Operations Research in Flood Protection Management

Annett Schädlich, Sören Koch & Gerhard Wäscher, Magdeburg

1 Introduction

River floods are part of the natural hydrologic cycle and may occur several times per year, caused by heavy downpours and snowmelt. However, in recent years, often attributed to global warming, an increasing number of extreme flood events could be observed in central Europe. Moreover, these events appear to have more severe consequences due to higher flood peaks, but also due to more intensive land utilization in areas close to river banks and former flood plains. For instance, estimations of the damage done by the so-called »hundred-year flood« of 2002 amounted to more than 9 billion euros [1] for Germany alone.

Efficient flood protection management is therefore a vital issue for each community located in a zone vulnerable to river floods. In this article, we will demonstrate how Operations Research can contribute to the operative management and control of such events. We report on a project which has been carried out in cooperation with the local authorities of the city of Magdeburg, in order to enable the city to organize a more effective response to floods.

2 Background of Investigation

The city of Magdeburg, capital of the state of Saxony-Anhalt, is located on the River Elbe, one of the major rivers in Europe which has its source in the Bohemian Mountains and flows – after some 1,100 km – into the North Sea, having passed on its way large parts of the Czech Republic and Germany, with about 25 million people living in its catchment area. Magdeburg has been affected by three extreme floods of this river recently. In the summer of 2002, the hundred-year flood [cf. Figure 1] raised the water level, which normally peaks at 1.95 m, to 6.72 m. Again, already in the winter of 2003, the city faced a flood with a water level of 6.37 m. This flood appeared to be particularly challenging for the protection of the city, since it occurred under very difficult weather conditions, i.e. freezing temperatures, ice and snow. The last extreme flood event took place in the spring of 2006 and had a flood peak of 6.25 m.

Generally, management can deal with such floods on the strategic, tactical and operative level. On the strategic level, central issues concern the identification of future risks (e.g. continuously increasing flood peaks) and structural weaknesses of current flood protection systems (e.g. inadequate, weakly-dimensioned dike systems), as well as the development of general and sustainable strategies of flood prevention and protection (e.g. recreation of former flood plains). On the tactical level, decisions regarding the infrastructure (e.g. pumps, boats, rescue vehicles) and the organizational structure (e.g. responsibilities, command structures) are made and executed. On the operative level, short-term measures concerning the immediate reaction to approaching or already materialized floods are taken into account (e.g. measures for evacuating residents in areas at risk, providing emergency aid).

Figure 1: Hundred-Year Flood in Magdeburg in 2002

Figure 2: Mobile Dike System

The main focus of this article is on operative measures of flood protection, for which the Professional Fire Brigade is responsible in the city of Magdeburg. The central instruments are mobile dike systems, which primarily consist of sandbags [cf. Figure 2] and are erected in places critical to the flooding of inhabited areas and infrastructural assets [2] like roads, railways, power lines, etc. Where mobile dikes have to be built – the *scenes of action* – can be seen from a so-called flooding map developed by the Land Surveying Office of Magdeburg. It provides information about the consequences of potential flood peaks for the city.

In this respect, operative flood protection consists of three kinds of logistic operations: the filling of sandbags with a sand mixture, the transportation of the filled sandbags to the scenes of action where flooding is predicted to occur, and the piling of the sandbags to form walls. The sand mixture is purchased from a gravel plant located in the north of the city. In the past, the plant itself has been used as a location for filling the bags. However, this solution has been questioned by the authorities, since the plant is located in a remote area far away from any potential scene of action and transportation of the sandbags therefore appeared to be the most time-consuming operation in the erection of mobile dikes. This gave rise to the question whether one or several additional or even alternative filling locations would allow for reacting to approaching floods faster and probably also at reduced costs.

3 Problem Analysis

3.1 Flood Scenarios

On the River Elbe, an early warning system has been installed upriver from the city of Magdeburg, which continuously monitors the water level and allows for issuing a flood alert three to five days in advance of the actual flood. Whether any measures of flood protection are required can only be predicted with reasonable accuracy three days in advance in the worst case. Given that it takes a full day to set up the filling locations and to install the project organization, only two days remain for the completion of all necessary logistic operations.

The available actions which can be taken within those two days differ with respect to the time of the year in which a flood occurs. As a consequence, we decided to distinguish between two seasons, *summer* and *winter*, in our study.

The expected flood peak is a pivotal aspect in operative flood protection management. As a consequence of a higher water level, the demand for sandbags will increase and, likewise, the number of locations which have to be protected. Indirectly, the water level also determines the volume of the required logistics operations and the corresponding input of manpower, transportation vehicles, technical equipment, etc. In cooperation with the Professional Fire Brigade of Magdeburg, it has been decided that the aforementioned conditions should be further differentiated into three distinct situations: flood peaks of *6.25 m*, *6.80 m* and *7.00 m*.

These two aspects »season« and »flood peak« resulted in six scenarios which were considered in our study.

3.2 Decisions on Actions

A location where the sandbags are to be filled – a *filling site* – cannot be selected arbitrarily. In fact, it has to comply with certain requirements related to accessibility, trafficability, size, etc. Each site has to provide sufficient road access for the transport vehicles and enough space for the sandbag-filling operations. It should be equipped with facilities for sheltering the response personnel under bad weather conditions and should permit the installment of sanitary facilities.

In cooperation with staff from the Professional Fire Brigade, potential locations for filling sites have been identified and analyzed. In the end it was found that – apart from the gravel plant – two sites would be suitable for both summer and winter, while another three sites could be used in summer and another two in winter only. Figure 3 depicts the location of these sites within the boundaries of the city of Magdeburg, as well as the possible scenes of action.

Since the complexity of the logistic processes and corresponding organizational requirements increase significantly as the number of filling sites grows, probably beyond manageable size, it has been decided to consider only a limited number of potential combinations of filling sites, namely the following options (*location strategies*):

- one single filling site at the gravel plant,
- one single, alternative filling site, and
- two filling sites.

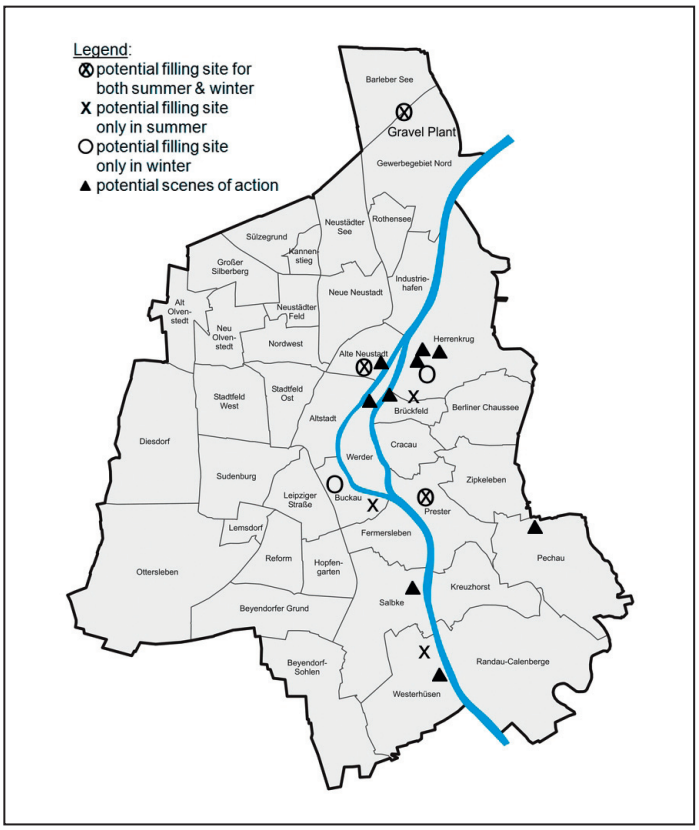

Figure 3: Location of Potential Filling Sites and Potential Scenes of Action (*Courtesy of J. Schönebaum*)

In addition to the selection of filling sites, the technology used for filling the sandbags (*filling technology*) has to be planned. Generally, three different technologies can be made available:

- manual filling,
- combined mechanical and manual filling by means of spreader vehicles (gritters) which are normally used for winter services, and
- combined mechanical and manual filling by means of a sandbag filling machine.

All three filling technologies only require unskilled personnel who can always be made available in the necessary numbers. Manual filling, therefore, is characterized by an unlimited capacity, but also by a low productivity. The technical equipment for combined mechanical and manual filling is limited, thus its capacity is also limited, but it features a high productivity.

The number of spreader vehicles is limited to two in summer, while they cannot be made available in winter as they are then scheduled for road services. There is one filling machine available both in summer and winter. It has to be noted that daylight limits the number of working hours to ten per day in summer and only eight per day in winter.

The number of filling sites and their locations determine the number of transport vehicles which are necessary to move the required sandbags to the scenes of actions. The city of Magdeburg can only provide a specific pool of transport vehicles (including drivers) whose capacity ranges between 30 and 300 filled sandbags. At additional costs, additional vehicles (with an average capacity of 360 sandbags) may be rented from local truck rental companies.

3.3 Goals and Objectives

The safety of human beings and assets is the main goal of flood protection management. In order to attain this goal, it has to be ensured for each relevant scenario that a sufficient number of filled sandbags is provided at each scene of action within the given time window. As a secondary goal, the respective locations of the filling sites, the filling technology and the assignment of staff to the filling and piling processes and of trucks to the transportation processes have to be determined in such a way that the corresponding total costs are minimized.

4 Problem Representation and Implementation

The single-stage, capacitated Warehouse Location Problem (SC_WLP) [3, 4] served as the basis for the development of a model for the described operative flood management problem. The filling locations correspond to the warehouses, the scenes of actions to the clients and the filled sandbags are the goods to be transported.

For each potential location of a filling site a binary variable has been introduced which indicates whether the site will be used or not. Another set of binary variables describes which filling technologies are utilized at the chosen sites, and real variables represent the corresponding number of staff which has to be assigned. Further variables are related to the number of sandbags which have to be transported from the filling site(s) to the scenes of action. These variables are differentiated further with respect to the type of vehicle which is used and with respect to the time period (hour) in which the transport is carried out.

The capacity of the filling site(s) is limited by the filling technology which is used for filling the sandbags and characterized by a corresponding productivity. Constraints, like in the basic SC_WLP, express these limitations in our model. Further constraints have been introduced in order to guarantee the total satisfaction of the demand for filled sandbags at each scene of action and to represent the limitation of the transportation process (e.g. just transporting bags which have already been filled).

Since the above-described model turned out to be too large and too time-consuming for the analysis of different scenarios under different data, three sub-models (according to the location strategies described before) have been derived which were used for the subsequent analysis. Model I analyzes the use of the gravel plant as a single filling location. Within the framework of Model II, an alternative single filling location is determined, while Model III deals with the case of two filling locations, among which the gravel plant is included.

Season	Summer - Time Window: 2 Days with 10 Hours each						Winter - Time Window: 2 Days with 8 Hours each					
Flood Peak	**6.25 m**		**6.80 m**		**7.00 m**		**6.25 m**		**6.80 m**		**7.00 m**	
One Filling Location: Gravel Plant (Model I)	Total Costs:	16,720 €	Total Costs:	49,698 €	Total Costs:	52,203 €	Total Costs:	17,082 €	Total Costs:	53,296 €	Total Costs:	55,911 €
	Man Hours Filling:	270	Man Hours Filling:	978	Man Hours Filling:	1,046	Man Hours Filling:	270	Man Hours Filling:	1,176	Man Hours Filling:	1,242
	Filling Technology:	Sandbag Filling Machine Spreader Vehicle	Filling Technology:	Sandbag Filling Machine Spreader Vehicle Manual Filling	Filling Technology:	Sandbag Filling Machine Spreader Vehicle Manual Filling	Filling Technology:	Sandbag Filling Machine	Filling Technology:	Sandbag Filling Machine Manual Filling	Filling Technology:	Sandbag Filling Machine Manual Filling
	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	8 Yes (2)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	13 Yes (10)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	16 Yes (10)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	9 Yes (2)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	18 Yes (11)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	19 Yes (12)
One Alternative Filling Location (Model II)	Filling Location:	**Do-It-Yourself Center**	Filling Location:	**Sports Hall**	Filling Location:	**Sports Hall**	Filling Location:	**Do-It-Yourself Center**	Filling Location:	**Exhibition Hall**	Filling Location:	**Exhibition Hall**
	Total Costs:	16,429 €	Total Costs:	47,176 €	Total Costs:	49,220 €	Total Costs:	16,586 €	Total Costs:	50,554 €	Total Costs:	52,363 €
	Man Hours Filling:	270	Man Hours Filling:	978	Man Hours Filling:	1,046	Man Hours Filling:	270	Man Hours Filling:	1,176	Man Hours Filling:	1,242
	Filling Technology:	Sandbag Filling Machine Spreader Vehicle	Filling Technology:	Sandbag Filling Machine Spreader Vehicle Manual Filling	Filling Technology:	Sandbag Filling Machine Spreader Vehicle Manual Filling	Filling Technology:	Sandbag Filling Machine	Filling Technology:	Sandbag Filling Machine Manual Filling	Filling Technology:	Sandbag Filling Machine Manual Filling
	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	7 Yes (2)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	9 Yes (3)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	10 Yes (3)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	[illegible]	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	10 Yes (3)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	10 Yes (3)
Two Filling Locations (Model III)	Filling Location 1:	**Fire Station**	Filling Location 1:	**Sports Hall**	Filling Location 1:	**Sports Hall**	Filling Location 1:	[illegible]	Filling Location 1:	**Exhibition Hall**	Filling Location 1:	**Exhibition Hall**
	Filling Location 2:	**Do-It-Yourself Center**	Filling Location 2:	**School Yard**	Filling Location 2:	**School Yard**	Filling Location 2:	[illegible]	Filling Location 2:	**Do-It-Yourself Center**	Filling Location 2:	**Do-It-Yourself Center**
	Total Costs:	15,989 €	Total Costs:	46,781 €	Total Costs:	48,654 €	Total Costs:	[illegible]	Total Costs:	50,095 €	Total Costs:	51,960 €
	Man Hours Filling:	270	Man Hours Filling:	978	Man Hours Filling:	1,046	Man Hours Filling:	[illegible]	Man Hours Filling:	1,176	Man Hours Filling:	1,176
	Filling Technology:	Sandbag Filling Machine Spreader Vehicle	Filling Technology:	Sandbag Filling Machine Spreader Vehicle Manual Filling	Filling Technology:	Sandbag Filling Machine Spreader Vehicle Manual Filling	Filling Technology:	[illegible]	Filling Technology:	Sandbag Filling Machine Manual Filling	Filling Technology:	Sandbag Filling Machine Manual Filling
	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	6 No	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	9 Yes (3)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	7 Yes (3)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	[illegible]	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	9 Yes (3)	Total No. of Transport Vehicles: Rent add. Transport Vehicles:	8 Yes (2)

Table 1: Results for Different Location Strategies and Scenarios

The three optimization models were generated by means of the modeling language AMPL (A Mathematical Programming Language) [5], whereas ILOG CPLEX 10.1 was used as an optimizer.

5 Results

For each scenario and each of the three location strategies a solution has been generated. For each combination (cf. Table 1), not only the locations chosen as filling sites are given, but also the filling technology that should be used, the number of hours of labor and the number of transport vehicles which are required. Also, the total (decision-relevant) costs are quoted.

Table 1 presents an example of a solution that has been generated for a winter flood with an expected flood peak of 6.80, given that two filling sites are to be chosen. According to this solution, the locations of the filling sites should be the »Exhibition Hall« and the (abandoned) »Do-It-Yourself Center«. The sandbag filling machine will be utilized, complemented by manual filling. This requires a total number of 1,176 hours of labor to be made available for the two eight-hour working days. The spreader vehicles cannot be used, because they are scheduled for winter road services. For the transportation of the filled sandbags nine transport vehicles are required, of which three have to be rented. The costs of this solution amount to approx. 50,100 euros which are composed of material costs of approx. 21,300 euros, transport costs of approx. 2,800 euros, personnel costs of approx. 25,600 euros and other (technical) costs.

More generally, it could be affirmed that for almost all scenarios the solution which has been used in the past is the most expensive one, i.e. implementing a single filling site at the gravel plant. Only for relatively low water levels, namely for a flood peak of not more than 6.25 m, should the gravel plant be taken into consideration as a filling site.

The costs of the solutions from Model II (one alternative filling site) and from Model III (two filling sites) do not differ significantly. Discussing this aspect with the Professional Fire Brigade revealed that a single site would definitely be preferred, since it would involve a less complex process organization.

Furthermore, it was found that the pool of transport vehicles that can be provided by the city of Magdeburg is not suited for being used for the transport of the sandbags. They have proven to be too small and, as a consequence, would have to shuttle far more frequently between the filling site(s) and the scenes of action than larger vehicles which could be rented at lower costs.

6 Summary and Outlook

In this paper we have reported on an OR project in which operating guidelines of flood protection management have been provided for different flood scenarios. Also some more general conclusions with respect to potential location strategies and the available pool of transportation vehicles could be drawn.

The value of the model which has been developed for this study goes far beyond these immediate results. It provides a sound basis for a series of additional analyses in future, e.g. concerning changes of the data (price of gasoline for the transportation vehicles), the introduction of additional equipment (additional filling machine), or even new scenarios (higher flood peaks due to global warming).

Acknowledgement

We would like to take this opportunity to thank the Professional Fire Brigade of the city of Magdeburg, and especially Dipl.-Ing. Armin Hilgers, who provided us with valuable information, as well as the Land Surveying Office of Magdeburg for the helpful and welcome cooperation.

Literature:

[1] Dister, E. (2003): *Nach der Flut die Zukunft verschlafen*. In: Süddeutsche Zeitung (11.08.2003).
[2] Brombach, H.; Dillmann, R.; Patt, H.; Richwien, W.; Vogt, R. (2001): *Hochwasserschutzmaßnahmen.* In: Patt, H. (Hrsg.) (2001): Hochwasser-Handbuch: Auswirkungen und Schutz. Springer Verlag: Berlin, Heidelberg, New York, p. 284-298.
[3] Klose, A. (2001): *Standortplanung in distributiven Systemen – Modelle, Methoden, Anwendungen.* Physica-Verlag: Heidelberg.
[4] Domschke, W.; Drexl, A. (1996): *Logistik: Standorte.* 4th edition, Oldenbourg Verlag: München.
[5] Fourer, R.; Gay, D.M.; Kernighan, B.W. (2003): *AMPL - A Modeling Language for Mathematical Programming.* 2nd edition, Thomson, Brooks, Cole: Pacific Grove.

THE MAGAZINE OF THE GOR
OR News
NO.36 / JUNE 2009 / ISSN 1437-2045