

Integrated Flood Risk Management for Urban Infrastructure: Managing the Flood Risk to Vienna's Heavy Rail Mass Rapid Transit System

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Abstract

Mass-transit systems represent major investments for urban communities. Planning for flood protection of mass transit systems, as for many large scale infrastructure components, often relies on simple deterministic cost-benefit analyses that are subject to considerable uncertainty. In this report, the results of a stochastic decision support model designed to explicitly evaluate uncertainties in hydraulic and economic impacts is presented. The goal of the model is to evaluate a mixed strategy approach to flood management for the mass transit system that combines structural mitigation measures with financial measures.

A catastrophe model implemented in MATLAB has been adapted from that used by IIASA for evaluation of flood-defense options along the Tisza River [1, 2]. The development of a stochastic hydraulic model that serves as a hydraulic module of the flood risk management model is described in [3]. The loss estimation module takes as input the conditional probability of different flooding and structural failure scenarios and estimates the distribution of direct damages to the subway. These losses are input to the policy module to determine the distribution of the direct losses among different actors (transportation agency, insurers, and local and federal governments). The model is being used to probabilistically explore a mixed strategy combining engineered measures (e.g., levees/walls, portable floodwalls, retention basin upgrades) and financial measures (e.g., insurance, contingent credits, catastrophe funds, post-disaster loans, etc.). Model development has thus far focused on development of the simulation model. The upcoming phase of model development will be focused on the development of an optimization routine to investigate the effect of various constraints (e.g., the maximum annual disaster management budget, maximum probability of ruin of insurer, etc.) on the optimal strategy.

Introduction

Although great improvements in savings lives during floods have been made over the past century, financial and economic losses from flooding are mounting [4]. Extensive efforts in structural mitigation have helped to protect increasingly urbanized areas. However, extreme events can overwhelm structural mitigation measures such as levees and dams; conversely, unanticipated failures of the structural measures can occur during

less severe events. When this happens, the damages can be extreme. This is illustrated by the European floods of 2002 that occurred during the course of this research. Losses in several countries topped one billion euro, and the Europe-wide direct losses have been estimated at 20 billion euro, with an additional economic loss of 15 Billion euro [5].

One of the significant components of impacts from floods is the possibility of damage to transportation infrastructure. Subway¹ lines are particularly vulnerable to flooding, as they are often located below grade and thus can be completely inundated when surface water levels are only tens of centimeters. Because of the interconnections between sub-grade systems, floodwaters can be routed for considerable distances away from the source of the flooding. A striking example of this is the 1992 Chicago tunnel flood, in which construction work in the Chicago River damaged an abandoned, century old coal delivery tunnel. The water from the Chicago river caused extensive damages to the downtown area, as basements of office buildings in the business district were interconnected with the abandoned tunnel system.

Managing the risks to subways can pose dilemmas for decisionmakers. Implementing or improving structural measures to protect against very rare events can become very costly. Although structural measures may be designed to be very robust, they cannot be made perfect. In addition, when such measures rely on human decisions and actions, considerable uncertainty about the reliability of the system can be introduced. At some point, difficult decisions about the management of residual risk will have to be taken.

In this paper, we consider only financial risks in the form of direct damages. We do not consider indirect losses (such as loss of income), economic losses, or issues of protection of human life. We begin with an examination of case studies of severe flooding of subways, which we take as cases where reported direct repair costs exceeded \$10 million. This is used to develop a damage function to express the projected damage to a severely flooded subway system. The next step is the construction of a stochastic decision-support model to aid in decision making regarding structural and non-structural measures for flood mitigation. This model is applied to the subway system of the city of Vienna.

The goals of this study are as follows:

1. Probabilistically examine the costs and benefits of selected structural measures for protection of the Vienna subway system.
2. Probabilistically examine the financial options for managing residual risks after completion of structural measures

The paper is structured as follows. Case studies of major (reported damages greater than 10 million euro) flooding on subways are used to identify the range of damages

¹ In this paper, the colloquial term "subway" will be used. However, not all subways are located below ground; in fact, some are elevated above ground. To complicate matters, the word "subway" is also sometimes used to refer to a simple underground pedestrian passageway. A more precise term would be a heavy rail system, defined by the American Public Transport Association as "A transit mode that is an electric railway with the capacity for a heavy volume of traffic. It is characterized by high speed and rapid acceleration passenger rail cars operating singly or in multi-car trains on fixed rails; separate rights-of-way from which all other vehicular and foot traffic are excluded; sophisticated signaling, and high platform loading." (<http://www.apta.com/info/define/mode.htm>).

likely under cases of severe inundation. A Monte Carlo-based simulation model is then used to simulate the potential direct repair costs to the Vienna subway in the event of severe flooding. Tentative conclusions are based on the the results of modeling several alternative mitigation scenarios.

Case Studies of Subway Flooding

A review of news reports was carried out to identify cases of flooding on subways. There have been a number of cases of flooded subways reported in the last decade. In December 1992, a powerful storm near New York City resulted in coastal flooding that inundated part of the rail and subway systems, causing a temporary shutdown of service [6]. In June 1999, heavy rainfall resulted in the inundation of several subways in the city of Fukuoka, Japan, due to the sudden overtopping of the Mikasa River [7]. On 17 December 1999, the subway system in Caracas (Venezuela) was shutdown as a result of flooding [8]. Several days of rain in Chile in June 2000 shut down the subway systems in Santiago and Valparaiso [9]. However, damages from these cases were not reported.

However, there have been three cases (now four, with the recent inundation of the Prague Metro in August 2002), where floods were reported to have caused direct damages (repair costs) of greater than 10 million euro and service outages of more than a week. These cases (Boston, October 1996; Seoul, May 1998; and Taipei, September 2001) will be described below.

Boston, Massachusetts - The Green Line Flood of 1996

The Massachusetts Bay Transport Authority operates four rapid transit lines comprising 100 km in the metropolitan Boston area known locally as the "T". One of these, which includes the oldest subway system in the United States, is the 40 km Green Line (so named because it runs along the park system designed by Frederick Law Olmstead known as the "Emerald Necklace" of Boston).

On the weekend of October 19-20 1996, a powerful nor'easter delivered over 250 mm of rain in Massachusetts. The rainfall caused a tributary of the Charles River known as the Muddy River to overflow its banks near its junction with the Charles River. This, combined with the backing-up of the local drainage systems due to the high stage in the Muddy River, caused floodwaters to enter the subway system between the Kenmore Square and Hynes Convention Center / ICA stop. The majority of the damages were associated with the 53,000 m³ of water that filled the Kenmore Square Station to a depth of over seven meters. Other less-flooded stations included Symphony, Prudential, Hynes, Copley, and Arlington. The total length of track flooded was approximately 2-3 km. [10, 11, 12].

The design standard of the Boston metro was not reported, although the storm was reported to be an approximately 200-year event. Damage was quite extensive. Damaged items included track switch motors, signalling systems, power distribution systems, tracks, and escalators [11, 13]. Much of the system was restored to operation within a week, although signalling and track switching was done on a manual basis due to the loss of the electrical and communication systems. No deaths or injuries were reported.

The total damage was estimated to possibly exceed \$10 million, and the total cost of upgrades to the signaling system was over \$30 million [14]. A portion of the repair and upgrade costs were to be financed by the federal government through the Federal Emergency Management Agency.

An interesting aspect of the Kenmore Square flooding is the failure of a portable floodbarrier system that had been installed after a catastrophic flood in 1962 (12, 15). Although the slots for a barrier had been installed, the board used to block the system could not be located in time to prevent the floodwaters from entering the station. Although sandbags were placed to try to prevent waters from entering the station, the efforts failed, as they had in 1962. The revised operating plan calls for provisions to adequately secure the boards used to complete the floodbarrier, including keeping the boards "under lock and key near the tunnel entrance"[12]. The system has been implemented four times since the 1996 floods.

Seoul, South Korea

Subway line seven, owned and operated by the Seoul Metropolitan Rapid Transit Corporation, links northeast and southwest Seoul. Construction on line 7 began in 1994 and was completed in 2000 at a total cost of 868.4 billion won (approximately 800 million euro). The total line comprises 42 stations over a distance of 45 km between the Jangam and Onsu Stations [16].

A review of press reports yielded relatively little data on the flooding that damaged the line on May 2, 1998. The flooding occurred when retaining walls installed at a construction site on subway line six installed along the Chungnang Stream were breached at 7:30 in the morning during a heavy rainfall. The water flowed into the Taenung Station on line seven nine minutes later, and proceeded to inundate eleven stations over a length of approximately 11 km with approximately 800,000 m³ of water. The primary damage was to flooded electric facilities and communication systems. The damages were reported to amount to approximately 45 billion won (approximately \$35 million). Line seven was completely out of operation for nine days, and was operated at reduced capacity for a further 35 days. The line suffered a decline in ridership of approximately 40% (from 500,000 to 300,000 commuters per day) as a result of the reduced capacity. (17, 18).

Taipei, Taiwan

The Taipei Rapid Transit Corporation (TRTC), a joint stock company primarily financed (74%) by the Taipei City government, operates six subway lines which total 66.7 km of track in the Taiwanese capital city of Taipei [19].

On September 16-17 2001, Typhoon Nari dumped 425 mm of rain over Taipei, causing the worst flood in over 400 years [20]. The rains caused extensive flooding of the metro, resulting in the suspension of operation of all subway lines with the exception of the elevated Mucha line [21]. The heavy rains flooded the control center in the basement of the Taipei Main Station, the Kunyang Station, and damaged the "third rail" between the Pannan and Longshan Temple Station on the Pannan line. The flooding of the main railway station occurred twelve hours after the flooding of the Kunyang

Station. The floodwaters entered at the Kuyang station and through a 6 m² hole in the basement of the Chunghsiao-Fuhsing station. The hole in the basement of the Chunghsiao-Fuhsing station was apparently remaining from constructing of the station and was required to be filled in when construction was completed. The contractor had failed to fill in the opening as required [22].

Attempts to sandbag the high point in the line at the YungChun station were apparently unsuccessful, and the floodwaters entered the Taipei Main Station at 11:45 AM on September 17. The MRT Control Station is located in the third lower level of the Taipei main station, and the computer servers and power supply are located on the fourth lower level. By 1400 the floodwaters from the main railway line had also entered the Taipei Main Station. By late afternoon the control center had to be abandoned. Approximately 30% of the computers and screens were lost, and all of the power supplies and cables [23].

The line between Kuting and Nansihchiao was reopened on September 20, and the north-south Tamsui-Hsientien line was back in limited operation on October 1 with the exception of the Shuanlien stop and the Taipei Main Station. The Panchiao-Nankang line between Hsinpu and Hsimen was restored to operation on October 14, with the Hsiaonanmen extension opening on October 17. By October 14, the system was up to 58% of its pre-typhoon daily average of 900,000 passengers per day. The line between Hsimen and Chunghsiao-Fuhsing was reopened on October 27. [24, 25, 26, 27, 28, 29, 30, 31]

The design standard for flood protection of the Taipei metro was a 200-year flood event, which was exceeded by Typhoon Nari. According to Kuo Tsai-ming, deputy director of the TRTC, the most affected systems were "communications equipments, escalators, fire safety equipment, the drainage system, and the wire and ventilation systems installed in the ceiling" [30, 31]. Another report indicates that the repair of the electrical systems was "by far the most daunting task" [32]. No deaths or injuries were reported as a result of the subway flooding, although approximately 100 persons were killed during the typhoon, mainly as a result of mudslides in the north of Taiwan.

Reports of the estimated direct repair costs for the flooded subway ranged between 66-140 million (NT\$2-4 billion) damage [23, 33]. A final report on the total repair bill was lowered to \$53 million, due to cost savings associated with "donations of construction materials and reduced prices from companies not wanting to be seen making a profit from the typhoon's aftermath" [32]. Funding for repairs were sought from the municipal Department of Rapid Transit Systems, which sought to raise such funds from both the central government as well as from "austerity measures" from other municipal bureaus and departments (Shu-Ling, 2001). The system is insured only against fire and lightning damage [34]. There is no insurance against typhoons, earthquakes, or windstorms. According to Lee Po-Wen, chairman of the TRTC, the system was not insured against typhoons due to the high premiums (annual premiums of 3.3 million, or NT\$100 million per year) (23).

Summary

A summary of the damages resulting from flooding on subways is given below.

Table 1: Summary of Reported Damages in Subway Flooding Incidents

M	Boston, 1996	Seoul, 1998	Taipei, 2001
Total System Cost	N/r	790*	15,000**
Total Construction cost per km	N/r	18	~180
Km Track Flooded	2.5-8	11	12-67
Reported Flood damage	~10	40	60-140
Computed damage per km	1.3-4	~3.6	0.9-12

*Line 7 only

**Entire system (86 km)

Damages were reported to be primarily associated with electrical/electronic components such as power supply systems, communications and signaling, escalators, ventilation, etc. Systems were completely out of operation for weeks to months and were operated on the basis of temporary measures (manual signalling, etc) for up to several months. Although there was significant loss of life during the events in Taiwan and South Korea, none of this were reported to be due to flooding on the subway. Reported deaths during these events were primarily associated with mudslides, drowning in swollen rivers, and electrocution from damaged electrical equipment. However, during the 1999 Fukuoka subway flood in Japan, an employee of a restaurant located in an underground space died when trapped by the floodwaters [7]. **Methodology**

The previous discussion discussed the consequences that could occur in the event of major flooding. In this section, the development of a model that simulates the financial damages to the Vienna subway system is developed. The model considers two structural mitigation measures and two financial mitigation measures. The two structural measures considered are the upgrades to retention basins and the installation/upgrading of portable flood barriers. Although there are a variety of mechanisms available for managing financial risks, only two financial mitigation measures are considered in this model. These are contributions to a dedicated catastrophe fund, which can be either a one-time lump sum payment at $t=0$ and/or a constant annual contribution, and borrowing after the fact. In order to simplify calculations, all financial amounts are measured in real terms (i.e., inflation adjusted). Inflation is included implicitly by specifying real rates of return and real interest rates on post-disaster loans. Discounting was not applied to the expected damages or costs.

Model Structure

One useful feature of MATLAB is what is known as "vectorization". Rather than using `for` loops which call a random number generator at each iteration, a complete matrix of random numbers can be generated. This results in significant savings in computational time, but introduces some complexities. The model is implemented using vectorization. In order to generate adequate statistics for evaluation of rare events, importance sampling is used. Where appropriate, two random matrices are generated, one to represent the value of the variable under the condition that the catastrophe does occur, and one under the condition that it does not. The size of the two matrices must be proportional to the probability of occurrence. In order to evaluate the total probability,

the two matrices are concatenated and the appropriate statistical evaluations are applied to the joined matrix. The variables and equations used for simulation are given below.

Control variables

SimNum (Input): SimNum is the number of simulations for the Monte Carlo simulation *of the least likely event*. Increasing simNum increases the accuracy of the simulation. In order to evaluate cases where results from a case where the catastrophe occurs must be combined with results from the case that the catastrophe does not occur, two (or more) matrices are generated: *Variable_Occur*, of dimension (1xSimNum), to represent the value of variable under the case that the catastrophe occurs, and *Variable_NotOccur* of dimension (1xSimNum*P_NotOccur/P_Occur). The binary case (Occur/NotOccur) could be extended to an arbitrary number of cases to simulate cases where more than one type of catastrophic event can occur, provided that the size of the matrices is kept proportional to the relative probability.

SimulationLength (Input): Simulation length is the amount of time over which the simulation is to be conducted. This can be seen as the planning horizon, and should be set to approximately the expected lifetime of the system to which the loss could occur.

FloodProbability (Input): FloodProbability is the annual probability of a discharge of Q in the model reach. The probability of at least one flood over the entire planning period is simply $1-(1-p)^T$, where T is the planning period. For a thousand year flood, $p=0.001$, and the probability of at least one thousand flood (or greater) over a 50 year planning period is approximately 5%.

Time of first occurrence (tau): The model computes up until the time of the first catastrophe exceeding a specified threshold (e.g., the first hundred year flood or the first thousand year flood). It is assumed that each year represents an independent trial; i.e., the occurrence of a thousand year flood in a given year is independent of the past history of floods. It can be shown that the arrival time of the first catastrophe of magnitude exceeding the specified magnitude is a geometric random variable. However, for rare events, it can be shown that the conditional distribution of arrival times of the first catastrophe is approximately uniform. In other words, given that a thousand year event occurs within a fifty year planning horizon, the distribution of arrival times within that fifty-year period is approximately uniform.

```
tau=unidrnd(SimulationLength,1,SimNum);
```

Variables describing Structural Measures

FloodgateReliability: It is presumed that portable flood barriers can be installed to protect critical junctions. The floodgate reliability is the expected reliability of the portable flood barriers, expressed as a decimal from 0 to 1, where 0 is complete failure on every trial and 1 is 100% reliability on every trial.

Floodgate Failure Type: The floodgate failure type is simply a 0/1 random variable based on the floodgate probability. A failure type of 0 is no failure, whereas a failure type of 1 is complete failure. A failure type of 0 therefore occurs with probability equal to the floodgate reliability.

```
FloodgateFailureType=(rand(1,SimNum)>FloodgateReliability)
```

MitigationCost: MitigationCost is the total cost of all mitigation measures. It is used for estimation of net benefits.

Variables describing Damages

The description of damages is the point of intersection between the hydraulic model described in [3] and the policy model. Specifically, the description of the damage multiplier is based directly on the distribution function of overflowing water.

Damage Multiplier: Not all flood events can be expected to result in the same amount of damage. Some flood may not result in any overtopping. A slight overtopping that results in only a few tens of cubic meters of water entering the subway clearly would not cause the same damage as a massive collapse of the floodwall that resulted in the entry of hundreds of cubic meters per second into the subway. This is reflected in the damage multiplier, which is a multiple applied to the damages to account for the severity of the flooding. This function is derived from output of the hydraulic model, and is essentially a transformation of the distribution function for water flowing into the subway. An example of this is given for the case of a system with an upgraded set of retention basins. For cases where the upgrades have been implemented, it is given as:

DamageMultiplier

$$=0*(X<0.63)+0.5*((X\geq 0.63)\&(X<0.75))+((X\geq 0.75)\&(X<0.87))+1.5*(X\geq 0.87);$$

Length Flooded: The length of track flooded is starting point for estimating damages. In this case, it is assumed that the subway consists of two sections. One section is not protected by a floodgate and is inundated in every case if there is a catastrophe (although the damages may be equal to zero; see below for the definition of the damage multiplier). However, because the inundation can occur at any point along the section, the length flooded is a random variable. We presume that this section is 5 km long, and that inundation is equally likely along any section of this track. This results in a U(0,5) random variable. The other section is protected by a floodgate. If the floodgate works (FloodgateFailureType=0), none of the section is flooded. If the floodgate fails (FloodgateFailureType=1), all of this section is flooded. In this model implementation, it is assumed that 16.7 km of subway is protected by the floodgate (see discussion below).

LengthFlooded=unifrnd(0,5,1,SimNum)+26.*FloodgateFailureType;

Damage Function: The damage function is defined on the basis of damage per kilometer of track flooded. As discussed above, this value can range from one to ten million euro per kilometer of track flooded. There is insufficient data to estimate the distributional form, and for this reason a simple uniform distribution U(1,10) is used.

DamageFunction=unifrnd(1,10,1,SimNum);

Damage: Given the preceding variables, damages are estimated using a simple multiplicative equation. Two separate matrices are developed for the variable representing the damages. **Damage_Occur** and **Damage_NotOccur**. **Damage_Occur** is the damage in the case that a catastrophe does occur, computed by a multiplicative equation of **DamageFunction**, **DamageMultiplier**, and **LengthFlooded**, and is represented by a matrix of dimension 1xSimNum. **Damage_NotOccur** is the damage in

the case that a catastrophe does not occur, which is simply a matrix of zeros of dimension $1 \times \text{SimNum} \times \text{P_NotOccur} / \text{P_Occur}$.

```
Damage_Occur=DamageFunction.*DamageMultiplier.*LengthFlooded;
```

```
Damage_NotOccur=zeros(1,round(SimNum*P_NotOccur/P_Occur));
```

Variables describing Financial Measures and Impacts

AnnualPayment_CatFund / InitialContribution_CatFund: Annual contribution to the catastrophe fund. This is assumed to be constant over the entire time period. The initial contribution is the amount of money in the catastrophe fund at $t=0$.

ExpectedYield: It is assumed that the return on investment of the instrument in which the fund is invested is a normally distributed random variable with an expected value equal to **ExpectedYield** and a standard deviation of 0.01 (1%). It is assumed that the payments are begun immediately ($t=0$) and continue at a constant real rate. Two separate matrices are developed for the variable representing the yield: **Yield_Occur** and **Yield_NotOccur**. **Yield_Occur** is the return in the case that a catastrophe does occur, and is represented by a matrix of dimension $1 \times \text{SimNum}$. **Yield_NotOccur** is the return in the case that a catastrophe does not occur, and is represented by a matrix of dimension $1 \times \text{SimNum} \times \text{P_NotOccur} / \text{P_Occur}$. The two matrices are drawn from the same distribution; only the size of the matrix is different.

MaxAcceptableLoss (Input): This is the maximum annual acceptable loss that the loss bearer is willing to accept. This is used only to compute critical exceedence percentiles. The maximum acceptable loss is a decision variable based upon the resources available to the loss-bearer to pay for recovery efforts. For example, the transport agency may have a contingency fund or loan guarantee available for infrastructure improvements or disaster response, and may be interested in the likelihood that losses exceed this amount.

Fund Balances

The fund balances at the time of the first catastrophe are computed given the variables above. The first fund balance to be estimated is the total amount of funds accumulated in the catastrophe fund.

```
AccumulatedFunds_Occur
```

```
=AnnualPayment_CatFund.*(((1+Yield_Occur).^tau)-1)./Yield_Occur;
```

```
AccumulatedFunds_NotOccur
```

```
=AnnualPayment_CatFund.*(((1+Yield_NotOccur).^SimulationLength)-1)./Yield_NotOccur;
```

The time at which the catastrophe occurred can be also be computed to determine the payments remaining, in case the total accumulated funds over the entire planning horizon are of interest. This will be significant for proper evaluation of cases where there are more frequent but smaller consequence events, and where determining statistics at the point of the catastrophe rather than over the entire planning horizon may introduce bias.

Subtraction of the damages from the balance in the catastrophe fund yields the fund balance.

```
FundBalance_Occur  
    =AccumulatedFunds_Occur-Damage;
```

This is then separated into two components, depending upon whether or not there are sufficient funds in the catastrophe fund to cover the damages. The Matlab “find” command is used to find the indexes of all matrix entries meeting a certain logical test, such as greater or less than zero. A new matrix can then be defined as a subset of the original matrix containing only those elements meeting the logical test. When the catastrophe fund is sufficient to cover the losses, (i.e., `FundBalance_Occur>0`) the remaining amount is termed the **CreditBalance**.

```
CreditBalance  
    =FundBalance_Occur(find(FundBalance_Occur>=0));
```

If not (i.e., `FundBalance_Occur<0`), the amount of deficit is termed the **LoanBalance**, reflecting the fact that a borrowing must be sought to cover the damages.

```
LoanBalance  
    =FundBalance_Occur(find(FundBalance_Occur<0));
```

In the case that result is a loan balance, the interest must be computed. In the case where losses exceed the maximum amount withdrawable from the catastrophe fund, borrowing is envisaged to cover the remaining cost. The interest is assumed to be a normally distributed random variable an expected value equal to **ExpectedInterest** and a standard deviation of 0.01 (1%). The expected interest is the mean value of the distribution describing the interest rate on the bond issue. The interest is represented as a matrix (**Interest**) of same dimension as **LoanBalance**. In cases where the cat fund contribution has been set to zero, this simply represents the total costs of borrowing to cover repair costs

```
Interest=  
    1+normrnd(ExpectedInterest,.01,1,size(LoanBalance,2));
```

The **LoanFactor** is a term representing the interest that must be paid. **LoanTerm** is the projected term of the bond (by default, ten years). The principal is given by **LoanBalance**.

```
LoanFactor  
    =((Interest.^LoanTerm).*LoanTerm.*(Interest-  
1)./((Interest.^LoanTerm)-1))-1;
```

Multiplication of the **LoanFactor** by **LoanBalance** yields the total amount paid, which is termed **AmortizedLoanBalance**.

```
AmortizedLoanBalance  
    =LoanBalance.*(1+LoanFactor);
```

The following steps are simply the recompilation of the matrices. In order to estimate the total balance in the catastrophe fund given that the catastrophe occurred, the **AmortizedLoanBalance** and the **CreditBalance** are concatenated. In order to estimate

the total distribution of balances in the catastrophe fund, the fund balance with and without occurrence of the catastrophe are concatenated.

```
AmortizedFundBalance_Occur
    =[AmortizedLoanBalance,CreditBalance];
FundBalance
    =[AccumulatedFunds_NotOccur,AmortizedFundBalance_Occur];
```

In the case that there is no catastrophe fund, the computed catastrophe fund balance is always less than or equal to zero. In this case, the fund balance represents simply the damages weighted by the loan costs. This can be then compared to the total damage distribution, which is simply the concatenation of the damages with occurrence and without occurrence.

```
DamageTotal
    =[Damage_Occur,Damage_NotOccur];
```

Concatenation of the damages with and without occurrence is necessary for estimation of the statistics of the total distribution of damages rather than simply the conditional distributions.

Several indicators are calculated. It is a simple matter to draw a histogram of the relevant fund balances using the Matlab “hist) command. Single point indicators include the expected values of loss and of the fund balance at the time of the first catastrophe or at the end of the planning horizon, whichever occurs first:

```
mean(DamageTotal)
mean(FundBalance)
```

An important indicator for management may also be the exceedence probabilities for losses or expenses. If a specified value is set for the maximum acceptable loss, for example, the probability of exceeding some critical level (see the discussion above) can be easily determined by computing the size of the matrix defined as the subset meeting the logical test. In this case, this is implemented using the “nonzeros” function. Application of a logical test to a matrix (e.g., “DamageTotal>MaxAcceptableLoss” yields a matrix with entries equal to zero where the test is false and 1 where it is positive. Application of the nonzeros function reduces the matrix by eliminating all entries equal to zero. Determining the size of the resulting matrix shows the total number of simulations which had met the logical test, and therefore when normalized by the total number of simulations yields the frequency of the event.

```
size(nonzeros(DamageTotal>0),1)/round(SimNum*P_NotOccur/P_Occur)
size(nonzeros(DamageTotal>MaxAcceptableLoss),1)/round(SimNum*P_NotOccur/P_Occur)
size(nonzeros(FundBalance<0),1)/round(SimNum*P_NotOccur/P_Occur);
size(nonzeros(FundBalance<=
MaxAcceptableLoss),1)/round(SimNum*P_NotOccur/P_Occur)
```

Application and Results

In this report, the model is applied to the Vienna subway system. The underground rail (U-bahn) network of the city of Vienna grew out of the Stadtbahn railway system first built by Otto Wagner. The original rail network ran along the Vienna River, a small river that rises in the Vienna Woods and runs through the middle of Vienna before emptying into the Danube. As the U-Bahn network was expanded after the Second World War, portions of the Stadtbahn were converted to serve as part of the U-bahn, renamed as the U4 line. The Vienna subway system is currently composed of five lines running over 66 km, and carries half of all daily public transport rides (900,000 rides per day out of 1.8 million rides per day). The owner (the Wiener Linien) invests 300 to 400 million euro per year in all traffic infrastructure (including trams and busses)

Because the U4 line runs along the Vienna River for much of its length, the original builders of the rail line had built a permanent stone floodwall (Trennmauer) between the river and rail line in order to prevent flooding of the tracks, and had constructed passive detention basins on the outskirts of the city to attenuate the floodpeak of large (hundred year) floods.



under normal flow conditions



1975 Flood: $Q = 375 \text{ m}^3/\text{s}$.
Return period 30-80 years according to extreme value statistics

Figure 1: Vienna River Trennmauer (source: MA45 "WienerWasserbau", Vienna Municipal Government)

However, it was recognized in the 1980's that these basins might fill too early to effectively attenuate a 1000-year flood. The vulnerability of the U-Bahn to catastrophic flooding in the Vienna River prompted the city to improve the flood defenses along the Vienna River. When completed, the network will be protected by three lines of defense: a strengthened separation wall, flood doors that can be installed on the U4 or the U6 subway lines to localize flooding to the aboveground portions of the U4 or U6 subway lines, and finally, manually controllable detention basins along the Vienna River to attenuate the flood crest to reduce the flood peak.



Figure 2: Portable Flood Barriers. Left: Naschmarkt; Right: Langenfeldgasse

Input Data

In the event of flooding that assumes that the flood doors hold, the U4 is assumed to be potentially flooded from Hietzing to the point where the U4 goes underground near the Naschmarkt, a distance of approximately 5 km. In our case, we indicate that the flooding could originate anywhere in this stretch, and the length of track flooded is therefore simulated as a Uniform(0,5) random variable. To simulate the effect of the floodgate, we presume that they either both hold or both fail. In the case that the floodgate does not hold, the following provides an estimate of the additional length of track that could be flooded:

Table 2: Estimation of Track Length flooded

Line	Length (km)	Stations	km per station	Stations Flooded	Length Flooded
U1	10	14	0.73	Reumanplatz to Vorgartenstrase (9)	6.5
U2	4	7	0.52	None (elevation above U4) (0)	0.0
U3	14	21	0.64	Volkstheater to Schlachthausgasse (7)	4.5
U4	17	20	0.83	Pilgramgasse to Landstrasse (5)	4.2
U6	18	24	0.74	Langenfeldgasse to Philadelphiabrücke (Wien Meidling) (2)	1.5
Total					16.7

We define two damage multipliers, one for the case that there are no upgrades, and one for the case that the basins are upgraded. In order to generate the damage multiplier, a uniform (0,1) random variable X is generated. No data was available to construct the no-upgrade damage multiplier. It was therefore assumed that the subway is inundated during all thousand-year floods. The damage is presumed to be either similar to that experienced in previous subway floods (50% probability) or up to 50%

greater, in the case of an exceptionally severe flood. The the damage multiplier is defined as:

$$\text{DamageMultiplier} = 1 * (X < 0.5) + 1.5 * (X \geq 0.5) ;$$

For cases where the upgrades have been implemented, the results are adapted from [3], and is given as:

$$\text{DamageMultiplier} = 0 * (X < 0.63) + 0.5 * ((X \geq 0.63) \& (X < 0.75)) + ((X \geq 0.75) \& (X < 0.87)) + 1.5 * (X \geq 0.87) ;$$

The results from the work described in [3] and the resulting damage multiplier curves are shown below.

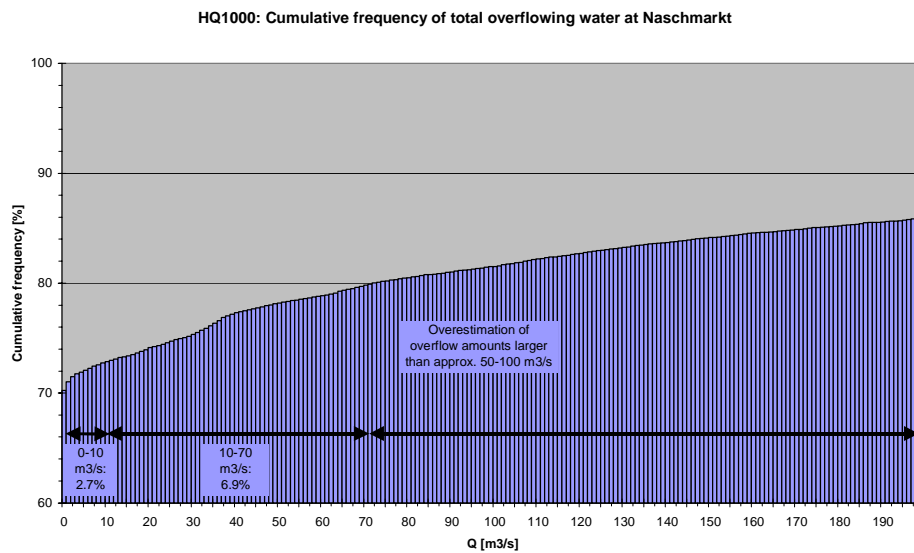


Figure 3: Conditional Probability of Overflowing Water Volumes [3]

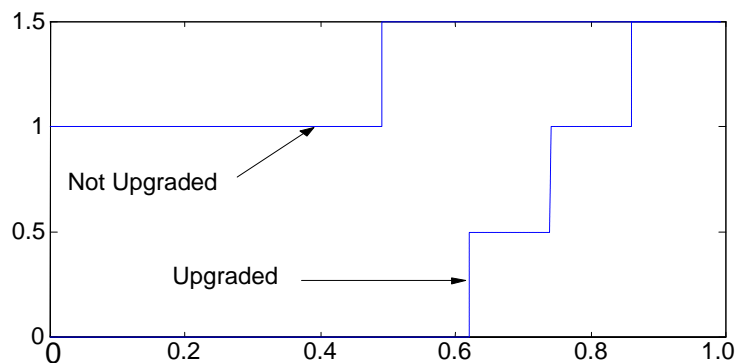


Figure 4: Constructed Damage Curves. The x-axis represents the probability. The y-axis represents the damage multiplier

The model was run with 10,000 simulations of the 1,000-year event over a 50-year planning horizon. The expected value of the interest rate on the loan was set at 10%, and the term was fixed at ten years. In this case, there are no contributions to the catastrophe fund, and the amount in the fund is simply the cost of the damages amortized over a ten-year period. The model was also run with a one time cat fund contribution of 8 M in order to compare this scenario with the purely structural mitigation measures. The expected real annual yield on investments was set at 5%.

Results

A summary of the results is given below.

Table 3: Summary of Results

Damage Multiplier	Floodgate Reliability	Alternative	Cost of Alternative (M)	P(Damages>0)	P(Damages>10M)	P(Fund Balance<0 (Bankruptcy))	P(Fund Balance<10M)	Expected Damages	Expected Repair Costs	Expected Repair and Mitigation Costs	Net Benefit (not considering loan costs)	Net Benefit (considering loan costs)
Base	0	Base Case	0	5.1%	5.1%	5.1%	5.1%	6.4	10.4	10.4	-6.4	-10.4
Upgraded	N/a	Retention Basin Upgrade (100% reliable)	8	0	0	0	0	0	0	0	-1.6	2.4
Upgraded	0	Retention Basin Upgrade Only	8	1.9%	1.9%	1.9%	1.9%	1.9	3.1	11.1	-3.5	-0.7
Base	90%	Flood wall only	0.05	5.1%	3.3%	5.1%	3.9%	1.4	2.2	2.3	5	8.1
Upgraded	90%	Flood wall and Retention Basin upgrade	8.05	1.9%	1.0%	1.9%	1.3%	0.4	0.7	8.7	-2	1.7
Base	0	One time cat fund only	8	5.1%	5.1%	4.7%	4.6%	6.4			90	
Base	90%	One time cat fund and floodgate	8.05	5.1%	3.3%	1.7%	1.3%	1.4			97	

The expected costs and benefits of various options can be seen in the figure below.

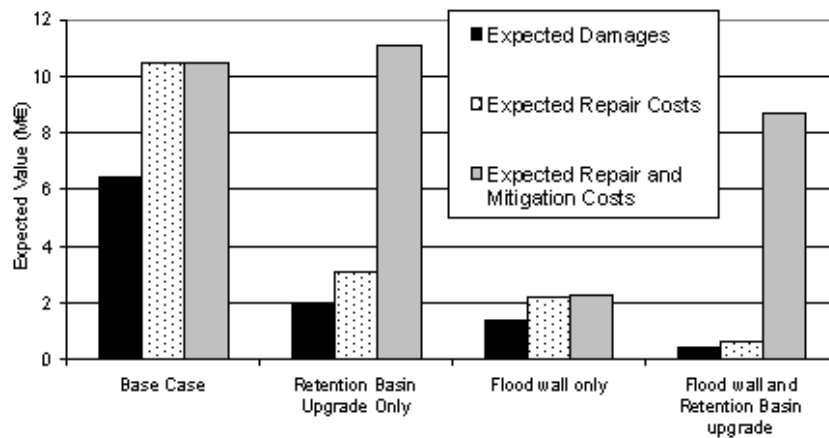


Figure 4: Expected Values of Selected Indicators

It can be seen that the portable flood barriers, provided they operate with a 90% reliability or better, are very effective at preventing losses. Because of their (assumed) low cost and (assumed) high reliability, these barriers have a significant effect on the distribution of losses. The cost-benefit ratio of upgrades to the retention basins is considerably more ambiguous when evaluated in financial terms. If we assume that the basins are 100% effective – which is not possible, but represents a limiting case - the basin upgrades are cost beneficial only if loan costs are considered, with an expected net benefit ranging between -1.6 M (no loan costs) to 2.4M (assuming loan costs). However, if the basins are assumed to be characterized by the reliability given by [3], the net benefit drops to -3.5M (no loan costs) to -0.7M (assuming loan costs). The combined strategy (flood walls and retention basin upgrades) is also cost beneficial only when loan costs are considered. Under the assumption of 100% basin reliability, the net benefits of the combined strategy are identical to those given above. However, if the basins are assumed to be characterized by the reliability given by [3], the net benefit drops to -2 M (no loan costs) to 1.8M (assuming loan costs). However, this net benefit is largely the result of the flood door, not the flood basins, as can be seen by comparing the floodoor only alternative to the combined alternative.

Another way to view the problem is to examine certain critical exceedence probabilities. An actor facing significant constraints may be more motivated by the desire to avoid certain highly undesirable outcomes, such as the chance of very high losses. This is the basis for insurance, in which a guaranteed smaller loss (the annual premium) is accepted in return for the avoidance of a potential higher loss. This is presumably a significant motivator in this case, as the probability of observing any loss whatsoever is only 5.1%, based on the rarity of the thousand-year flood. To examine this, we consider 10M to be a maximum acceptable loss. Of course, under the assumption that the basins are 100% reliable, the probability of sustaining any loss drops from 5% to (by design) zero percent. However, using the reliabilities given by [3], if the basins are upgraded, the probability that losses will be incurred is still significantly reduced, to 1.9%. However, if there are losses, the likelihood is that they will be high, as the probability that the losses will be more than 10M is also 1.9%. It can be seen that the upgrading of the flood basins is better when measured by this criteria than the installation of 90% reliable flood doors, for which the probability that losses will be incurred is 5.1%, and the probability that the losses will be more than 10M is 3.3%. For the combined strategy, there is a 1.9% chance of costs exceeding zero and 1.3% chance of costs exceeding 10M .

Comparison of investment in flood basins versus the alternative of investment in a catastrophe fund is handled by assuming that the 8M used for basin construction is invested instead in a fund. The expected value of the fund after fifty years, based on an expected yield of 5%, is 90 M . The net benefit is therefore 84 M . Investing 8M in a cat fund and installing the floodgates would cause the expected value of the investment after fifty years to rise to 97M and the resulting expected net benefit to rise to 91 M . The probability that the fund will be insufficient to cover losses is 4.7%, and the probability of costs exceeding 10M is 4.6%. This is in contrast to the case of basin upgrades, in which the probability that losses will be incurred is only 1.9%, although the probability that the losses will be more than 10M is also 1.9%. However, if the flood doors are installed in addition to the initial investment in a cat fund, the probability of fund bankruptcy drops to 1.7%, and the probability of the fund being bankrupt by more

than 10M is 1.3%. This is comparable to the case of the the combined strategy (1.9% chance of costs exceeding zero and 1.3% chance of costs exceeding 10M).

One of the reasons for these results is the extreme rarity of a thousand year flood. These results are sensitive to the probability of the base event. This can be examined by using the same parameters but changing the probability of the base event from 0.001 to 0.05 (i.e., assuming that the U4 would be inundated by a 200 year event rather than a 1000 year event). Under these assumptions, the expected damage is 29M and the expected cost is 47 M , with a 28% probability of exceeding 10M . One time investment of 10M in a cat fund would yield the same expected damages, an expected benefit of 69 M , and a 25% chance of exceeding 10M in losses. Investment in a flood control system would yield expected damages of 8.7 M and expected costs of 14 M . If this cost 10M , the net benefit would be 10.3 M if no loan costs are considered and 23 M if loan costs were considered. However, the chances of exceeding losses of 10 M would drop to 10%. If we were discussing a hundred year flood, the damages would be expected to be 52 M , the expected costs would be 84 M , and a 65% chance of exceeding a loss of 10M . A one time cat fund would yield an expected benefit of 21 M but at the cost of a 55% chance of losing more than 10 M . A 10M investment in flood control would yield an expected loss of 16 M , and an expected cost of 26 M , with a 24 chance of losing more than 10M . The net benefit of flood protection in this case would be 26 M if loan costs were not considered, and 48 M if loan costs were considered. The chances of exceeding 10 M in costs would drop from 65% to 55% for the cat fund but from 65% to 24% for the structural measure. These results are summarized below.

Table 4: Sensitivity of Results to Postulated Return Period

Type of Event		Expected Damage	Expected Loss	Total Benefit	P(Loss>10 M)
1000	Base Case	6.4	10.4		5.1%
	Retention Basin Upgrade	1.9	3.1	7.3	1.9%
	Catastrophe fund	6.4	-90	??	1.3%
200	Base Case	29	47		28%
	Retention Basin Upgrade	8.7	14	33	10%
	Catastrophe fund	29	-69	??	25%
100	Base Case	52	84		65%
	Retention Basin Upgrade	16	26	58	24%
	Catastrophe fund	52	-21	??	55%

Concluding Discussion

The model as currently implemented has several substantial limitations. The model is currently a purely financial model, in the sense that it only considers direct costs. Other costs, such as business interruption, are not counted. Also, there is no time dependency of uncertainty in yields or interest rates or of the probability of catastrophic event (i.e., climate or watershed change, degradation of protection structures, etc.).

However, several observations can be drawn from this simulation exercise. The first is that inclusion of loan costs *may* be significant, particularly if there are significant

constraints on revenues for loan service. Failure to consider the costs of loans to cover repair works in the event of damage can substantially underestimate the benefits yielded by flood-control measures.

In this case, the effectiveness of the portable flood barriers - due to the characteristics of the Vienna River and the U4 - raises several interesting questions for decisionmakers. One question regards the reliability of such systems. It can be seen that the two flood control barriers have a very high benefit, and the further improvement yielded by upgrading of the retention basins comes at a substantially higher cost. One question that remains is the reliability of such systems, including the reliability of the human factors – will there be adequate warning time to install the barriers, and if there are no major floods in the next ten to thirty years, what the the likelihood that the components will be lost or otherwise rendered inoperable, as was apparently the case in Boston in 1996? The second, and considerably more difficult question, arises to to the dilemma that such a system poses, namely: should elements which cannot be inexpensively protected be „sacrificed“ in the case of rare events? On other words, should the open stretch of the U4 be allowed to flood, given that other areas can be protected relatively inexpensively? It is worth noting that although an assessment of potential lives lost is not included, it is likely that the majority of the potential fatalities would be associated with flooding of the deep covered sections. Flooding of the open sections of the U4 may inundate two or three station platforms, all of which are easily evacuable. However, flooding of the entire system could flood many more stations to a far greater depth, including major junctions such as Karlsplatz and Landstrasse. The relative benefit of the flood doors in terms of averted casualties may actually be higher than in terms of pure repair costs averted. If so, then the question would be made even more acute.

A final question is whether or not simply investing the available funds in a catastrophe fund is a viable alternative. Investment in the combined strategy yields no possibility of profit (assuming that the upgrades are not dual-use, e.g. that they have no recreational benefit), only averted losses, and there is no probability of using the funds for alternate purposes, such as to reduce losses from some other catastrophe or to mitigate losses to a different actor. The problem, of course, is that such a fund may not stay intact. Furthermore, such a fund introduces an additional risk - namely, that of exposure to market losses. The other problem was that the indirect cost of loss of ridership or the economic value of delays was not considered. Although valuation of these factors is very difficult, it is clear that shutdowns of the subway necessary to install the flood barriers may not be necessary if the flood peak could be reduced and the benefits from averted service interruptions could be substantial.

References

- 1 Ermolieva, TY., Y.M. Ermoliev, J. Linnerooth-Bayer, and I. Galambos (2001). "The Role of Financial Instruments in Integrated Catastrophic Flood Management". Proceedings of the 8th Annual Conference of the Multinational Financial Society, Garda, Italy, 23-27 June 2001, pp. 121-122
- 2 Brouwers, L. Spatial and Dynamic Modeling of Flood Management Policies in the Upper Tisza. (IR-03-002). International Institute for Applied Systems Analysis, Laxenburg, Austria (Jan 2003)
- 3 Faber, R. and H. P. Nachtnebel (2002). "Flood Risk Assessment in Urban Areas: Development and Application of a Stochastic Hydraulic Analysis Method Considering Multiple Failure Types", Second Annual IIASA-DPRI Meeting on Integrated Disaster Risk Management, Laxenburg, Austria, 29 - 31 July 2002
- 4 White, G. F., R. W. Kates, and I. Burton. "Knowing better and losing even more: the use of knowledge in hazards management". *Environmental Hazards* 3:81-92
- 5 <http://europe.cnn.com/2002/WORLD/europe/08/29/flooding.fund>
- 6 Beardsley, C. (1993). "Simple Solutions." *Mechanical Engineering - CIME*, 115(2):4.
- 7 Toda, K. and K. Inoue (2002). "Characteristics of Recent Urban Floods in Japan and Countermeasures against Them", Second International Symposium On Flood Defence (ISFD '2002), Beijing, Sep. 10-13, 2002
- 8 Jones, B. *The Columbian*, 17 December 1999
- 9 UPI, 14 June 2000
- 10 CDM (2001). Draft Environmental Impact Report (DEIR) for the Muddy River Restoration Project (EOEA 11865), December 2001.
- 11 Moore, S. and G. Chiasson (1996). "The Green Line Flood of 1996". Web page available at <http://members.aol.com/nettransit8/flood/flood.html>, last accessed 16 Jan 2003.
- 12 Mercurio, P.S. (2002). "Flooding on the MBTA: Symptoms of a Larger Problem", student research paper provided by Prof. William Anderson, Boston University
- 13 Brown, L. "MBTA acts to bring flood-damaged Green Line up to speed", *Boston Herald*, 16 November 1996
- 14 Brown, L. "MBTA damage may top \$10M", *Boston Herald*, 23 Oct 1996, pg.6
- 15 Moore, S. (1997). "100 Years of the Tremont Street Subway", Web page available at <http://members.aol.com/nettransit/private/tss/tss.html>, last accessed 16 Jan 2003.
- 16 "No. 7 Subway Line to Launch Full Operations Tomorrow", *Korea Times*, 30 July 2000
- 17 *Korea Herald*, 16 June 1998. Available at <http://www.metro.seoul.kr/eng/news/1998/0616-subway.html>
- 18 *Korea Herald*, 5 May 1998. Available at <http://www.metro.seoul.kr/eng/news/1998/0504-floodsub.html>
- 19 <http://www.trtc.com.tw/>
- 20 Chang, C.C. (2001). "Managing Taiwan's Catastrophic Risk", 2001 Annual Convention of The Actuarial Institute of The Republic of China, Taipei, Taiwan, November 13, 2001
- 21 Hsu, C. (2001). "Taiwan counts the cost as Nari leaves", *Taipei Times*, Sep 20 2001
- 22 Chuang, J. "Mayor Ma questioned over Nari", *Taipei Times*, 25 Oct 2001
- 23 Kearns, P. (2001). "Head of MRT says flood insurance `too expensive'" *Taipei Times*, Nov 26 2001, Page 18

-
- 24 Shu-Ling, K. "North-south MRT returns to service", Taipei Times, 2 Oct 2001
- 25 Shu-Ling, K. "Officials deny faulty construction led to floods", Taipei Times, 20 Sep 2001
- 26 Shu-Ling, K. "Mayor Ma willing to beg", Taipei Times, Oct 04 2001
- 27 Shu-Ling, K. "Panchiao-Nankang line will be partly running by Oct. 15", Taipei Times, Oct 06 2001
- 28 Shu-Ling, K. "Portion of damaged MRT line to reopen", Taipei Times, Oct 14, 2001
- 29 Shu-Ling, K. "Another MRT line back in action", Taipei Times, Oct 27 2001
- 30 Shu-Ling, K. "MRT slowly gets back on track", Taipei Times, Nov 14 2001
- 31 Shu-Ling, K. "Taipei says MRT's Pannan line back by mid-December", Taipei Times, Nov 22 2001
- 32 Chou, W. "Main Taipei Station repairs typhoon damage", 23 Nov 2001. available at <http://publish.gio.gov.tw/FCJ/past/01112333.html>, accessed 25 March 2002.
- 33 Surenkok, I. (2001). "The Wrath of Nari", Vickers Ballas/Primasias, 21 September 2001
- 34 Guy Carpenter (2002). Natural Hazards Review of the Year 2001. Guy Carpenter & Company, Inc., New York, NY