIS-based statistical presentations used to analyse different risk categories for different rainfall events (UNESCO-IHE 2007).

makers who make use of this information. If necessary, further classification, quantification and dimensions of flood-affected properties, infrastructure, land and roads can easily be made.

Some of the other actions that relate to the pre-disaster phase, which are currently being considered by St Maarten disaster management authorities, include:

- establishing emergency communications procedures for different scenarios;
- developing and testing plans;
- training relevant response personnel on operational implementation;
- considering and planning the finances and capital required;
- fully implementing the real-time flood warning system;
- establishing or refining procedures regarding the real-time flood warning system (once it is implemented and becomes functional); and
- introducing a public education plan to inform the community of this system.

4.4. *During the disaster phase*

This is the phase of combating the impacts of the flood disaster and providing immediate assistance to affected persons and sections of the community. There are several scenarios identified as critical for St Maarten, and all necessary measures and actions are currently being worked out. Figure 14 depicts one of the decision trees, which are being developed for each significant stormwater catchment on the island.

The Meteorological Service of the Netherlands Antilles and Aruba (MDNAA) has been established to provide meteorological information on tropical storms that (may) form a threat to the islands of Netherlands Antilles and Aruba. In particular, MDNAA will issue information such as cyclone messages and track charts. Typically, such information is distributed by e-mail, while certain authorities also receive these messages by fax. When critical information is issued by MDNAA, the St Maarten disaster management team is placed on alert and the rainfall across the island is monitored carefully. The initial disaster management activities are then triggered based on actual rainfall measurements received from the network of raingauges as well as from the local reports from residents. In addition, there is a plan to establish a network of water level gauges in waterways and connect them to the same system that receives information from raingauges. Later, in 2008, it is planned to purchase a weather radar facility, which will be used to track all approaching storms (including those that could be also devastating for St Maarten but not necessarily registered by the MDNAA) and their corresponding intensities.

Once the flood-related emergency is identified, the first task for a disaster coordinator (during working hours) or for an on-call duty officer (outside working hours) is to assess the situation and inform people on a need-to-know basis. The coordinator (or an officer) then verifies and associates the actual situation with one of the scenarios described in the disaster management plan, and advises other people on appropriate immediate actions by referring to the disaster actions of the selected scenario as set out in the plan (Figure 14). The plan differentiates actions on the basis of different rainfall scenarios (including those with the potential of spreading waterborne diseases owing to mixing of stormwater and wastewater and those with drinking water contamination owing to the infiltration of stormwater/wastewater within the pipe network system). Each set of actions concerning the

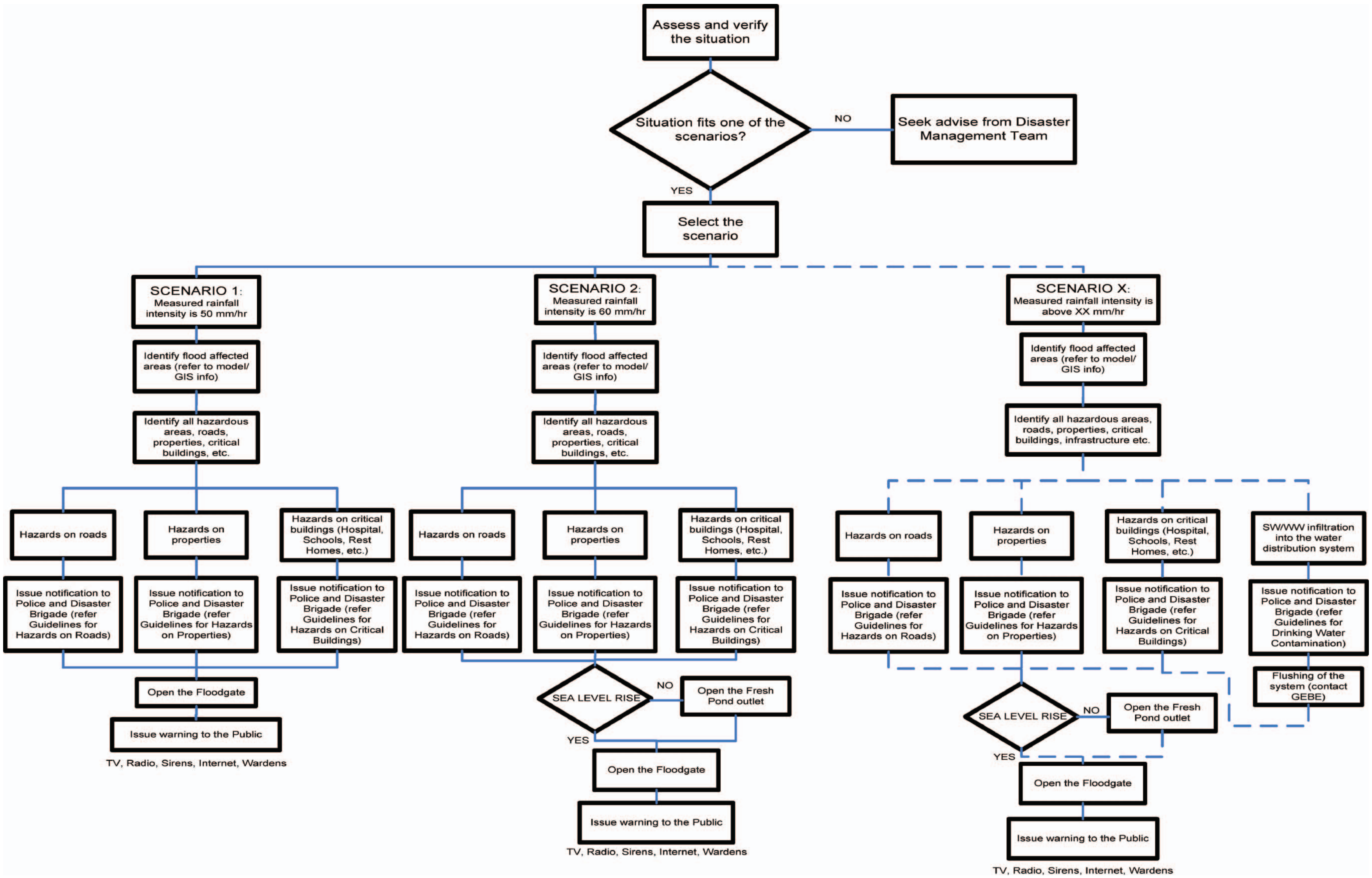

Figure 14. Example of a decision tree for different flood disaster scenarios.

different scenarios has been derived according to the potential distribution of flood hazards based on model simulations for a range of storms.

When a flood-related disaster is declared, the disaster management team's office is the focal point for event-related information, for implementing disaster management priorities and for coordinating response and recovery after the disaster. It maintains regular liaison and communications with community leaders and with authorities.

4.5. *Post-disaster phase*

Guidelines on how to assess the causes and effects of the flood are being produced for the post-disaster (or restoration) phase. Typically, these activities lead towards recommendations that improve preparedness for the next event and reduce future flood losses. The main objective of the reconstruction phase is to facilitate flood-affected communities, properties and services to return to their pre-disaster condition. Rehabilitation includes repairing and reconstructing houses, commercial establishments, public buildings, and infrastructure, restoring and coordinating vital community service, and so on. Recovery can take a few weeks or several years, depending on the magnitude of the disaster and the availability of reconstruction resources. The most important recommendation for reconstruction and rehabilitation projects is that they should reduce future vulnerability and avoid recreating prior vulnerable conditions.

The flood visualisation component of the framework developed for St Maarten (which is evolving into a formal web-based information management system) is designed so that the disaster management team can become familiar with the potential behaviour of flooding including rates of rise, evolution of flood extents, areas of high flood hazard and lead times prior to roads being cut. Although design floods rarely, if ever, represent real events, they nonetheless provide a good indication of potential flood coverage, and they often replicate the rising stages of a major flood when the evacuation process is underway. Further refinements to the built environment and associated demographic changes will be considered, because they are likely to be initiated after any significant flood event. What the flow visualisation does in this situation therefore is to act as an awareness-raising tool and as a simulator.

5. Conclusions

This paper presents and describes the digital city concept as a means of managing in an affordable way the urban stormwater cycle, and in particular the extremes that may affect the cycle and their potentially disastrous consequences for the urban society. The particular focus of the paper is on urban flood disaster management. Such floods are generated either by flows originating from outside the urban area, which then pass through it, and/or by excess rainfall-runoff on the urban area itself. Controlling factors for a corresponding disaster include a large volume of water accumulating rapidly (and perhaps unexpectedly), or involving high velocities which sweep away vehicles and buildings, or the dislodging of soil and other materials in generating landslides. The topography of the local urban area is often critical in affecting the degree of flooding and therefore the potential disaster. With the development of new information and communication technologies, and in particular facilities such as GIS and modelling in the context of internet for communication, a range of possibilities is opened up to reduce the risk associated with disasters, improve communications and proactive activities in response to emergencies, and reduce delays in assisting recovery from the disaster event. Some of the features of better disaster management practice are highlighted in application to urban flooding on the Caribbean island of St Maarten.

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