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Revised flood risk assessment: Quantifying epistemic uncertainty emerging from different sources and processes

Dissertation

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“I know that I know nothing”

Socrates (c.469/470 B.C.-399 B.C.)

Content

Figures

Tables

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Abstract

The assessment of flood risk considers individual risk, economic risk and environmental risk yielding qualitative and quantitative statements which are typically subjected to substantial uncertainties. Flood risk assessment comprises hazard assessment and vulnerability assessment. In the frame of hazard assessment flood events are analysed by means of recurrence intervals and spatio-temporal flood characteristics. Within vulnerability assessment flood prone utilisations are typically characterised by stage-damage functions or risk curves.

The objective of the dissertation is to revise flood risk assessment methodologies and to quantify inherent epistemic uncertainty emerging from different sources and processes. This work comprises scientific publications with emphasis on fundamental aspects of flood risk: (1) uncertainty analysis, (2) environmental flood risk assessment, (3) economic flood risk assessment and (4) individual flood risk assessment. Conclusions were drawn on the basis of specific case studies, mainly within the federal territory of Austria.

(1) Uncertainty was analysed with emphasis on flood hazard assessment. Therefore, the processes of hydrological input hydrograph generation, hydrodynamic modelling and sediment transport were considered to enable an identification of process related uncertainty sources. Besides uncertain precipitation measurement and monitoring methodologies the simulation based on simplified concepts, approaches and assumptions leads to incomplete information utilised as input to hydrodynamic models. In the frame of hazard assessment, referring to state-of-the-art approaches, it is implicitly assumed that the river bed elevation will not vary - neither during flood events nor during long term sedimentation or deposition. This neglect of relevant processes of course leads to highly uncertain results. The implementation of sediment transport and river bed dynamics to a revised flood risk assessment concept proofed that various cross sections within a case study site would be inundated, regardless of flood protection measures.

(2) Environmental flood risk for ground water bodies, protected areas, recreational areas, etc. was assessed, based on analysing the consequences of flooding of waste disposal sites in Austria. By means of case studies and hydrodynamic simulations, flood impacts on the disposal sites and emission impacts on protected goods were assessed based on four parameters: (i) spatio-temporal flood characteristics, susceptibility to erosion due to (ii)

flow velocity and (iii) shear stress as well as (iv) emission behaviour due to water saturation of the waste body. Roughly, one third of considered sites in Austria showed a remarkable long term risk for humans and the environment. The developed methodology enables a qualitative assessment by means of categories like “minor risk”, “moderate risk” and “serious risk”, providing a decision support aid to identify landfills with risk for humans and the environment. Considerable sources of uncertainty were identified by the (a) accuracy of data sets describing attributes and locations of waste disposals, (b) reliability of the hazard assessment tool HORA due to the neglect of protection measures, (c) scarce topographic data (d) a lack of documented historical flood events for calibration and validation purposes and (e) a lack of information related to possible emissions.

(3) Economic flood risk was analysed by an Austrian case study in the frame of an international research program. The objective was to calculate the effectiveness and efficiency of structural and non-structural flood protection and mitigation measures. Spatial planning, by imposing a building ban as well as adapting existing flood protection schemes by implementing a spillway proofed to be highly effective and efficient. A refined approach to assess the vulnerability of residential buildings and industrial sites was presented. Detailed mapping, considering census data, analysed questionnaires and conducted interviews with chief operating officers, provided reliable results.

(4) Individual flood risk reduction strategies were analysed by estimating the effectiveness and efficiency of spillways. Hydrodynamic simulations showed that a remarkable reduction of people exposed to floods can be achieved due to the virtual implementation of a spillway to flood protection schemes. Further, an increase of the protection scheme reliability is expected by avoiding uncontrollable overtopping scenarios and hence, dyke breaching. Although considerable benefits are expected by implementing spillways to existing flood mitigation measures, an obstacle in the frame of political decision making is predictable – regardless of the spillway location, there will be complaints and resistance by people feeling disadvantaged, if the benefits are not communicated in an understandable way.

Kurzfassung

Die Beurteilung von Hochwasserrisiko berücksichtigt die Aspekte Individualrisiko, ökonomisches Risiko und ökologisches Risiko. Daraus ergeben sich qualitative und quantitative Risikoaussagen, die typischerweise mit nennenswerten Unsicherheiten behaftet sind. Im Rahmen der Hochwasserrisikobeurteilung werden einerseits die Gefährdung (Hochwasser und dessen räumlich-zeitliche Auftrittswahrscheinlichkeit) und andererseits die Vulnerabilität (Verletzlichkeit von Schutzgütern wie Wohnhäuser und Industriestandorte) analysiert.

Das Ziel dieser Arbeit ist es Methoden zu überarbeiten, sowie damit einhergehende Unsicherheiten, bezogen auf unterschiedliche Prozesse und Quellen, zu quantifizieren. Die Dissertation fasst eine Reihe von wissenschaftlichen Publikationen zusammen, die den wesentlichen Themenschwerpunkten der Risikoanalyse zuzuordnen sind: (1) Unsicherheitsanalyse (2) ökologische Risikobeurteilung, (3) ökonomische Risikobeurteilung und (4) Beurteilung des Individualrisikos. Die Analysen wurden an Hand von spezifischen Fragestellungen im Rahmen von Fallstudien durchgeführt.

(1) Die Unsicherheit resultierend aus der Berücksichtigung zusätzlicher Prozesse (flussmorphologische Dynamik, raum-zeitliche Niederschlagscharakteristika) wurde an Hand der Gefährdungsanalyse quantifiziert. Beginnend bei der hydrologischen Modellierung von (Teil-)Einzugsgebieten zur Generierung von Hydrographen bestimmter Jährlichkeit wurden nennenswerte Unsicherheiten identifiziert. Die Simulationsergebnisse dienten als Input für die hydrodynamische Modellierung, die die Grundlage zur Analyse der Auswirkung von flussmorphologischen Prozessen auf die Wasserspiegellagen bildete. Durch die Berücksichtigung der flussmorphologischen Aktivität zeigte sich, dass zahlreiche, als hochwassersicher ausgewiesene Flussprofile, plötzlich nicht mehr als hochwassersicher gegenüber dem Bemessungsereignis charakterisiert werden konnten.

(2) Die Analyse von umweltrelevanten Konsequenzen, verursacht durch die Überflutung von Deponien und Altablagerungen, diente der Entwicklung eines qualitativen Ansatzes zur Beurteilung des ökologischen Folgerisikos für Schutzgüter wie Grundwasserkörper, Schutz- und Schongebiete etc. An Hand von Fallstudien und hydrodynamischen Simulationen wurden die Einwirkungen auf unterschiedliche Ablagerungsstandorte und die Auswirkung auf die umliegenden Nutzungen bewertet. Zur qualitativen Beurteilung

wurden vier wesentliche Parameter berücksichtigt: (i) räumlich-zeitliche Hochwassercharakteristik, Erosionsanfälligkeit durch auftretende (ii) Fließgeschwindigkeiten und (iii) Sohlschubspannungen sowie (iv) Emissionsverhalten durch Wassersättigung des Deponiekörpers. Für rund ein Drittel der begutachteten Standorte wird auf Grund der Studie von erheblichem Langzeitrisiko für Mensch und Umwelt ausgegangen. Die wesentlichen Quellen von Unsicherheit in der Risikobeurteilung wurden für folgende Punkte identifiziert: (a) Güte der Datensätze, die Zusammensetzung und Lage von Ablagerungen beschreiben, (b) Güte der Grundlage zur Gefährdungsanalyse (HORA), die im Wesentlichen Hochwasserschutzeinrichtungen vernachlässigt, (c) Mangel an topographischen Daten (d) Mangel an dokumentierten historischen Hochwasserereignissen zur Kalibrierung und Validierung von Modellen und (e) Mangel an Information über mögliche Emissionen aus Deponien und Altablagerungen.

(3) Ökonomisches Hochwasserrisiko wurde an Hand der Effektivität und Effizienz von strukturellen und nicht strukturellen Hochwasserschutzmaßnahmen analysiert. Die besonders effektive und effiziente Wirkung von Raumplanung (Bauverbot in Überflutungsflächen) und Adaptierung von bestehenden Schutzsystemen (Einbau einer Überströmstrecke) konnte im Rahmen einer internationalen Studie ausgewiesen werden. Weiters wurde ein erheblich verfeinerter Ansatz zur Beurteilung der Vulnerabilität von Wohnhäusern und Industriestandorten an Hand von Gebietsbegehungen, Berücksichtigung von Volkszählungsdaten, Auswertung von Fragebögen sowie einer Reihe von Interviews mit Betriebsleitern abgeleitet.

(4) Strategien zur Senkung des Individualrisikos wurden an Hand der Bewertung von Effektivität und Effizienz von Überströmstrecken analysiert. Mittels hydrodynamischen Simulationen wurde nachgewiesen, dass die Implementierung einer Überströmstrecke in ein bestehendes Hochwasserschutzsystem zu einer erheblichen Reduktion potentiell betroffener Personen führt. Weiters kann durch diese Maßnahme eine erhebliche Steigerung der Betriebssicherheit von Hochwasserschutzdeichen erreicht wird, da unkontrollierbares Überströmen und somit Deichbruch vermieden werden. Das wesentliche Problem, das im Rahmen der Anordnung von Überströmstrecken in dicht besiedeltem und wirtschaftlich intensiv genutztem Hinterland zu erwarten sein wird, ist der Widerstand von potentiell Betroffenen, die sich durch die gesteuerte Flutung benachteiligt fühlen, sofern sie nicht über die Gründe nachvollziehbar informiert werden.

Introduction

Although substantial amounts of money were invested in flood protection and flood mitigation during the past decades the reported damages increased tremendously and continuously (Munich Re, 2007). Referring to the database compiled by the Centre for Research on Epidemiology Disasters (www.em-dat.net), floods are the type of natural disasters that affected the highest number of people in the period of 1900-2009 world-wide.

One of the main causes is the change in land use in former flood plains from agricultural utilization to industrial and residential areas (Kenyon et al., 2008; Neuhold & Nachtnebel, 2008; Schanze et al., 2009). Obviously, these modifications led to a remarkable increase of the damage potential (BMFLUW, 2009). The directive 2007/60/EC of the European Parliament and of the council on the assessment and management of flood risks (EU, 2007) emphasises:

(1) Floods have the potential to cause fatalities, displacement of people and damage to the environment, to severely compromise economic development and to undermine the economic activities of the community.

(2) Floods are natural phenomena which cannot be prevented. However, some human activities (such as increasing human settlements and economic assets in floodplains and the reduction of the natural water retention by land use) and climate change contribute to an increase in the likelihood and adverse impacts of flood events.

During the past centuries partly contradicting state-of-the-art approaches, varying from river training and straightening to river restoration, were applied to cope with flood events. Traditional approaches of structural flood protection measures are nowadays increasingly replaced by flood management approaches (de Vried, 2005; Samuels et al., 2005). Recent flood experience, consideration of residual risk as well as the understanding of non achievable total safety supported the change to an integrated flood risk management approach (Hall et al., 2003; Hooijer et al., 2004; Nachtnebel & Faber, 2009; Plate, 2002). The aim of flood risk management is to minimise human, economic and environmental losses. One strategy is to protect flood prone areas up to a predefined design level and to simultaneously minimize the residual risk (overtopping, dyke failure, etc.).

The assessment of flood risk considers aspects of individual risk, economic risk and environmental risk yielding qualitative and/or quantitative statements which are typically subjected to substantial uncertainty. Flood risk assessment comprises hazard assessment and vulnerability assessment (Compton et al., 2009; Kelman, 2003; Merz et al., 2010; Merz, 2006; Merz et al., 2004; Munch Re, 2009; Neuhold et al., 2009; Thieken et al., 2008; UN, 2009;).

> ***Hazard:*** *"A potentially damaging physical event, phenomenon or human activity, which may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation." (U.N. ISDR 2002, 24)*
>
> ***Vulnerability:*** *"Vulnerability is defined as the susceptibility of life, property or the environment to damage if a hazard occurs." (May 2000, p. 6)*

In the frame of hazard assessment, flood events are analysed by means of recurrence intervals and spatio-temporal flood characteristics (inundated area, inundation depth, flow velocity, inundation duration, etc.). Within vulnerability assessment, flood prone utilisations are typically characterised by stage-damage functions or risk curves (Bateman et al., 1991; BUWAL, 1999a & b; DEFRA, 2001; Gemmer, 2004; IKSR, 2001; IPCC, 1991; Klaus, 1994; Kok et al., 2004; Meyer, 2005; Penning-Rowsell, 2005; Penning-Rowsell & Chatterton, 1977; Statistik Austria, 2005a & b).

Due to the amount of inherent processes and aspects, flood risk assessment is highly complex and exhibits a high degree of uncertainty. To assess flood risk, numerous inputs (data, concepts, models, calculations, assumptions, simplifications, etc.) from different disciplines (meteorology, hydrology, hydraulic engineering, social sciences, etc.) can be utilised (Bateman et al., 1999; BMFLUW, 2004; Brent, 2006; Buck, 1999; BWG, 2002; Eberstaller et al., 2004; Faber, 2006; Garrod & Willis, 1999; Green et al., 1994; Hanley & Splash, 1993; HYDROTEC, 2004; Johnson et al., 2000; Kraus, 2004; Landefeld & Seskin, 1982; Liu et al., 2000, Merz, 2006; Merz et al., 2004; Nachtnebel, 2007; Nachtnebel et al., 2005; Nachtnebel & Faber, 2007; Neuhold & Nachtnebel, 2008; Niekamp, 2001; Penning-Rowsell et al., 2005, Rodriguez, 2005; Schanze et al., 2008; Schmidke, 2000; Sendi et al., 2002; Smith & Ward, 1998; van der Veen et al., 2003).

Flood risk assessment is inherent to considerable uncertainty emerging from different sources and processes (Plate, 1992). In the frame of uncertainty analysis, a distinction has to be made between reducible (epistemic) and irreducible (aleatoric) uncertainty (Apel et al., 2008; Cullen & Frey, 1999; Ferson & Ginzburg, 1996; Haimes, 1998; Hall & Solomatine, 2008; Helton & Oberkampf, 2004; Hoffman & Hammonds, 1994; Merz, 2006; Morgan & Henrion, 1990; Plate, 1992; van Asselt & Rotmans, 2002; Zio & Apostolakis, 1996). Aleatoric uncertainty results from the variability and unpredictability of the considered natural processes. Epistemic uncertainty is a product of imperfect knowledge of the examined system. Murphy (1998) subsumes three origins of uncertainties: (1) the incompleteness of considered scenarios and assumptions (Kaplan & Garrick, 1981; Merz, 2006) as well as simplifications inherent to (2) models and (3) model parameters (Apel et al., 2008; Apel et al., 2006; Ferson & Ginzenburg, 1996; Haimes 1998; Kuikka & Varis, 1997; Merz, 2006; Plate, 1992; Rabinovich, 1993).

(1) Scenario uncertainty

Risk analysis is typically characterized by sets of a few damage scenarios. Obviously, these scenarios cannot cover all the possible future events and their definition is based, to a larger extent, on subjective expert judgements. There are always scenarios that will not be considered because of:

- Low probability of recurrence and therefore, a negligible (“not significant”) influence on the overall expected losses
- Lack of data and methodologies to calculate or describe rare events
- Deficit of experience and analytical skills of the person responsible

Incompleteness and representation of a collection of damage scenarios are fundamental problems in the frame of risk assessment (Kaplan and Garrick, 1981). Incompleteness leads to uncertain results and accordingly, the underestimation of risk. Uncertainty can be reduced by experience and sound methodological approaches. It is essential that the chosen scenarios are representative for the overall considered system. The set of scenarios should also include the worst case scenario even though it might have little impact on the result due to its recurrence interval.

(2) Model uncertainty

The overall uncertainty of many surveys is dominated by model uncertainty (Kuikka and Varis, 1997). Merz (2006) stated that model uncertainty emerges from:

- Model assumptions and composition
- Model sufficiency (completeness)
- Model domain and resolution

Precipitation-runoff models, hydrodynamic models and sediment transport models rest upon simplified model assumptions. To some extent, there are alternative or even contradicting assumptions or theories of model development. Models are approximations of natural processes - their composition demands decisions upon which processes should be described and which accuracy and abstraction is necessary or possible. Moreover, the spatial and temporal discretisation of models influences uncertainty and should be determined as a compromise of computing time and approximation degree. To summarise, a maxim can be stated: a model should be composed as simply as possible but as complex as necessary (Popper, 1982).

(3) Natural variability and parameter uncertainty

Parameter uncertainty comprises uncertainty related to model parameters and variables. These are mainly parameters and variables representing measurable attributes of the considered system e.g. intensity of precipitation, infiltration capacity of soil, failure rate of system components or costs due to blocking roads. Uncertainty of parameters and variables results from:

- *Variability:* Processes triggering extreme flood events are subjected to natural variability. The parameters representing these processes vary over time and space (Haimes, 1998). Plate (1992) stated that this variability is inherent to all natural processes. Regardless of how high the monitoring effort might be, it will never be possible to fully predict and describe these processes by means of a deterministic model. Uncertainty related to variability is traditionally covered by probabilistic methods (Apel et al., 2006, Apel et al., 2008, Merz, 2006).

- *Limited information:* Frequently there are statistical dependencies between variables used for risk analyses. In many cases data availability is not sufficient to describe these dependencies, which leads to an additional source of uncertainty in the frame of risk analyses (Merz, 2006).
- *Parametric uncertainty:*
  - Measurement inaccuracy leads to random variation in measurements. To detect these *random errors* statistic methods (standard deviation, confidence interval etc.) are applied (Rabinovich, 1993).
  - However, *systematic errors* can occur due to e.g. inaccurate calibration and experiment design. Systematic errors are rarely known since the true value is not determinable (Rabinovich, 1993, Ferson and Ginzenburg, 1996).
  - Parameter uncertainty can result from simplified descriptions – *approximations* – of data and parameters, e.g. by representing a continuous random variable with a discrete one.

As a supplement to variables there are indicators and parameters representing ideals and moral concepts (e.g. value of human life expressed in salvage expenses or risk aversion factors) which influence the risk analysis (Haimes, 1998). These parameters represent a significant source of uncertainty in the frame of risk analysis.

Objectives and thematic outline

The objectives of the dissertation are to revise flood risk assessment methodologies and to quantify related epistemic uncertainty emerging from different sources and processes based on case studies. To achieve both aims following research questions are posed:

1. *How does the incorporation of additional processes - compared to the state of the art - influence flood risk assessment results?*
2. *How does the incorporation of additional data sources influence the flood risk assessment accuracy?*
3. *What kinds of revisions are needed for flood risk assessment concepts to reduce epistemic uncertainty?*

This work comprises seven scientific publications with emphasis on fundamental thematic aspects of flood risk assessment:

- *Uncertainty analysis (paper 1)*
- *Environmental flood risk assessment (papers 2-4)*
- *Economic flood risk assessment (paper 5 and 6)*
- *Individual flood risk assessment (paper 7)*

Uncertainty analysis

Alluvial river beds are subjected to severe morphological changes during flood events which have significant implications for the water level (Nachtnebel & Debene, 2004). This effect has to be considered in the delineation of flood endangered riparian zones. Risk zonation maps are mostly derived from design floods which represent hazards based on specified return periods. The respective delineation of inundated areas and the estimation of flow depths and flow velocities are fundamental inputs for flood risk estimation of exposed objects. For this purpose in most cases 2D hydrodynamic unsteady models are applied (BMFLUW, 2006c). State of the art flood risk assessment concepts implicitly assume that the morphology will not change; neither during flood events nor by long term erosion or deposition. However, it is obvious that the river bed elevation can change quickly and drastically. Observed morphological developments during and after flood events indicate partly tremendous changes in river bed elevation due to river morphological processes. The occurrence of such processes clearly underlines the necessity of incorporating calculated or estimated morphological changes to the flood risk assessment procedure. Therefore, the influence of sediment transport on the respective water surface elevation and related uncertainties, were investigated (Neuhold et al., 2009). Special interest was put on the analysis of uncertainty associated with flood hazard assessment. Therefore, the processes of hydrological input hydrograph generation, hydrodynamic modelling and sediment transport were considered to enable an identification of process related uncertainty sources. The implementation of sediment transport and river bed dynamics to a revised flood risk assessment concept proofed that various cross sections within a case study site would be inundated, regardless of flood protection measures.

Environmental flood risk assessment

Waste disposal sites are mostly located in lowland areas close to residential areas inducing a long term risk of potential environmental contamination due to flooding. Maintenance and decomposition durations for waste disposals are assessed to 200 to 500 years depending on waste composition, climatic conditions and applied assessment methodologies (Belevi & Baccini; 1989; Ehring & Krümpelbeck 2001; Stegmann & Heyer 1995). Hence, even sites with protection levels up to a 100 years flood are highly likely to be inundated before hazardous landfills are decomposed. It has to be assumed that inundated waste disposals become water saturated which leads to a substantial mobilisation of pollutants, since the presence of water enhances decomposition and transport processes (Bogner & Spokas, 1993; Christensen et al., 1996; Klink & Ham, 1982). Additionally, water saturation of waste disposals may lead to reduced stability (Blight & Fourie, 2005). Therefore, a permanent risk potential for humans and the environment has to be expected emerging from flooded waste disposals (Laner et al., 2009; Nachtnebel et al., 2009). In the recent past, the erosion of landfill material and therefore the release of pollutants were monitored (Habersack & Moser 2003; Young et al., 2004). Related to inundated landfills Geller et al. (2004) observed increased concentrations of hazardous substances in floodplain soils and river sediments caused by the 2002 Elbe River flood. Blight & Fourie

(2005) provide a review of catastrophic failures of waste landfills highlighting the impact of such disasters on both, the environment and the population. Therefore, Laner et al., 2008; Neuhold & Nachtnebel, 2010a; Neuhold & Nachtnebel, 2009 derived an environmental flood risk assessment methodology for ground water bodies, protected areas, recreational areas, etc., based on analysing the consequences of waste disposal site flooding in Austria.

Economic flood risk assessment

Economic flood risk was analysed by calculating the effectiveness and efficiency of structural and non-structural flood protection and mitigation measures (Neuhold & Nachtnebel, 2008a; Schanze et al., 2008). The investigated alternatives referred to existing and conceivable flood mitigation measures in an Austrian municipality. A revised, more detailed, approach to assess the vulnerability of residential buildings and industrial sites was presented. Detailed mapping, census data, questionnaires and conducted interviews with chief operating officers provided reliable results. The simulated inundation lines, water depths and flow velocities were linked to the land use information to estimate the damage potential of the flood prone area. The overall costs, individual object related damage functions and land use data provided the input for cost-effectiveness as well as benefit-cost analysis. The results indicated that the effectiveness and efficiency of non structural and structural mitigation measures are within the same range. Spatial planning by means of an imposed building ban as well as adapting existing flood protection schemes (spillway) proofed to be highly effective and efficient.

Further, the case study aimed to analyse the consequences of hinterland development with respect to flood vulnerability and flood risk. Vulnerability assessment referred to two different stages of land use were analysed – the development status prior to the implementation of flood mitigation measures and after a decade of development of the former flood plain. By applying a micro scale flood risk assessment procedure (BUWAL, 1999a & b; Neuhold et al., 2009; Neuhold & Nachtnebel, 2008a, Neuhold & Nachtnebel, 2008b) the overall flood risk was analysed considering (1) economic criteria by means of the damage potential of every single object located in the flood prone area and (2) intangible aspects by estimating the overall number of people exposed, based on census data.

Individual flood risk assessment

Individual flood risk reduction strategies were derived by analysing the effectiveness and efficiency of spillways (Neuhold & Nachtnebel, 2010b). The main function of a spillway is to protect the dyke itself during extreme events. Spillways help to avoid dyke failures by releasing excess water – water beyond the design level – to the hinterland without endangering the protective structure. The hazards posed by inappropriate spillways might approach or even exceed damages that would have occurred under natural flood conditions without the existence of dykes (Haimes, 2009). Due to the controlled flooding of pre-selected areas catastrophic events can mostly be avoided and therefore, an increase of the reliability of flood mitigation measures can be achieved (Neuhold & Nachtnebel, 2008a). Dyke failure events are a considerable threat to socio-economic and ecologic values. Their failure mechanisms need to be investigated to predict breach locations. For temporal and spatial breach development uncertain functional relationships have yet been found due to highly complex breaching mechanisms (Singh, 1996). In case of dyke failure, losses of lives and economic damages have to be expected as consequences, depending on the inundation depth, flow velocity, early warning and exposure (Zagonjolli, 2007). To prevent dykes from failing due to overtopping the implementation of spillways proofed to be an adequate strategy (BMFLUW, 2006a). Hydrodynamic simulations showed a remarkable reduction of people exposed due to the virtual implementation of a spillway to flood protection schemes (Neuhold & Nachtnebel, 2010b). Further, an increase of the protection scheme's reliability is expected by avoiding uncontrollable overtopping scenarios and hence, dyke breaching. Although considerable benefits are expected by implementing spillways to existing flood mitigation measures, an obstacle in political decision making is predictable: regardless of the spillway location, there will be complaints, objections and resistance by people feeling disadvantaged and endangered, if the benefits are not communicated in an understandable way.

References:

Apel, H., Merz, B. & Thieken (2008), A.H.: Influence of Dike Breaches on Flood Frequency Estimation, Computers and Geosciences, article in press, doi: 10.1016/j.cageo.2007.11.003.

Apel, H., Thieken, A.H., Merz, B. & Blöschl, G. (2006): A probabilistic Modelling System for Assessing Flood Risks, Natural Hazards, 38 (1-2), 79-100.

Bateman, I.J. & Willis, K.G. (1999): Valuing Environmental Preferences – Theory and Practice of the Contingent Valuation Method in the US, EU and Developing Countries, Oxford University Press, Oxford.

Bateman, I., Bateman, S., Brown, D., Doktor, P., Karas, J.H.W., Maher, A. & Turner, R.K. (1991): Economic Appraisal of the Consequences of Climate-Induced Sea Level Rise: A case study of east Anglia. Report to the Ministry of Agriculture, Fisheries and Food. University of East Anglia. Norwich.

Belevi, H. & Baccini, P. (1989): Long-Term Behaviour of Municipal Solid Waste Landfills. Waste Manage Res 1989; 7: 43-56.

Blight, G.E. & Fourie, A. (2005): Catastrophe revisited – disastrous flow failures of mine and municipal solid waste. Geotechnical and Geological Engineering 2005; 23: 219-248.

BMFLUW (Bundesministerium für Forst- und Landwirtschaft, Umwelt und Wasserwirtschaft) (2009): Flood Risk II: Vertiefung und Vernetzung zukunftsweisender Umsetzungsstrategien zum integrierten Hochwassermanagement, Endbericht. www.lebensministerium.at.

BMFLUW (2006a): Freibord – Überströmstrecken: Leitfaden zur Festlegung des erforderlichen Freibords anhand projektspezifischer Rahmenbedingungen einschließlich der Kriterien für die Anordnung von Überströmstrecken. Fassung 2006. www.lebensministerium.at.

BMFLUW (2006b): Federal Waste Management Plan 2006. Federal Ministry of Agriculture and Forestry, Environment and Water Management, Vienna, pp. 320.

BMFLUW (2006c): Hochwasserrisikozonierung Austria – HORA, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, www.hochwasserrisiko.at.

BMFLUW (2004): Analyse der Hochwasserereignisse vom August 2002 – Flood RISK, WP Donau TP 05, Operative Maßnahmen Donau, 2004.

Bogner, J. & Spokas, K. (1993): Landfill CH4: Rates, fates, and role in global carbon cycle. Chemosphere 1993; 26: 369-386.

Buck, W. (1999): Auswertung der HOWAS-Datenbank: HY 98/15. Karlsruhe: Institut für Wasserwirtschaft und Kulturtechnik, Universität Karlsruhe, 1999.

BUWAL (1999a): Risikoanalyse bei gravitativen Naturgefahren – Methode. Umwelt-Materialien Nr. 107/I, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft.

BUWAL (1999b): Risikoanalyse bei gravitativen Naturgefahren – Fallbeispiele und Daten. Umwelt-Materialien Nr. 107/II, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft.

BWG (2002): Methode BWG Abschätzung des Schadenspotentials bei Überschwemmung und Übermurung. Arbeitshilfe 1.2.

Christensen, T. H., Kjeldsen, P. & Lindhardt, B. (1996): Gas-generating processes in landfills. In: Christensen, T. H. (Ed.): Landfilling of waste: biogas. Proceedings, pp. 27-44, E&FN Spon, London, UK.

Compton, K.L., Faber, R., Ermolieva, T.Y., Linnerooth-Bayer, J. & Nachtnebel, H.P., (2009): Uncertainty and Disaster Risk Management. Modelling the Flash Flood Risk to Vienna and Its Subway System, IIASA, Laxenburg, Austria.

Cullen, A.C. & Frey, H.C., (1999): Probabilistic techniques in exposure assessment. A handbook for dealing with variability and uncertainty in models and inputs, Plenum Press, New York, London.

DEFRA (Department for Environmental, Food and Rural Affairs) (2001): National appraisal of assets at risk from flooding and coastal erosion, including the potential impact of climate change. Final Report.

De Vried, H. (2005): State of the art in flood management research, Proc. of the 3rd International Symposium on flood defence, Nijmegen, the Netherlands.

Eberstaller et al. (2004): Raumordnung und Hochwasserschutz am Beispiel der Traisen – Siedlungsentwicklung und Schadensanalyse. TP 02 - Naturgefahren BWV. In: Analyse der Hochwasserereignisse vom August 202 – Flood Risk. Hrsg: BMLFUW.

Ehrig, H.J. & Krümpelbeck, I. (2001): The Emission Behaviour of Old Landfills in the Aftercare Phase. In: Christensen TH, Cossu, R. & Stegmann, R., editor. Proceedings Sardinia 2001, Eigth International Waste Management and Landfill Symposium. IV. CISA, S. Margherita di Pula, pp. 313-323.

EU (2007): Richtlinie 2007/60/EG des europäischen Parlaments und des Rates über die Bewertung und das Management von Hochwasserrisiken.

Faber, R. (2006): Flood risk analysis: Residual risk and uncertainties in an Austrian context. Dissertation. Institute of Water Management, Hydrology and Hydraulic Engineering, Vienna: BOKU.

Ferson, S. & Ginzenburg, L.R. (1996): Different methods are needed to propagate ignorance and variability. Reliability Engineering and System Safety, 54, 133-144.

Garrod, G. & Willis, K.G. (1999): Economic Valuation of the Environment, Edward Elgar, Cheltenham, UK and Northhampton, MA, USA.

Geller, W.; Ockenfeld, K.; Böhme, M. & Knöchel, A. (2004): Schadstoffbelastung nach dem Elbe-Hochwasser 2002. Final report of the ad-hoc-project 'Schadstoffuntersuchungen nach dem Hochwasser vom August 2002 - Ermittlung der Gefährdungspotentiale an Elbe und Mulde'. UFZ - Umweltforschungszentrum Leipzig-Halle GmbH,, Magdeburg.

Gemmer, M. (2004): Decision support for flood risk management at the Yangtze river by GIS/RS-based flood damage estimation. Dissertation at the University of Giessen.

Green, C., van der Veen, A., Wierstra, E. & Penning-Rowsell, E.C. (1994): Vulnerability refined: analysing full flood impacts. In: Penning-Rowsell, E.C. & Fordham M. (Eds.) Floods across Europe – Flood hazard assessment, modelling and management. Middlesex University Press, London.

Habersack, H. & Moser, A. (2003): Ereignisdokumentation - Hochwasser August 2002, Final Report published by the University of Natural Resources and Applied Life Sciences, Vienna.

Hall, J., Meadowcroft, I., Sayers, P. & Bramley, M. (2003): Integrated flood risk management in England and Wales, Natural Hazards Rev. Volume 4, Issue 3, pp. 126-135

Hall, J. & Solomatine, D. (2008): A framework for uncertainty analysis in flood risk management decisions, International Journal of River Basin Management, 6(2) pp. 85-98.

Haimes, Y.Y. (2009): Risk modelling, assessment and management, Wiley series in systems engineering and management, 3rd edition.

Haimes, Y.Y. (1998): Risk modelling, assessment and management. Wiley Series in Systems Engineering, John Wiley and Sons, Inc., 726 p.

Hanley, N. & Splash, C.L. (1993): Cost-Benefit Analysis and the Environment, Edward Elgar, Brookfield.

Helton, J.C. & Oberkampf, W.L., (2004): Alternative representations of epistemic uncertainty. Special Issue, Reliability Engineering and System Safety, 85, 1-369.

Hoffman, F.O. & Hammonds, J.S., (1994): Propagation of uncertainty in risk assessment: The need to distinguish between uncertainty due to lack of knowledge and uncertainty due to variability. Risk Analysis, 14(5), 707-712.

Hooijer, A., Klijn, F., Pedroli, B. & Van Os, A. (2004): Towards sustainable flood risk management in the Rhine and Meuse river basins; synopsis of the findings of IRMA-SPONGE, River Research and Application, 20 (3), 343-357

HYDROTEC (2004): Hochwasser-Aktionsplan Sieg http://www.stua-si.nrw.de/sieg/b1/.

IKSR (2001): Atlas der Überschwemmungsgefährdung und möglichen Schäden bei Extremhochwässern am Rhein. Online publication: www.iksr.org.

IPCC (Intergovernmental Panel on Climate Change) (1991): Assessment of the Vulnerability of Coastal Areas to Sea Level Rise – A common methodology. Report of the Coastal Zone Management Subgroup of IPCC Working Group III, Den Haag.

Johnson, F.R., Banzhaf, M.R. & Desvousges, W.H. (2000): Willingness to pay for improved respiratory and cardiovascular helth: a multiple-format, stated-preference approach. Human Health 9(4): 295-317.

Kaplan, S. & Garrick, B.J. (1991): On the quantitative definition of risk. Risk Analysis, 1(1), 11-27.

Kelman, I. (2003): Defining Risk. In. FloodRiskNet Newsletter, Issue 2 Winter 2003.

Kenyon, W., Hill, G. & Shannon, P. (2008): Scoping the role of agriculture in sustainable flood management Land Use Policy, Volume 25, Issue 3, Pages 351-360.

Klaus, J., Pflügner, W., Schmidke, R.F., Wind, H. & Green, C. (1994): Models for Flood Hazard Assessment and Management. In: Penning-Rowsell E.C. & Fordham M. (Eds.) Floods across Europe. Hazard assessment, modeling and management. London, pp. 67-106.

Klink, R.E. & Ham, R.K. (1982): Effects of moisture movement on methane production in solid waste landfill samples. Resources and Conservation 1982; 8: 29-41.

Kok, M., Huizinga, H.J., Vrouwenfelder, A.C.W.M. & Barendregt, A. (2004): Standard Method 2004. Damage and casualties caused by Flooding. Client: Highway and Hydraulic Engineering Department, Delft.

Kraus (2004): Wirtschaftlichkeit und Priorisierung von Schutzmaßnahmen vor Wildbächen, Erosion und Lawinen: IAN Report 94: Workpackage (WP) Naturgefahren Wildbach- und Lawinenverbauung (WLV) Teilprojekt (TP) 03 in BMFLUW.

Kuikka, S. & Varis, O. (1997): Uncertainties of climate change impacts in Finnish watersheds: a Bayesian network analysis of expert knowledge. Boreal Env. Res., 2, 109-128.

Landefeld, J.S. & Seskin, E.P. (1982): The economic value of life: linking theory to practice. American Journal of Public Health 72 (6): 555-566.

Laner, D.; Fellner, J. & Brunner, P.H. (2009): Flooding of municipal solid waste landfills – a long-term environmental hazard? Science of the total environment, 407 (12), 2009, pp 3674-3680.

Laner, D.; Fellner, L. & Brunner P.H. (2008a): Gefährdung durch Deponien und Altablagerungen im Hochwasserfall – Risiko und Analyse (GEDES), Dokumentation zum Arbeitspaket 1, Zwischenbericht, TU-Wien IWA, pp. 54.

Laner, D.; Fellner, J.; Brunner, P.H.; Neuhold, C. & Kolesar, C. (2008b): Environmental Relevance of Flooded MSW Landfills in Austria, In: ISWA/WMRAS, ISWA/WMRAS World Congress 2008 - East meets Waste, Singapore Nov 3-6.

Liu, J.-T., Hammitt, J.K. Wang, J.-D. & Liu, J.-L. (2000): Mother's willingness to pay for her own and her child's health: a contingent valuation study in Taiwan. Human Health 9(4), pp 319-326.

May, Fred. 2000. Concepts and Terminology: Developing Local Hazard and Risk Analyses. Downloaded from http://www.hazmit.net.SHMO101/HazTerms.htm

Merz (2006): Hochwasserrisiken – Grenzen und Möglichkeiten der Risikoabschätzung, E. Schweizerbart´sche Verlagsbuchhandlung (Näglele u. Obermiller), Stuttgart.

Merz, B., Hall, J., Disse, M. & Schumann, A. (2010): Fluvial flood risk management in a changing world. Nat. Hazards Earth Syst. Sci., 10, 509-527.

Merz, B., Kreibich, H., Thieken, A. & Schmidke, R. (2004): Estimation uncertainty of direct monetary flood damage to buildings. Natural Hazards and Earth System Sciences (4) 153-163

Meyer, V. (2005): Methoden der Sturmflut-Schadenspotentialerhebung an der deutschen Norseeküste, Dissertation at the University of Hannover, UFZ-Dissertation 3/2005.

Morgan, M.G. & Henrion, M., (1990): Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis. Cambridge University Press. 332 pp.

Munich Re (2007): Edition Wissen, Zwischen Hoch und Tief, Wetterrisiken in Mitteleuropa. www.munichre.com

Munich Re (2009): Topics Geo. Natural catastrophes 2009. Analyses, assessments, positions. www.munichre.com

Murphy, B.L. (1998): Dealing with uncertainty in risk assessment. Human and Ecological Risk Assessment, 4(3), 685-699.

Nachtnebel, H.P. (2007): Cost-benefit evaluation of risk reduction options, Proceedings, European Symposium on Flood Risk Management Research (EFRM 2007), 6th – 7th February 2007, Dresden, Germany.

Nachtnebel, H.P. & Debene, A. (2004): Suspended sediment balance in runoff river reservoirs along the Austrian Danube. "Schwebstoffbilanzierung im Bereich von Stauräumen an der österr. Donau". FloodRisk: Endbericht im Auftrag des Lebensministeriums. In: Habersack H., Bürgel J. and Petraschek A.: Analyse der Hochwasserereignisse vom August 2002- Flood Risk, 2004, BMLFUW, Wien, Österreich.

Nachtnebel, H.P. & Faber R. (2009): Assessment and management of flood risks in Austria, Structure and Infrastructure Engineering, 5:4, 333-339.

Nachtnebel, H.P., Faber, R. & Leroch K. (2005): Risikoanalyse des bestehenden Hochwasserschutzes Stadt Gleisdorf und Umgebung. River Basin Agenda, Wien: IWHW, BOKU.

Nachtnebel, H.P.; Holzmann, H.; Neuhold, C.; Haberl, U.; Kahl, B. & Bichler, A. (2009): GEDES: Gefährdung durch Deponien und Altablagerungen im Hochwasserfall - Risikoanalyse und Minimierung - Teilbericht 2, Wien.

Neuhold, C. & Nachtnebel, H.P.(2010a): Assessing flood risk associated with waste disposals: methodology, application and uncertainties. In press: Natural Hazards.

Neuhold, C. & Nachtnebel, H.P. (2010b): Reducing life-threatening conditions during extreme flood events - Benefits from implementing spillways to dykes. In: Custer, R.; Sutter, C. & Ammann, W.J. (eds): International Disaster and Risk Conference IDRC Davos 2010 Proceedings: short and extended abstracts.

Neuhold, C. & Nachtnebel, H.P. (2009): A qualitative approach to assess flood risk associated with landfills. In: Van Gelder, Proske & Vrijling, 7th International Probabilistic Workshop, 343-357; ISBN: 978-3-00-025048-4.

Neuhold, C., Stanzel, P. & Nachtnebel, H. P. (2009): Incorporating river morphological changes to flood risk assessment: uncertainties, methodology and application. Natural Hazards and Earth System Sciences, 9, 789-799; ISSN 1561-8633.

Neuhold, C. & Nachtnebel, H.P. (2008a): Flood risk assessment in an Austrian municipality comprising the evaluation of effectiveness and efficiency of flood mitigation measures. In: Taylor & Francis Group, London, UK, Flood Risk Management-Research and Practise, S 135; ISBN: 978-0-415-48507-4.

Neuhold, C. & Nachtnebel, H.P. (2008b): Detailed residual risk assessment in an Austrian municipality. In:European Geosciences Union, Volume 10, 2008, EGU General Assembly 2008, 14.04.2008-18.04.2008, Wien, ISSN 1029-7006.

Niekamp (2001): Hochwasserschäden. In: Hochwasser–Handbuch. Auswirkungen und Schutz / Hrsg.: Heinz Patt. Springer.

Penning-Rowsell E C, Johnson C, Tunstall S, Tapsell S, Morris J, Chatterton J. & Green C. (2005). The Benefits of Flood and Coastal Risk Management: A Manual of Assessment Techniques, Middlesex University Press, London (The Multi-Coloured Manual).

Penning-Rowsell, E.C. & Chatterton, J.B. (1977): The benefits of flood alleviation: a manual of assessment techniques (The blue manual). Aldershot, UK: Gower Technical Press.

Plate, E.J. (1992): Stochastic design in hydraulics: concepts for a broader application , In: Kuo, J.-T. and Lin, G.F. (eds.), Stochastic Hydraulics ´92, Proc. 6th IAHR International Symposium on Stochastic Hydraulics, Taipei, Taiwan, May, 18-20, 1992, Dept. Civil Engineering, National Taiwan University, Taipei, Taiwan, 663-670.

Plate, E.J. (2002): Flood risk and flood management, Journal of Hydrology, 257 (1-2), 2-11

Popper, K. (1982): The open universe. Hutchinson, London, 185pp.

Rabinovich, S. (1993): Measurement errors: Theory and practice. American Institute of Physics, New York.

Rodriguez (2005): Hochwassergefahrenkarten für Deutschland – Zusammenfassung und Vorschlag für ein koordiniertes Vorgehen der Bundesländer. Teil 1: Voraussetzungen für die Erstellung von Hochwassergefahrenkarten. In: Hochwassergefahrenkarten KLEEBERG, H.-B. (Hrsg. 2005): Hochwasser-Gefahrenkarten. Beiträge zum Erfahrungsaustausch am 24. November 2004 in Erfurt. Heft 08.05 137 Seiten, 32 Abbildungen, ISBN 3-937758-48-8.

Samuals, P., Klijn, F. & Dijkman, J. (2005): River flood risk management policies in different parts of the world: Synsthesis of spezial session by NCR, Proc. Of the 3rd International Symposium on Flood Defence, Nijmegen, the Netherlands.

Schanze, J.; Hutter, G.; Penning-Rowsell, E.; Nachtnebel, H. P.; Meyer, V.; Königer, P.; Neuhold, C.; Harris, T.; Kuhlicke, C. & Olfert, A. (2008): Evaluation of Effectiveness and Efficiency of non-structural measures in Flood Risk Management. Proceedings of the 4th International Symposium on Flood Defence, 4, 10-ff.

Schanze, J., Hutter, G., Harris, T., Koeniger, P., Kuhlicke, C., Meyer, V., Nachtnebel. H.P., Neuhold, C., Olfert, A., Parker, D., Penning-Rowsell E. & Schildt A. (2008): Systematisation, Evaluation and Context Conditions of Structural and Non-Structural Measures for Flood Risk Reduction. FLOODERA joint report, published by ERA-NET CRUE, London.

Schmidke (2000): Klimaveränderung – sozioökonomische Konsequenzen. Karlsruhe: Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), 269-276. http://www.kliwa.deStatistik Austria (2005 a): Ein Blick auf die Gemeinde http://www.statistik.at/blickgem/gemList.do?bdl=6.

Sendi, P., Gafini, A. & Birch, S. (2002): Opportunity costs and uncertainty in the economic evaluation of health care interventions. Human Health 11(1): 23-31.

Singh, V.P. (1996): Dam breach modelling technology, Kluwer Academic Pub.

Smith, K. & Ward, R. (1998): Floods – Physical processes and human impacts. Chichester.

Statistik Austria (2005 a): Ein Blick auf die Gemeinde http://www.statistik.at/blickgem/gemList.do?bdl=6.

Statistik Austria (2005 b): Leistungs- und Strukturstat. http://www.statistik.at/unternehmen/lse3_05.pdf.

Stegmann, R. & Heyer, K.-U. (1995): Langfristiges Gefährdungspotential und Deponieverhal-ten von Ablagerungen. Statusseminar Deponiekörper, Wuppertal.

United Nations, International Strategy for Disaster Reduction (ISDR). 2002. Living With Risk: A Global Review of Disaster Reduction Initiatives (preliminary version). Geneva: UN ISDR, July.

UN (2009): 2009 Global Assessment Report on Disaster Risk Reduction. Risk and poverty in a changing climate. United Nations.

van Asselt, M.B.A. & Rotmans, J., (2002): Uncertainty in integrated assessment modelling. Climate Change, 54 (1), 75-105.

Veen, A. van der, Steenge, A.E., Bockarjova, M. & Logtmeijer, C.J.J. (2003): Structural economic effects of large scale inundation: a simulation of the Kimpen kike breakage,. EUR Report 20997 EN. Office for Official Publications of the European Communities. Burxelles: European Commission.

WebFinance, 2010: BusinessDictionary.com. online query

Young, S., Balluz, L. & Malilay, J. (2004): Natural and technologic hazardous material re-leases during and after natural disasters: a review. Science of The Total Environment 322, pp. 3-20.

Zio., E. & Apostolakis, G.E., (1996): Two methods for the structured assessment of model uncertainty by experts in performance assessments of radioactive waste repositories. Reliability Engineering and System Safety, 54, 225-241.

Zagonjolli, M. (2007): Dam break modelling, risk assessment and uncertainty analysis for flood mitigation, dissertation, Delft University of Technology.

Uncertainty analysis

***Neuhold, C.**, Stanzel, P.,& Nachtnebel, H. P. (2009): Incorporating river morphological changes to flood risk assessment: uncertainties, methodology and application*

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Abstract:

Risk zonation maps are mostly derived from design floods which propagate through the study area. The respective delineation of inundated flood plains is a fundamental input for the flood risk assessment of exposed objects. It is implicitly assumed that the river morphology will not vary, even though it is obvious that the river bed elevation can quickly and drastically change during flood events. The objectives of this study were to integrate the river bed dynamics into the flood risk assessment procedure and to quantify associated uncertainties. The proposed concept was applied to the River Ill in the Western Austrian Alps. In total, 138 flood and associated sediment transport scenarios were considered, simulated and illustrated for the main river stem. The calculated morphological changes of the river bed at the moment of peak flow provided a basis to estimate the variability of possible water surface levels and inundation lines which should be incorporated into flood hazard assessment. In the context of vulnerability assessment an advanced methodological approach to assess flood risk based on damage probability functions is described.

Introduction and objectives

Alluvial river beds are subjected to severe morphological changes during flood events which have significant implications for the water level (Nachtnebel and Debene, 2004). This effect has to be considered in the delineation of flood endangered riparian zones. Risk zonation maps are mostly derived from single design floods which represent a hazard based on a specified return period. The respective delineation of inundated areas and the estimation of flow depths and flow velocities are fundamental inputs for flood risk estimation of exposed objects. For this purpose in most cases 2D hydrodynamic unsteady models are applied (BMFLUW, 2006 a). It is implicitly assumed that the morphology will not change; neither during flood events nor by long term erosion or deposition. However, it is obvious that the river bed elevation can change quickly and drastically. Quantitatively and qualitatively observed morphological developments during and after flood events indicate, to some extent, tremendous changes in river bed elevation due to sediment transport, log jam, rock jam, etc. The occurrence of such processes clearly implies the necessity of incorporating calculated or estimated morphological changes to the flood risk assessment procedure. Therefore, the influence of sediment transport on the respective water surface elevation which is in most cases neglected during flood events and related uncertainties are investigated.

It is obvious that uncertainty increases as an additional process is considered. The identification of partially known impacts on the water surface elevation and accordingly the possible inundation depth as well as delineation could, however, lead to an increase of awareness and an adaptation of flood risk management strategies. The study focuses on uncertainties related to hazard assessment covering aspects of hydrology, hydraulics and sediment transport. Furthermore, the study aims to enhance methodologies of vulnerability assessment and therefore, damage estimation by providing a direct link of probability distribution functions of inundation depths with the respective damage functions of flood-prone utilisations (damage-probability relationship).

The concept was tested on the Ill catchment which has suffered three major floods during the recent past (1999, 2000 and 2005). The considered catchment area is characterized by torrential tributaries, hydraulic structures, hydropower plants and partially complex morphological characteristics. Therefore, it was crucial to apply a model with no restrictions and limitations regarding internal and external boundary conditions. Apart from these demands, a calculation in different fractions of sediment was required.

The paper gives an overview of sources of uncertainty to outline complexity and lack of approaches as well as methodologies to quantify risk. Following this introduction the study area is characterized, the applied methodology is described in detail and the results of the conducted study is presented before conclusions are given.

Uncertainties

The assessment of flood damage imports uncertainties from the climatic, hydrologic and hydraulic domain, adds some of its own uncertainties and exports the resulting composite uncertainties to the decision domain (Messner et al., 2007). Contemplating the above mentioned uncertainties, a distinction has to be made between reducible (epistemic) and irreducible (aleatoric) uncertainty (Merz, 2006, Apel et al., 2008, Hall and Solomatine, 2008). Aleatoric uncertainty results from the variability and unpredictability of the considered natural processes. Epistemic uncertainty is a product of imperfect knowledge (lack of research, measurements and models) of the examined system. Murphy (1998) subsumes three origins of uncertainties: the incompleteness of considered **scenarios** and assumptions as well as simplifications inherent to **models** and **model parameters** as described in the following sections.

Scenario uncertainty

Risk analysis is typically characterized by sets of a few damage scenarios. Obviously, these scenarios cannot cover all the possible future events and their definition is based, to a larger extent, on subjective expert judgements. There are always scenarios that will not be considered because of:

- Low probability of recurrence and therefore, a negligible ("not significant") influence on the overall expected losses
- Lack of data and methodologies to calculate or describe rare events
- Deficit of experience and analytical skills of the person responsible

Incompleteness and representation of a collection of damage scenarios are fundamental problems in the frame of risk assessment (Kaplan and Garrick, 1981). Incompleteness leads to uncertain results and accordingly, the underestimation of risk. Uncertainty can be reduced by experience and sound methodological approaches. It is essential that the chosen scenarios are representative for the overall considered system. The set of scenarios should also include the worst case scenario even though it might have little impact on the result due to its recurrence interval.

Model uncertainty

The overall uncertainty of many surveys is dominated by model uncertainty (Kuikka and Varis, 1997). Merz (2006) stated that model uncertainty emerges from:

- Model assumptions and composition
- Model sufficiency (completeness)
- Model domain and resolution

Precipitation-runoff models, hydrodynamic models and sediment transport models rest upon simplified model assumptions. To some extent, there are alternative or even contradicting assumptions or theories of model development. Models are approximations of natural processes - their composition demands decisions upon which processes should be described and which accuracy and abstraction is necessary or possible. Moreover, the spatial and temporal discretisation of models influences uncertainty and should be determined as a compromise of computing time and approximation degree. To summarise, a maxim can be stated: a model should be composed as simply as possible but as complex as necessary (Popper, 1982).

Natural variability and parameter uncertainty

Parameter uncertainty comprises uncertainty related to model parameters and variables. These are mainly parameters and variables representing measurable attributes of the considered system e.g. intensity of precipitation, infiltration capacity of soil, failure rate of system components or costs due to blocking roads. Uncertainty of parameters and variables results from:

- **Variability:** Processes triggering extreme flood events are subjected to natural variability. The parameters representing these processes vary over time and space (Haimes, 1998). Plate (1992) stated that this variability is inherent to all natural processes. Regardless of how high the monitoring effort might be, it will never be possible to fully predict and describe these processes by means of a deterministic model. Uncertainty related to variability is traditionally covered by probabilistic methods (Apel et al., 2006, Apel et al., 2008, Merz, 2006).

- **Limited information:** Frequently there are statistical dependencies between variables used for risk analyses. In many cases data availability is not sufficient to describe these dependencies, which leads to an additional source of uncertainty in the frame of risk analyses (Merz, 2006).
- **Parametric uncertainty**
    - Measurement inaccuracy leads to random variation in measurements. To detect these **random errors** statistic methods (standard deviation, confidence interval etc.) are applied (Rabinovich, 1993).
    - However, **systematic errors** can occur due to e.g. inaccurate calibration and experiment design. Systematic errors are rarely known since the true value is not determinable (Rabinovich, 1993, Ferson and Ginzenburg, 1996).
    - Parameter uncertainty can result from simplified descriptions – **approximations** – of data and parameters, e.g. by representing a continuous random variable with a discrete one.

As a supplement to variables there are indicators and parameters representing ideals and moral concepts (e.g. value of human life expressed in salvage expenses or risk aversion factors) which influence the risk analysis (Haimes, 1998). These parameters represent a significant source of uncertainty in the frame of risk analysis.

Study area

The presented survey was carried out in the Ill river basin with a catchment area of 1300 km², situated in the Western Austrian Alps (Fig. 1). The River Ill, with a mean annual discharge of 66 m³/s, is the main river catchment in south-eastern Vorarlberg, the most-western federal state of Austria. Hydro-meteorological observations of precipitation, air temperature and runoff were gathered. Elevations range from 400 to 3000 m. a. s. l. and the mean annual precipitation averages 1700 mm. A 100-year flood event is estimated at 820 m³/s. Current, as well as historical surveying data (since 1978), were provided for 60 km of the River Ill and, altogether, 15 km of 8 tributaries comprising cross section measurements (with distances of 100 m on average) and airborne laser scan data. Sediment samples were drawn in 71 locations. Additional information on geographical features of the catchment (elevation, land cover, cadastral information and soil type) and on hydropower influence on the runoff regime was considered (Nachtnebel and Neuhold, 2008, Nachtnebel and Stanzel, 2008).

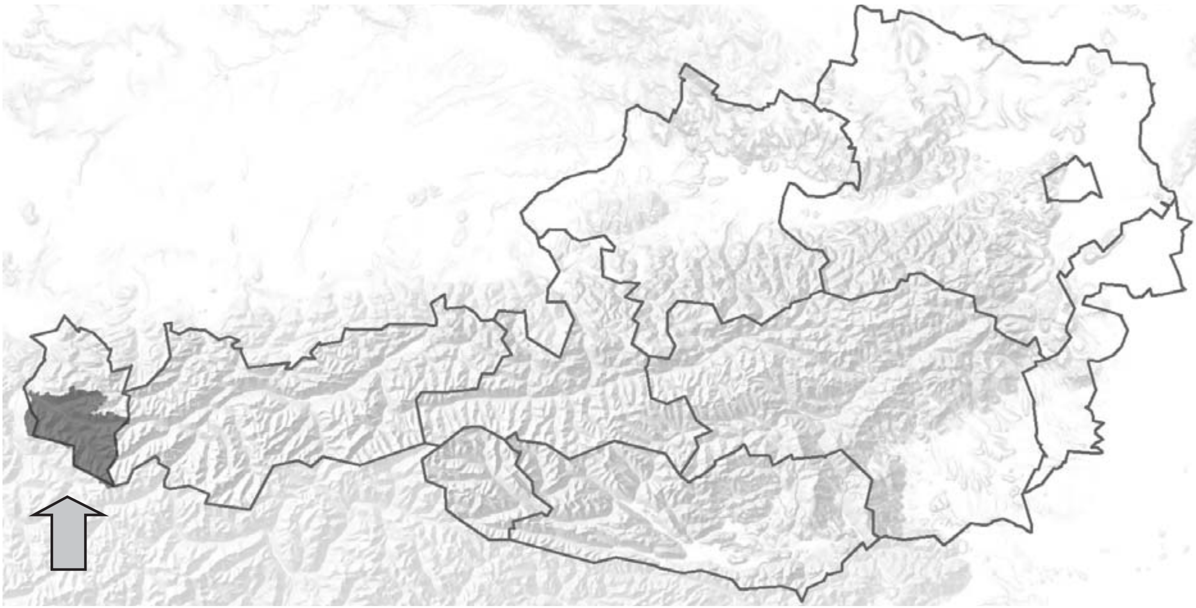

Fig. 1: Study area: Austria and the Ill river catchment in the west

Methodology

The applied methodological approach was elaborated to analyse and quantify variability and uncertainty of single steps in the frame of hazard assessment and to enhance methodologies of vulnerability assessment. Therefore, the derivation of hydrological input, possible changes in river bed elevation due to sediment transport and the effects on water surface elevations and subsequent potential dyke overtopping and inundation were dissected. Vulnerability analyses and damage estimation tools were methodologically improved by connecting the overtopping probability, the variability of inundation depths and object related damage functions to obtain a damage-probability relationship (Fig. 2).

Initially, the hydrology of the catchment was simulated with a semi-distributed precipitation-runoff model. Variability of the hydrograph was obtained by generating numerous scenarios with different initial moisture conditions and by considering different spatial and temporal distributions, durations and amounts of rainfall. The hydrologic model provided runoff scenarios which were subsequently used as an input for the hydraulic and sediment transport model. Additionally, the variability of possible morphological changes due to torrential sediment entry was analysed. For this purpose scenarios with randomly drawn sediment loads from torrential inflows based on probability distribution functions were developed to account for the uncertainty caused by sediment input to the system. The calculated morphological changes of the river bed provided a basis to estimate the variability of water surface levels and inundation lines which should be considered in flood hazard maps and flood risk maps. For each scenario the water table, river bed elevation and the respective inundation lines as well as inundation depths were obtained. Therefore, each exposed object can be linked to a distribution function consisting of estimated damages related to flood inundation height and inundation probability.

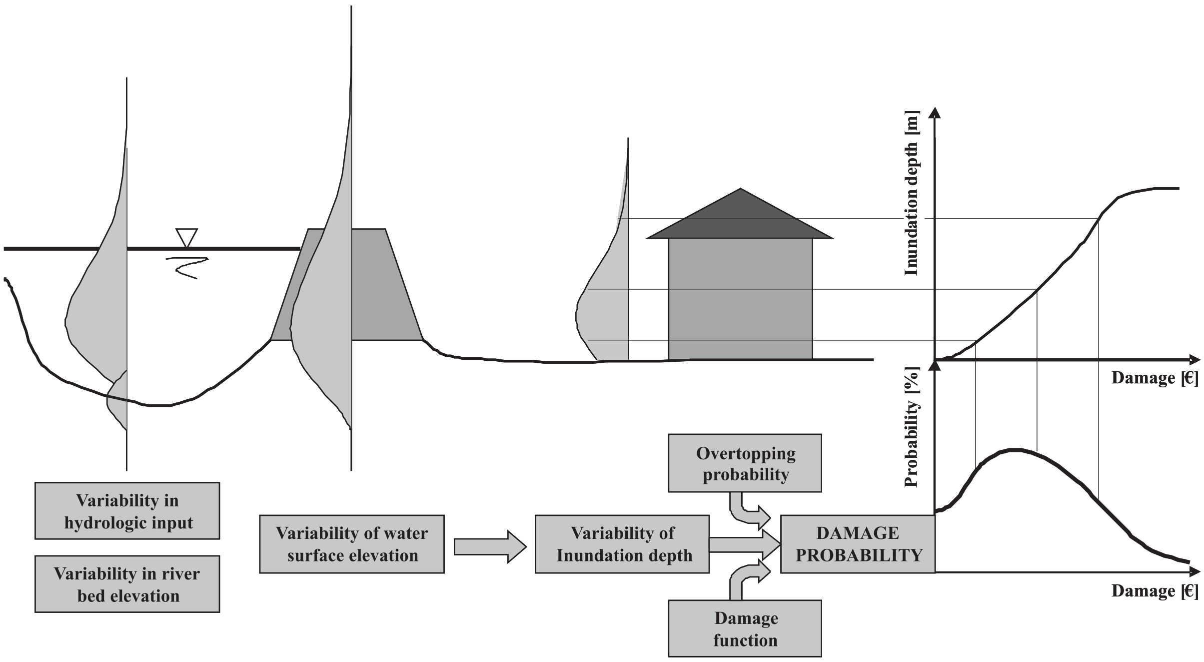

Fig. 2: Scheme of methodological approach to derive the damage probability of vulnerable utilisations

Hydrology

The continuous, semi-distributed rainfall-runoff model, COSERO, developed by the Institute of Water Management, Hydrology and Hydraulic Engineering, BOKU (Nachtnebel et al., 1993, Kling, 2002 among others) was applied to the Ill catchment. This model accounts for processes of snow accumulation and melt, interception, evapotranspiration, infiltration, soil storage, runoff generation and routing. Separation of runoff into fast surface runoff, inter flow and base flow is calculated by means of a cascade of linear and non-linear reservoirs. Spatial discretisation relies on the division of the watersheds into sub-basins and subsequently into hydrologic response units (HRUs).

The Ill watershed was divided into 37 sub-basins, based on the location of runoff gauges, anthropogenic diversions and reservoirs, with sub-basin areas ranging from 10 to 200 km² (Fig. 3). 828 HRUs, with a mean area of 1.6 km², were derived by intersection of 200 m-elevation bands with soil type data (Peticzka and Kriz, 2005) and land use data (Fürst and Hafner, 2005).

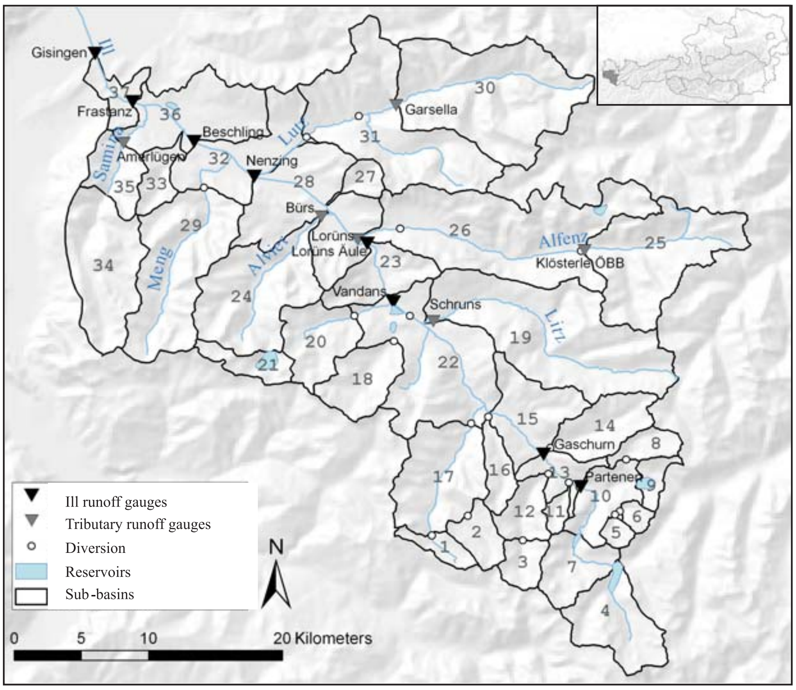

Fig. 3: Watershed of the River Ill and its sub-basins

The model was calibrated and validated based on observed discharge hydrographs of 6 years with continuous daily records and hourly records for 16 flood periods, measured at 14 gauges. Calibrated parameters of gauged sub-basins were transferred to neighbouring ungauged sub-basins. Storage coefficients for base flow and interflow, which correlated well with catchment size for the calibrated sub-basins, were assigned according to this relation. After this, storage coefficients for fast runoff were allocated in order to achieve characteristics of runoff separation into surface flow, interflow and base flow as simulated in neighbouring calibrated sub-basins with similar physical features. Nash-Sutcliffe model efficiencies (Nash and Sutcliffe, 1970) between 0.80 and 0.90 for the calibration period and between 0.75 and 0.85 for the validation period were achieved. Mean relative peak errors of the 16 simulated flood periods ranged between -15 % and +10 %.

After calibration, the rainfall-runoff model was applied to simulate flood runoff scenarios. Design storms with assumed return periods of 100 years were used as input. The underlying assumption of using design storms with a 100-year recurrence interval is that they may produce flood peaks of the same return period. While this premise can be regarded as appropriate for design purposes, it is clear that a rainstorm with a given return period may cause a flood with a higher or lower return period (Larson and Reich, 1972). This is mainly due to factors affecting the runoff peak like the distribution of rainfall in time and space or antecedent soil moisture. Therefore, several scenarios, with variations of major influencing factors, were defined. Precipitation scenarios were obtained by varying total precipitation depth, storm duration and temporal and spatial distributions. Each rainfall scenario was combined with three different initial catchment conditions, which were selected from simulated state variables of historical flood periods.

Storm duration of 12 and 24 hours were selected for the assessment. Recorded events leading to floods in the years 2000, 2002 and 2005 showed rainfall duration within this range. These assumptions are also in accordance with the common procedure of testing storm duration up to twice the concentration time which is estimated as being 11 to 13 hours for the Ill catchment (BMLFUW, 2006 b). Precipitation depths of 100-year storms with 12 hours duration were provided by a meteorological convective storm event model (Lorenz and Skoda, 2000). Design storms based on these meteorological modelling results are recommended by Austrian authorities (BMLFUW, 2006 b) and therefore, are a common basis for design flood estimations in Austria. The values given by this model refer to point precipitation. Areal precipitation, to be used as input for rainfall-runoff modelling, is obtained by reducing the point precipitation values with areal reduction factors (ARF). The developers of the convective storm event model recommend two different procedures to determine such factors, both depending on catchment area, precipitation depth and duration of the storm (Lorenz and Skoda, 2000, Skoda et al., 2005). ARF resulting from these two calculations varied considerably and defined the range of ARF values used to reduce mean 12-hour point precipitation depths for the Ill catchment. As the analysis of longer events was also intended, precipitation depths of 24-hour storms were based on statistical extreme value analyses provided by local Austrian authorities and values from the Hydrological Atlas of Switzerland (Geiger et al., 2004).

Total precipitation depth was disaggregated to 15-minute time steps applying three different temporal distributions, with peaks at the beginning, in the middle or at the end of the event. Three different spatial distributions were considered: a uniform distribution, a distribution with higher precipitation in the south and another with higher precipitation in the north of the watershed. The spatial patterns of the two non-uniform distributions correspond with typical distributions of precipitation in the catchment.

The described variations in the parameters: storm duration, areal reduction factors as well as associated precipitation depths and temporal plus spatial distributions of rainfall, generated 42 precipitation scenarios. The combination with three different initial catchment conditions led to 126 runoff scenarios (Fig. 4).

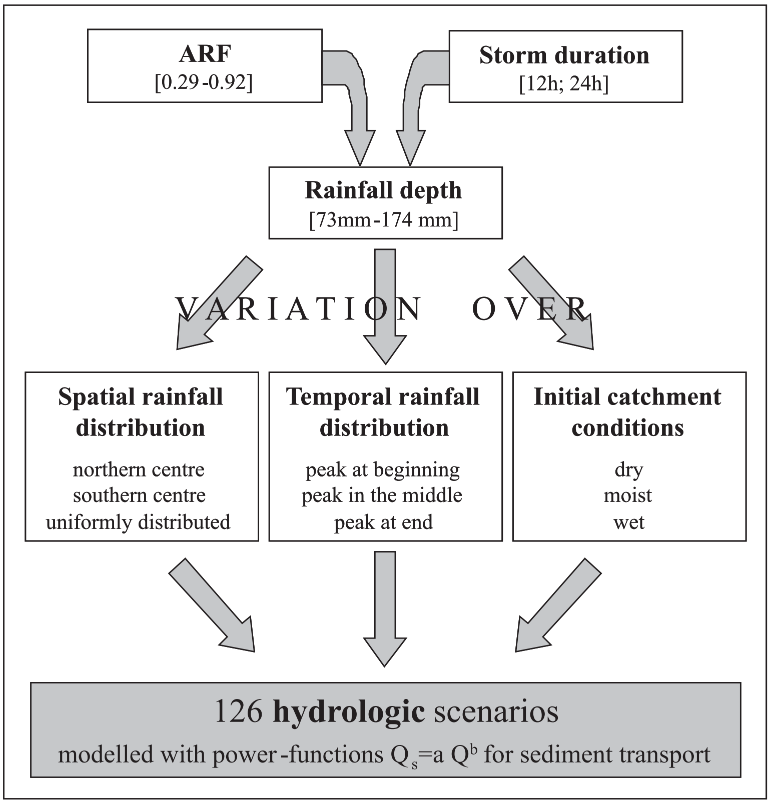

Fig. 4: Derivation of scenarios for hydrologic input variation

Hydrodynamics and sediment transport

The software package GSTAR-1D Version 1.1.4, developed by the U.S. Department of the Interior (Huang and Greimann, 2007), which includes 16 different sediment transport algorithms was applied. GSTAR-1D (Generalized Sediment Transport for Alluvial Rivers – One Dimension) is a one-dimensional hydraulic and sediment transport model for use in natural rivers and man-made canals. It is a mobile boundary model with the ability to simulate steady or unsteady flows, internal boundary conditions, looped river networks, cohesive and non-cohesive sediment transport, and lateral inflows. The model uses cross section data and simulates changes of the river bed due to sediment transport. It estimates sediment concentrations throughout a waterway given the sediment inflows, bed material, hydrology and hydraulics of that waterway. Resulting from the one-dimension solutions for flow simulation the limitations are the neglection of cross flow, transverse movement, transverse variation and lateral diffusion. Therefore, the model cannot simulate such phenomena as river meandering, point-bar formation and pool-riffle formation. Additionally, local deposition and erosion caused by water diversions, bridges and other in-stream structures cannot be simulated (Huang and Greimann, 2007).

The model was calibrated and validated with runoff data from seven gauging stations by varying calculated roughness coefficients based on sediment samples. The sediment transport was calibrated and validated on historical cross section measurements (1978-2006) and the respective runoff time series as well as by balancing the calculated volumes of transported sediments. Hydrological input to the model was delivered by the precipitation-runoff model. Boundary conditions as well as initial conditions concerning sediment transport were defined and derived from 71 drawn sediment samples.

A focus point of the study was to analyse and quantify modifications of river morphology and potential sediment inputs from torrential tributaries for extreme runoff scenarios (HQ_1, HQ_5, HQ_{30} and HQ_{100}). Considerable uncertainty rested upon the estimation of the input from torrential inflows. Therefore, the observed flood event from 2005, with an estimated recurrence interval of 100 years, was investigated in more detail. This approach accounts for the uncertainty of design-flood-event-based approaches, like state-of-the-art methodologies for flood hazard mapping, whenever influences of morphological changes are neglected.

Sediment transport models were compiled for the main river system and eight tributaries. Two river bed conditions were defined for each tributary. The first of these assumed a fully-armoured upper layer with a mean layer thickness of 15 cm and the second model scenario calculated a river bed without any armouring. Therefore, this second state estimated the river’s potential of sediment transport. Hence, two restricting transport functions were defined for each observed, measured and simulated tributary river (eight torrential inflows, see example for the River Alfenz in Fig. 5).

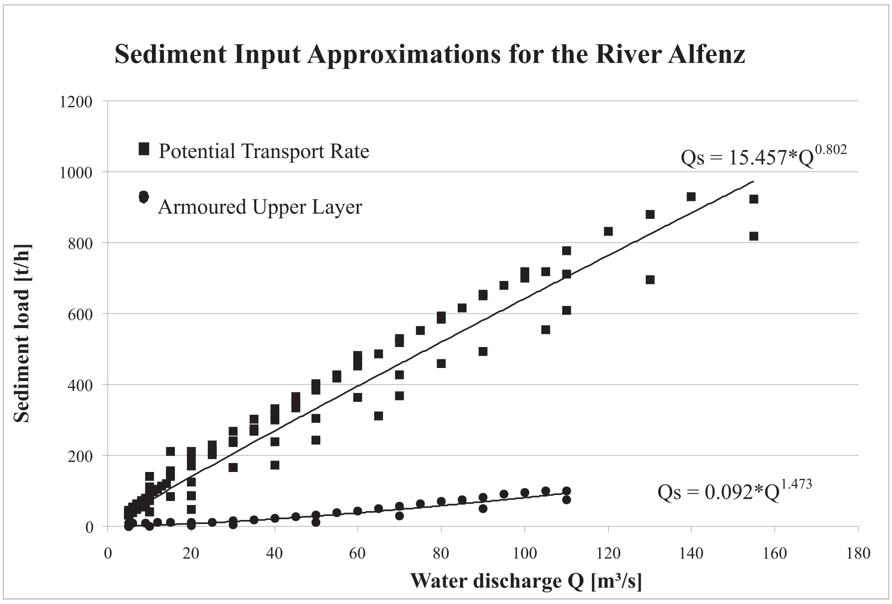

Fig. 5: Upper and lower sediment input boundary condition for the River Alfenz

Input functions for 47 unobserved torrents were estimated on the basis of simulation results of observed tributaries. Sediment routing was solved with the Meyer-Peter and Müller formula (1948, Eq. (1)), which is appropriate for alpine gravel-bed rivers:

$$q_b^{2/3}\left(\frac{\gamma}{g}\right)^{1/3}\frac{0.25}{(\gamma_s-\gamma)d}=\frac{(K_s/K_r)^{2/3}\gamma RS}{(\gamma_s-\gamma)d}-0.047 \qquad (1)$$

Where γ and γ_s = specific weights of water and sediment, respectively, R = hydraulic radius, S = energy slope, d = mean particle diameter, ρ = specific mass of water, q_b = bed load rate in under water weight per unit time and width, K_s = conveyance, K_r = roughness coefficient and $(K_s/K_r)S$ = the adjusted energy slope that is responsible for bed-load motion.

In addition to 126 scenarios related to varying input hydrographs (Fig. 6), 12 scenarios were generated to elaborate the influence of randomly chosen sediment input events on bed elevation behaviour during high floods. Therefore, a minimum (armoured upper layer for all tributaries) and a maximum (no armouring for all tributaries) scenario, related to the restricting transport functions (Fig. 5), were defined. Within these extremes, 10 scenarios were compiled by randomly drawing input capacities of each torrential inflow dependent on the magnitude of the associated flood peak in the torrential sub-catchment. Thereby, maximum input represents an extreme event in the tributary itself and minimum input accounts for lower rainfalls in the sub-catchment.

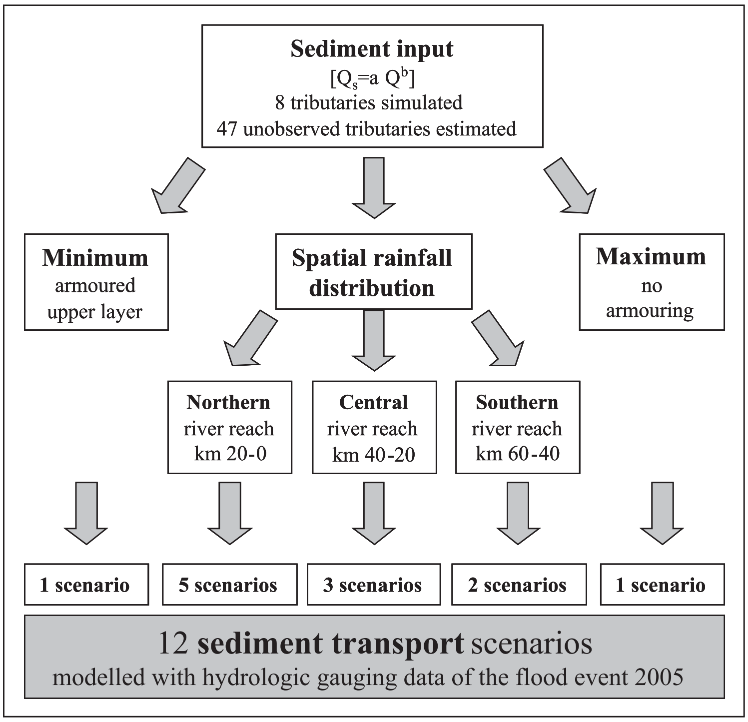

Fig. 6: Derivation of scenarios for sediment input variation

The catchment area was divided into three sections of varying sediment input intensity (river kilometres 60-40, 40-20 and 20-0) to obtain realistic input distributions. In the frame of the 10 scenarios only one of the three sections was allowed to be dominant by means of sediment input. Furthermore, a boundary condition for the acceptance of a randomly chosen scenario was defined: a minimum percentage of 50 % related to the section's torrential catchment areas had to deliver maximum sediment input to account for rainfall clusters. The 12 resulting scenarios were simulated with observed and revised runoff data taken from the 2005 flood event with an estimated recurrence interval of 100 years (Fig. 6).

Risk assessment

The methodological enhancement was based on the risk assessment approach by BUWAL (1999 a, b) which is characterised by a three-stage procedure. Each stage represents a self-contained step for risk analysis. Stages 1, 2 and 3 are arranged in increasing order of analytical detail. Risk can be analysed in one or more of the stages depending on the desired accuracy. In stage 1, the hazard map is overlaid with a land use map to identify potential objects at risk.

In stage 2, the risks for spatial elements are quantified. Risks can, however, be analysed directly in stage 2 which is based on standardized damage values obtained by analyzing various ex-ante as well as ex-post damage estimations and documentations (Buck, 1999, BMFLUW, 2004, BUWAL, 1999 a, b, BWG, 2002, Eberstaller, 2004, Faber, 2006, Nachtnebel and Faber, 2007, HYDROTEC, 2004, Kraus, 2004, Merz et al., 2004, Merz, 2006, Nachtnebel et al., 2005, Nachtnebel, 2007, Neuhold and Nachtnebel, 2008 a, b, Niekamp, 2001, Rodriguez, 2001, Schanze et al., 2008, Schmidke, 2000, Statistik Austria, 2005 a, b).

In stage 3, risks are analysed on a micro scale level by specific investigations of individual objects (e.g. a building or section of a transport route at risk) (BUWAL, 1999 a, b) and linking them to damage functions (inundation depth related to damage estimates).

Based on the micro scale level of stage 3 and, additionally, accounting for the variability of single processes (hydrology, hydrodynamics and sediment transport), derivations of probability distribution functions for object related inundation depths can be obtained. Whereas, the variability of the water surface elevation (V_{WSE}) is dependent on the variability of the bed elevation (V_{BE}), as well as on the variability of the hydrologic input (V_{HI}).

$$V_{WSE} = f(V_{BE} | V_{HI}) \tag{2}$$

Relating the resulting variability of the water surface elevation (Eq. (2)) with the dyke top edge elevation (h), the variability of inundation depth (V_{ID}) can be obtained on a micro scale basis (Eq. (3)).

$$V_{ID} = f(V_{WSE} | h) \tag{3}$$

Corresponding to utilisation related damage functions (f_D), typically based on the inundation depth (h_I) and the associated damage (D), a damage probability function (f_{DP}) can be derived by multiplying the damage function (inundation depth dependent) with the variability of the inundation depth (Fig. 2, Eq. (4)).

$$f_{DP} = V_{ID} * f_D(D | h_I) \tag{4}$$

Results

The following describes the variability and uncertainty related to the processes hydrology, hydrodynamics and sediment transport as well as risk assessment based on the scenario analyses. The results of hazard assessment are expressed quantitatively, the results of vulnerability assessment qualitatively.

Hydrology

Fig. 7 illustrates 126 resulting 100-year flood waves as described in Fig. 4 for the catchment outlet at Gisingen as well as the relative distribution of the associated peak discharges. The effects of the applied parameter variations, which can be seen as a way of taking into account various uncertainties related to the hydrological assessment of design floods, are shown in Tab. 1.

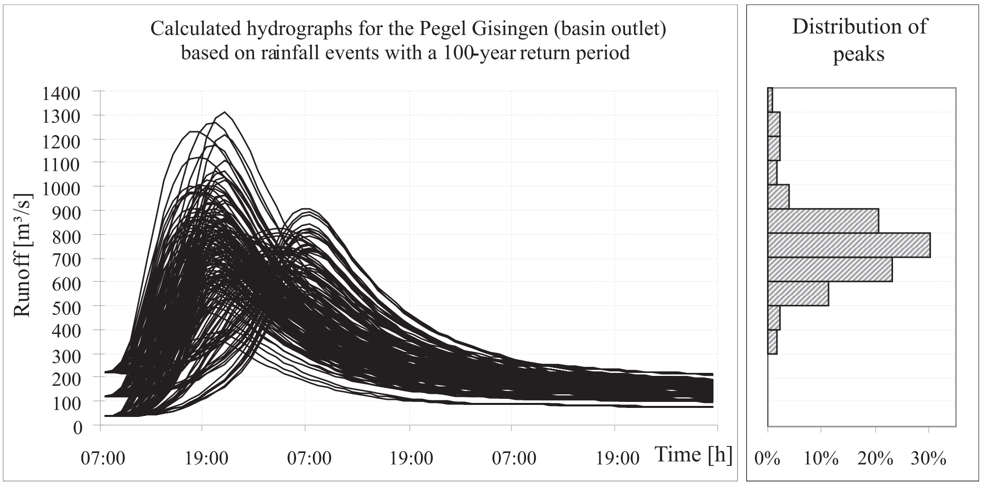

Fig. 7: Calculated hydrographs for 100-year rainfall events and distribution of simulated peak values

Tab. 1: Sensitivity of flood peaks due to input variation for Gisingen (basin outlet)

Varied Parameter	Mean variation of simulated runoff peaks at Gisingen
Spatial rainfall distribution	4 %
Temporal rainfall distribution	11 %
Initial catchment conditions	27 %
Areal reduction factor	88 %

Each variation of a single parameter over the full range of applied values – while keeping the others constant – yielded a maximum variation in resulting runoff peaks. For a relative measure this value was related to the mean of runoff peaks. The values given in Table 1 are the mean of relative peak variations for all considered scenarios. This mean relative variation shows the sensitivity of the flood simulation to changes in the respective parameter and establishes an evaluation approach for the respective uncertainty.

Regarding the basin outlet at Gisingen, the spatial distribution of rainfall had the smallest impact on flood peaks, because it is averaged over the catchment area. Obviously, this impact was much higher at the most-upstream gauges with a smaller catchment area (with either high or low precipitation), with relative runoff peak variations of up to 117 %. The mean variation for all Ill gauges was 41 %. Even though only three different spatial patterns were tested in this study, this shows that the importance of considering uncertainty of spatial rainfall distribution for design flood simulations depends on the spatial focus of the subsequent assessment. Other parameter variations lead to similar runoff peak variations at the basin outlet and at upstream gauges. The variation of ARF for 12-hour storms had by far the largest effect on simulated flood hydrographs, as it directly altered the total depth of a precipitation scenario. Storm duration, the second parameter influencing total precipitation depth could not directly be assessed for the River Ill, because 12-hour and 24-hour storms were determined with different methods and other factors apart from duration influenced the resulting total depth. An evaluation of 2 to 12-hour storms resulting only from the described meteorological convective storm model for Ill tributary sub-catchments showed mean variations in simulated runoff peaks of 20 % (Stanzel et al., 2007). In this analysis also uncertainty related to the estimation of fast runoff model parameters was investigated. Resulting runoff peak variations in tributary rivers were rather small (5 %) – as better observations were available for calibration on the River Ill, the effects of uncertainty in parameter estimation is assumed to be even smaller when regarding the entire basin.

In relation to the normative 100-year design value of 820 m³/s at the gauge in Gisingen, the simulated peaks ranged from 45 % to 160 %. Several peaks were far below as well as over the 90 % confidence interval of statistical extreme value analyses of observed runoff, underlining that 100-year rainfall events produce flood events of different return periods. Yet, the large range of hydrographs shows how much of the possible variability of flood waves is disregarded by a design flood approach.

Hydrodynamics and sediment transport

Hydrodynamic and sediment transport simulation results are, as an example, illustrated for a highly dynamic section (km 30 to 29) chosen from the considered 60 km. The selected river section is characterised by a torrential inflow located at the upper boundary. The sediment input function of this torrential inflow is documented in Fig. 6. The first 300 m of the considered reach are dominated by hydraulic structures (in- and outflow for energy generation, weir and chute) which cause spacious accumulations of sediment due to a reduction of flow velocity and accordingly to lower shear stress (Nachtnebel and Neuhold, 2008). In the case of higher discharge the accumulated sediment moves downstream where a dynamic river bed is encountered.

In Fig. 8 the modifications of river bed elevations due to hydrological and sediment input variations are illustrated. The three lines represent the maximum (dark grey), the mean (dashed grey) and the minimum (light grey) calculated bed elevation changes resulting from varying the discharge (Fig. 7) by means of 126 scenarios (Fig. 4). The inflow of the tributary just before km 30 leads to locally calculated accumulations of almost 0.80 m. The black vertical lines indicate the station of the considered cross sections and display the range of calculated bed elevation changes due to randomly selected sediment input of torrential inflows. The magnitude is based on the simulation of 12 input scenarios (Fig. 6) with a minimum input due to assumed armoured bed layers and a maximum sediment input represented by the restricting transport functions (Fig. 5).

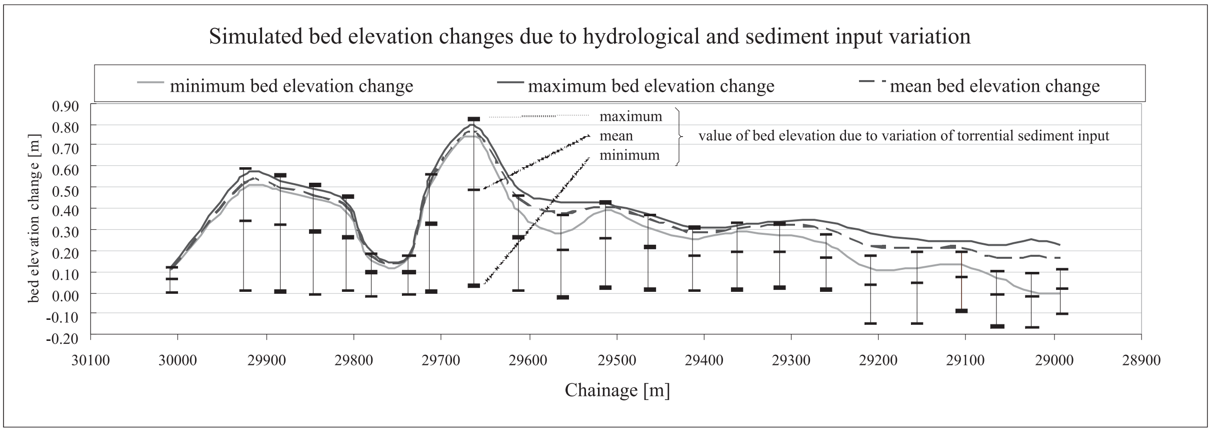

Fig. 8: Changes of river bed elevations due to hydrological and sediment input variation

Fig. 9 outlines the maximum and minimum differences between water surface elevation and embankment elevation. The continuous lines correspond to the orographic right-hand hinterland where numerous utilisations such as private housing are situated. The thicker lines define the limits due to hydrological input variation and the thinner ones, the limits due to sediment input scenarios. Corresponding to the orographic left-hand side, where no utilisations worthy of protection were recorded, results are represented by grey dashed lines (thick for hydrology and thin for sediment input). The value 0.00 represents a water surface elevation equal to the dyke top edge. Overtopping occurs when displayed lines show positive values.

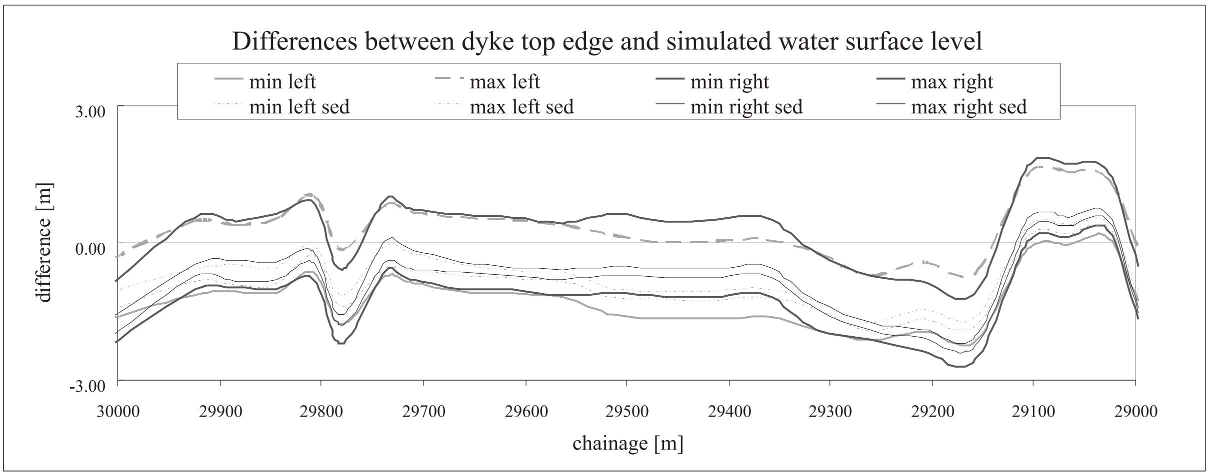

Fig. 9: Differences of water surface elevations and dyke top edge

Due to hydrologic input variation (126 scenarios – 25 % of them exceed the design water level, see Fig. 7), a high probability of overtopping is indicated. Considering sediment input variation (12 scenarios) based on discharge data of a 100-year flood (2005) only the lower part of the section is subjected to inundation. From chainage 29,100 m to 29,000 m even the minimum values of calculated water surface elevations lead to inundation of the flood plain. Therefore, damages have to be expected prior to the design value of the protection scheme (recurrence interval of 100 years, including freeboard).

Risk assessment

The associated uncertainty of results obtained by design-flood-based procedures (BMFLUW, 2006 a) is emphasized by the overtopping probability caused by 138 considered scenarios (Fig. 10). Alongside the River Ill settlements and utilisations are mainly protected by dykes and natural barriers with an estimated flood safety up to a recurrence interval of 100 years. Fig. 10outlines the probability of overtopping along the 60 km due to variation of discharge input (126 scenarios).

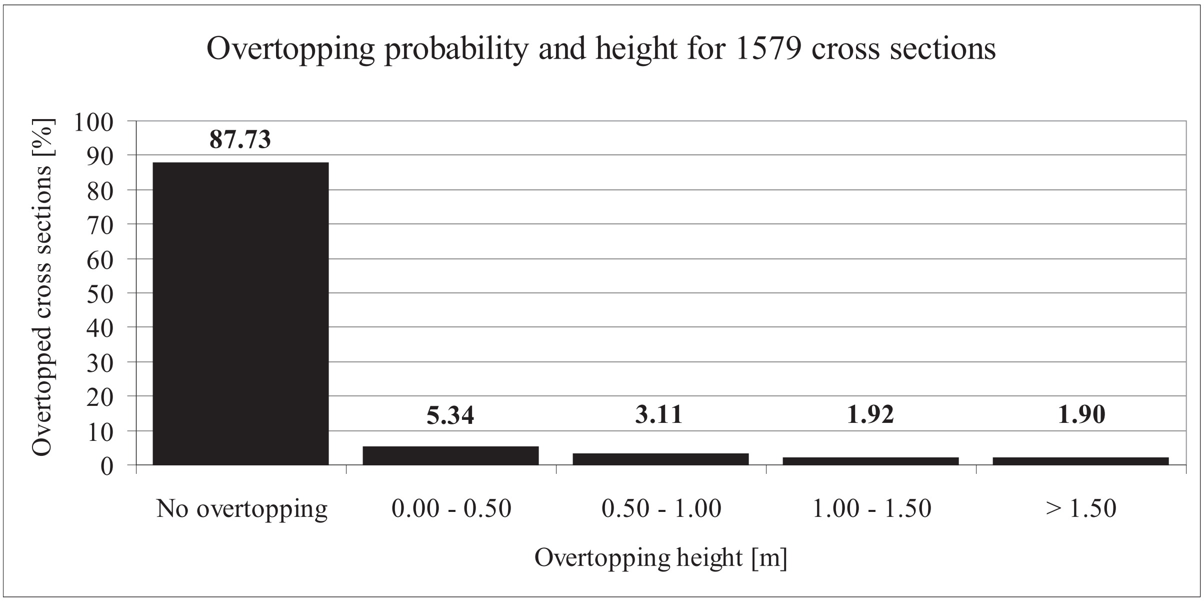

Fig. 10: Overtopping probability and height

The calculated overtopping probability of 12.27 % indicates that 7.4 km are not protected against floods caused by 100-year rainfall events which had not been previously identified as such. In the frame of this study affected utilizations were not elaborated in detail. The analysis of the section displayed in Fig. 9 (km 30-29) proves that there are also settlements in the inundated areas. Referring to the results of the hydrological input variation, it has to be distinguished, that considered discharges resulting from 100-year rainfall events lead to as much as 160 % of the applied design value discharge (normative 100-year flood event) for the gauge furthest downstream. Analysing scenarios by means of sediment input variation obtained by an observed 100-year flood event in the year 2005 the overtopping probability equals 1.59 % for the entire reach. Nevertheless, at 40 cross sections dykes or barriers are overtopped and therefore most likely to break.

Conclusions

The key issues of the survey were to integrate river morphological changes during floods into risk estimation tools and to assess the associated uncertainties. Hydrological, hydrodynamic, sediment transport and risk assessment aspects were considered and analysed. Obviously, uncertainty increases by including additional processes such as sudden changes of the river bed. However, the opportunity to identify related uncertainty is provided. Hence, flood risk management strategies can be reviewed with regard to implementing the EU Flood Directive to national legislation.

In the frame of this survey risk assessment was adapted by substituting the scenario approach (a few normatively defined design floods) through a multi scenario approach by means of variation of input hydrographs and sediment load. Due to the incorporation of the impacts of hydrological and morphological processes on water surface tables, a refined hazard assessment approach is provided which was quantitatively applied to the presented case study. Vulnerability analyses and damage estimation tools were improved methodologically by interrelating the overtopping probability, the variability of inundation depth and a damage function to obtain a damage-probability relationship. Therefore, uncertainty and sensitivity are implicitly comprised in the probability distribution function of the expected damage.

Discharge input scenarios were obtained by rainfall-runoff simulations with different 100-year rainfall events. Sediment input scenarios were simulated based on a flood event with an estimated recurrence interval of 100 years by randomly drawing loads of torrential inflows. A sensitivity analysis indicated that the discharge input variation leads to flood peaks as high as 160 % of the normative 100-year design flood. Hence, a higher probability of inundations of vulnerable utilizations like settlements, infrastructure, etc. resulted from discharge input variation (12.3 %) than from sediment input variations (1.6 %). Therefore, the hazard assessment outlines that damage has to be assumed where safety was expected.

Regarding the magnitude of bed elevation changes, however, the influence of sediment input variation was found to be much higher than the influence of discharge input variations. Consequently, the derivation of sediment input functions appears to be the most important task wherever the incorporation of sediment transport calculations or estimations are applicable. In this context scarce data availability seems to be the restricting factor (Nachtnebel and Neuhold, 2008). Therefore, an enhancement of continuous sediment gauges as well as the volumetric survey of accumulations, especially after flood events, is desirable. By means of an extended data base the derivation of sediment input functions as well as calibration and validation of sediment transport models would be more feasible and should be adaptable to further river types and scales.

References

Apel, H., Merz, B. and Thieken, A.H.: Influence of Dike Breaches on Flood Frequency Estimation, Computers and Geosciences, article in press, doi: 10.1016/j.cageo.2007.11.003, 2008.

Apel, H., Thieken, A.H., Merz, B. and Blöschl, G.: A probabilistic Modelling System for Assessing Flood Risks, Natural Hazards, 38 (1-2), 79-100, 2006.

BMFLUW (Bundesministerium für Forst- und Landwirtschaft, Umwelt und Wasserwirtschaft): Analyse der Hochwasserereignisse vom August 2002 – Flood RISK, WP Donau TP 05, Operative Maßnahmen Donau, 2004.

BMFLUW: Richtlinien zur Gefahrenzonenausweisung für die Bundeswasserbauverwaltung: Fassung 2006. Wien: BMFLUW, 2006 a.

BMLFUW: Niederschlag-Abfluss-Modellierung. Arbeitsbehelf zur Parameterermittlung (in German). Federal Ministry of Agriculture, Forestry, Environment and Water Management, Vienna, 2006 b.

Buck, W.: Auswertung der HOWAS-Datenbank: HY 98/15. Karlsruhe: Institut für Wasserwirtschaft und Kulturtechnik, Universität Karlsruhe, 1999.

BUWAL: Risikoanalyse bei gravitativen Naturgefahren – Methode. Umwelt-Materialien Nr. 107/I, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft, 1999 a.

BUWAL: Risikoanalyse bei gravitativen Naturgefahren – Fallbeispiele und Daten. Umwelt-Materialien Nr. 107/II, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft, 1999 b.

BWG: Methode BWG Abschätzung des Schadenspotentials bei Überschwemmung und Übermurung. Arbeitshilfe 1.2, 2002.

Eberstaller, J.: Raumordnung und Hochwasserschutz am Beispiel der Traisen – Siedlungsentwicklung und Schadensanalyse. TP 02 - Naturgefahren BWV. In: Analyse der Hochwasserereignisse vom August 2002 – Flood Risk. Hrsg: BMLFUW, 2004.

Faber, R.: Flood Risk Analysis: Residual Risks and uncertainties in an Austrian context, Dissertation, University of Natural Resources and Applied Life Sciences, 143, 2006.

Ferson, S. and Ginzenburg, L.R.: Different methods are needed to propagate ignorance and variability. Reliability Engineering and System Safety, 54, 133-144, 1996.

Fürst, J. and Hafner, N.: Land cover. In: Federal Ministry of Agriculture, Forestry, Environment and Water Management (Ed.). Hydrological Atlas of Austria, 2nd Edition. Vienna, 2005.

Geiger, H., Röthlisberger, G., Stehli, A. and Zeller, J.: Extreme point rainfall of varying duration and return period. In: Swiss National Hydrological and Geological Survey (Ed.) 2004. Hydrological Atlas of Switzerland. Bern, 2004.

Haimes, Y.Y.: Risk modeling, assessment and management. Wiley Series in Systems Engineering, John Wiley and Sons, Inc., 726 p, 1998.

Hall, J. and Solomatine, D.: A framework for uncertainty analysis in flood risk management decisions, International Journal of River Basin Management, 6(2) pp. 85-98, 2008.

Huang, J.V. and Greimann, B.: US Department of Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group. User´s Manual for GSTAR-1D. 1-81, 2007.

HYDROTEC: Hochwasser-Aktionsplan Sieg http://www.stua-si.nrw.de/sieg/b1/, 2004.

Kaplan, S. and Garrick, B.J.: On the quantitative definition of risk. Risk Analysis, 1(1), 11-27, 1991.

Kling, H.: Development of tools for a semi-distributed runoff model. Master thesis, Institute of Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Applied Life Sciences, Vienna, Austria, 2002.

Kraus, D.: Wirtschaftlichkeit und Priorisierung von Schutzmaßnahmen vor Wildbächen, Erosion und Lawinen: IAN Report 94: Workpackage (WP) Naturgefahren Wildbach- und Lawinenverbauung (WLV) Teilprojekt (TP) 03 in BMFLUW, 2004.

Kuikka, S. and Varis, O.: Uncertainties of climate change impacts in Finnish watersheds: a Bayesian network analysis of expert knowledge. Boreal Env. Res., 2, 109-128, 1997.

Larson, C.L. and Reich, B.M.: Relationship of observed rainfall and runoff recurrence intervals. In: Schulz, E.F., Koelzer, V.A. and Mahmood, K., (Eds.). *Floods and Droughts*, Water Resources Publications, Fort Collins, pp. 34–43, 1972.

Lorenz, P. and Skoda, G.: Bemessungsniederschläge kurzer Dauerstufen (D ≤ 12 Stunden) mit inadäquaten Daten (in German). Report of the hydrographical service in Austria, Nr. 80, Vienna, 2000.

Merz, B., Kreibich, H., Thieken, A. and Schmidke, R.: Estimation uncertainty of direct monetary flood damage to buildings. Natural Hazards and Earth System Sciences 4: 153–163, 2004.

Merz, B.: Hochwasserrisiken – Grenzen und Möglichkeiten der Risikoabschätzung, E. Schweizerbart´sche Verlagsbuchhandlung (Näglele u. Obermiller), Stuttgart, 2006.

Messner, F., Penning-Rowsell, E., Green, C., Meyer, V., Tunsall, S. and van der Veen, A.: Evaluating flood damages: guidance and recommendations on principles and methods, report number T09-06-01, www.floodsite.net, 2007.

Meyer-Peter, E. and Müller, R.: “Formula for bed-load transport” Proc. of the Int. Assoc. for Hydraulic Research, 2nd Meeting, Stockholm, 1948.

Murphy, B.L.: Dealing with uncertainty in risk assessment. Human and Ecological Risk Assessment, 4(3), 685-699, 1998.

Nachtnebel, H.P., Baumung, S. and Lettl, W.: Abflussprognosemodell für das Einzugsgebiet der Enns und Steyr (in German). Report, Institute of Water Management, Hydology and Hydraulic Engineering, University of Natural Resources and Applied Life Sciences Vienna, Austria, 1993.

Nachtnebel, H.P. and Debene, A.: Suspended sediment balance in runoff river reservoirs along the Austrian Danube. “Schwebstoffbilanzierung im Bereich von Stauräumen an der österr. Donau“. FloodRisk: Endbericht im Auftrag des Lebensministeriums. In: Habersack H., Bürgel J. and Petraschek A.: Analyse der Hochwasserereignisse vom August 2002- Flood Risk, 2004, BMLFUW, Wien, Österreich, 2004.

Nachtnebel, H.P., Faber, R. and Leroch K.: Risikoanalyse des bestehenden Hochwasserschutzes Stadt Gleisdorf und Umgebung. River Basin Agenda, Wien: IWHW, BOKU, 2005.

Nachtnebel H.P. and Faber, R.: Assessment and management of flood risks in Austria. Structure and infrastructure Engineering. Vol. DOI:10,1080/15732470701189530, 2007.

Nachtnebel, H.P.: Cost-benefit evaluation of risk reduction options, Proceedings, European Symposium on Flood Risk Management Research (EFRM 2007), 6th – 7th February 2007, Dresden, Germany, 2007.

Nachtnebel, H.P. and Neuhold, C.: Schutzwasserbauliche Bestandserhebung Ill - AP5: Hydraulik/Geschiebe/Schwebstoffe . Amt der Vorarlberger Landesregierung, 164, 2008.

Nachtnebel, H.-P. and Stanzel, Ph.: Schutzwasserbauliche Bestandserhebung Ill – AP 4: Hydrologie. Amt der Vorarlberger Landesregierung, 161 S, 2008.

Nash, J.E. and Sutcliffe, J.V.: River Flow Forecasting through Conceptual Models. Journal of Hydrology, 10 / 3, 1970.

Neuhold, C. and Nachtnebel, H.P.: Detailed residual risk assessment in an Austrian municipality. In: European Geosciences Union, Volume 10, 2008, EGU General Assembly 2008, EGU General Assembly 2008, 14.04.2008-18.04.2008, Wien, 10; ISSN 1029-7006, 2008 a.

Neuhold, C. and Nachtnebel, H.P.: Flood risk assessment in an Austrian municipality comprising the evaluation of effectiveness and efficiency of flood mitigation measures, FLOODrisk2008. Proceedings. London: Taylor and Francis, 2008 b.

Niekamp, O.: Hochwasserschäden. In: Hochwasser–Handbuch. Auswirkungen und Schutz / Hrsg.: Heinz Patt. Springer, 2001.

Peticzka, P. and Kriz, K.: General soil map. In: Federal Ministry of Agriculture, Forestry, Environment and Water Management (Ed.). Hydrological Atlas of Austria, 2nd Edition. Vienna, 2005.

Plate, E.J.: Stochastic design in hydraulics: concepts for a broader application , In: Kuo, J.-T. and Lin, G.F. (eds.), Stochastic Hydraulics ´92, Proc. 6th IAHR International Symposium on Stochastic Hydraulics, Taipei, Taiwan, May, 18-20, 1992, Dept. Civil Engineering, National Taiwan University, Taipei, Taiwan, 663-670, 1992.

Popper, K.: The open universe. Hutchinson, London, 185pp, 1982.

Rabinovich, S.: Measurement errors: Theory and practice. American Institute of Physics, New York, 1993.

Rodriguez, R.: Hochwassergefahrenkarten für Deutschland – Zusammenfassung und Vorschlag für ein koordiniertes Vorgehen der Bundesländer. Teil 1: Voraussetzungen für die Erstellung von Hochwassergefahrenkarten. In: Hochwassergefahrenkarten, 2005.

Skoda, G., Weilguni, V. and Haiden, T.: Heavy Convective Storms – Precipitation during 15, 60 und 180 minutes. In: Federal Ministry of Agriculture, Forestry, Environment and Water Management (Ed.) 2005. Hydrological Atlas of Austria, 2nd Edition. Vienna, 2005.

Schanze, J., Hutter, G., Harries, T., Holzmann, H., Koeniger, P., Kuhlicke, C., Meyer, V., Nachtnebel, H.P., Neuhold, C., Olfert, A., Parker, D., Penning-Rowsell, E., Schildt, A. and Werritty, A.: Systematisation, evaluation and context conditions of structural and non-structural measures for flood risk reduction ERA-NET CRUE funding initiative, 131, 2008.

Schmidke, R.F.: Klimaveränderung – sozioökonomische Konsequenzen. Karlsruhe: Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), 269-276. http://www.kliwa.de, 2000.

Stanzel, Ph., Neuhold, C. and Nachtnebel, H.P.: Estimation of design floods for ungauged basins in an alpine watershed. In: European Geosicences Union, Geophysical Research Abstracts, Volume 9, 2007, EGU General Assembly, 15-20 April 2007, Vienna, 2007.

Statistik Austria: http://www.statistik.at/blickgem/gemList.do?bdl=6, Ein Blick auf die Gemeinde, 2005 a.

Statistik Austria: http://www.statistik.at/unternehmen/lse3_05.pdf, Leistungs- und Strukturstatistik, 2005 b.

Environmental flood risk assessment

***Neuhold, C.**; Nachtnebel, H.P.(2010a): Assessing flood risk associated with waste disposals: methodology, application and uncertainties.*

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Abstract

Waste disposal sites are mostly located in lowland areas close to residential areas inducing a long term risk of potential environmental contamination due to flooding. During recent flood events these areas were reportedly exposed to inundations. This paper aims to develop a qualitative approach to assess flood risk associated with flood prone waste disposals at the basis of Austrian case studies. Risk is investigated as a function of the probability of an event and the consequences of that event. The presented assessment approach is characterized as qualitative as consequences are expressed in risk categories but not in expected (monetary) losses. The probability of inundation, the hydrodynamic impacts on considered waste disposal sites and the expected consequences to the environment (potential emissions of hazardous substances) were linked. Derived risk categories from "minor risk" to "serious risk" were used to express flood risk to environmental goods like groundwater bodies, nature reserves, recreation areas, etc. A screening of 1064 waste disposals yielded roughly 30 % of sites located within or close to flood risk zones. Three representative case study areas were selected and investigated in detail by applying 2D hydrodynamic models to calculate flow depths and shear stress and by developing emission scenarios. The hydrodynamic modelling covered three hydrologic scenarios with statistical recurrence intervals of 30, 100 and 300 years. Derived leaching scenarios ranged from minor emissions up to total erosion of the waste disposal site. Based on four parameters representing flood characteristics, the susceptibility to erosion (flow velocity and shear stress) and the estimated leaching behaviour, a flood risk evaluation matrix (FREM) was elaborated. The study outlines that in case of flooding the hazardous emissions could lead to partly tremendous impacts on environmental goods. Identified uncertainties associated with considered processes were considerably high. However, the developed qualitative approach provides a decision support aid to identify waste disposals with imminent risk for humans and the environment.

Introduction

Waste disposal sites are mostly located in lowland areas close to residential areas inducing a long term risk of potential environmental contamination due to flooding. Risk is investigated as a function of the probability of an event and the consequences of that event (EU, 2007) and identifies the extent of a hazard and therefore, provides the basis for determining the need for action (BUWAL, 1999). The focus of this paper is to derive and to apply a qualitative flood risk assessment approach for waste disposal sites in flood plains. The presented assessment approach is characterized as qualitative as environmental consequences are expressed in risk categories but not in expected (monetary) losses. Due to flooding of waste disposal sites economic, social and environmental impacts caused by emission of hazardous substances have to be expected. The assessment approach considers negative effects on environmental goods like groundwater bodies, nature reserves, recreation areas, etc. by means of potential contamination. The study considered municipal solid waste (MSW) landfills and old waste deposits within the federal territory of Austria (Fig. 11). The inventory of landfill sites in Austria is based on information provided by the Austrian Federal Waste Management Plan (Krammer et al., 1992; BMFLUW, 2006 a), several waste management reports published by federal as well as local authorities and the Austrian Federal Environment Agency (AFEA, 2008 a). The considered inventory of landfills in Austria comprises of 1064 locations, with 103 sites characterised as controlled landfills (black crosses) and 961 sites identified as old deposits (red dots) with overall volumes of more than 25000 m³ (AFEA, 2008 a).

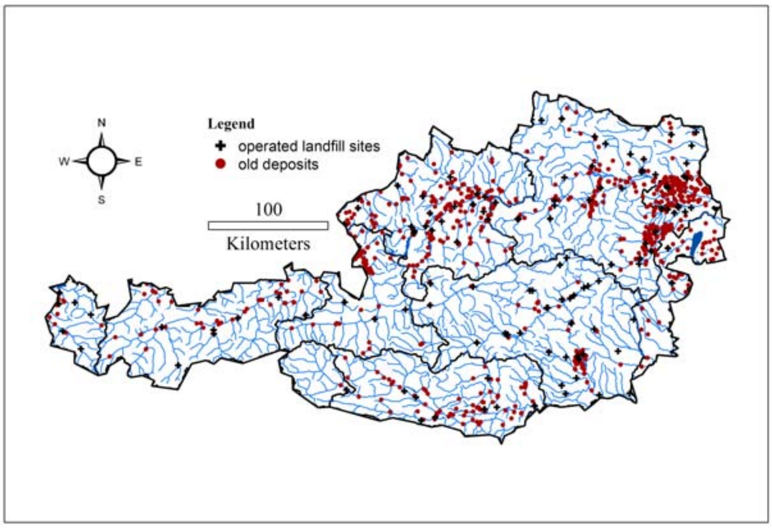

Fig. 11: Considered sites of MSW landfills and old waste deposits in Austria (AFEA, 2008 a, BMFLUW, 2007)

Maintenance and decomposition durations for waste disposals are assessed to 200 to 500 years depending on waste composition, climatic conditions and applied assessment methodologies (Ehring & Krümpelbeck 2001, Stegmann & Heyer 1995, Belevi & Baccini 1989). Hence, even sites with protection levels up to a 100 years flood are highly likely to be inundated before hazardous materials are decomposed. It has to be assumed that inundated waste disposals become water saturated which leads to a substantial mobilisation of pollutants, since the presence of water enhances decomposition and transport processes (Christensen et al., 1996; Bogner & Spokas, 1993; Klink & Ham, 1982). Additionally, water saturation of waste disposals may lead to mechanical stability losses (Blight & Fourie, 2005). Therefore, a tremendous and permanent risk potential for humans and the environment has to be expected emerging from flooded waste disposals (Laner et al., 2009; Nachtnebel et al., 2009). In the recent past the erosion of landfilled material and therefore the release of pollutants were monitored (Young et al., 2004; Habersack & Moser 2003). Related to inundated landfills Geller et al. (2004) observed increased concentrations of hazardous substances in floodplain soils and river sediments caused by the 2002 Elbe River flood. Blight & Fourie (2005) provide a review of catastrophic failures of waste landfills, highlighting the impact of such disasters on both, the environment and the population.

The objectives of this paper are:

- to identify flood exposed waste disposal sites in Austria
- to conduct 3 case studies to quantify possible impacts on inundated waste disposal sites by analysing hydrological and leaching scenarios as well as hydrodynamic characteristics
- to assess flood risk for environmental goods qualitatively
- to discuss uncertainties related to the assessment approach

Methodology

Screening approach to identify flood exposed waste disposal sites

The assessment of flood exposure of waste disposal sites was based on the HORA data set provided by the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMFLUW, 2006 b; Merz et al., 2006). This data base delineates potential flood inundation zones along rivers for discharges with statistical return periods (T) of 30, 100 and 200 years (Fig. 12). Substantial uncertainties arise due to the applied inaccurate digital elevation model and generally disregarded technical flood mitigation measures within HORA (BMFLUW, 2006 b) as well as neglected river morphological processes like sediment transport (Neuhold et al., 2009).

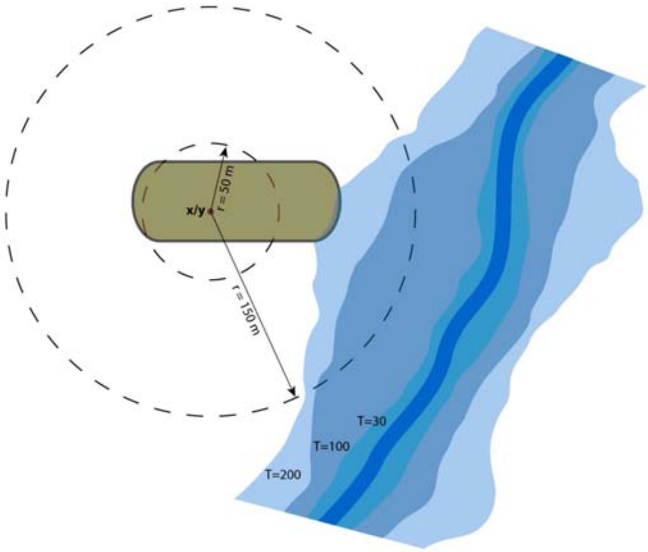

Fig. 12: Schematic illustration (Laner et al., 2009) of the procedure to evaluate the flood exposure of waste disposals in Austria, based on the HORA data set (BMFLUW, 2006 b) and site information (AFEA, 2008 a)

The distances of waste disposal sites, represented by a pair of x/y point coordinates, to scenario based inundation lines (HQ_{30}, HQ_{100} and HQ_{200}) were calculated with the help of a geographic information system (GIS). Buffers of various radii were assigned to waste disposal site coordinates to assess risk categories from low to high probabilities of inundation (Fig. 12). Landfills showing high probabilities of flooding (the site is situated within or near a flood risk zone with a recurrence interval of 200 years or less) were considered for further investigations and analyses. In order to verify the results, a visual assessment was conducted under aid of areal photographs, which proofed that the approximation to represent an average landfill topology by a circle of 150 m is sufficient for preselecting possible case study sites. Nevertheless, for an individual, site-specific analysis of flood risk exposure, the individual topology of landfill bodies and the existence of technical flood protection measures have to be taken into account.

Identification of case study sites

To support the elaboration of a qualitative risk assessment approach three case studies were conducted. Therefore, particularly endangered sites were identified by screening the inventory of landfills and waste deposits including their attributes (AFEA, 2008 a), the HORA data set as well as an online platform accounting for ecological goods (Geoland, 2009). Thresholds and required site characteristics were defined to rank the significance of waste disposal sites depending on exposure, composition and size:

- immediate vicinity to environmental goods
- waste disposal volumes of more than 100.000 m³
- landfilling after 1980
- no sufficient flood protection scheme

The queries yielded one controlled landfill site and two old waste deposits (Fig. 13) which were investigated in detail and will be discussed in following sections.

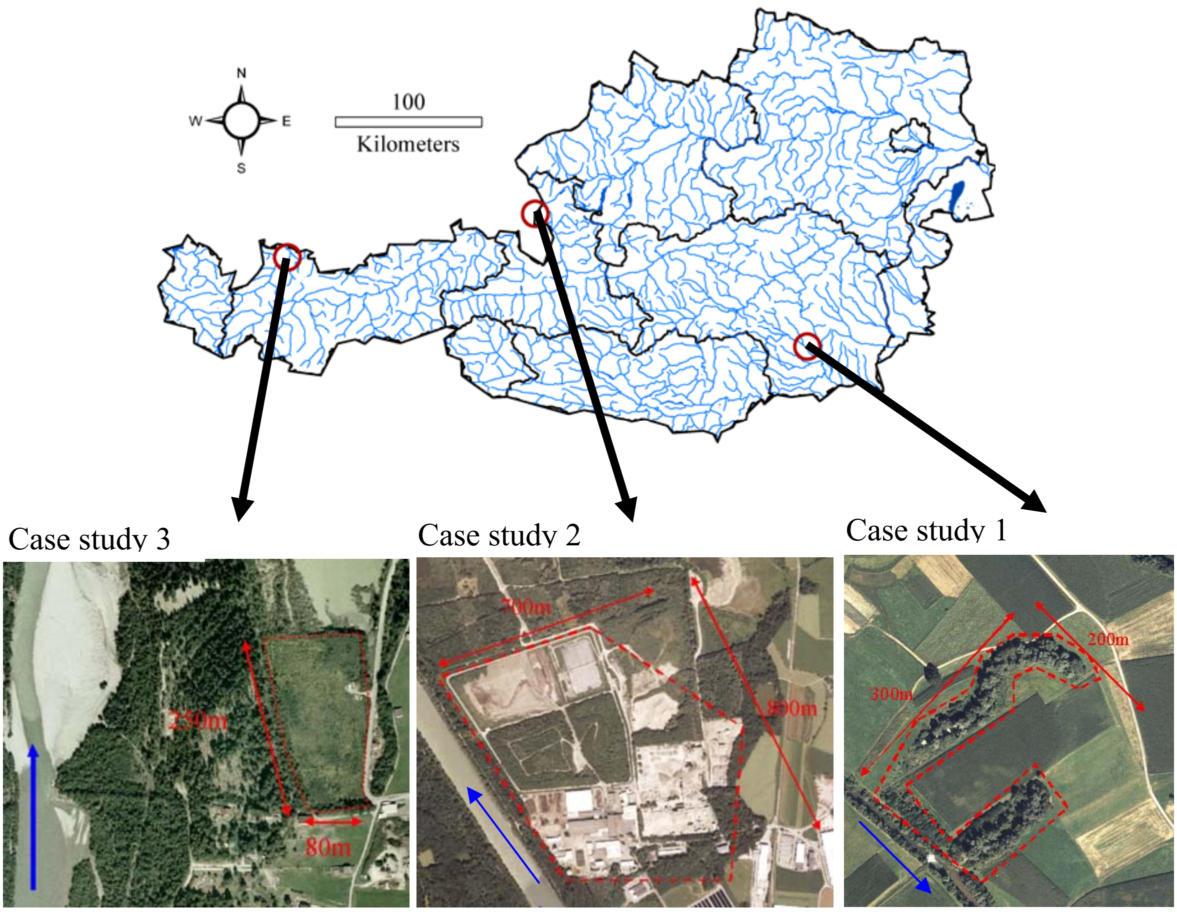

Fig. 13: Considered case study sites to quantify the possible impacts on waste disposal bodies on a micro scale level (Nachtnebel et al., 2009; BMFLUW, 2007)

Case Study 1:

The old deposit Dietersdorf with an area of approximately 2 hectares is situated at the left bank of the Kainach River. This site used to be a meander of the Kainach River until it was cut off and filled with domestic waste. Due to a lower elevation, compared to the agricultural hinterland, the landfill site serves as sink, enhancing the dwell time and therefore, triggering emissions to the surrounding ground water bodies. The thresholds and required site characteristics of exposure, composition and size were fulfilled (immediate vicinity to environmental goods, 130000 m³ waste disposal volume, landfilling after 1980, no flood protection).

Case Study 2:

The old deposit Pflach comprises of 2.5 hectares and is situated at the right bank of the Lech River. At this site uncontrolled landfilling heavily affected the ground water body as no base seal was implemented prior to the restoration of the landfill site in 2008. The disposal volume was estimated at 130000 m³ and comprises of domestic dump, construction waste, bulky waste, etc. The site was operated from 1976-1993 and showed no sufficient flood protection prior to the restoration.

Case Study 3:

The landfill Siggerwiesen is situated at the right bank of the Salzach River and comprises of 50 hectares including service buildings. Although, the landfill shows a flood protection scheme up to a 100-years flood event, the case study site was identified as flood prone within the pre-assessment procedure. The landfill is still operated with an overall volume of landfilled and treated municipal solid waste of approximately 2.2 Mio. m³.

Hydrologic scenarios and hydrodynamic modelling

Three hydrologic scenarios following national and international guidelines for flood risk assessment (BMFLUW, 2008 a; EU, 2007; Messner et al, 2007, Merz, 2006) were considered: (1) HQ_{30}, (2) HQ_{100} and (3) HQ_{300}. To analyse impacts on case study sites on a refined spatial scale, hydrologic scenarios were simulated applying hydrodynamic 2-dimensional models to delineate the inundation area and to calculate inundation depth, flow velocities and shear stress. It was contemplated to take climate change influences on hydrologic scenarios into account but surveys outlined that no significant trend, neither for increase nor for decrease of flood peaks, was identified for the overall federal territory of Austria (BMFLUW, 2009; Nachtnebel et al., 2001).

Due to available model setups (compiled in the frame of flood protection project planning) three different models based on the depth-averaged Navier-Stokes equation have been adapted and applied:

- Case study 1: Kainach River (lowland river morphology): CCHE-2D (Zhang, 2006; Zhang & Jia, 2007),
- Case study 2: Salzach River (Alpine/Alpine foreland river morphology, heavily modified by river engineering works): Hydro_AS-2D (HYDROTEC, 2008) and
- Case study 3: Lech River (Alpine river morphology): River2D (Blackburn & Steffler, 2002).

Landfill leaching scenarios

Emissions during flood events were estimated based on four substance release scenarios (Laner et al., 2008 a, b; Laner et al., 2009). The scenarios I-III assume an increased release of soluble substances as a consequence of water saturation of waste zones with the intensities from (I) low to (II) medium and (III) high. Scenario IV considers a stability loss of the waste body due to erosion and therefore, the full release of the deposited waste emission potentials. The soluble content of substances during water saturation (scenarios I-III) was roughly estimated using data of Belevi and Baccini (1989), who performed leaching experiments on waste samples taken from MSW landfill sites. The pollution potential of single substances for scenario IV was assessed according to investigations of Baccini et al. (1987) and Döberl et al. (2002), who determined transfer coefficients for C, N, P, Cl, Fe, Pb, Cu, Zn and Cd in dependence of landfill age. Basically, it is assumed that up to 70 % of the deposited waste releases its soluble substances during a flood (scenarios I-III).

Flood risk evaluation matrix (FREM)

A flood risk evaluation matrix (FREM) including a colour scheme (Fig. 14) was developed based on information on the flood characteristics, the susceptibility to erosion and the landfill's leaching behaviour. Three basic categories were chosen to express the risk originating from flooded landfills: "minor risk - yellow", "moderate risk - orange" and "serious risk - red", with possible intersections of categories (minor/moderate and moderate/serious) to enable a more nuanced assessment. The category “no risk” was avoided due to residual risk such as unexpected failure scenarios. The first input parameter to the FREM represents the flood characteristics and is based on the percentage of inundated landfill area and inundation depths for all considered scenarios (HQ_{30}, HQ_{100} and HQ_{300}). Minor risk was defined for landfill sites where solely boundary areas are inundated. Moderate risk (inundation up to 50 %) and serious risk (50 % to 100 % inundated) has been defined for directly affected waste disposals. Average inundation depths of more than 1 m induced the selection of a higher risk category. The susceptibility to erosion was assessed by the parameters flow velocity and shear stress. The impact on two separate areas was estimated: (1) boundary area and flood mitigation measures and (2) landfill body. The definition of risk categories was based on values for critical flow velocity and shear stress calculated by Lange & Lechner (1993). The assessment of susceptibility to erosion for boundary areas and flood mitigation measures was based on values for lawn. Values for medium to coarse gravel built the basis for the estimation of critical conditions for the landfill body itself. The fourth parameter was defined by the overall evaluation of emissions due to leaching processes within the disposal body. Therefore, a water volume was calculated which is able to dissolve substances during a flood event (Nachtnebel et al., 2009):

$$V_d = \left(\frac{A_v}{A_h} * v_{mean} \right) * b_A * h_{mean} * t \qquad (1)$$

V_d Water volume available for dissolving substances [m³/s]

A_v Area of landfill where flow velocities > 0 [m²]

A_h Area of landfill where water depth is > 0 [m²]

v_{mean} mean flow velocity [m/s]

b_A wetted width of landfill [m]

h_{mean} mean water depth [m]

t time [s]

The water volume available for dissolving substances (V_d) was subsequently multiplied by the values of chemical emissions of landfill leaching scenarios and compared to thresholds defined for controlled landfill conditions related to the general emission act (BMFLUW, 1996). Moderate and even serious risk categories have to be assumed for emissions within threshold levels because values of V_d are extensively higher than emission volumes of controlled landfills. The overall risk was derived from the mean colour and demands additional expert judgment for results in between two categories by means of weighting the significance of single FREM parameters and their impact on the overall environmental risk.

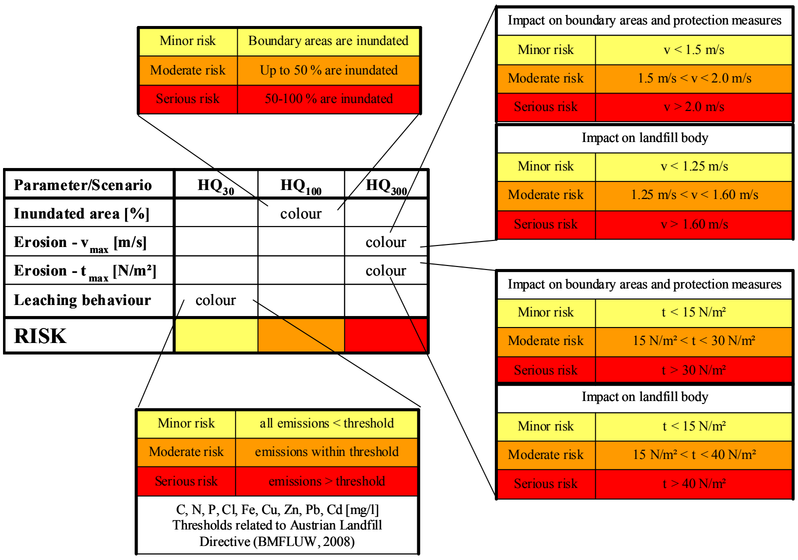

Fig. 14: The Flood Risk Evaluation Matrix (FREM), description of input parameters and threshold levels

Application of the qualitative approach

The results of case study 1 will be presented in detail as this was the most significant and influencing one for deriving a flood risk assessment methodology. Case studies 2 and 3 were subjected to severe uncertainties. According to the HORA database, the site of case study 1 – old deposit Dietersdorf/Kainach – is exposed to floods with a statistical return period of 30 years. The composition of the waste disposal site was classified as municipal solid waste with an overall volume of 130000 m³ which was deposited later than 1980 by filling a cut meander. Due to a lack of measurement and laser scan data the terrain was modelled by utilising 10x10 m grid information (BEV, 2008). Available river cross section data were imbedded into the digital elevation model. 2D-hydrodynamic simulations were run for discharge peaks of 320 m³/s (HQ_{30}), 410 m³/s (HQ_{100}) and 480 m³/s (HQ_{300}). The results (Tab. 2) show inundation of the waste deposit and the overall hinterland. Hence, broad distribution of hazardous emissions has to be expected.

Tab. 2: Evaluation parameters utilised as input to the FREM, grouped in to hydrologic scenarios (columns). Grey shaded fields were compared to pre-defined threshold levels.

Scenario	HQ_{30}	HQ_{100}	HQ_{300}
Evaluation parameter water depth (h)			
maximum [m]	3.47	3.55	3.60
mean [m]	1.38	1.46	1.50
affected disposal area with h > 0 [m²]	63600	63600	63800
percentage of total area [%]	99.7	99.7	100.0
Evaluation parameter flow velocity (v)			
maximum [m/s]	2.48	2.47	2.54
mean [m/s]	0.24	0.28	0.30
affected disposal area with v > 0 [m²]	43300	48400	53300
percentage of total area [%]	67.9	75.9	83.5
Evaluation parameter shear stress (τ)			
maximum [N/m²]	50.32	48.74	50.57
mean [N/m²]	3.13	2.83	1.38
affected disposal area with τ > 0 [m²]	7400	10600	47500
percentage of total area [%]	11.6	16.6	74.5
Volume available to dissolve [m³/s]	**66.24**	**91.98**	**112.50**
Leaching behaviour [qualitatively]	**moderate**	**min/mod**	**min/mod**

The calculated values of the 2D hydrodynamic model runs were prepared as 10 * 10 m grid information to intersect the results within a GIS. Inundation percentages of more than 50 % were categorised as “serious risk” (Tab. 3). Simulated inundation depths with mean water depths higher than 1 m supported the choice of “serious risk”. The susceptibility to erosion related to mean and maximum values of flow velocity was assessed with “minor risk” for the hydrologic scenario HQ_{30} and “moderate risk” for the scenarios HQ_{100} and HQ_{300}. Although the calculated values were similar, the percentage of the affected disposal area of more than ¾ led to the choice of a higher risk category. Due to a low affected disposal area of 11.6 % and 16.6 % related to the scenarios HQ_{30} and HQ_{100} as well as to low mean shear stress values the evaluation parameter shear stress led to a categorisation of “minor risk” due to a 30 years flood and a 100 years flood. The calculations for a HQ_{300} yielded a substantial increase of the affected disposal area were shear stress occurs, hence, “moderate risk” was assessed. An increasing water volume availability to dissolve substances due to higher discharges within the simulation runs led to decreasing emission concentrations and therefore, to assessed risk categories of moderate (HQ_{30}) and minor/moderate for HQ_{100} and HQ_{300}. Considering the data provided by the hydrodynamic calculations and the assessed emission concentrations the overall flood risk was assessed with “minor/moderate risk” for a 30 years flood, “moderate risk” related to a 100 years flood and “serious risk” for extreme events like a HQ_{300}.

Tab. 3: Simulation results of case study 1 including associated risk related colours (yellow: minor risk; yellow/orange: minor to major risk; orange: major risk; orange/red: major to serious risk; red: serious risk)

Evaluation parameter	HQ_{30}	HQ_{100}	HQ_{300}
Inundation [%]			
Erosion - v_{max} [m/s]			
Erosion - τ_{max} [N/m²]			
Leaching behaviour			
Overall environmental risk			

Discussion and Conclusions

Exposure to floods

103 controlled MSW landfills and 961 old waste deposits with at least 25000 m³ of volume were assessed with respect to the probability of flooding. One third (34) of controlled landfill sites were identified as highly probable to be inundated by floods. Referring to the HORA data base, 26 % of these sites are directly located within an inundation area with a recurrence interval of 200 years or less. Roughly 30 % of old waste deposits were identified as highly endangered by floods. It can be concluded, that one third of considered sites is exposed to flooding with respect to HORA (BMFLUW, 2006 b). Information about flood protection measures was collected from landfill operators. The analysis of the data shows that the majority (60 %) of active controlled landfills are protected by technical measures like dykes as it is required by the Austrian Landfill Directive (BMFLUW, 2008 b). In particular, large landfills in flood prone areas that are still operated are protected against flood events with a statistical recurrence interval of 100 years or more. Nevertheless, the majority (70 %) of closed sites has no flood protection at all. Altogether flood protection measures are reported for roughly 40 % of controlled MSW landfills. For old waste deposits this information was not available, as they have been operated by local firms without any documentation. In general it has to be assumed that these sites are not

protected at all (Laner et al., 2009). Hence, numerous waste disposal sites pose imminent risk for individuals, environmental and economic goods.

Landfill leaching scenarios

For landfill sites exposed to floods (they were identified as near to or within flood inundation lines) four emission potentials of pollutants during flood events were estimated (Laner et al., 2008a, b; Laner et al., 2009; Nachtnebel et al., 2009). Compared to conventional landfill conditions, emissions during a flood event might increase by two (e.g. P, Cl) to four orders of magnitude (e.g. Zn) for the scenarios I-III and three (e.g. Cl) to six orders of magnitude (e.g. Cd, Cu, Fe, Pb, Zn) for scenario IV.

Uncertainties

To outline deficits of the presented assessment approach problems arising on examining three case studies (Nachtnebel et al., 2009) are discussed, providing an overview with respect to lack of knowledge, lack of data and data uncertainty. Considerable sources of uncertainty were identified by elaborating three case studies under special consideration of the vicinity to ecological goods, the waste composition, the volume of the waste body and the land-filling period.

The representation of partly large MSW landfills by one pair of x/y coordinates is not sufficient. First of all it disregards the site topography and case study 3 outlined that the accuracy of denoted coordinates are by no means exact. Subsequently to the choice of case study 3 – an area defined as waste deposit according to available data sets (AFEA, 2008 a) – a single document (AFEA, 2008 b) reported the falseness of coordinates and the category (old waste deposit) without implementation to the GIS database which was provided (AFEA, 2008 a). The limping update of the GIS based data collection with single reports led to a serious misinterpretation and initially the analysis of a wrong site before the error was detected. Therefore, existing datasets describing attributes and locations of waste disposals have to be validated, enhanced and corrected.

The neglect of mitigation measures within the HORA data set (BMFLUW, 2006 b) leads to an overestimation of exposed landfills. Case study 2, chosen based on HORA (where protection measures are generally neglected) showed a flood safety level up to a recurrence interval of 300 years within the simulation runs. HORA therefore can only be utilised as rough decision aid to identify sites that might possibly be affected. For in-depth analysis hydrodynamic modelling including numerous simulation runs is by all means necessary to gain reliable results.

For case study 1 the selection criteria were verified – the waste deposit proofed to be within flood risk zones and the coordinates to identify the landfill site were correct. In the frame of the 2D model development the scarce data availability led to uncertain results because no actual measurement or airborne laser scan data were available. Therefore, a digital elevation model (BEV, 2008) was used (knowing that the z-coordinates can vary up to ± 6 m) and cross section information based on measurements were imbedded. The information provided by the BEV (2008) was validated by some available point information of measurements and proofed to vary in between some mm up to several dm. Further, a lack of documented historical flood events was identified which makes calibration and validation of simulated extreme events impossible.

Due to a lack of information related to possible emissions from landfills during flood events four leaching scenarios were investigated. The results illustrate that compared to controlled landfill conditions, the load of pollutants from flooded landfills might increase by up to six orders of magnitude, depending on the substance and the underlying assumption of the scenarios. Thus, the flows of substances from flooded waste disposals to the environment and therefore, the risk are potentially high. Despite the high dilution potential during a flood event the Austrian Water Quality Standards for discharge into rivers are highly likely to be exceeded.

The paper highlighted considerable uncertainties related to each sub-step of the presented qualitative approach to assess flood risk related to waste disposal sites. Nevertheless, the study outlines that in case of flooding or erosion of waste disposals the hazardous waste released to the environment could lead to partly tremendous damages. The developed methodology enables a qualitative assessment by means of categories like “minor risk”, “moderate risk” and “serious risk” providing a decision support aid to identify landfills with imminent risk for humans and the environment.

Acknowledgements:

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References:

AFEA (2008 a): Austrian Federal Environment Agency – Umweltbundesamt, GIS data supply http://www.umweltbundesamt.at/umweltschutz/altlasten/.

AFEA (2008 b): Austrian Federal Environment Agency – Umweltbundesamt, Altlast T10 "Deponie Pflach" Beurteilung der Sicherungsmaßnahmen. www. umweltbundesamt.at

Baccini, P.; Henseler, G.; Figi, R.; Belevi, H. (1987): Water and Element Balances of Municipal Solid Waste Landfills. Waste Manage Res 1987; 5: 483-499.

Belevi, H.; Baccini, P. (1989): Long-Term Behaviour of Municipal Solid Waste Landfills. Waste Manage Res 1989; 7: 43-56.

BEV (2008): Bundesamt für Eich- und Vermessungswesen, GIS data supply digital elevation model, http://www.bev.gv.at.

Blackburn, J.; Steffler, P. (2002): River2D, Two-Dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat, Introduction to Depth Averaged Modelling and User's Manual, University of Alberta, http://www.river2d.ualberta.ca/.

Blight, G.E.; Fourie, A. (2005): Catastrophe revisited – disastrous flow failures of mine and municipal solid waste. Geotechnical and Geological Engineering 2005; 23: 219-248.

BMFLUW (2009): Flood Risk II, Vertiefung und Vernetzung zukunftsweisender Umsetzungsstrategien zum integrierten Hochwassermanagement, Synthesebericht.

BMFLUW (2008 a): Kosten-Nutzen-Untersuchung im Schutzwasserbau: Richtlinie, impressum.lebensministerium.at/filemanager/download/26589/.

BMFLUW (2008 b): Austrian Landfill Directive. Verordnung über die Ablagerung von Abfällen, http://www.lebensministerium.at/article/articleview/26629/1/6969/.

BMFLUW (2007): Digital Hydrologic Atlas Austria http://www.boku.ac.at/iwhw/hao/.

BMFLUW (2006 a) Federal Waste Management Plan 2006. Federal Ministry of Agriculture and Forestry, Environment and Water Management, Vienna, pp. 320.

BMFLUW (2006 b): Hochwasserrisikozonierung Austria – HORA, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, www.hochwasserrisiko.at.

BMFLUW (1996): Bundesgesetzblatt für die Republik Österreich, 186. Verordnung: Allgemeine Begrenzung von Abwasseremissionen in Fließgewässer und öffentliche Kanalisationen (AAEV). Wien.

Bogner, J.; Spokas, K. (1993): Landfill CH4: Rates, fates, and role in global carbon cycle. Chemosphere 1993; 26: 369-386.

BUWAL (1999): Risikoanalyse bei gravitativen Naturgefahren – Methode. Umwelt-Materialien Nr. 107/I, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft.

Christensen, T.H.; Kjeldsen, P.; Lindhardt, B. (1996): Gas-generating processes in landfills. In: Christensen, T.H.: editor. Landfilling of waste: biogas. 27-44. E&FN Spon, London.

Döberl, G.; Huber, R.; Fellner, J.; Cencic, O.; Brunner, P.H. (2002): Neue Strategien zur Nachsorge von Deponien und zur Sanierung von Altlasten (Projekt STRANDEZA). Abteilung Abfallwirtschaft und Stoffhaushalt, Technische Universität Wien, pp. 267.

EU (2007): Richtlinie 2007/60/EG des europäischen Parlaments und des Rates über die Bewertung und das Management von Hochwasserrisiken.

Ehrig, H.J.; Krümpelbeck, I. (2001): The Emission Behaviour of Old Landfills in the Aftercare Phase. In: Christensen TH, Cossu, R. & Stegmann, R., editor. Proceedings Sardinia 2001, Eigth International Waste Management and Landfill Symposium. IV. CISA, S. Margherita di Pula, pp. 313-323.

Geller, W.; Ockenfeld, K.; Böhme, M.; Knöchel, A. (2004): Schadstoffbelastung nach dem Elbe-Hochwasser 2002. Final report of the ad-hoc-project 'Schadstoffuntersuchungen nach dem Hochwasser vom August 2002 - Ermittlung der Gefährdungspotentiale an Elbe und Mulde'. UFZ - Umweltforschungszentrum Leipzig-Halle GmbH,, Magdeburg.

Geoland (2009): Geodatenbank der österreichischen Länder, www.geoland.at.

Habersack, H.; Moser, A. (2003): Ereignisdokumentation - Hochwasser August 2002, Final Report. University of Natural Resources and Applied Life Sciences, Vienna, pp. 184.

Hydrotec (2008): Das 2D Strömungsmodell Hydro_AS-2D, Hydrotec Igenieurgesellschaft http://www2.hydrotec.de/unternehmen/hydrothemen/hydrothemen07/hydro-as-2d/

Klink, R.E.; Ham, R.K. (1982): Effects of moisture movement on methane production in solid waste landfill samples. Resources and Conservation 1982; 8: 29-41.

Krammer, H.J.; Domenig, M.; Striedner, J.; Vogel, G. (1992): Materialien zum Bundesabfallwirtschaftsplan (BAWP), Band 3: Kommunale Abfälle. Bundesministerium für Umwelt, Jugend und Familie, Wien, pp. 180.

Laner, D.; Fellner, J.; Brunner, P.H. (2009): Flooding of municipal solid waste landfills – a long-term environmental hazard? Science of the total environment, 407 (12), 2009, pp 3674-3680.

Laner, D.; Fellner, L.; Brunner P.H. (2008 a): Gefährdung durch Deponien und Altablagerungen im Hochwasserfall – Risiko und Analyse (GEDES), Dokumentation zum Arbeitspaket 1, Zwischenbericht, TU-Wien IWA, 2008a, pp. 54.

Laner, D.; Fellner, J.; Brunner, P.H.; Neuhold, C.; Kolesar, C. (2008 b): Environmental Relevance of Flooded MSW Landfills in Austria, In: ISWA/WMRAS, ISWA/WMRAS World Congress 2008 - East meets Waste, Singapore Nov 3-6.

Lange, G.; Lechner, K. (1993): Gewässerregelung & Gewässerpflege – Naturnahe Ausbau und Unterhaltung von Fließgewässern. Verlag Paul Parey, 3.Auflage, Hamburg/Berlin.

Merz, B. (2006): Hochwasserrisiken – Grenzen und Möglichkeiten der Risikoabschätzung, E. Schweizerbart´sche Verlagsbuchhandlung (Näglele u. Obermiller), Stuttgart.

Merz, R.; Blöschl, G.; Humer, G.; Hofer, M.; Hochhold, A.; Wührer, W. (2006): Hochwasserrisikoflächen Österreich (HORA) – Hydrologische Arbeiten (Technical Report). Institut für Wasserbau und Ingenieurhydrologie, TU Wien, Wien.

Messner, F.; Penning-Rowsell, E.; Green, C.; Meyer, V.; Tunsall, S.; van der Veen, A. (2007):Evaluating flood damages: guidance and recommendations on principles and methods, report number T09-06-01, www.floodsite.net.

Nachtnebel, H.P.; Fuchs, M.; Schober, S.; Hebenstreit, K.; Diernhofer, W.; Blum, M. (2001): Die Hydrologie Österreichs unter dem Einfluß von Szenarien einer möglichen Klimaänderung. Endbericht Teil I-III, Universität für Bodenkultur, IWHW, Wien.

Nachtnebel, H.P.; Holzmann, H.; Neuhold, C.; Haberl, U.; Kahl, B.; Bichler, A. (2009): GEDES: Gefährdung durch Deponien und Altablagerungen im Hochwasserfall - Risikoanalyse und Minimierung - Teilbericht 2, Wien.

Neuhold, C.; Stanzel, P.; Nachtnebel H.P. (2009): Incorporation river morphological changes to flood risk assessment: uncertainties, methodology and application, Natural Hazards and Earth System Sciences, 2009, 9, pp. 789-799.

Stegmann, R.; Heyer, K.U. (1995): Langfristiges Gefährdungspotential und Deponieverhalten von Ablagerungen. Statusseminar Deponiekörper. BMBF, Wuppertal.

Young, S.; Balluz, L.; Malilay, J. (2004): Natural and technologic hazardous material releases during and after natural disasters: a review. Sci Total Environ 2004; 322: 3-20.

Zhang, Y. (2006): Technical Report No. NCCHE-TR-2006-03, CCHE-GUI – Graphical Users Interface for NCCH Model, User´s Manual – Version 3.0, NCCHE, The University of Mississippi.

Zhang, Y.; Jia, Y. (2007): Technical Report No. NCCHE-TR-2007-01, CCHE-Mesh: 2D Structured Generator, User´s Manual – Version 3.0, NCCHE, The University of Mississippi.

***Neuhold, C.**; Nachtnebel, H.P. (2009): A qualitative approach to assess flood risk associated with landfills*

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Abstract.

Landfills induce a long term risk by means of potential environmental contamination due to flooding. In consequence of the complex composition of deposits as well as temporal and spatial flood characteristics there is yet no assessment standard available. This paper aims to develop a qualitative approach to assess flood risk associated with flood prone landfills at the basis of Austrian case studies. The inventory of controlled landfills and documented old waste deposits was evaluated for the federal territory of Austria. The collected data set was subsequently compared with flood risk zones. Out of 1064 screened landfills, roughly 30 % are located within or close to flood risk zones. Three representative case study areas were investigated in detail by applying a 2D hydrodynamic model to simulate flow depths and shear stress as well as by developing four chemical emission scenarios. The landfill leaching scenarios ranged from minor emissions up to total erosion of the landfill. The hydrodynamic modelling covered three hydrologic scenarios in the range of a 30-year up to a 300-year flood event. Based on four parameters representing the flood characteristics, the susceptibility to erosion (flow velocity and shear stress) as well as the estimated leaching behaviour of a saturated landfill a flood risk evaluation matrix (FREM) was elaborated to assess the ecologic risk associated with landfills qualitatively. The study outlines that in case of flooding or erosion of landfills the hazardous waste released to the environment could lead to partly tremendous ecologic damages. Further, the uncertainties associated to the considered processes were considerably high hence the derivation of a quantitative risk assessment approach would not yet lead to feasible results. However, the developed qualitative approach provides a decision support aid to identify landfills with imminent risk for humans and the environment.

Introduction and objectives

This paper discusses a qualitative approach to assess flood risk associated with landfills. Risk assessment aims to provide an answer to the question "what can possibly happen?" (BUWAL, 1999a). Risk is investigated as a function of the probability of an event and the consequences of that event (EU, 2007). Risk identifies the extent of a hazard and therefore, provides the basis for determining the need for action (BUWAL, 1999a).

Flood risk can be classified into (1) risk for individuals, (2) risk for property and (3) consequential risk, arising as a subsequent process (EGLI, 1996; EU, 2007; BUWAL, 1999a, b; WBGU, 1999; MERZ, 2006). This study focuses on consequential risks related to the environment. Special attention was drawn on municipal solid waste (MSW) landfills which pose a tremendous and permanent risk potential for humans and the environment (LANER et al. 2009, NACHTNEBEL et al., 2009). Due to assessed maintenance durations of 200 to 500 years depending on waste composition, climatic conditions and applied methodologies (EHRING & KRÜMPELBECK 2001, STEGMANN & HEYER 1995, BELEVI & BACCINI 1989) even sites showing flood mitigation measures are highly likely to be inundated.

During a flood event it has to be assumed that an inundated landfill body becomes water saturated which leads to a substantial mobilisation of pollutants, since the presence of water enhances decomposition and transport processes (KLINK & HAM, 1982; BOGNER & SPOKAS, 1993; CHRISTENSEN et al., 1996). Additionally, water saturation of landfilled waste may lead to mechanical stability loss, which cause shear and sliding fractures (BLIGHT & FOURIE, 2005).

In the recent past the erosion of landfilled material and therefore the release of pollutants were monitored (HABERSACK & MOSER 2003; YOUNG et al., 2004). For instance GELLER et al. 2004 observed increased inputs of pollutants into floodplain soils and river sediments during the 2002 Elbe River flood emerging from inundated landfills. BLIGHT & FOURIE 2005 provide a review of catastrophic failures of waste landfills, highlighting the impact of such disasters on both, the environment and the population.

Hence, the objectives of this paper were:

- the collection of the inventory of controlled landfills and documented old waste deposits for the federal territory of Austria
- the evaluation of the exposure to floods
- the definition of landfill leaching scenarios as well as the analyses of release mechanisms
- the derivation of case study sites to enable the analyses on a micro scale level
- the analysis of hydrological scenarios including 2D hydrodynamic simulation runs to assess the impacts on landfills
- the interpretation of consequences on protected properties (ground water bodies, nature reserves, protected landscape, settlements, ...) due to flooding of landfills
- the assessment of the overall resulting risk for ecological goods

Consequential, a flood risk evaluation matrix (FREM) was elaborated to assess the ecologic risk associated with landfills based on parameters representing the flood characteristics, the susceptibility to erosion as well as the estimated leaching behaviour of a saturated landfill.

Methodology

This section discusses the available database and a qualitative approach to assess flood risk related to landfills for the federal territory of Austria. Sub-steps as well as associated uncertainties are documented to allow a feasible conclusion of the significance of the derived risk assessment procedure.

Inventory of landfills and their exposure to floods

The section describes the determination of the inventory of flood prone landfills in Austria by assessing their exposure to floods. The compilation of data sets related to landfill sites in Austria is based on information provided by the Austrian Federal Waste Management Plan (KRAMMER et al., 1992; BMFLUW, 2006a) and several waste management reports published by federal as well as local authorities (LUNZER et al., 1998; KÄRNTEN, 2000;

FLÖGEL, 2002; TIROL, 2002; ROLLAND and OLIVA, 2004; BURGENLAND, 2005; NIEDERÖSTERREICH, 2005; VORARLBERG, 2005) and the collaboration with the Austrian Federal Environment Agency (AFEA, 2008).

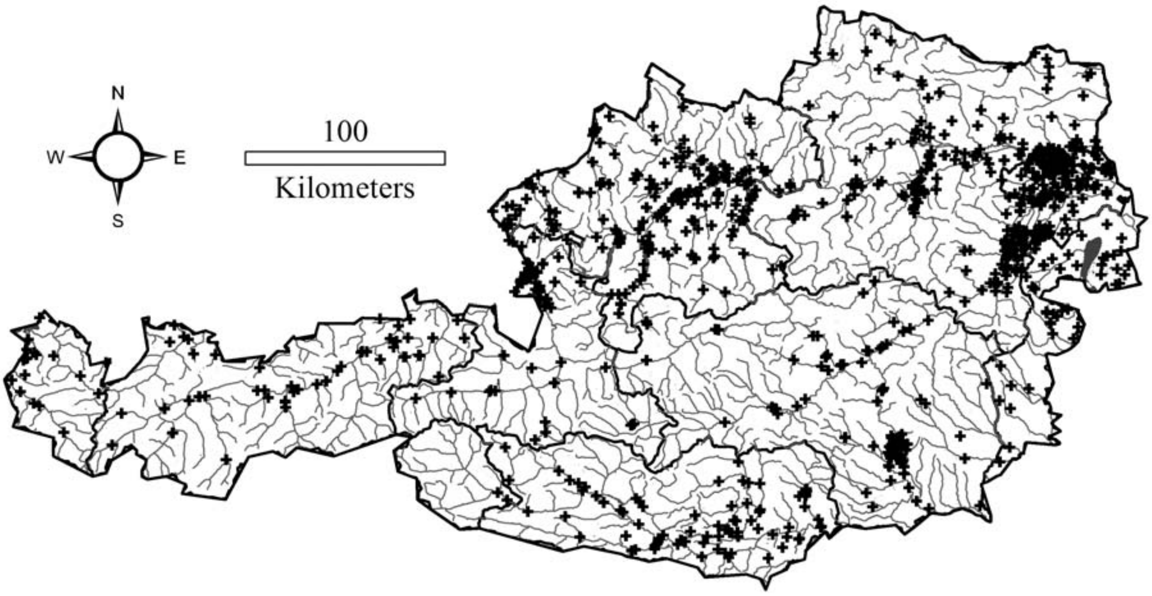

Fig. 15: Reported sites of MSW landfills in Austria (BMFLUW, 2007)

The elaborated data set of landfills in Austria comprises of 1064 locations (Fig. 15), whereas 103 sites are characterised as controlled landfills and 961 sites are identified as old deposits with overall volumes of more than 25000 m³ (AFEA, 2008).

Although the list of landfills is clearly not comprehensive – the degree of data ascertainment for old waste deposits in the AFEA database is supposed to be less than 70% (SKALA et al., 2007 – it represents an unbiased sample for the estimation of flood risk related to MSW landfills in Austria (LANER et al., 2009).

The evaluation of flood exposure is based on the HORA data set provided by the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMFLUW, 2006b; MERZ et al., 2006). This data delineates potential flood inundation zones along rivers for discharges with statistical return periods of 30, 100 and 200 years (Fig. 16). Substantial uncertainties arise due to disregarded technical flood mitigation measures and neglected processes like sediment transport, rock jam and log jam (NEUHOLD et al., 2009). The queries can therefore be characterised as an indicator for risk potentials, considering residual risk by means of failure of structural mitigation measures.

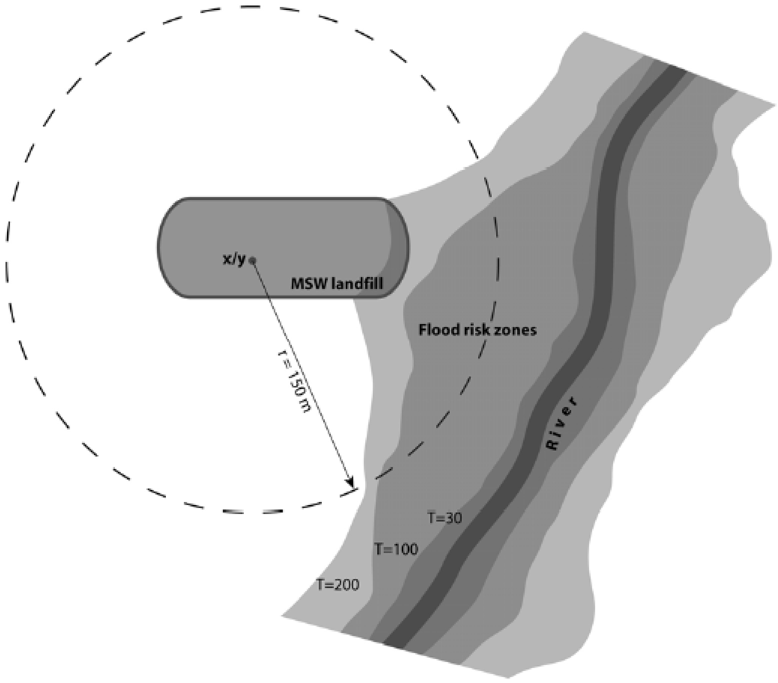

Fig. 16: Schematic illustration of the procedure to evaluate the flood risk probability landfills in Austria, based on the HORA data set (LANER et al., 2009)

The proximity of landfills, represented by a pair of x/y point coordinates, to inundation lines was evaluated under aid of a geographic information system (GIS) whereby the individual landfill geometries could not be taken into consideration by this procedure. Therefore, buffers of various radii were defined to assess risk categories from low to high probabilities (Fig. 16). Landfills showing high probabilities of flooding (the site is situated within or near – 150 m – a flood risk zone with a recurrence interval of 200 years or less) were considered for further investigations and analyses.

The disadvantage of this procedure and hence, substantial uncertainties were identified in the representation of landfills by point coordinates extended by 150 m Buffers (Fig. 16). In reality the landfill geometry is generally not circular and site coordinates are not located necessarily in the centre of the landfill body (LANER et al., 2009).

In order to verify the results, a visual assessment was conducted using the online HORA tool (BMFLUW, 2006b), with imbedded areal photographs, which proofed that the approximation to represent an average landfill topology by a circle of 150 m is sufficient. Nevertheless, for an individual, site-specific analysis of flood risk exposure, the individual geometry of landfill bodies and the existence of technical flood protection measures have to be taken into account (LANER et al., 2009).

Landfill leaching scenarios

For landfills identified as flood exposed, emission potentials and substance releases during flood events were estimated whereas the metabolism of flooded MSW deposits is widely unknown. Therefore, the emissions during flood events were based on the estimation of four substance release scenarios. The scenarios I-III assume an increased discharge of soluble substances as a consequence of water saturation of previously dry waste zones with the intensities from (I) low to (II) medium and (III) high. Scenario IV considers a loss of stability of the waste body due to erosion and therefore, the full emission potential of deposited waste.

Zones of low water contents within landfills are reported by various investigations (MALOSZEWSKI et al., 1995; BENDZ & SINGH, 1999; ROSQVIST & DESTOUNI, 2000; FELLNER et al., 2003). They are the result of preferential flow paths that shortcut water flow in landfills. Since the presence of water (POHLAND, 1975; LECKIE et al., 1979; KLINK & HAM, 1982; BOGNER & SPOKAS, 1993) and its redistribution (CHRISTENSEN et al., 1996) are essential for leaching and biochemical degradation processed, the initial pollution load of mostly dry waste zones remains unaltered over long time. However, during flooding it has to be assumed that the whole landfill body gets saturated with water. Consequently, biochemical processes in previously dry zones are restored, resulting in intensified generation of leachate and landfill gas.

The soluble content of substances during water saturation of the waste (scenarios I-III) was roughly estimated using data of BELEVI and BACCINI (1989), who performed leaching experiments on waste samples taken from MSW landfill sites. The available pollution potential of single substances for scenario IV was assessed according to investigations of BACCINI et al. (1987) and DÖBERL et al. (2002), who determined transfer coefficients for C, N, P, Cl, Fe, Pb, Cu, Zn and Cd in dependence to landfill age.

Basically, it is assumed that approximately 70 % of the deposited waste releases its soluble substances during a flood (scenarios I-III). Obviously, this is a rough estimate representing rather upper limits of substance releases than real conditions in case of flooding. However, with respect to the large uncertainties regarding the metabolism of flooded MSW bodies, and as emission scenarios are aimed to illustrate potential emission loads, the selected approach seems to be justified (LANER et al., 2009).

Derivation of case study sites

Supporting the derivation of a qualitative risk assessment approach three case studies were conducted. Therefore, particularly endangered sites were identified under aid of the inventory of landfills, the HORA data set as well as an online platform accounting for ecological goods (GEOLAND, 2009). Criteria were defined to rank the significance of landfill sites by means of exposure, composition and size. Following attributes were considered as relevant:

- Immediate vicinity to ecological goods
- Municipal solid waste composition
- A volume of at least 100.000 m³
- Landfilling after 1980
- No sufficient flood protection measures
- Data availability

The queries yielded one controlled landfill site and two old waste deposits which were investigated in detail (NACHTNEBEL et al., 2009).

Hydrologic scenarios and hydrodynamic modelling

It was contemplated to consider climate change influences on hydrologic scenarios but numerous surveys outlined that no significant trend, neither for increase nor for decrease of flood peaks, was identified for the overall federal territory of Austria (BMFLUW, 2009; NACHTNEBEL et al., 2001). Therefore, three hydrologic scenarios following national and international guidelines for flood risk assessment (BMFLUW, 2008; EU, 2007; MESSNER et al, 2007,) were considered: HQ_{30}, HQ_{100} and HQ_{300}. Hydrologic scenarios were simulated under aid of hydrodynamic 2-dimensional models to assess the impacts on landfills for three case study sites (Fig. 17).

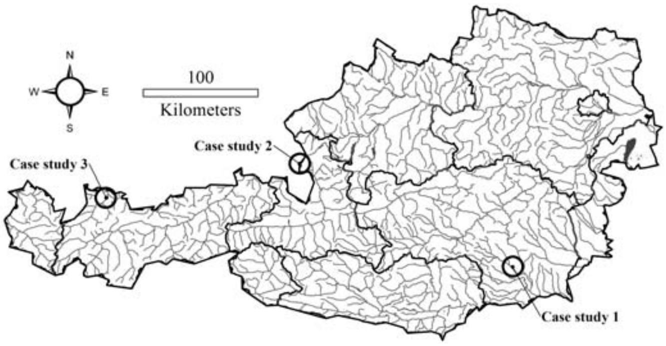

Fig. 17: Case study sites: (1) Kainach, (2) Salzach, (3) Lech (BMFLUW, 2007)

Due to the large variety of the case study sites:

1. Kainach River: lowland river morphology
2. Salzach River: Alpine/Alpine foreland River morphology, heavily modified by river engineering works
3. Lech River: Alpine River morphology

three different models based on the depth-averaged Navier-Stokes equation have been applied. The three model developers followed different philosophies:

- CCHE-2D (ZHANG, 2006; JHANG & JIA, 2007) – applied on the lowland river
  - Developed to simulate flow and sediment transport
  - Finite-Element-Method
  - Mesh-Generator and Graphical user interface
- Hydro_AS-2D (HYDROTEC, 2008) – applied on the Alpine foreland river
  - Developed to simulate dyke breach and flood wave propagation
  - Finite-Volume-Method
  - Mesh generation and post processing by SMS (SSG, 2008)
- River2D (BLACKBURN & STEFFLER, 2002) – applied on the Alpine river
  - Developed to simulate flow and fish habitat availability (WADDLE, 2001)
  - Finite-Element-Method
  - Modular composition (river morphology, ice cover, mesh generation, calculation)

Flood risk evaluation matrix (FREM)

Based on information on the flood characteristics, the susceptibility to erosion and the landfill's leaching behaviour a flood risk evaluation matrix (FREM) including a grey scale scheme (the higher the risk – the darker the shade of grey) was developed (Fig. 18). Three basic categories were chosen to express the consequential risk emanating from flooded landfills: "minor risk", "moderate risk" and "serious risk". The category "no risk" was knowingly avoided due to residual risk such as unexpected failure scenarios, wrong flood risk management decisions, exeedance of calculation parameters, etc.

The first input parameter to the FREM represents the flood characteristics based on the percentage of inundated landfill area for all considered scenarios (HQ_{30}, HQ_{100} and HQ_{300}) represented by single columns. Moreover, the inundation depth is calculated representing a decision aid if the overall risk is in between two categories (widely high inundation depth > 1 m leads to the selection of the higher risk category). Minor risk has been defined for landfill sites whereas boundary areas are inundated. Moderate risk (inundation up to 50 %) and serious risk (50 % to 100 % inundated) has been defined for directly affected MSW deposits. The susceptibility to erosion has been assessed by the parameters flow velocity and shear stress whereas the impact on two separate areas was estimated: (1) boundary and flood mitigation measures and (2) landfill body. The definition of risk categories was based on critical shear stress values calculated by LANGE & LECHNER (1993).

The assessment of susceptibility to erosion for boundary areas and flood mitigation measures was based on values for lawn. Values for medium to coarse gravel built the basis for the estimation of critical conditions for the landfill body itself. The fourth parameter is defined by the overall evaluation of emissions due to leaching processes within the MSW landfill body. Therefore, a water volume has to be calculated which is able to dissolve substances during a flood event (NACHTNEBEL et al., 2009):

$$V_d = \left(\frac{A_v}{A_\tau} * v_{mean} \right) * b_A * h_{mean} * t \qquad (1)$$

V_d Water volume available for dissolving substances [m³/s]
A_v Area of landfill where flow velocities > 0 [m²]
A_τ Area of landfill where shear stress is > 0 [m²]
v_{mean} mean flow velocity [m/s]
b_A wetted width of landfill [m]
h_{mean} mean water depth [m]
t time [s]

The water volume available for dissolving substances (V_d) was subsequently multiplied by the values of landfill leaching scenarios (sec. 0) and compared to thresholds defined for controlled landfill conditions related to the general emission act (BMFLUW, 1996). Moderate and even serious risk categories have to be assumed for emissions within threshold levels because values of V_d are extensively higher than emission volumes of controlled landfills. The overall risk is derived from the mean grey scale and demands additional expert judgment for results in between two categories by means of weighting the significance of single FREM parameters and their impact on the consequential risk.

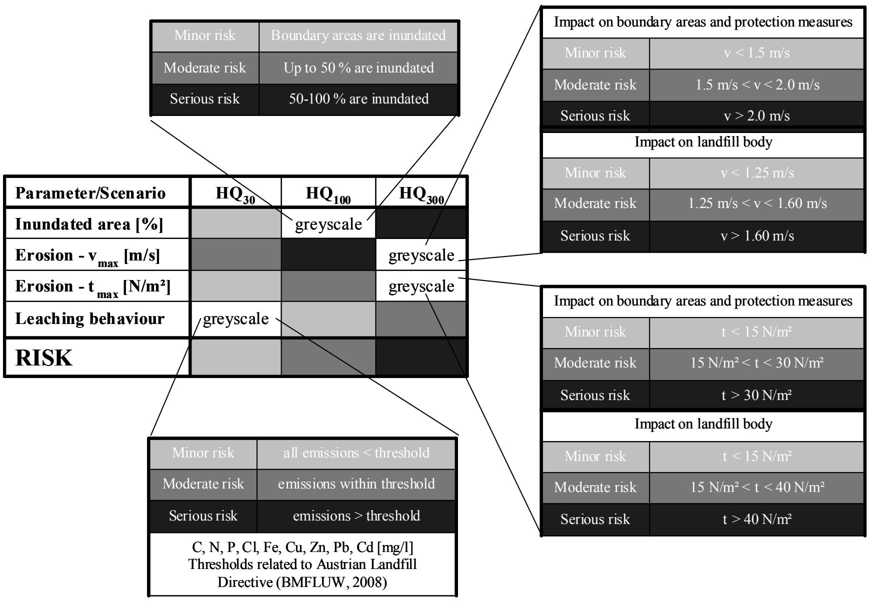

Fig. 18: Description of input parameters and thresholds to the flood risk evaluation matrix

Results and discussion

Exposure to floods

The results on flood risk exposure are based on a sample of 103 controlled MSW landfills and 961 old waste deposits with at least 25000 m³ of volume. The point coordinate based site information was intersected with a nationwide dataset of flood risk zones – the HORA data base (BMFLUW, 2006). With respect to the MSW landfill sites, one third (34) of controlled landfills were highly probable to be inundated by floods. 26 % of these sites are directly located within an inundation area with a recurrence interval of 200 years or less. Roughly 30 % of old waste deposits were identified as highly endangered by floods. The data set of 1064 considered landfills indicates that one third is highly vulnerable to floods, when technical flood mitigation measures are neglected.

Information about flood protection measures was collected from landfill operators. The analysis of the data shows that the majority (60 %) of active controlled landfills are protected by technical measures like dykes as it is required by the Austrian Landfill Directive (BMFLUW, 2008). In particular, large landfills in flood prone areas that are still operated are protected against flood events with a statistical recurrence interval of 100 years or higher. Nevertheless, the majority (70 %) of closed sites has no flood protection at all.

Altogether flood protection measures are reported for roughly 40 % of controlled MSW landfills. For old waste deposits this information was not available, as they have been operated on an informal basis. In general it has to be assumed that these sites are not protected at all (LANER et al., 2009).

Landfill leaching scenarios

For landfill sites which proofed to be vulnerable to floods (they were identified as near to or within flood inundation lines) four emission potentials of pollutants (scenario I-III: emission of potentially mobile substances during an event; scenario IV: loss of landfill stability and erosion of landfill body) during flood events were estimated (LANER et al., 2008a, b; LANER et al., 2009; NACHTNEBEL et al., 2009).

Compared to conventional landfill conditions, emissions during a flood event might increase by three (e.g. Cl) to six orders of magnitude (e.g. Cd, Cu, Fe, Pb, Zn) for scenario IV. For the scenarios I-III emissions are estimated smaller, but they still exceed ordinary emissions by two (e.g. P, Cl) to four orders of magnitude (e.g. Zn).

Case study findings, uncertainties and conclusion

This section serves to outline deficits in the frame of applying the qualitative approach to assess flood risk associated with landfills. Sect. 0 discusses problems arising on examining three case studies (NACHTNEBEL et al., 2009). Hence, an overview with respect to lack of knowledge, lack of data and data uncertainty can be provided.

Flooding of MSW landfills has been observed during major flood events, resulting in the contamination of surface water, groundwater and soil. In the frame of evaluating the inventory of landfills and their exposure to floods roughly 30 % were identified as highly vulnerable. Hence, numerous landfills pose imminent risk for individuals, ecologic and economic goods. Three case studies were derived under special consideration of the vicinity to ecological goods, the waste composition, the volume of the waste body and the land-filling period. Within this query two considerable sources of uncertainty had been identified.

First of all the representation of partly large MSW landfills by one pair of x/y coordinates is not sufficient due to the disregard of site attributes. Moreover, case study 3 outlined that the accuracy of denoted coordinates are by no means exact. Subsequently to the choice of case study 3 – an area defined as waste deposit according to available data sets (AFEA, 2008) – a single document reported the falseness of coordinates and the category (old waste deposit) without being implemented to the GIS database used. The limping update of the GIS based data collection with single reports lead to a serious misinterpretation and the analyses of a wrong site.

Secondly, the neglect of mitigation measures within the HORA data set (BMFLUW, 2006) leads to an overestimation of exposed landfills. Case study 2, chosen based on HORA, showed a protection level up to a recurrence interval of 300 years within the simulation runs. HORA therefore, can only be utilised as rough decision aid to identify sites that might possibly be affected. For in-depth analyses hydrodynamic modelling including numerous simulation runs is by all means necessary to gain feasible results. Therefore, the datasets describing waste deposits and controlled landfills have to be validated, enhanced and corrected.

For case study 1 the selection criteria were verified – the waste deposit proofed to be within flood risk zones referring to the HORA data set and the coordinates to identify the landfill site were correct. In the frame of the model development the scarce data availability lead to uncertain results because no actual measurement or airborne laser scan was available. Therefore, a digital elevation model (Digitales Höhenmodell, BEV, 2008) was used (knowing that the z-coordinates vary up to ± 6 m) and cross section information based on measurements were imbedded. The information provided by the BEV was validated by some available point informations of measurements and proofed to vary in between some mm up to several dm. Further, a lack of documented historical flood events was identified whereas calibration and validation of simulated extreme events seems to be impossible.

Due to a lack of information related to possible emissions from landfills during flood events four leaching scenarios were investigated. The results illustrate that compared to controlled landfill conditions, the load of pollutants from flooded landfills might increase by up to six orders of magnitude, depending on the substance and the underlying assumption of the scenarios. Thus, the flows of substances from flooded MSW landfills to the environment and therefore, the ecological risk are potentially high. Despite of the high dilution potential during a flood event the Austrian Water Quality Standards for discharge into rivers are highly likely to be exceeded.

The paper clearly highlighted considerable uncertainties related to each sub-step of the presented qualitative approach to assess flood risk related to landfills. Hence, the derivation of a quantitative approach would not yet lead to feasible results. The evaluation of the inventory of potentially affected old waste deposits and controlled landfills outlined that a judgment, based on point coordinate and not yet updated data sets leads to misinterpretations. Moreover, the neglect of flood mitigation measures within the HORA database leads to an overestimation of flood exposed sites. A lack of methodologies regarding the evaluation of emissions due to saturated conditions has been identified which leads to uncertain quantification of impacts on ecological goods.

Nevertheless, the study outlines that in case of flooding or erosion of landfills the hazardous waste released to the environment could lead to partly tremendous ecologic damages. The developed methodology enables a qualitative assessment by means of categories like “minor risk”, “moderate risk” and “serious risk” providing a decision support aid to identify landfills with imminent risk for humans and the environment.

References:

AFEA, Austrian Federal Environment Agency – Umweltbundesamt, GIS data supply http://www.umweltbundesamt.at/umweltschutz/altlasten/, 2008.

Baccini, P.; Henseler, G.; Figi, R.; Belevi, H.: Water and Element Balances of Municipal Solid Waste Landfills. Waste Manage Res 1987; 5: 483-499.

Belevi, H.; Baccini, P.: Long-Term Behaviour of Municipal Solid Waste Landfills. Waste Manage Res 1989; 7: 43-56.

Bendz, D.; Singh V.P.: Solute transport under steady and transient conditions in municipal solid waste. Water Resour Res 1999; 35: 2333-2345.

BEV: Bundesamt für Eich- und Vermessungswesen, GIS data supply digital elevation model, http://www.bev.gv.at, 2008.

Blackburn, J.; Steffler, P.: River2D, Two-Dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat, Introduction to Depth Averaged Modelling and User's Manual, University of Alberta, http://www.river2d.ualberta.ca/ 2002.

Blight, G.E.; Fourie, A.: Catastrophe revisited – disastrous flow failures of mine and municipal solid waste. Geotechnical and Geological Engineering 2005; 23: 219-248.

BMFLUW: Flood Risk II, Vertiefung und Vernetzung zukunftsweisender Umsetzungsstrategien zum integrierten Hochwassermanagement, Synthesebericht, 2009.

BMFLUW: Austrian Landfill Directive. Verordnung über die Ablagerung von Abfällen, http://www.lebensministerium.at/article/articleview/26629/1/6969/, 2008a.

BMFLUW: Kosten-Nutzen-Untersuchung im Schutzwasserbau: Richtlinie, impressum.lebensministerium.at/filemanager/download/26589/, 2008b.

BMFLUW: Digital Hydrologic Atlas Austria http://www.boku.ac.at/iwhw/hao/, 2007.

BMFLUW. Federal Waste Management Plan 2006. Federal Ministry of Agriculture and Forestry, Environment and Water Management, Vienna, 2006a, pp. 320.

BMFLUW. Hochwasserrisikozonierung Austria – HORA, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, www.hochwasserrisiko.at, 2006b.

BMFLUW: Bundesgesetzblatt für die Republik Österreich, 186. Verordnung: Allgemeine Begrenzung von Abwasseremissionen in Fließgewässer und öffentliche Kanalisationen (AAEV). Wien, 1996.

Bogner, J.; Spokas, K.: Landfill CH4: Rates, fates, and role in global carbon cycle. Chemosphere 1993; 26: 369-386.

Burgenland: Umwelterklärung des Burgenländischen Müllverbandes, Oberpullendorf., 2005.

BUWAL: Risikoanalyse bei gravitativen Naturgefahren – Methode. Umwelt-Materialien Nr. 107/I, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft, 1999 a.

BUWAL: Risikoanalyse bei gravitativen Naturgefahren – Fallbeispiele und Daten. Umwelt-Materialien Nr. 107/II, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft, 1999 b.

Christensen, T.H.; Kjeldsen, P.; Lindhardt, B.: Gas-generating processes in landfills. In: Christensen, T.H.: editor. Landfilling of waste: biogas. 27-44. E&FN Spon, London, 1996.

Döberl, G.; Huber, R.; Fellner, J.; Cencic, O.; Brunner, P.H.: Neue Strategien zur Nachsorge von Deponien und zur Sanierung von Altlasten (Projekt STRANDEZA). Abteilung Abfallwirtschaft und Stoffhaushalt, Technische Universität Wien, 2002, pp. 267.

EU: Richtlinie 2007/60/EG des europäischen Parlaments und des Rates über die Bewertung und das Management von Hochwasserrisiken, 2007.

Egli, T.: Hochwasserschutz und Raumplanung. Schutz vor Naturgefahren mit Instrumenten der Raumplanung – dargestellt am Beispiel vom Hochwasser und Murgängen. ORL-Bericht 100/1996, ETH Zürich, 1996, 165 pp.

Ehrig, H.J.; Krümpelbeck, I.: The Emission Behaviour of Old Landfills in the Aftercare Phase. In: Christensen TH, Cossu, R. & Stegmann, R., editor. Proceedings Sardinia 2001, Eigth International Waste Management and Landfill Symposium. IV. CISA, S. Margherita di Pula, 2001, pp. 313-323.

Fellner, J.; Huber, R.; Döberl, G.; Brunner, P.H.: Hydraulics of MSW landfills and its Implications for Water Flow Modelling. In: Christensen, T.H.; Cossu, R.; Stegmann, R.: editor. Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium. CISA, S. Margherita di Pula, 2003.

Flögl, W.: Klimarelevanz der Deponien in Oberösterreich. Dr. Flögl Hydro Consulting Engineers, Linz, 2002.

Geller, W.; Ockenfeld, K.; Böhme, M.; Knöchel, A.: Schadstoffbelastung nach dem Elbe-Hochwasser 2002. Final report of the ad-hoc-project 'Schadstoffuntersuchungen nach dem Hochwasser vom August 2002 - Ermittlung der Gefährdungspotentiale an Elbe und Mulde'. UFZ - Umweltforschungszentrum Leipzig-Halle GmbH,, Magdeburg, 2004.

Geoland: Geodatenbank der österreichischen Länder, www.geoland.at, 2009.

Habersack, H.; Moser, A.: Ereignisdokumentation - Hochwasser August 2002, Final Report. University of Natural Resources and Applied Life Sciences, Vienna, 2003, pp. 184.

Hydrotec: Das 2D Strömungsmodell HYDRO_AS-2D, Hydrotec Ingenieurgesellschaft http://www2.hydrotec.de/unternehmen/hydrothemen/hydrothemen07/hydro-as-2d/, 2009

Kärnten: Kärntner Abfallbericht und Abfallwirtschaftskonzept. Amt der Kärntner Landesregierung, Abteilung 15 - Umweltschutz und Technik, Klagenfurt., 2000.

Klink, R.E.; Ham, R.K.: Effects of moisture movement on methane production in solid waste landfill samples. Resources and Conservation 1982; 8: 29-41.

Krammer, H.J.; Domenig, M.; Striedner, J.; Vogel, G.: Materialien zum Bundesabfallwirtschaftsplan (BAWP), Band 3: Kommunale Abfälle. Bundesministerium für Umwelt, Jugend und Familie, Wien, 1992, pp. 180.

Laner, D.; Fellner, J.; Brunner, P.H.: Flooding of municipal solid waste landfills – a long-term environmental hazard? Science of the total environment, 407 (12), 2009, pp 3674-3680.

Laner, D.; Fellner, L.; Brunner P.H.: Gefährdung durch Deponien und Altablagerungen im Hochwasserfall – Risiko und Analyse (GEDES), Dokumentation zum Arbeitspaket 1, Zwischenbericht, TU-Wien IWA, 2008a, pp. 54.

Laner, D.; Fellner, J.; Brunner, P.H.; Neuhold, C.; Kolesar, C.: Environmental Relevance of Flooded MSW Landfills in Austria, In: ISWA/WMRAS, ISWA/WMRAS World Congress 2008 - East meets Waste, Singapore Nov 3-6, 2008b.

Lange, G.; Lechner, K.: Gewässerregelung & Gewässerpflege – Naturnahe Ausbau und Unterhaltung von Fließgewässern. Verlag Paul Parey, 3.Auflage, Hamburg/Berlin, 1993.

Leckie, J.O.; Halvadakis, C.; Pacey, J.G.: Landfill Management with Moisture Control. J Environ Eng 1979; 105: 337-355.

Lunzer, H.; Domenig, M.; Rosian, J.; Mostbauer, P.; Häusler, G.: Hausmülldeponien in Österreich. Umweltbundesamt, Wien, 1998.

Maloszewski, P.; Moser, H.; Stichler, W.; Trimborn, P.: Isotope hydrology investigations in large refuse lysimeters. J Hydrol 1995; 167: 149-166.

Merz, B.: Hochwasserrisiken – Grenzen und Möglichkeiten der Risikoabschätzung, E. Schweizerbart´sche Verlagsbuchhandlung (Näglele u. Obermiller), Stuttgart, 2006.

Merz, R.; Blöschl, G.; Humer, G.; Hofer, M.; Hochhold, A.; Wührer, W.: Hochwasserrisikoflächen Österreich (HORA) – Hydrologische Arbeiten (Technical Report). Institut für Wasserbau und Ingenieurhydrologie, TU Wien, Wien, 2006.

Messner, F.; Penning-Rowsell, E.; Green, C.; Meyer, V.; Tunsall, S.; van der Veen, A.:Evaluating flood damages: guidance and recommendations on principles and methods, report number T09-06-01, www.floodsite.net, 2007.

Nachtnebel, H.P.; Fuchs, M.; Schober, S.; Hebenstreit, K.; Diernhofer, W.; Blum, M.: Die Hydrologie Österreichs unter dem Einfluß von Szenarien einer möglichen Klimaänderung. Endbericht Teil I-III, Universität für Bodenkultur, IWHW, Wien, 2001.

Nachtnebel, H.P.; Holzmann, H.; Neuhold, C.; Haberl, U.; Kahl, B.; Bichler, A.: GEDES: Gefährdung durch Deponien und Altablagerungen im Hochwasserfall - Risikoanalyse und Minimierung - Teilbericht 2, Wien, 2009.

Neuhold, C.; Stanzel, P.; Nachtnebel H.P.: Incorporation river morphological changes to flood risk assessment: uncertainties, methodology and application, Natural Hazards and Earth System Sciences, 2009, 9, pp. 789-799.

Niederösterreich: Niederösterreichischer Abfallwirtschaftsbericht 2005. Amt der NÖ Landesregierung, Gruppe Raumordnung, Umwelt und Verkehr, St. Pölten, 2005.

Pohland, F.G.: Sanitary landfill stabilization with leachate recycle and residual treatment. USEPA, Cincinnati, OH, 1975.

Rolland, C.; Oliva, J.: Erfassung von Deponiegas - Statusbericht Österreichischer Deponien. Umweltbundesamt, Wien, 2004.

Rosqvist, H.; Destouni, G.: Solute transport through preferential pathways in municipal solid waste. J Contam Hydrol 2000; 46: 39-60.

Skala, C.; Kanovsky, A.; Ortmann, M.; Schamann, M.; Weihs, S.; Jobstmann, H.: Altlastensanierung in Österreich - Effekte und Ausblick. Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien, 2007, pp. 191.

SSG: Scientific Software Group, SMS-Surface Water Modelling System, current version 10.0, http://www.scientificsoftwaregroup.com/, 2008

Stegmann, R.; Heyer, K.U.: Langfristiges Gefährdungspotential und Deponieverhalten von Ablagerungen. Statusseminar Deponiekörper. BMBF, Wuppertal, 1995.

Tirol: Abfallbewirtschaftung in Tirol. Tiroler Landesrechnungshof, Innsbruck, 2002.

Vorarlberg: Abfallwirtschaftsdaten Vorarlberg 2005. Amt der Vorarlberger Landesregierung, Abteilung Abfallwirtschaft., Bregenz, 2005.

Waddle, T.J.: PHABSIM for Windows: user's manual and exercises: U.S. Geological Survey Open-File Report 01-340, 2001, 288 p.

WBGU: Wissenschaftlicher Beirat Globale Umweltveränderungen, Welt im Wandel: Wege zu einem nachhaltigen Umgang mit Süßwasser, Jahresgutachten 1997, Springer-Verlag, Berlin, 1999, 419 pp.

Young, S.; Balluz, L.; Malilay, J.: Natural and technologic hazardous material releases during and after natural disasters: a review. Sci Total Environ 2004; 322: 3-20.

Zhang, Y.: Technical Report No. NCCHE-TR-2006-03, CCHE-GUI – Graphical Users Interface for NCCH Model, User´s Manual – Version 3.0, NCCHE, The University of Mississippi, 2006.

Zhang, Y.; Jia, Y: Technical Report No. NCCHE-TR-2007-01, CCHE-Mesh: 2D Structured Generator, User´s Manual – Version 3.0, NCCHE, The University of Mississippi, 2007.

Laner, D.; Fellner, J.; Brunner, P.H.; ***Neuhold, C.****; Kolesar, C. (2008): Environmental Relevance of Flooded MSW Landfills in Austria*

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Abstract.

Municipal solid waste (MSW) landfills pose a large, long-lasting risk potential for humans and the environment. The emissions occurring under average conditions in a landfill were subject to numerous research studies within the last decades and are therefore well documented. In contrast, landfill behaviour and associated emissions in extreme cases such as flooding are widely unknown. However, a review of existing reports about environmental damages caused by landfills during floods indicates, that the released substances might be of environmental concern. It is the aim of this paper to determine the proportion of Austrian MSW landfills endangered by flooding, and to evaluate their potential environmental significance.

The risk of flooding is evaluated for MSW landfill sites in Austria using data about flood risk zones (HORA). Based on the topology of the site and the flood risk zones, three categories of flood risk exposure are distinguished: “endangered”, “probably endangered”, and “probably not endangered”. Endangered and probably endangered sites are located in a potential inundation area or close to a flood risk zone. For landfills assigned to one of these two categories, the potential emissions during a flood event are estimated by two substance release scenarios. The scenarios include intensified leaching processes of waste compounds, and loss of stability of the waste body due to erosion. The emissions based on these scenarios are used to evaluate the environmental relevance of flooded landfills.

The results reveal that one third of Austrian MSW landfills is located in flood prone areas (within or next to areas flooded statistically once in 200 years), with only a small portion having flood protection facilities. According to the scenario analysis, and compared to average landfill conditions, emissions during a flood event might increase by up to six orders of magnitude, subsequently exceeding Austrian water quality standards for discharge into rivers. Based on these results, further research into landfill metabolism and associated geotechnical landfill properties seems justified and necessary.

Introduction

Municipal solid waste (MSW) landfills and their emissions have been investigated by numerous studies during the last decades. Most of these studies focussed on leachate and landfill gas emissions under conventional landfill conditions and did not consider exogenous states of emergency. Based on these reports, it was concluded that landfill emissions will stay above a environmentally compatible level for several hundreds of years (cf. Belevi and Baccini, 1989; Stegmann and Heyer, 1995; Ehrig and Krümpelbeck, 2001). Consequently, MSW landfills contain a large pollution potential over a long period of time.

In case of landfill flooding it has to be assumed that the waste body becomes water saturated and that the emission behaviour of the landfill changes significantly. Due to the importance of water availability for decomposition and transport processes (e.g. Klink and Ham, 1982) an increased mobilisation of pollutants as a consequence of flooding might be expected. In addition the water saturation of the waste body may decrease the mechanical stability of the land-fill (cf. Blight and Fourie, 2005). Therefore, and because of the long residence time of MSW landfills in the environment, the risks associated with flooded MSW landfills need further consideration. Hence, it is the aim of this paper to determine the portion of Austrian MSW landfills endangered by flooding (for a recurrence interval of up to 200 years) and to evaluate their potential environmental significance.

Water pollution originating from flooded MSW landfills has been reported by several authors (e.g. Habersack and Moser, 2003; Geller et al., 2004; Young et al., 2004). They attributed pollution with heavy metals and organic contaminants to MSW landfills, but did not systematically investigate the specific contribution of flooded landfills. Studies addressing emissions from flooded landfills are rare and their results are found to be not readily transferable to flooded MSW landfills. Grischek et al. (1999) investigated the acid buffering effect of lignite ashes in a landfill submerged with acidic groundwater. They found that the emission loads (i.e. metals release) from a flooded waste deposit did not increase significantly compared to un-saturated conditions. However, they investigated a waste body sited in the groundwater and containing a large portion of inorganic material. A study conducted by Hao et al. (2008) found that organic degradation of MSW is significantly enhanced under oversaturated conditions, but as these results are derived from lab-scale experiments with fresh MSW of low density, they are not applicable to flooded

MSW landfills. Hence, although landfill emissions under normal conditions are well documented, little information is available about emissions from submerged MSW landfills.

In order to evaluate the portion of MSW landfills endangered by flooding, information about flood risk zones in Austria is combined with data about the location of MSW landfills. For landfills sited in flood prone areas the potential emission loads during a flood event are calculated using a scenario-based approach and their potential environmental significance is discussed. Finally, existing uncertainties and future research needs are highlighted drawing on the presented results.

Material and Methods

The data about MSW landfills in Austria was compiled from former editions of the Austrian Federal Waste Management Plan (Krammer et al., 1992; Lebensministerium, 2006a), several reports published by federal and local authorities (e.g. Lunzer et al., 1998), and information obtained from the Austrian Federal Environment Agency (AFEA). Data was gathered for con-trolled and old MSW landfills in Austria. The distinction between these two types of landfills originates from the legal framework for financing brownfield remediation in Austria (ALSAG, 1989) and is based on the time of waste disposal. Old landfills were operated mainly before 1989, whereas at controlled landfills most of the deposition took place after the year 1989. As there are also differences with respect to other characteristics (e.g. size, waste composition, etc.) of these types of landfills, they are also discussed individually in this paper.

The sample for evaluating the flood risk exposure of Austrian MSW landfills consists of 103 controlled MSW landfills and 961 old MSW landfills. The list of old MSW landfills includes only MSW deposits with a minimum volume of 25.000 m3 and is based on queries in the AFEA database about old landfills. Although this compilation of controlled and old MSW landfills is not comprehensive (e.g. the portion of existing old MSW landfills represented in the AFEA database is estimated to be approx. 70 % (cf. Skala et al., 2007)), it represents an unbiased sample of Austrian MSW landfills.

The risk of flooding at the landfill sites is evaluated using nation-wide data about the flood risk zones in Austria (HORA) (cf. Lebensministerium, 2006b). This information about flood risk exposure in Austria is provided for free by the Federal Ministry of Agriculture, Forestry, Environment and Water Management. Potential inundation areas are identified for recurrence intervals of 30, 100, and 200 years, respectively. As technical flood protection measures are not systematically included in the HORA data set, the delineated inundation zones indicate the potential risk of flooding.

The flood risk exposure of Austrian MSW landfills was assessed via three categories: sites may be “probably not endangered”, “probably endangered”, and “endangered” of flooding, with the latter two summarized as “potentially endangered” sites. The classification is based on the location of the landfill site (expressed as point coordinates) and the distance to a designated flood risk zone in HORA. Landfills referred to as

- **endangered**, are situated within a designated flood risk zone.
- **probably endangered**, are less than 150 m away from a designated flood risk zone.
- **probably not endangered**, do not have a designated flood risk zone within a distance of 150 m.

The criteria above can be queried using a geographical information system (GIS). However, these criteria do no take into account individual landfill geometries, as the point coordinates are not necessarily in the centre and also landfills are normally not of a circular shape (cf. Figure 1). Hence, in order to validate the categorisation based on GIS queries, the topology of the landfill body and the HORA flood risk zones is visually assessed for all the controlled MSW landfills using an online GIS application (Lebensministerium, 2006 b). It is found that all the landfills classified as “endangered” are at least partly sited in a flood risk zone corresponding to a recurrence interval of 30 years. “Probably endangered” sites were partly located in a flood risk zone or sited in direct proximity to a potential inundation area. Out of the land-fills classified as “probably not endangered” only two are located next to flood risk zones. Hence, the criteria used for evaluating the flood risk exposure of Austrian MSW landfills rep-resent a reasonable approximation of the real situation at the landfill site. Nevertheless, this categorisation has to be regarded as a coarse estimate of the flood risk exposure of a landfill. For a site-specific analysis of the risk of flooding, individual landfill characteristics and the existence of technical flood protection facilities have to be taken into consideration.

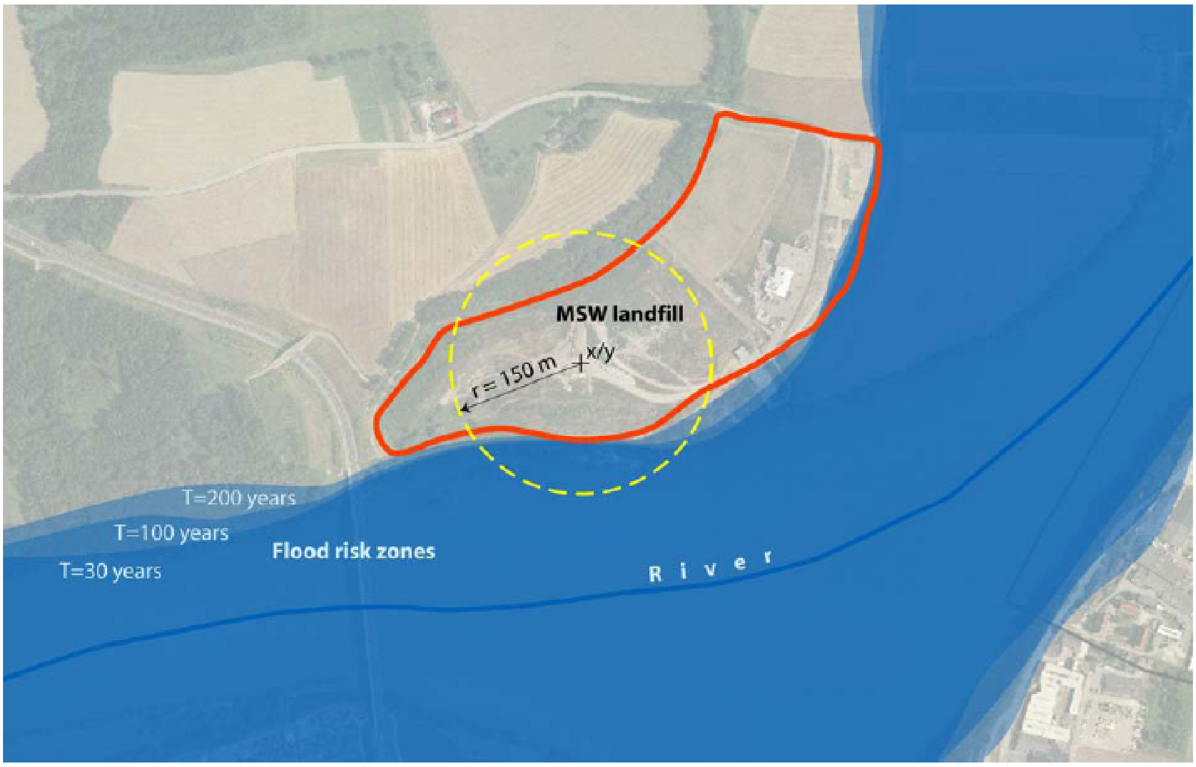

Fig. 19: Evaluation of the flood risk exposure of a landfill site based on the HORA data set

The emission potential and the substance release during a flood event are estimated using a scenario-based approach. The scenarios are calculated for potentially endangered controlled and "endangered" old MSW landfills.

Substance release scenarios for estimating potential emissions during a flood event have been developed since the metabolism of flooded landfills is largely unknown and hence, data con-cerning emissions from inundated landfill bodies are lacking. Altogether two scenarios have been developed in order to illustrate emissions from MSW landfills during a flood event. Scenario A assumes the loss of landfill stability and the complete erosion of the landfill body. Scenario B is based on the assumption of an increased substance discharge due to water saturation of waste zones with a previously very low water content. Such "dry" waste zones within landfills have been reported already by several authors (e.g. Maloszewski et al., 1995; Bendz and Singh, 1999). They are the result of preferential water flow as a consequence of the landfill bodies' heterogeneous character (Fellner et al., 2003). It is assumed that the pollution load of dry waste zones remains nearly constant over long time periods, as the presence of water and its redistribution are a prerequisite for biochemical degradation processes and leaching (cf. Pohland, 1975; Christensen et al., 1996). However, during a flood, as the landfill body gets saturated with water, biochemical processes in dry waste zones may be restored and consequently result in higher leachate and gas generation rates.

The available pollution load (during a flood event) of a substance i for scenario A (**SiA**) is estimated based on investigations by Baccini et al. (1987) and Döberl et al. (2002), who deter-mined transfer coefficients for various substances in dependence of the age of the waste de-posited. Their results show that even after 25 years the remaining pollution potential is very similar to the initially deposited substance inventory. The substance release of a single sub-stance i in scenario A was calculated according to equation 1.

(1) SiA = mW . ci . Ri

mW is the landfilled mass of waste [kg]
ci is the initial content of substance i of the landfilled waste [kg/kg]
(according to Belevi and Baccini, 1989)
Ri is the remaining fraction of initial content of substance i in the waste [-]
For C = 80 %, N = 90 %, Cl and P = 95 %, Fe, Pb, Cu, Zn, and Cd = 99 %.

The release of substance i for scenario B (**SiB)** is estimated based on data provided by Belevi and Baccini (1989). They determined the soluble content of various substances in MSW based on leaching experiments with ground waste samples taken from Suisse landfills. Hence, with respect to extractable substance loads in case of water saturation these estimates are supposed to represent an upper limit. Apart from the extractable fraction of the waste compounds also the heterogeneity of the water flow in the landfill body is taken into account in scenario B. In case of flooding previously dry zones get in contact with water, which results in intensified leachate and gas generation. Existing studies show that the fraction of the landfill body excluded from water flow **(1-F)** might be well between 40 to 95 % (e.g. Rosqvist and Bendz, 1999; Döberl et al., 2006). For this scenario the fraction excluded from water flow is assumed to be 70 % of the landfill body. Equation 2 shows the calculation of the emission loads for scenario B, assuming that only previously dry parts of the waste deposit contributed to the increased substance release during and after flooding.

(2) SiB = mW . qi . F

mW is the landfilled mass of waste [kg]
qi is the soluble content of substance i according to Belevi and Baccini (1989) [kg/kg]
(lower values of the presented data were used)
F is the fraction of the deposited waste volume participating in water flow [m3/m3]

The scenarios described above cannot provide a realistic estimate of emission loads from MSW landfills during a flood event. However, due to the huge uncertainties concerning the metabolism of flooded landfills and considering the aim of estimating potential emission loads, the selected approach seems to be reasonable.

Results and Discussion

Based on the methodology described in the previous chapter, it is found that out of 1064 Austrian MSW landfills around 30 % are located in or in direct neighbourhood to a zone flooded statistically once or more often in 200 years. In Figure 2 the results of the flood risk evaluation are presented for controlled and old MSW landfills referring to the number of flood prone landfills as well as to the waste volume landfilled at these sites.

One third of the 103 controlled landfills are assigned either to the category “endangered” (9 %) or to the category “probably endangered” (24 %) (together referred to as potentially endangered). This holds also with respect to the landfilled waste volume, with 17 % of the waste volume being deposited at probably endangered sites and another 17 % landfilled at endangered sites. However, although the potentially endangered portion is the same with respect to the number and the volume of controlled MSW landfills, it is apparent that “endangered” landfills have in average a larger volume then those classified as “probably endangered”.

Concerning the 961 old MSW landfills 165 of them are evaluated as “probably endangered” and 113 are assigned to the category “endangered”. Hence, around 30 % of old MSW landfill sites are located in a distance of not more than 150 m from a designated flood risk zone. With respect to the landfilled volume this portion is reduced to around 20 %. The main reason being that the three old MSW landfills with the largest volume account for around 30 % of the total landfilled waste volume and are not located in flood prone areas. However, even after correcting for their influence on the result, the portion of the potentially endangered volume is still a bit smaller (by 3 %) than the corresponding amount of old MSW landfill sites.

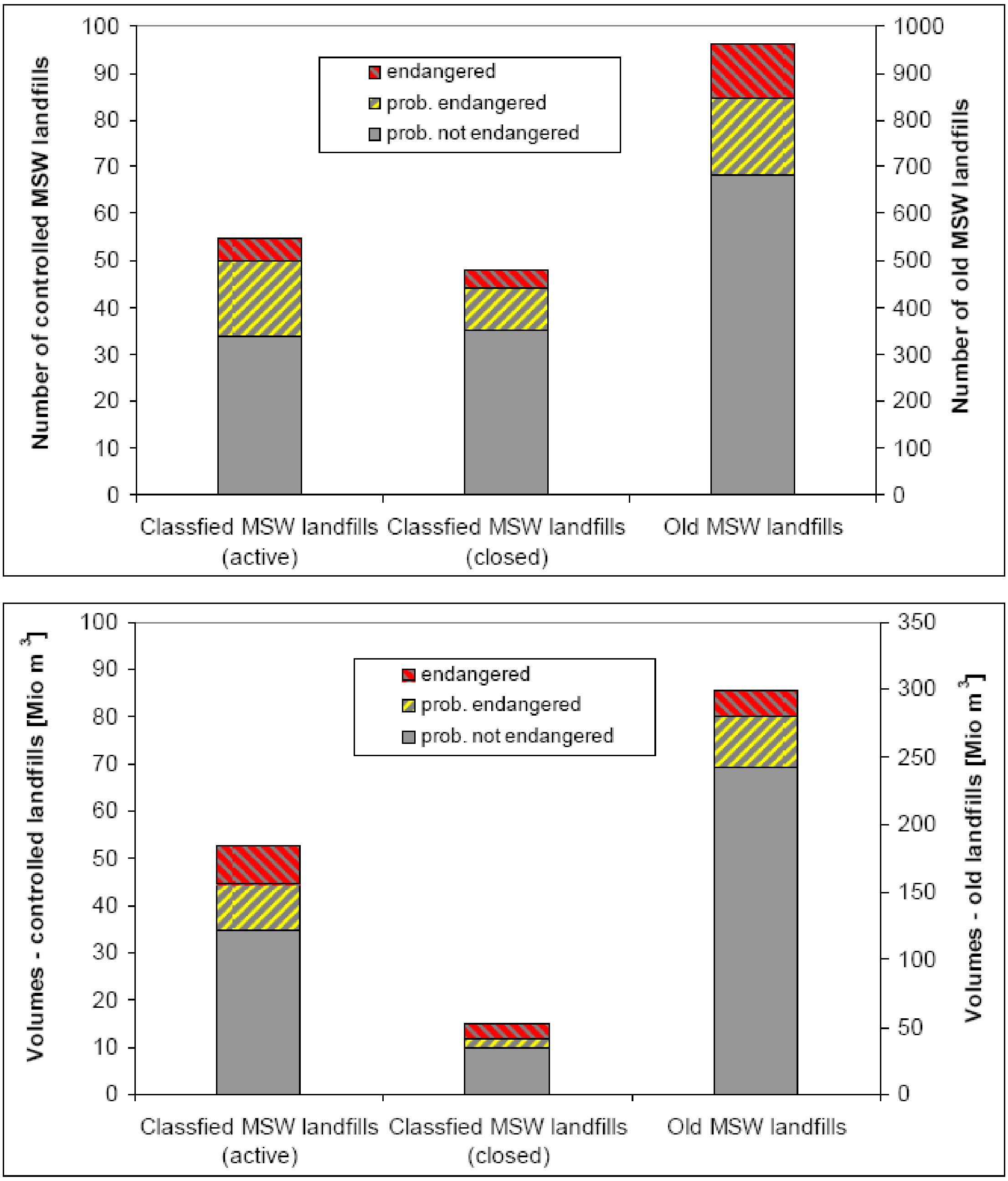

Fig. 20: Flood risk exposure of Austrian MSW landfills (top: based on the number of landfills, bottom: based on landfilled waste volume

As mentioned already above, the evaluation of the risk of flooding does not systematically consider, potentially existing, technical flood protection measures (i.e. dykes). Based on information provided by the responsible authorities or landfill operators the portion of controlled MSW landfills in possession of technical flood protection facilities was estimated (Fig. 21). Data was gathered only for controlled MSW landfills, because old MSW landfills were operated basically on an informal basis and are, hence, not supposed to have object-oriented flood protection measures.

From Fig. 21it is visible that most of the potentially endangered, controlled MSW landfills in operation are protected against flooding (57 % or 72 %, respectively), whereas only a very small portion (8 % or 17 %, respectively) of potentially endangered, closed, controlled MSW landfills are protected against flooding. The over-all portion of protected, controlled MSW landfills is 38 % referring to their number and 60 % referring to the protected waste volume. This reveals that controlled MSW landfills with a large waste volume are more likely to have object-oriented flood protection in place (referring to those sited in flood prone areas). However, provided that old MSW landfills do not possess flood protection facilities, only around 5 % of potentially endangered Austrian MSW landfills are protected against flooding.

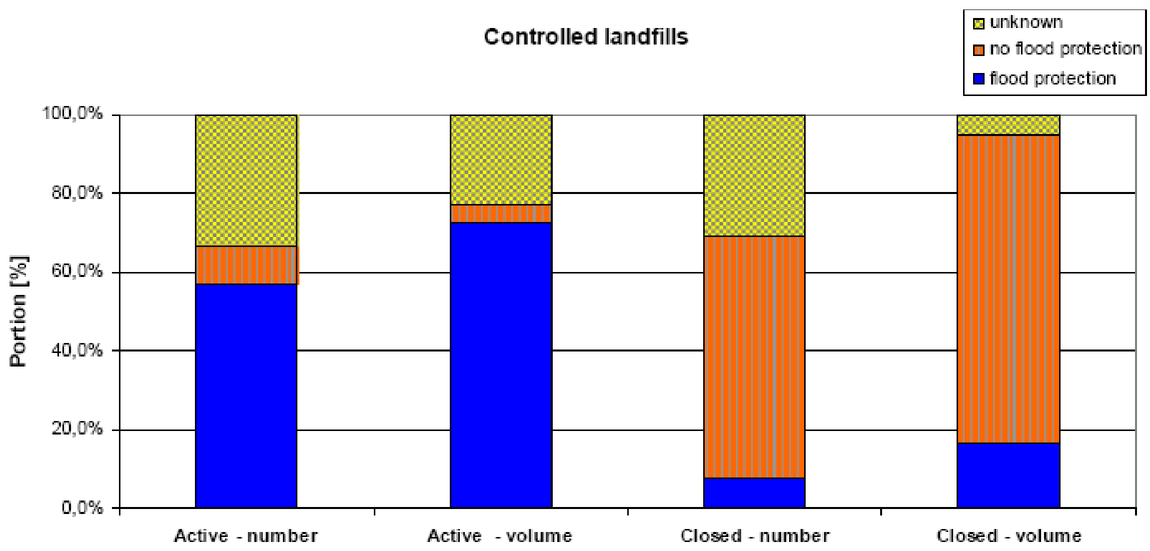

Fig. 21: Portion of "endangered" and "probably endangered" controlled MSW landfills equipped with flood protection facilities

The scenario-based substance releases during a flood event are presented for the average con-trolled MSW landfill and the average old MSW landfill (Tab. 4).This approach is taken for reasons of brevity and for clarity of presentation, as it is not useful to present the calculated substance loads for every single landfill.

Tab. 4: Characteristics of the average potentially endangered controlled MSW landfill and the endangered old MSW landfill

average landfill	age of landfilled waste [yrs]	water infiltration rate [mm yr^{-1} m^{-2}]	volume [m^3]	area [m^2]
Potentially endangered controlled MSW landfill	18	540	430.000	22.600
Endangered old MSW landfill	35	290	78.000	22.000

From Tab. 4 it is apparent, that the two types of MSW landfills differ substantially with respect to the average age of the deposited waste, the landfill volume, and the water infiltration rate. The latter is due to the fact, that most of the registered old MSW landfills are sited in the east of Austria with a predominantly drier climate. Based on the average characteristics of the MSW landfill types (Tab. 4) the leachate emissions under conventional landfill conditions were calculated based on the approach presented by Belevi and Baccini (1989). These standard emission loads were derived for a one week period (in Austria flood events generally last a few days) and then compared to the emission loads during a flood for the two substance release scenarios (Fig. 22).

In Fig. 22 the released substance loads are presented for Carbon, Nitrogen, Copper, and Cadmium. The specific substance loads of scenario A, based on a loss of landfill stability, are generally around two to three orders of magnitude higher than the substance loads calculated for scenario B, based on an increased discharge of potentially extractable substances. How-ever, it should be noted that the released substances in case of scenario A include substances still contained in waste goods (e.g. plastic bags) and are therefore not readily comparable to emissions of dissolved and suspended matter. Compared to emissions under conventional landfill conditions, the substance loads released during a flood event are three (e.g. N) to six (e.g. Cd) orders of magnitude higher for scenario A. In case of scenario B the emission loads increase by up to four orders of magnitude (e.g. Cu) compared to standard landfill conditions.

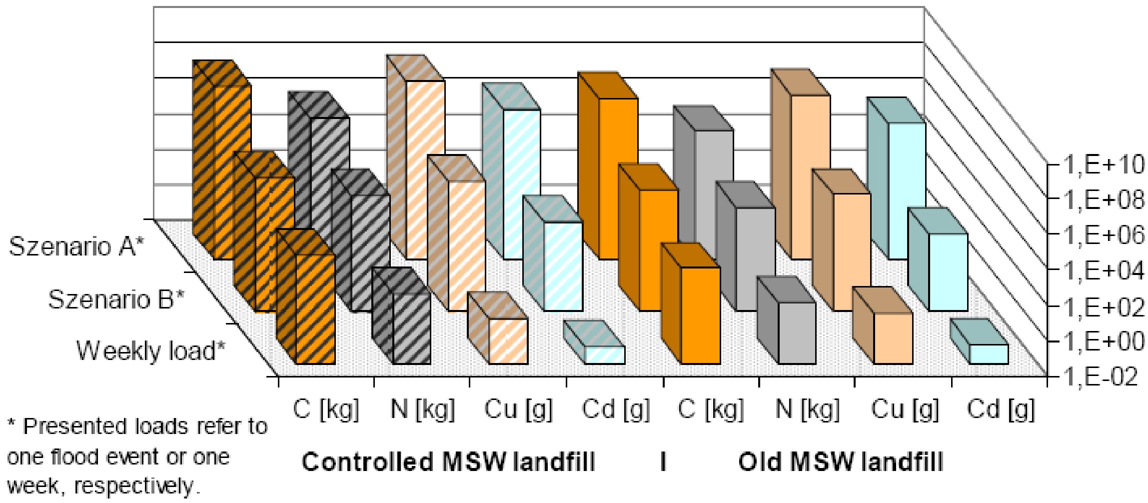

Fig. 22: Scenario-based emissions of selected substances during a flood event and under conventional landfill conditions

The results above show that emissions from submerged landfills are potentially large. Even considered the fact that the dilution potential of a receiving water body during a flood event might increase by a factor 10 up to 100, the increased emission load would still lead to a substantial increase in water pollution levels. However, due to the large knowledge gaps with respect to the metabolism of flooded landfills, their short- and long-term emissions, and their geotechnical properties, it has to be noted that, the calculated emission loads represent just a first estimate of potential substance releases from MSW landfills during flooding.

Conclusion and Outlook

In this paper it was shown that around one third of Austrian MSW landfills are sited in or in direct proximity to an area which is flooded on average once or more often in 200 years. The vast majority of these landfill sites are not equipped with flood protection facilities.

For flood prone landfill sites the potential substance release during a flood event was estimated via two scenarios. One assumed a loss of landfill stability due to erosion and the other one was based on an increased discharge of extractable substances from the deposited waste. These scenarios yield an increase of emission loads from flooded landfills of up to six and four orders of magnitude, respectively.

However, on the basis of the developed scenarios and the subsequent emission loads in case of landfill flooding it is not possible to evaluate whether flooded landfills pose a serious threat to the environment or not. Although landfills are reportedly (see above) responsible for environmental pollution during flood events, their specific contribution and the resulting environ-mental impacts are still largely unknown. Hence, it seems necessary and justified to investigate the metabolism of flood landfills. Further research is needed with respect to the short-, mid- and long-term emissions, also considering the influence of intensified emissions during flooding on necessary landfill aftercare periods. In addition, research on geotechnical characteristics of saturated MSW bodies as well as on the environmental impacts of the emitted pollutants is necessary.

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References:

ALSAG (1989): Altlastensanierungsgesetz (federal law for brownfield remediation). Bill number: Nr. 299/1989.

Baccini, P., Henseler, G., Figi, R. & Belevi, H. (1987): Water and Element Balances of Mu-nicipal Solid Waste Landfills. Waste Management & Research 5, pp. 483-499.

Belevi, H. & Baccini, P. (1989): Long-Term Behaviour of Municipal Solid Waste Landfills. Waste Management & Research 7, pp. 43-56.

Bendz, D. & Singh, V. P. (1999): Solute transport under steady and transient conditions in municipal solid waste. Water Resources Research 35, pp. 2333-2345.

Blight, G. E. & Fourie, A. (2005): Catastrophe revisited – disastrous flow failures of mine and municipal solid waste. Geotechnical and Geological Engineering 23, pp. 219-248.

Christensen, T. H., Kjeldsen, P. & Lindhardt, B. (1996): Gas-generating processes in landfills. In: Christensen, T. H. (ed.): Landfilling of waste: biogas. Proceedings, pp. 27-44, E&FN Spon, London, UK.

Döberl, G., Fellner, J., Allgaier, G., Brunner, P. H. & Stegmann, R. (2006): Eine neue Metho-de zur Charakterisierung des Stabilisierungsgrades großer Altablagerungen (Projekt EMSA). Report published by the Institute for Water Quality, Resources and Waste Management, Vienna University of Technology, Vienna.

Döberl, G., Huber, R., Fellner, J., Cencic, O. & Brunner, P. H. (2002): Neue Strategien zur Nachsorge von Deponien und zur Sanierung von Altlasten (Projekt STRANDEZA). Report published by the Institute for Water Quality, Resources and Waste Management, Vienna University of Technology, Vienna.

Ehrig, H. J. & Krümpelbeck, I. (2001): The Emission Behaviour of Old Landfills in the After-care Phase. In: Christensen, T. H., Cossu, R. & Stegmann, R. (eds.): Proceedings Sar-dinia 2001, Eigth International Waste Management and Landfill Symposium, IV, pp. 313-323. CISA, S. Margherita di Pula, Sardinia, Italy.

Fellner, J., Huber, R., Döberl, G. & Brunner, P. H. (2003): Hydraulics of MSW landfills and its Implications for Water Flow Modelling. In: Christensen, T. H., Cossu, R. & Steg-mann, R. (eds.): Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium. CISA, S. Margherita di Pula, Sardinia, Italy.

Geller, W., Ockenfeld, K., Böhme, M. & Knöchel, A (2004): Schadstoffbelastung nach dem Elbe-Hochwasser 2002. Final report of the ad-hoc-project 'Schadstoffuntersuchungen nach dem Hochwasser vom August 2002 - Ermittlung der Gefährdungspotentiale an Elbe und Mulde'. UFZ - Umweltforschungszentrum Leipzig-Halle GmbH,, Magde-burg.

Grischek, H., Andreas, L. & Bilitewski, B. (1999): Folgen der Flutung von Abfalldeponien in Tagebaurestlöchern. Wasser und Boden 51, pp. 38-58.

Habersack, H. & Moser, A. (2003): Ereignisdokumentation - Hochwasser August 2002, Final Report published by the University of Natural Resources and Applied Life Sciences, Vienna.

Hao, Y.-J., Wu, W.-X., Wu, S.-W., Sun, H. & Chen, Y.-X. (2008): Municipal solid waste decomposition under oversaturated condition in comparison with leachate recirculation. Process Biochemistry 43, pp. 108-112.

Klink, R. E. & Ham, R. K. (1982): Effects of moisture movement on methane production in solid waste landfill samples. Resources and Conservation 8, pp. 29-41.

Krammer, H. J., Domenig, M., Striedner, J. & Vogel, G. (1992): Materialien zum Bundesab-fallwirtschaftsplan (BAWP), Band 3: Kommunale Abfälle. Bundesministerium für Umwelt, Jugend und Familie, Vienna.

Lebensministerium (2006a): Federal Waste Management Plan 2006. Federal Ministry of Ag-riculture and Forestry, Environment and Water Management, Vienna.

Lebensministerium (2006b): Hochwasserrisikozonierung Austria -HORA (Online platform):

http://www.hochwasserrisiko.at (June 24th, 2008)

Lunzer, H., Domenig, M., Rosian, J., Mostbauer, P. & Häusler, G. (1998): Hausmülldeponien in Österreich. Umweltbundesamt, Vienna.

Maloszewski, P., Moser, H., Stichler, W. & Trimborn, P. (1995): Isotope hydrology investiga-tions in large refuse lysimeters. Journal of Hydrology 167, pp. 149-166.

Pohland, F. G. (1975): Sanitary landfill stabilization with leachate recycle and residual treat-ment. USEPA, Cincinnati.

Rosqvist, H. & Bendz, D. (1999): An experimental evaluation of the solute transport volume in biodegraded municipal solid waste. Hydrology and Earth System Sciences 3, pp. 429-438.

Skala, C., Kanovsky, A., Ortmann, M., Schamann, M., Weihs, S., Jobstmann, H., et al. (2007): Altlastensanierung in Österreich - Effekte und Ausblick. Bundesministeriums für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Vienna.

Stegmann, R. & Heyer, K.-U. (1995): Langfristiges Gefährdungspotential und Deponieverhal-ten von Ablagerungen. Statusseminar Deponiekörper, Wuppertal.

Young, S., Balluz, L. & Malilay, J. (2004): Natural and technologic hazardous material releases during and after natural disasters: a review. Science of The Total Environment 322, pp. 3-20.

Economic flood risk assessment

***Neuhold, C.**, Nachtnebel, H.P. (2008): Flood risk assessment in an Austrian municipality comprising the evaluation of effectiveness and efficiency of flood mitigation measures.*

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Abstract.

This paper aims to analyze several flood protection alternatives including structural and non structural measures by estimating their effectiveness and efficiency. The investigated alternatives referred to existing and conceivable flood mitigation measures in an Austrian municipality. In this process the mitigation measures were evaluated by analyzing historical data sets related to land use and hydrodynamic modelling. A micro scale flood risk assessment was conducted. The simulated inundation lines, water depths and flow velocities were linked to the land use information to estimate the damage potential of the flood prone area. The overall costs, the object related damage functions and the land use data provided the input for cost-effectiveness as well as benefit-cost analysis. The results indicated that the effectiveness and efficiency of non structural and structural mitigation measures are within the same range.

Introduction

Even though substantial amounts were invested in flood mitigation in Europe the reported damages increased tremendously in the last decade (Munich Re, 2007). One of the main causes was the frequently transformed land use in the former flood plains from agricultural utilization to industrial and residential areas. Obviously, these modifications led to a remarkable increase of the damage potential.

Case study area

This case study focused on the Austrian municipality Gleisdorf and an adjacent industrial park (Fig. 23). The study was conducted in the frame of the project FLOOD-ERA (ERA-NET CRUE) which was funded by the Federal State Government of Styria.

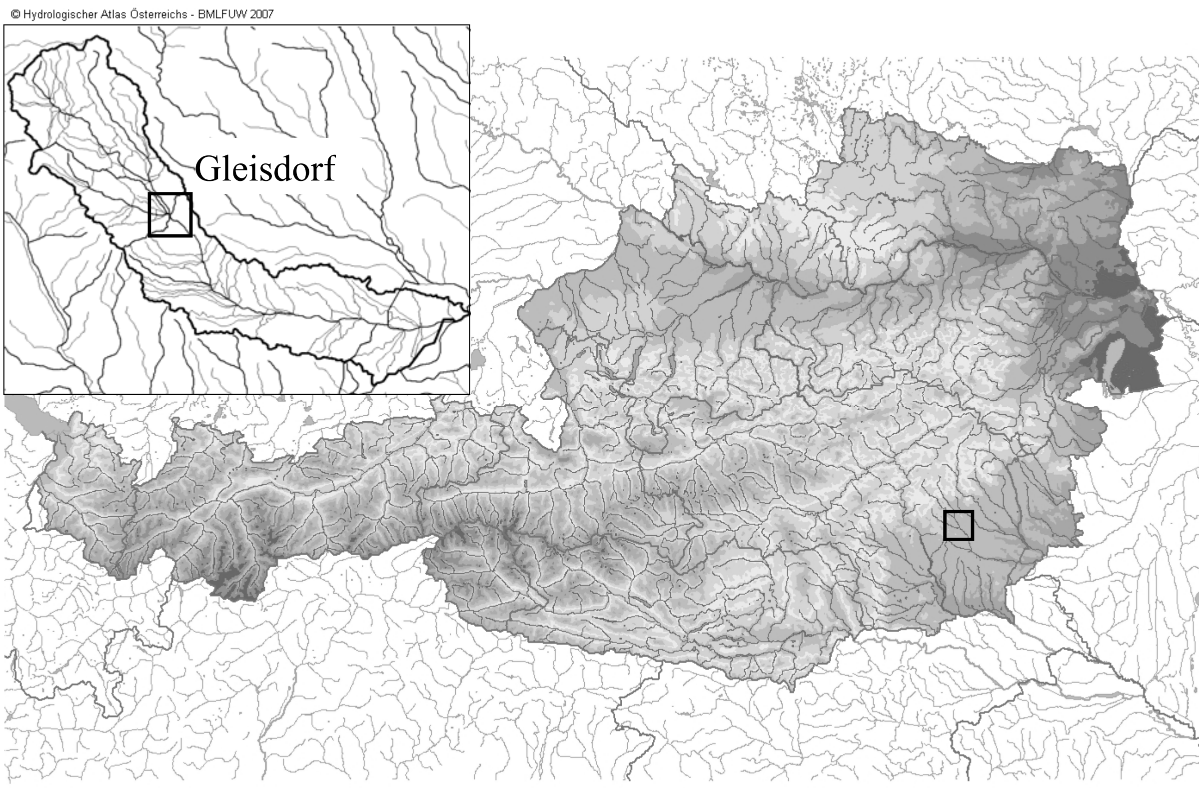


Fig. 23: Case study area Gleisdorf in the province of Styria

As residential areas were exposed to inundations of the Raab River, the partly existing flood protection scheme was upgraded by structural measures, designed to resist a 100-years flood. The protection measures which were implemented in 1999 are composed of dykes, floodwalls and a flood retention basin. Meanwhile, large parts of the former floodplain were developed as important industrial areas (Fig. 24) and as a consequence the vulnerability of the hinterland has increased substantially.

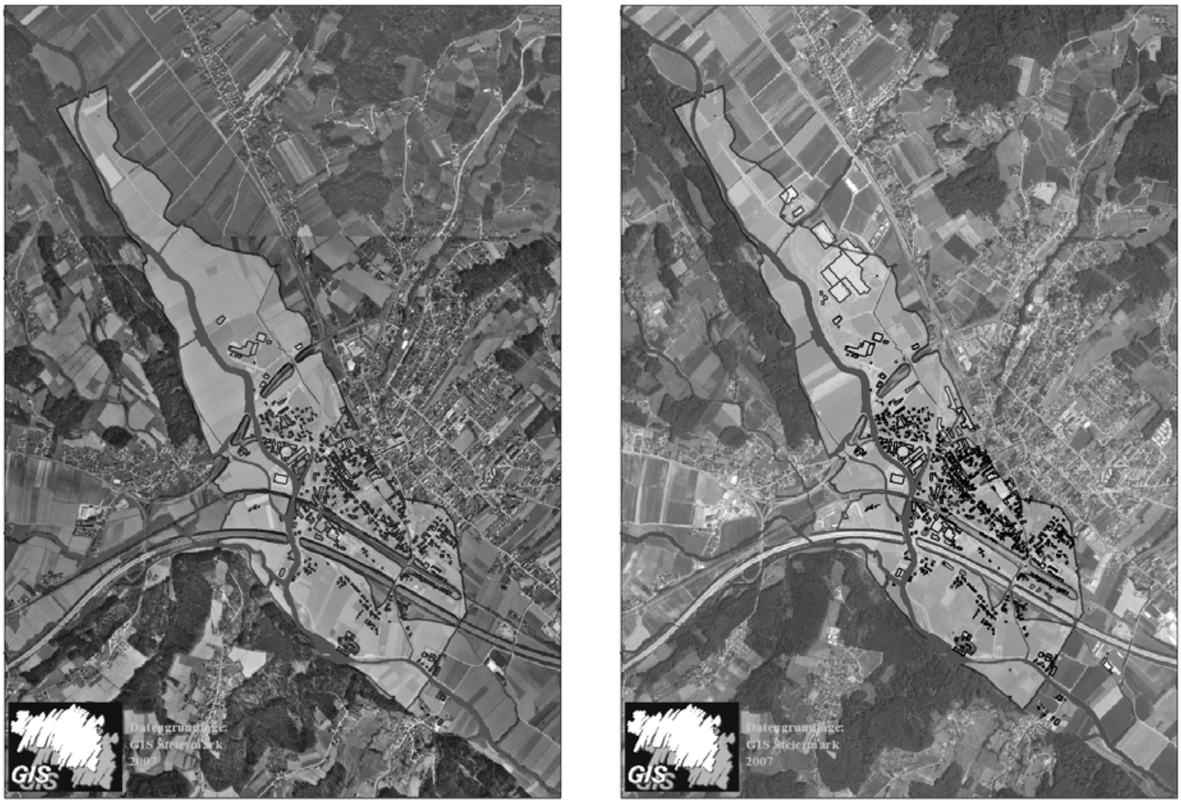


Fig. 24: Development of Gleisdorf 1999 (left) – 2008 (right)

The River Raab

The river Raab is one of the three major rivers in eastern Styria and its origin is located on 1150 m above sea level. The mouth into an anabranch of the Danube is at 118 m above sea level near Gyor (Hungary). The river length is about 250 km and the catchment area of the river Raab totals to 1020 km². The main land use is characterized by agricultural activities and medium scale industrial sites. Further, residential areas are continuously increasing, often expanding into the flood plain area. The river catchment draining to Gleisdorf ranges from altitudes of 360 m to 1800 m above sea level and totals up to 453 km² (BMFLUW, 2005).

Objectives

The objective of the case study was to analyze the effectiveness and efficiency of flood protection measures in and around the city of Gleisdorf. Several alternatives including structural and non structural measures were compared by conducting both, cost-effectiveness and benefit-cost analysis. The alternatives referred to existing and conceivable flood mitigation measures along the river Raab. In this process the structural measures (SM) “dyke”, “flood wall” and “flood retention basin” as well as the non structural measures (NSM) “spatial planning-building ban” and “spillway” were evaluated by analyzing historical data sets related to land use and simulation runs by means of hydrodynamic modelling. Therefore the catchment of the river Raab was simulated by a precipitation-runoff model to provide the input hydrographs to the hydrodynamic simulations. The SM and NSM alternatives were analyzed for normative scenarios referring to different design floods as well as log jam and dyke breach scenarios. The simulated inundation areas, water depths and flow velocities were linked to the land use information to estimate the damage potential of the flood prone area related to different flood events, also including a 5000-years flood (comparable to the August 2002 event on the river Kamp in Lower Austria).

One main focus of the case study was to validate, refine and adjust damage functions of published data related to recorded (ex-post) and estimated (ex-ante) flood damages (Buck, 1999; BMFLUW, 2004; BUWAL, 1999 a, b; BWG, 2002; Eberstaller et al., 2004; HYDROTEC, 2004; Kraus, 2004; Merz, 2004; Merz, 2006; Niekamp, 2001; Rodriguez, 2001; Schmidke, 2000; Statistik Austria, 2005 a, b, Nachtnebel et al., 2005). Two building categories were assumed as most influencing in this case study: first, residential buildings and second, medium scale industrial enterprises and were therefore analyzed in detail. Based on a three-stage-methodology developed by BUWAL (1999 a, b), a micro scale flood risk assessment was conducted. By integrating the scenario-based damage estimates and their respective probability the expected annual losses were calculated.

Methodology

Recently the applied research project FLOOD-ERA was carried out in the frame of the ERA-NET CRUE funding initiative (Schanze et al., 2008). Furthermore, the data set, methodological tools and results of the research project of Nachtnebel et al. (2005) were considered and enhanced. The contents of these projects comprise of data analysis (precipitation and runoff), hydrological (semi-distributed: COSERO; Nachtnebel et al., 2005) and hydrodynamic (coupled 1D-2D: Mike FLOOD; DHI, 2004) runoff modelling, scenario analysis of flood types as well as mitigation measures and economical analysis by means of damage function estimation, calculation of expected annual losses, cost-effectiveness analysis and benefit-cost analysis (Nachtnebel et al., 2005; Faber, 2006; Schanze et al., 2008).

The scenarios are based on different flood events which were generated by the hydrological model simulating the runoff for the upstream part. The propagation of the floods in the Gleisdorf area was simulated by the hydrodynamic model.

The results were achieved by detailed analyses of the utilizations in the case study area, the damage potential estimation and assessed loss functions related to potentially affected residential houses, small trade, sensible objects and enterprises.

Precipitation Runoff Model: COSERO

The applied model COSERO is a continuous, semi-distributed rainfall-runoff model developed by the Institute of Water Management, Hydrology and Hydraulic Engineering at the BOKU (Nachtnebel et al., 1993; Fuchs, 1998; Kling, 2002; among many others). It accounts for processes of snow accumulation and melt, interception, evapotranspiration, infiltration, soil storage, runoff generation and routing. Separation of runoff into fast surface runoff, inter flow and base flow is calculated by means of a cascade of linear and non-linear reservoirs, following the design of the HBV model (Bergström, 1995). Spatial discretization relies on the division of the watersheds into sub-basins and subsequently into hydrologic response units (HRU) based on available spatial information on sub-catchment boundaries, soil types, land cover and 200m elevation bands (Nachtnebel et al., 2005).

Hydrodynamic Model: Mike FLOOD

The system for the hydrodynamic analysis covered the river network with its bridges and weirs, the dykes, the flood retention basin and the floodplain topography and was modelled and simulated by the DHI Mike FLOOD software (DHI, 2004). The coupled 1D/2D software package was selected to simulate the flood propagation in the project area. Water tables together with flow velocities were obtained for each grid element.

The impact of bridges, gates, weirs and possible log jams at the bridges were simulated by the 1D component of the package (Mike 11) while the flow pattern in the hinterland was modelled by the 2D flow model (DHI, 2004). In Mike 11, the depth-averaged flow computations base on the conservation of mass and momentum, whereas the balancing equations are solved with the implicit finite difference algorithm (Abbott & Ionescu, 1967). This algorithm alternately calculates points of flow and water depth. The friction losses were computed by the formula of Gaukler, Manning and Strickler (Strickler, 1923). For bridge computations, the FHWA WASPRO (Federal HighWay Administration, WAter Surface PROgram) method was used, as it accounts for various discharge conditions, ranging from a free water surface to the overflowing of submerged decks. Lateral and inline weirs were computed by means of Poleni’s formula with an adaptation to consider free flow and submerged overflow conditions. Further, there were routines for damping numerical instabilities.

Considered Alternatives and Scenarios

To evaluate the effectiveness and efficiency of mitigation measures a broad set of scenarios was analyzed. The scenarios are based on a combination of different mitigation measures, subsequently called alternatives, and different design floods:

Tab. 5: Considered alternatives and scenarios

Alternative 1: dyke, flood wall, flood retention basin
Normative: HQ_{30}, HQ_{100} and HQ_{300} – no implemented mitigation measures Normative: HQ_{100}, HQ_{300}, HQ_{1000}, HQ_{5000} Dyke break: HQ_{300}, HQ_{1000}, HQ_{5000} Log jam: HQ_{100}
Alternative 2: spatial planning – building ban
Normative: HQ_{30}, HQ_{100} and HQ_{300} – no implemented mitigation measures
Alternative 3: spillway
Normative: HQ_{300}, HQ_{1000}

The structural measures refer to the existing flood protection scheme which comprises dykes, flood walls and a flood retention basin. The non structural measures are characterized by the implementation of a spillway into the existing dyke and the administrative tool of spatial planning, by means of a building ban in the potentially affected flood prone area (HQ300 inundation line, state of no implemented mitigation measures).

Data base

The data base from Nachtnebel et al. (2005) was refined by collecting additional details about the objects. Related to residential buildings this was done by refining the classification, mapping and evaluation of attributes of each single object. Emphasis was put on the attributes “structural age”, “equipment”, “heating system” and “size”. These census data evaluated in 2001 and provided by Statistik Austria (2005) were implemented into the data set on a 250 m grid base.

To cover the areal development a micro scale mapping was conducted for the flood prone area. In the framework of this investigation the attributes “equipment”, “recent state”, “utilization”, “number of levels”, “basement”, “garage”, “entrance level” and “obvious weak points” of every single object were recorded. To improve the damage analysis the broad category residential buildings had to be subdivided into eight categories with different weights in the context of expected flood damages. By considering Austrian micro census data, published data and individual inspections of the objects a refined estimate of the value of properties could be achieved.

An upgrade of data had as well been done with respect to the category “company” by interviewing chief operating officers, including an informative meeting. Additionally a new questionnaire was distributed, to be able to estimate the potential losses of the regional economy considering direct losses and added value losses. Whereas oral interviews with chief operating officers improved the quality of the data base remarkably. Dispatched questionnaires did not contribute effectively to enhance the dataset. Using this information, damage functions for 20 of the most important enterprises were calculated.

Combining the refined data sets with damage values of ex-ante and ex-post analysis for small trade, office buildings, retail trade, gastronomy and depots the expected annual losses for different states of utilization and variations of mitigation measures were calculated.

BUWAL approach

The BUWAL (Bundesamt für Umwelt, Wald und Landschaft, 1999 a, b) methodology is based on a three-stage procedure. Each stage represents a self-contained step for risk analysis. Stages 1, 2 and 3 are arranged in increasing order of analytical detail. Risk can be analyzed in one or more of the stages depending on the desired accuracy. In stage 1, the hazard map is overlaid with a land use map to identify potential objects at risk. In stage 2, the risks for spatial elements (area, linear and point elements) are quantified. Risks can, however, be analyzed directly in stage 2 which is based on standardized damage values which were obtained by compiling various damage reports. In stage 3, risks are analyzed by specific investigations of individual objects e.g. a building or section of a transport route at risk (BUWAL, 1999 a, b). In the frame of this case study the evaluation of the expected losses were based on Stage 3. The risk analysis considered all buildings, the transport infrastructure and economic activities.

Evaluation of effectiveness and efficiency

Cost-effectiveness analysis (CEA) and benefit-cost analysis (BCA) were applied to evaluate the considered mitigation measures. The overall construction, maintenance and opportunity costs, the object related damage functions, the added value estimates for the local economy and the land use data provided the input.

To analyze the cost-effectiveness the costs of the measure, or a combination of measures, maintenance costs and opportunity costs were linked to the thereby protected area. The benefit-cost analysis was based on the directive for BCA of the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMFLUW, 2008) which comprises the work steps listed below:

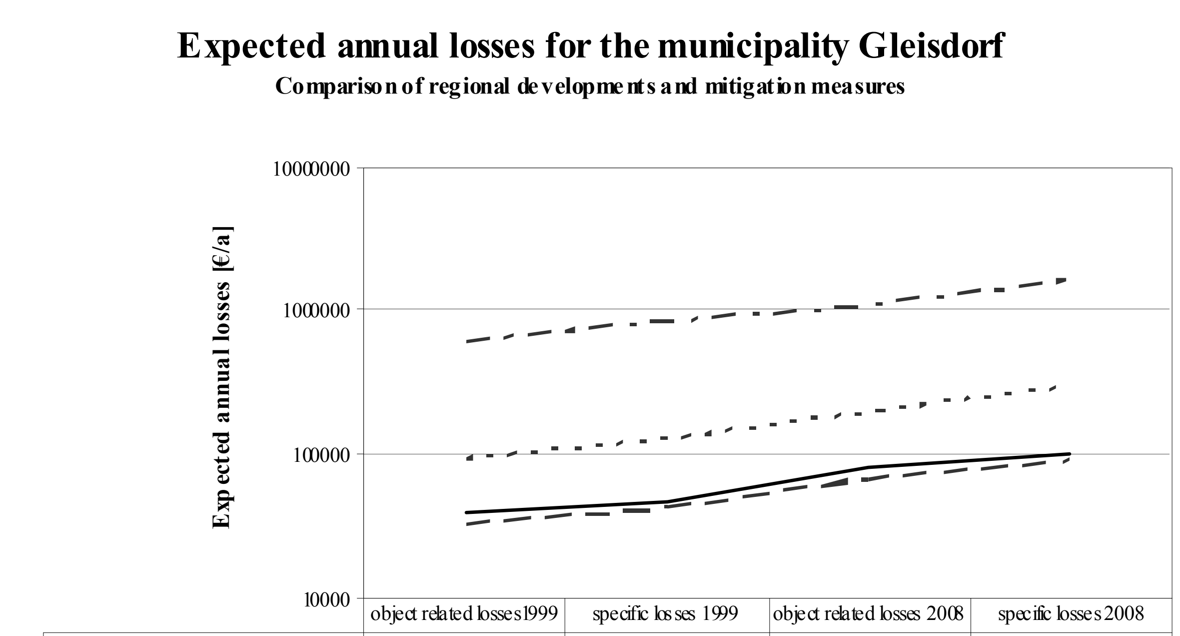
- Geoinformation of the area of interest
- Design floods of different probabilities
- Simulation of the hydrodynamic flood impact
- Land use, population, employees
- Vulnerability of different categories
- Expectation of loss
- Estimation of benefits
- Estimation of costs
- Benefit Cost Ratio and sensitivity analysis
- Evaluation of persons at risk
- Intangible, socio cultural and ecologic effects
- Comprehensive appraisal
- Comparison of alternatives - optimal solution
- Description of residual risks, necessary actions

Results

Expected annual losses

The expected annual losses (Fig. 25) were calculated by two approaches. The first one considers object related losses based on the enquiry of the number of affected buildings. Each building is linked to a damage function [€/building] depending on the utilization and the inundation depth. The second approach is based on the specific damages of inundated objects. The damage of a flooded object depends on its base area and the depth of inundation and is multiplied by the assessed specific losses [€/m²].

These enquiries are made for all utilizations except for the local economy, because studies indicated that the damage estimation based on the losses/m² overestimate the damage remarkably if enterprises are included (Nachtnebel et al., 2005; Faber, 2006). The local enterprises were assessed separately based on the inundation depth and the flooded area of each scenario supported by the interviews conducted with chief operating officers. This input led to damage functions for 20 enterprises.



	object related losses 1999	specific losses 1999	object related losses 2008	specific losses 2008
No mitigation measures	606454	822399	1056831	1597161
SM: scenario dyke break	91593	125830	193497	291778
SM: scenario no dyke break	38775	46379	78834	101566
SM: scenario implemented Spillway	32741	41661	66371	91060

Fig. 25: Calculated expected annual losses based on different enquiry approaches and different states of utilization

Fig. 25 clearly shows the increase of the expected annual losses due to the higher vulnerability triggered by land development. The implementation of a spillway would reduce the loss expectations by 10 to 15% depending on the estimation approach (dashed line). The continuous line (SM: scenario no dyke break) represents the calculations where the dyke resists overtopping which has to be seen as very unlikely. The dotted line includes the dyke break due to overtopping which leads to a tremendous increase (nearly 3 times) of the calculated damages. If no mitigation measures would have been implemented the expected annual losses would be dramatically higher (dash dotted line). Considering the development in the past 10 years (Fig. 24) the increase of the vulnerability is represented by remarkably higher expected annual losses. If this in-crease of vulnerability would have been avoided by stating a building ban after the implementation of the protection scheme, applied on the former flood prone area, the non structural measure "spatial planning" has to be seen as very effective and efficient.

Cost-Effectiveness Analyses

As one result of the cost-effectiveness analysis a matrix of protected area related to the utilizations was created (Tab. 6). Furthermore, the costs for protecting one m² of flood prone land against a 100-years flood were calculated. Due to the implementation of the protection scheme an area of 180 ha is considered of being without damages during a flood event up to a recurrence interval of 100 years:

Tab. 6: Cost-Effectiveness Analyses

	Requirement for protection [Hectare]	Not worth being protected [Hectare]
Utilization		
Building land	22	
Public infrastructure	19	
Technical facilities	04	
Stock ground	36	
Agricultural land		66
Miscellaneous		33
Summation	81	99

Considering the construction costs of nearly 4.2 Mio € and the discounted maintenance costs for a life expectancy of 80 years (BMFLUW, 2008) of 1.1 Mio € the protection of 1 m² of land (requirement for protection) will be 6.6 €. Including all utilizations the protection of one m² would cost 3.0 €. Additional opportunity costs have to be included (WIFO, 2003). The opportunity costs equal the revenue of the project (construction) costs (WIFO, 2003). This leads to additional costs of 26 cent per m² every year (requirement for protection). These values seem to be small but for a typical Austrian property of 1000 m² the investment would equal 6572 € nonrecurring plus opportunity costs of 263 € every year.

Regarding the overall protected area, the protection of one hectare land would cost 29575 € nonrecurring plus 1183 € opportunity costs every year. Due to the fact that approximately 60 % of the protected area is considered as not worth being protected e.g. agricultural land, solely the opportunity costs are equal to 3-10 times the tenancy cost for farming land per year and hectare which is quite expensive and considered as not efficient.

Benefit-Cost Analyses

Due to the increasing utilization in the hinterland during the past 10 years (Fig. 24), the vulnerability and accordingly the benefits of mitigation measures increase (Tab. 7). The remarkably developed industrial park and the increase of residential areas are clearly shown by a tremendous raise of the benefit-cost ratio (utilization in 1999-2008). Contemplating the evaluated measures the most efficient measure is the existing protection scheme, improved by a spillway (Scenario: Spillway). Depending on the enquiry approaches (object related losses [€], specific losses [€/m²]) the BCR are listed in Tab. 7 (first number: object related losses, second number: specific losses, third number: average):

Tab. 7: Benefit-Cost Ratios

Scenario	Utilization state 1999	Utilization state 2008
Spillway	2.88/3.92/3.40	4.98/7.57/6.27
No dyke break	2.85/3.90/3.38	4.91/7.51/6.21
Dyke break	2.59/3.50/3.04	4.34/6.56/5.44

The two states of “Utilization in 1999” and “Utilization in 2008” were analyzed to evaluate the efficiency of the non structural measure “spatial planning”. The “Utilization in 1999” reflects the BCR considering a building ban after the implementation of the mitigation measures. By means of benefit-cost analysis three alternatives were investigated in detail:

- The implemented flood mitigation measures improved by a spillway (SM: scenario implemented spillway) where no dyke break will occur because of the enhanced reliability
- The implemented flood mitigation measures when no dyke break occurs by overtopping (SM: scenario no dyke break)
- The implemented flood mitigation measures considering dyke break due to overtopping (SM: scenario dyke break)

The results of the BCR distinguish that the efficiency of the implemented structural measures dyke, flood wall and flood retention basin could be tremendously improved if construction works in the former flood prone area would have been banned. Furthermore, the implementation of a spillway would lead to an increase of the efficiency, because a dyke break can be avoided and uncontrollable overtopping would be very unlikely.

Nevertheless we must not forget that the results are more or less miss-leading when we consider the expected annual losses. This case shows that a higher BCR, i.e. a more efficient mitigation measure, does not include lower remaining risk (emerges due to consideration of possible failure and/or overtopping of mitigation measures) for the hinterland.

Conclusions

The case study aimed to contribute to the development of a methodology to evaluate the effectiveness and efficiency of structural and non structural flood mitigation measures. A micro scale risk assessment for the municipality of Gleisdorf was conducted where besides hydrological and hydrodynamic modelling a large quantity of attributes and data sets was utilized to establish a damage function for each single object in the flood prone area.

The evaluation tools of cost-effectiveness analysis and benefit-cost analysis proofed to be adjuvant but also sometimes the results could be miss-leading. More precisely: a higher BCR does not mean a more effective mitigation scheme but it expresses a more efficient one due to a higher vulnerability and therefore higher benefits in the hinterland. That means, the higher the expected annual losses, the higher the BCR will be. Considering this result the cost-effectiveness seemed to be the preferential evaluation method due to the fact that a miss-interpretation of the results is very unlikely. Additionally, the CEA has the advantage that benefits do not have to be expressed in monetary terms.

The analyzed alternatives clearly showed that a combination of all considered measures would be the most effective and efficient mitigation measure. The simulation results of a 300-years flood for the recent state of utilization proofed that a densely populated area which would be free of flooding by implementing a spillway into the existing flood protection scheme. In connection with a building ban the most feasible combination could be achieved.

Due to the implementation of a spillway to the flood levee system even the persons at risk in residential houses could be reduced from 254 to 53 (status of 2001).

References:

Abbott & Ionesco (1967): On the numerical computation of nearly-horizontal flows. J.Hyd.Res., 5, pp. 97-117

Bergström, S. (1995): The HBV model. In: Singh VP (ed.), Computer Models of Watershed Hydrology, Water Resources Publications, Highlands Ranch, CO, 443-476.

BMFLUW (2004): Analyse der Hochwasserereignisse vom August 2002 – Flood RISK, WP Donau TP 05, Operative Maßnahmen Donau

BMFLUW (2005): Hydrologischer Atlas Österreichst: 3. Lieferung. Wien: BMFLUW

BMFLUW (2008): Kosten-Nutzen-Untersuchung im Schutzwasserbau: Richtlinie. Wien: BMFLUW

Buck (1999): Auswertung der HOWAS-Datenbank: HY 98/15. Karlsruhe: Institut für Wasserwirtschaft und Kulturtechnik, Universität Karlsruhe

BUWAL (1999 a): Risikoanalyse bei gravitativen Naturgefahren – Methode. Umwelt-Materialien Nr. 107/I, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft

BUWAL (1999 b): Risikoanalyse bei gravitativen Naturgefahren – Fallbeispiele und Daten. Umwelt-Materialien Nr. 107/II, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft

BWG (2002): Methode BWG Abschätzung des Schadenspotentials bei Überschwemmung und Übermurung. Arbeitshilfe 1.2

DHI (2004): MIKE FLOOD Reference Manual.

Eberstaller et al. (2004): Raumordnung und Hochwasserschutz am Beispiel der Traisen – Siedlungsentwicklung und Schadensanalyse. TP 02 - Naturgefahren BWV. In: Analyse der Hochwasserereignisse vom August 202 – Flood Risk. Hrsg: BMLFUW (2004)

Faber (2006): Flood risk analysis: residual risk and uncertainties in an Austrian context. Dissertation. Institute of Water Management, Hydrology and Hydraulic Engineering, Vienna: BOKU

Fuchs M. (1998): Modeling snow-melt runoff in an alpine watershed. Master thesis, Institute of Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Applied Life Sciences, Vienna, Austria.

HYDROTEC (2004): Hochwasser-Aktionsplan Sieg http://www.stua-si.nrw.de/sieg/b1/

Kling H. 2002. Development of tools for a semi-distributed runoff model. Master thesis, Institute of Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Applied Life Sciences, Vienna, Austria.

Kraus (2004): Wirtschaftlichkeit und Priorisierung von Schutzmaßnahmen vor Wildbächen, Erosion und Lawinen: IAN Rwport 94: Workpackage (WP) Naturgefahren Wildbach- und Lawinenverbauung (WLV) Teilprojekt (TP) 03 in BMFLUW (2004)

Land Steiermark (2008): Hochwasserschutz an der Raab (Gleisdorf, Albersdorf-Prebuch, Ludersdorf-Wilfersdorf) www.wasserwirtschaft.steiermark.at

Merz, B. et al. (2004): Estimation uncertainty of direct monetary flood damage to buildings. Natural Hazards and Earth System Sciences (2004) 4: 153–163

Merz (2006): Hochwasserrisiken – Grenzen und Möglichkeiten der Risikoabschätzung, E. Schweizerbart´sche Verlagsbuchhandlung (Näglele u. Obermiller), Stuttgart

Munich Re (2007): Edition Wissen, Zwischen Hoch und Tief, Wetterrisiken in Mitteleuropa

Nachtnebel et. al (2005): Risikoanalyse des bestehenden Hochwasserschutzes Stadt Gleisdorf und Umgebung. River Basin Agenda, Wien: IWHW, BOKU

Nachtnebel H.P., Baumung S., Lettl W. (1993). Abflussprognosemodell für das Einzugsgebiet der Enns und Steyr (in German). Report, Institute of Water Management, Hydology and Hydraulic Engineering, University of Natural Resources and Applied Life Sciences Vienna, Austria.

Niekamp (2001): Hochwasserschäden. In: Hochwasser–Handbuch. Auswirkungen und Schutz / Hrsg.: Heinz Patt. Springer, 2001

Rodriguez (2005): Hochwassergefahrenkarten für Deutschland – Zusammenfassung und Vorschlag für ein koordiniertes Vorgehen der Bundesländer. Teil 1: Voraussetzungen für die Erstellung von Hochwassergefahrenkarten. In: Hochwassergefahrenkarten KLEEBERG, H.-B. (Hrsg. 2005): Hochwasser-Gefahrenkarten. Beiträge zum Erfahrungsaustausch am 24. November 2004 in Erfurt. Heft 08.05 137 Seiten, 32 Abbildungen, ISBN 3-937758-48-8

Schmidke (2000): Klimaveränderung – sozioökonomische Konsequenzen. Karlsruhe: Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg (LUBW), 269-276. http://www.kliwa.de

Statistik Austria (2005 a): Ein Blick auf die Gemeinde http://www.statistik.at/blickgem/gemList.do?bdl=6

Statistik Austria (2005 b): Leistungs- und Strukturstat. http://www.statistik.at/unternehmen/lse3_05.pdf

Strickler (1923): Beiträge zur Frage der Geschwindigkeitsformel und der Rauhigkeitszahlen für Ströme, Kanäle und geschlossene Leitungen, Mitteilung Nr. 16 des Amtes für Wasserwirtschaft, Eidgenössisches Department des Inneren, Bern, 1923

WIFO (2003): Hochwasserschutz in der Wachau: Eine Kosten-Wirksamkeitsanalyse von Baumaßnahme in Dürnstein, Spitz und Weißenkirchen.

Schanze, J.; Hutter, G.; Penning-Rowsell, E.; Nachtnebel, H. P.; Meyer, V.; Königer, P.; ***Neuhold, C.****; Harris, T.; Kuhlicke, C.; Olfert, A. (2008): Evaluation of Effectiveness and Efficiency of non-structural measures in Flood Risk Management*

Proceedings of the 4th International Symposium on Flood Defence, 4, 10-ff

Abstract.

Non-structural measures for risk reduction play still a minor role in strategies of flood risk management. One reasons for that can be missing evaluation capacities. The paper therefore presents a European study which deals with the evaluation of non-structural measures and their comparisons with structural measures. To do so it firstly provides a systematization of both kinds of measures. It than gives an overview over the state of the art of evaluating flood risk reduction measures and shows advanced methods for the evaluation of structural measures. Finally the context conditions of decision makers are investigated to understand the possible impacts of enhanced evaluation capacities and to identify other barriers and enables for a more balanced consideration of both kinds of measures.

Introduction

Decisions about deploying structural (SM) and non-structural measures (NSM) for pre-flood risk management are made under manifold context conditions of decision makers. One of the context factors is supposed to be the availability of an appropriate evaluation capacity to determine the complex and partly uncertain consequences of risk reduction measures. Evaluation problems can particularly arise due to a lack in indicators, criteria, methods, knowledge and data. Since there is already some experience in evaluating SM, a research project is being carried out to deal with the evaluation and comparison of both kinds of measures with an emphasis on NSM. The following objectives have been set:

- To systemise structural and non-structural measures;
- To develop an outline methodology for the evaluation of the effectiveness and efficiency of structural and especially non-structural measures;
- To analyse context conditions like risk perception of decision makers with a potential to influence the choice of structural and non-structural measures;
- To identify the site-specific effectiveness and efficiency of such measures and the influence of selected context conditions on their choice; and,
- To derive recommendations for the improvement of flood risk management strategies.

To cover all these items, a combined research design has been chosen with (i) the systematisation of SM and NSM, (ii) a normative approach on the evaluation of SM and NSM, and (iii) a descriptive approach to analyse the context conditions of decision makers (Fig. 26). Research encompasses the derivation of generic conceptual findings and empirical work in six European case studies in Germany, United Kingdom and Austria.

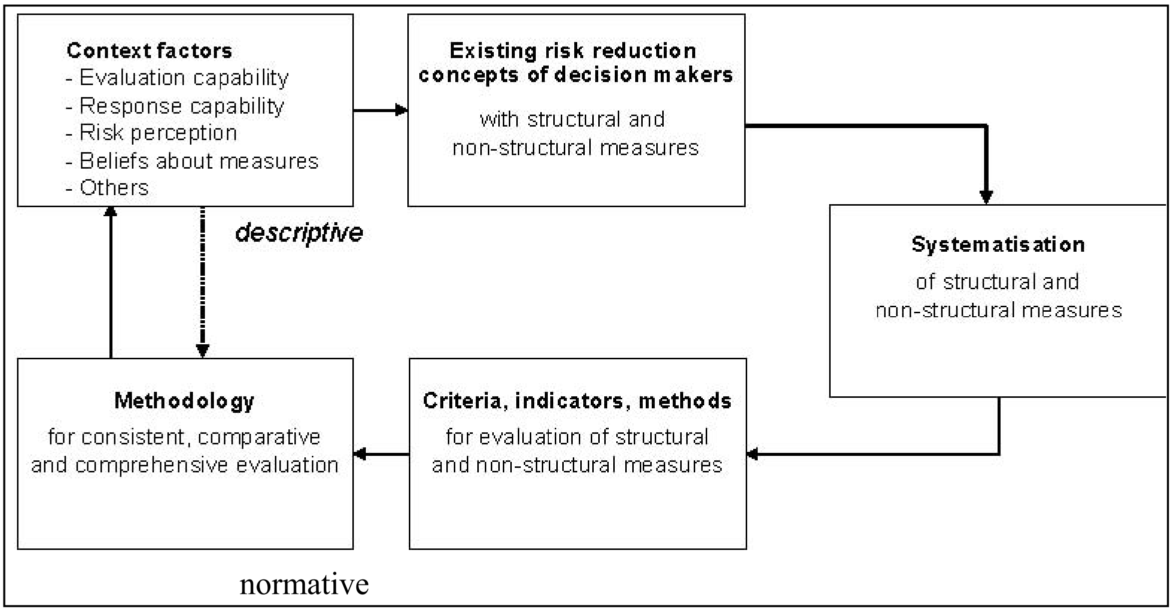


Fig. 26: Combined research design with systematization, descriptive and normative approach

Systematisation of structural and non-structural measures

It cannot be expected to find a single valid classification for SM and NSM. Instead the classification like in other fields depends on the purpose of distinctions and clustering. In terms of flood risk management there seems to be at least three major aspects for sorting measures.

- the *construction* of measures;
- the *effect* of measures; and,
- the *function* of measures.

The first aspect puts emphasis on the technical design of a measure. It contrasts structural works of hydraulic engineers with other kinds of measures and is the background for the distinction of structural and non-structural measures. The second aspect differentiates water-related and receptor-related risk reduction and thus addresses effects on reducing either the flood hazard or the flood vulnerability (cf. Cooper et al., 2007). It makes especially sense for promoting a risk-based approach including the mitigation of vulnerability. The third aspect reflects the functionality of measures. It indicates the way how the intervention in the flood risk system works. On the highest level it distinguishes physical measures and policy instruments, below it clusters different mechanisms such as control, retreat and so forth (Olfert & Schanze, 2007).

For this study at least the first aspect is set by the call of ERA-NET CRUE and of course is reasoned by the historical and common use of the terms structural and non-structural measures in science and practice. The distinction between both types of measure is rather simple in defining structural measures and leaving all other measures as non-structural (cf. e.g. Marsalek et al., 2000, Petry, 2002). This lead to the following understanding:

- Structural measures (SM) are interventions in the flood risk system based on (structural) works of hydraulic engineering; and,
- Non-structural measures (NSM) are all other interventions.

In contrast to the previous use of the term structural measures here it is recommended not to include the intended effects of flood control and protection in the definition. One reason for that is that also nonstructural measures like land management and sediment dredging can contribute to lowering the flood discharge or the water level respectively. Another reason is that risk reduction effects cannot be measured on the basis of the hazard only. And not at least, the applied understanding facilitates a sharp distinction between the description of a measure and its evaluation (e.g., in terms of indicators to assess the effectiveness of NSM).

Tab. 8: Proposed systematization of structural and non-structural measures (Schanze et al., 2008)

Functional group	Type of measure	Examples	Underlying nonstructural measure
Structural measures			
Flood control and defence	Flood water storage	Flood polder	Flood protection standards; investment program
	River training	By-pass channel	
	Flood protection	Dike	
	Drainage and pumping	Urban drainage system	
Non-structural measures			
Flood control and defence	Adapted land use in source area	Conservation tillage	Restriction of land use (in source areas)
	River management	Dredging of sediments	Investment program
Use and retreat	Land use in flood-prone area	Avoiding land use in flood prone areas	Building ban; hazard and risk maps; adapted insurance premium
	Flood proofing	Adapted construction	Forecasting and warning; civil and disaster protection act
	Evacuation	Evacuation of assets	
Regulation	Water management	Flood protection standards; restriction of land use	
	Civil protection	Civil and disaster protection act	
	Spatial planning	Building ban	
Financial stimulation	Financial incentives	Investment program	
	Financial disincentives	Insurance premium according to flood zone	
Information	Communication/Dissemination	Information evens	
	Instruction, warning	Hazard and risk maps; Forecasting and warning	
Compensation	Loss compensation	Public relief	

Since the differentiation of SM and NSM does not allow for further clustering, it is proposed to enhance the systematisation applying the third aspect. The latter refers to intervention mechanisms of measures without specifying their effects. Accordingly no restrictions appear with respect to comparative evaluation of different measures. The following functions are derived from Olfert & Schanze (2007) and Parker (2007): Flood control, use and retreat, regulation, financial stimulation, information and compensation. For each functional group further types of measures can be indentified. Tab. 8 presents an overview of the resulting systematization considering the first and third criterion, the types of measures and examples of concrete measures. In addition, the last column indicates relations between measures. Especially the realization of physical measures normally depends on preceding regulatory, financial and planning instruments (see Olfert & Schanze, 2007).

Outline methodology for the evaluation of effectiveness and efficiency

The study aims at a significant step towards systematic evaluation and comparison of the effectiveness and efficiency of SM and NSM. It therefore compiles state of the art evaluation knowledge, enhances methods for the evaluation of NSM and comparison of SM and NSM and finally includes all findings in the framework of an outline methodology for the evaluation practice. Hereby, evaluation is understood as a systematic and transparent way of investigating an evaluand's worth and merits based on comprehensible, empirical qualitative and/or quantitative data. It is assumed that each evaluation requires:

- Indicators for describing intended and unintended effects;
- Criteria as evaluation concepts; and,
- Methods for calculating criteria values.

Indicators of effects

Indicators are the practical units of evaluation applied for the measurement of obtained effects, mobilized resources or accomplished outputs (EVALSED, 2007). They can refer to intended and unintended effects and consider hydrological/hydraulic, socio-cultural, economic, and ecological aspects (cf. Olfert, 2007). Hydrological and hydraulic effects describe common primary services of many flood risk reduction measures. Despite they do not constitute effects in terms of risk reduction, they are important milestones in the evaluation of related measures.

Criteria effectiveness

Effectiveness serves as evaluation criterion to asses the extent to which interventions achieved or are expected to achieve a given objective. The assessment considers only intended effects, while unintended effects lacking an objective are disregarded (Messner, 2006). Objectives are case specific quantified expectations for certain effects described by indicators. Effectiveness is represented by the degree of goal achievement in % related to the related effect.

Criteria efficiency

The efficiency criterion is dedicated to the assessment of the relationship of input and output. Two main types of efficiency assessment can be differentiated from an economic point of view:

- Cost-effectiveness analysis (CEA);
- Cost-benefit analysis (CBA).

Cost-effectiveness analysis (CEA)

The aim of the CEA is to determine the intervention which delivers the highest degree of performance at lowest costs compared to alternative measures or portfolios. Two main approaches can be distinguished. The *league table approach* focuses the maximization of output in the scope of available resources. The *threshold approach* seeks to achieve a given standard at minimum costs (Rheinsberger & Weck-Hannemann, 2007). In the case of evaluating measures, cost effectiveness states whether the given target of safety or remaining risk is achieved by minimal costs or whether risk reduction is maximized by a given budget. According to the explanation of effectiveness, the inevitable prerequisite for the costeffectiveness is to set a specific aim or to give financial budget as threshold to analyze the costeffectiveness. Like effectiveness, also cost-effectiveness is limited to the measurement of performance to that given objective, while other potentially beneficial effects are neglected (Messner, 2006).

Cost-benefit analysis (CBA)

The CBA balances both cost and benefits in monetary terms. For example, the present value of all costs of a decision alternative is compared to the present value of all benefits associated with that alternative. The overall goal is to select the most efficient alternative from a list of options (Hanley & Spash, 1993). Hereby, economic efficiency (or pareto optimality) is defined as an allocation of resources such that no further reallocation is possible that would create gains in production or consumption for some persons without simultaneously imposing losses to others. In other words, at least in theory, cost-benefit analysis is aiming at providing evidence for maximizing social welfare. For the evaluation of flood risk reduction measures this means that intended or unintended, tangible or intangible and positive or negative effects need to be taken into account. − Production costs of measures can be accompanied by transaction costs which again can be divided into 1) transaction costs of decision making and 2) transaction costs of implementing these management decisions (Birner & Wittmer, 2004, 669).

Methods for calculating criteria values for non-structural measures

To enhance the evaluation capabilities with respect to the effectiveness and efficiency of NSM a number of these measures were investigated applying methods for the evaluation of SM or developing new tools specifically dedicated to NSM. The following measures with according methods were considered: Spatial planning with building ban, resettlement, flood forecasting and warning, community based flood protection, flood proofing, emergence response, insurance and public education and awareness.

Selected measures with according methods and derived findings are described in the following. This encompasses both single NSM as well as their comparison with SM.

Spatial planning / building ban (Raab River, Austria)

Measure: A building ban is assumed which would have ruled out any new settlement that had been developed in the floodplain during the last 10 years.

Method: An enhanced flood risk assessment based on a three-stage-methodology developed by BUWAL (1999 a, b) was conducted. Therefore the catchment of the river Raab was simulated by the semidistributed rainfall-runoff model COSERO (Kling, 2002) to provide the input data sets for the hydrodynamic model MIKE FLOOD (DHI, 2004 a, b, c). Normatively defined scenarios assume (i) a dike, flood wall and offline retention basin, (ii) a building ban, and (iii) a spillway. For some scenarios additionally logjam and dike breach were considered. The simulated inundation lines, water depths and flow velocities were linked to the land use information to estimate the damage potential of the flood prone area related to a 5000-years flood (comparable to the August 2002 event on the river Kamp in Lower Austria). By integrating the scenario-based damage estimates and their respective probability, a detriment was calculated. A valuable input to the assessment of the damage potential was delivered by the survey of numerous ex-ante and ex-post analyses as well as by detailed mapping of the residential buildings and the local companies and census data.

Findings: Due to the increasing utilization in the hinterland, the vulnerability and accordingly the benefits of mitigation measures increase. The remarkably improved industrial park and the increase of utilization by residential houses are clearly shown by a tremendous raise of the benefit-cost ratio. Contemplating the evaluated measures, the most efficient measure is the existing protection scheme, improved by a spillway. However, investigations also show that a higher benefit-cost ratio, i.e. a more efficient mitigation measure, does not include lower remaining risk for the hinterland.

Resettlement (Mulde River, Germany)

Measure: For a small village we compared an already constructed ring dike as a SM with a hypothetical resettlement as a non-structural alternative.

Method: The efficiency of both alternative measures is determined by cost-benefit analysis. The benefits of the SM in terms of damage reduction were evaluated based on a standard meso-scale approach. For the evaluation of the benefits of the resettlement a nearly complete reduction of flood damage apart from agricultural damages is assumed. In order to estimate the costs of the resettlement we estimated compensation payments based on market values of properties. Sensitivity analyses are conducted with regard to the uncertainties in benefit and cost figures as well as different discount rates.

Findings: Cost-benefit analysis shows that both alternatives are not efficient, i.e. the costs exceed the benefits. However, the ring dike is evaluated better than the resettlement. With regard to effectiveness both measures achieve the official target of protecting settlements against 1/100 floods, but the ring dike achieves this target at lower costs.

Flood forecasting and warning (Lower Thames River)

Measure: Brings emergency responders to a state of readiness to manage a flood incident, including operating any control or diversion structures that can reduce flood peaks. It also allows the to warn members of the public at risk from flooding.

Method: Empirical research approach to identify the proportion of total flood damage potential which is likely to be saved by members of the public (in this case predominantly householders) moving damageable household inventory out of the path of floodwaters (Parker et al., 2007).

Findings: Limited effectiveness of flood warning response, as well as the limited effectiveness of the flood warning service and the availability of householders to receive warnings. Effective response was achieved by only 55% of those receiving a warning with a lead time of < 8 hours, and 71% of those receiving a warning with a lead time of > 8 hours.

Community based flood protection (Lower Thames River)

Measure: Emerging form of flood defence as communal measures including local ground raising, permanent flood wall/bund and demountable barrier protection for groups of properties.

Method: Costs are based upon capital costs, maintenance costs and other expenditures arising from ground investigation, design, land negotiations and legal costs, calculated over a 50 year period at a discount rate of 3.5%. Flood damages are assessed using Multi-Coloured Manual data (Penning-Rowsell et al., 2005). Benefits are based upon the average annual damage calculated from the potential flood damages in the 5, 10, 20, 50, 65, 100 and 200 year floods.

Findings: The study indicates that, on the basis of analysis of the pilot and initial sites (comprising a total of 851 properties), these measures are economically efficient, but not as economically efficient as say, flood diversions channels. However, the economic efficiency of these measures varies considerably from area to area within the floodplain and B:C ratios range from 8.6 to 0.42 to 1.

Flood proofing (Elbe River, Germany)

Measure: Individual property protection measures comprising flood boards and gates, orifice capping measures and evacuation of mobile goods.

Method: For the analysis a fictive portfolio of small scale private measures is applied to single buildings. Exposed buildings are classified by using representative building types for which analytic damage functions are applied (cf. Deilmann et al, 2008). The building stock is treated at four hypothetic exposure levels which are differently exposed to flooding with the lowest expectable flooding starting at the level of a 1:10 flood. As a result, each single flood event will differently hit the buildings at the four levels. The loss potential is determined for a hypothetic 100 years return period. Based on investigations for comparable combinations of measures (Olfert 2007) different required costs and assumed effectiveness rates are applied to the building stock to describe costs of the measures and the avoided losses. A progression factor for exposed values is considered. Finally, for efficiency evaluation the net present value and benefit-cost ratio are calculated for different scenarios of future development.

Findings: The portfolio is regarded in comparison to a structural protection line. For the case that no further development takes place, the portfolio of small scale measures shows a considerably better result in terms of B:C ratio (11 against 6) and an even slightly better net present value. This result becomes even clearer if assuming a dike breach in the time period (11 against 3). However, if permitting housing development in the protected area, the protection line improves its performance in comparison to private measures. But, seeing the results must be kept in mind that only economic criteria are considered disregarding existing monument conservation status of the area, public amenity and other aspects.

Procedure of the outline methodology

State of the art descriptions of the evaluation criteria together with the methods developed and tested for NSM provide the background for a procedure which assist in going through all evaluation steps and considering all relevant indicators, criteria and specific methods. The procedure makes use of experience in a number of European countries and therefore could additionally be seen a means of harmonization. The steps range from the definition of a measure with the condition of its implementation to the sensitivity analysis of its effectiveness and efficiency. Moreover, it provides items for critical reflection of the results.

Context conditions for choice of structural and non-structural measures

The evaluation capacity like it has been addressed before is supposed to influence the choice of structural and non-structural measures. On the one hand the performance of measures referring to societal values and goals may only be considered if they can be properly assessed. On the other hand comparison of structural and non-structural measures or of alternative portfolios required at least similar evaluation criteria. Accordingly it could be expected that a sound methodology will enhance the scope of measures which may be regarded in flood risk management. This especially should foster the application of non-structural measures, since evaluation capacities for these types of measures are currently limited due to a lack of appropriate methods.

While this is the principal assumption for developing an evaluation methodology, the anticipation of its effects on the application of non-structural measures needs a more comprehensive view on decision making. In the “real world”, it is much more complex and subjective than traditional theories of rational choice like for example the neoclassical theory of economic behaviour suggest. Decision makers need to integrate multiple aspects of strategy development which can be grouped as the *content* of flood risk management such as the effectiveness of risk reduction measures, the *context* of an individual decision maker and its institution as well a the *process* pattern of the formulation and implementation of strategies (see Figure 2).

It may be supposed that the context implicitly or explicitly influences the precedence of specific flood risk reduction measures. A wide range of internal and external context conditions are set by the cultural system, politics, legal regulations, physical requirements, personal knowledge, risk perception, previous experience, and so forth. However, up to now, it has been difficult to describe, explain and consider specific causal relationships between context and choice of SM and NSM. Hence, in our research case studies are conducted to consider this issue to some extent.

Preliminary results show that context conditions determine, for instance, the *relevance of criteria* to evaluate SM and NSM. Flood risk management in England and Wales is characterized by a tradition in using efficiency as a major criterion for assessing measures. In Germany, in contrast, evaluating measures is characterized through providing equal flood protection up to the 100-year-flood in as much flood-prone areas as possible. Efficiency considerations are becoming more important to allocate resources to increase the safety standard of protection assets in reaction to the flood in August 2002.

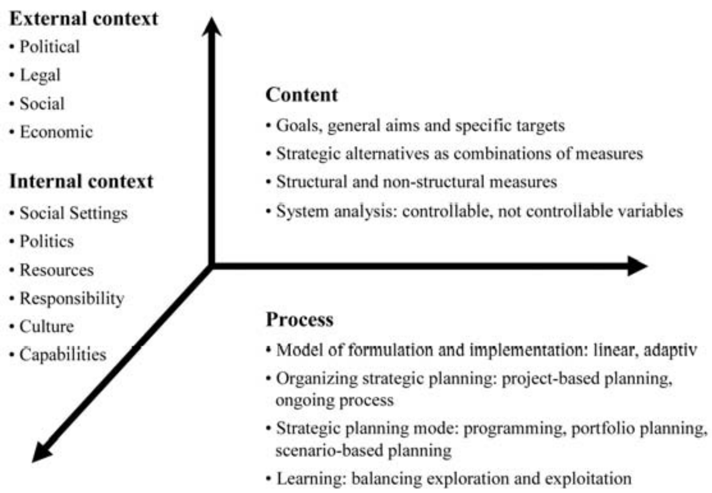


Fig. 27: Three dimensions of strategies for flood risk management (Hutter & Schanze 2008)

Furthermore, context conditions have a strong influence on which *measures* are taken into account to improve flood risk management. In a context with strong political influence to increasing the safety standard via structural measures due to commitments of politicians to a “feel-safe” orientation of citizens, it is unlikely that an evaluation methodologies have significant effects in terms of considering NSM as alternatives or complements to SM (for such an example in Dresden/Germany see Hutter 2007). Quickly, SM become the focus of decision-making

Conclusions

It is the final aim of the study to investigate the effectiveness and efficiency of SM and NSM in the light of the context conditions of decision makers involved. Although not all of the work has been completed yet, especially with regard to the derivation of the generic findings, some exemplary conclusions can be drawn from the case studies as follows.

In the English case study of the Lower Thames River, NSM are less efficient than SM, and are seen as likely to be less effective. The professionals engaged in this work do not see personal advancement coming from implementing NSM, and there are evaluation problems with NSM that make them "suspect". The public wants full protection, rather than the lesser protection that NSM brings. Politicians appear to support this position, against the policy drive of Defra as Environmental Ministry for a more balanced approach. Limitations on revenue expenditure also discourage NSM, which use this kind of finance, and the project appraisal guidance favours SM rather than NSM in its approach and language. Transaction costs appear not be important either way.

In the Scottish case study of the River Clyde in Glasgow the conclusions are that there appears to be a more pragmatic approach, using whatever measures enhance risk reduction and at the same time meet the parallel goals of pollution reduction, and urban regeneration; the three are inextricably linked. Benefit cost technique constraints on using NSM are there, but do not seem to dominate. Most flood risk engineers are located in local authorities rather than a stand-alone Agency as in England. As a result they are more flexible in adopting flood risk measures and subject to fewer professional constraints in favour of SM. National policy in Scotland seems to put NSM measures on the same footing as SM, and the target of the Commonwealth Games in Glasgow in 2014 means that pragmatism and "getting things done" appears to be the dominant thought mode.

In the Mulde River budget scarcity apparently does not influence decisions on flood mitigation measures due to the serious flood in 2002. This explains why measures are conducted even if they appear to be inefficient due to their high costs. Instead, the effectiveness with regard to the 1/100-protection goal plays a much more important role. This protection goal aims at a provision of safety by containing flood water and therefore promotes SM. Another important point is that flood risk management is structured in a way that there is a clear organisational division of labour between the authority responsible for structural flood protection, and the authority, responsible for the non-structural warning system. The main responsibility and funds are given to the first authority, an organisation with a strong professional engineering background. However, the tendency towards SM is not only caused top-down, also personal values, demands and resistances of the individuals influence decisions. We found out that the personality of decision makers and their beliefs about measures is an important internal context condition. Personal interests and engagement especially on the local level affect decisions on SM and NSM and facilitates their implementation. This influence can either tend towards SM as well as towards NSM.

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References

Birner, R., Wittmer, H. (2004): On the 'efficient boundaries of the state': the contribution of transaction costs economics to the analysis of decentralization and devolution in natural resource management.

Environment and Planning C: Governance and Policy 22 (5), 667-685.

BUWAL − Bundesamt für Umwelt, Wald und Landschaft. 1999 a, b. Risikoanalyse bei gravitativen Naturgefahren; Methode. Umwelt-Materialien 107/I Naturgefahren.

Cooper, J., Mlod, C., et al. 2007. Management of Residual Risk Using Non-structural Responses in the Thames Estuary, pp. 9, available at http://www.defra.gov.uk/environ/fcd/conference/2007/06-5.pdf (20.07.08).

Deilmann, C., Naumann, T. and Neubert, M. 2008. Modelling Vulnerability of Residential Properties by

Use of Synthetic Building Damage Functions and GIS. Proceedings of FLOODrisk 2008, 30th

September – 2nd October 2008, Oxford, UK (accepted).

DHI. 2004 a. MIKE 11 Reference Manual.

DHI. 2004 b. MIKE 21 Flow Model. Hydrodynamic Module. Scientific Documentation.

DHI. 2004 c. MIKE FLOOD Reference Manual.

EVALSED (Ed.) 2003. Evaluating Socio Economic Development. Sourcebook 2: Methods & Techniques. DG Regional Policy, available at http://www.evalsed.info.

Hanley, N.D. and Spash, C.L. 1993. Cost-Benefit Analysis and the Environment. Cheltenham: Edward Elgar Publishing Ltd.

Hutter G. 2007. Strategic Planning for Long-Term Flood Risk Management – Some Suggestions for How to Make Strategy at Regional and Local Level. International Planning Studies 10(3): 273-289.

Hutter G, Schanze J. 2008. Learning How to Deal with Uncertainty of Flood Risk in Long-Term Planning. Journal of River Basin Management. (in print)

Johnson C L, Tunstall S M, Penning-Rowsell E C. 2005. Floods as Catalysts for Policy Change: Historical Lessons from England and Wales, Water Resources Development 21(4): 561-575.

Kling, H. (2002). Development of Tools for a Semi-Distributed Runoff Model (COSERO). Institute of Water Management, Hydrology and Hydraulic Engineering (IWHW). Vienna, BOKU.

Marsalek, J., Watt, W. E., Zeman, E. and Sieker F. (Eds.) 2000. Flood Issues in Contemporary Water Management. Proceedings, NATO Advanced Research Workshop on Coping with Flash Floods: Lessons from Recent Experience, Malenovice, Czech Republic, May 16 - 21, 1999, NATO science series: Series 2, Environmental Security, Kluwer Academic Publishers, Dordrecht, London.

Messner, F. 2006. Applying Participatory Multicriteria Methods to River Basin Managment: Improving the Implementation of the Water Framework Directive. Environment and Planning C: Goverment and Policy, Vol. 24: 159-167.

Olfert, A. 2007. Risk Reduction in Residential and Commercial Buildings During the April 2006 Flood in Dresden - Case study. Contribution to FLOODsite Report T12-07-01, Leibniz Institute for Ecological and Regional Development (IOER), Dresden.

Olfert, A. and Schanze, J. 2007. Methodology for Ex-post Evaluation of Measures and Instruments in Flood Risk Management (postEval). Leibniz Institute for Ecological and Regional Development (IOER), FLOODsite Report T12-07-01, Dresden.

Parker, D.J. 2007. Analyzing Management Concepts at Program Level for Deploying Non-structural Measures. FLOOD-ERA working paper (unpublished), FHRC, London, 25pp.

Parker, D.J., Tunstall, S.M., McCarthy, S. 2007. New insights into the benefits of flood warnings: Results from a household survey in England and Wales, Environmental Hazards, Vol. 7: 193-210.

Penning-Rowsell E C, Johnson C, Tunstall S, Tapsell S, Morris J, Chatterton J, Green C. 2005. The Benefits of Flood and Coastal Risk Management: A Manual of Assessment Techniques, Middlesex University Press, London (The Multi-Coloured Manual).

Petry, B. 2002. Coping with Floods − Complementarity of Structural and Non-Structural Measures. Wu, B. (Ed.). Flood Defence 2002. Proceedings of the Second International Symposium on Flood Defence, Beijing, China, September 10 - 13, 2002, Science Press, Beijing, New York: 60-70, available at http://www.cws.net.cn/cwsnet/meeting-fanghong/v10106.pdf (accessed 22. June 2005).

Rheinsberger, C. and Weck-Hannemann, H. 2007. Economic Approaches to Risk Evaluation. Working paper, Zürich.

Schanze, J., Hutter, G., Harris, T., Koeniger, P., Kuhlicke, C., Meyer, V., Nachtnebel. H.P., Neuhold, C., Olfert, A., Parker, D., Penning-Rowsell E. and Schildt A. 2008. Systematisation, Evaluation and Context Conditions of Structural and Non-Structural Measures for Flood Risk Reduction. FLOODERA joint report, published by ERA-NET CRUE, London.

Individual flood risk assessment

***Neuhold, C.**, Nachtnebel, H.P. (2010b): Reducing life-threatening conditions during extreme flood events - Benefits from implementing spillways to dykes.*

In: Custer, R.; Sutter, C. & Ammann, W.J. (eds): International Disaster and Risk Conference IDRC Davos 2010 Proceedings: short and extended abstracts

Abstract.

The objective of the presented study is to analyse the benefits from integrating spillways to existing dykes. Numerous reports describe the catastrophic consequences of dyke failures due to overtopping and subsequent breach formation often leading to the collapse of the structure. Yet, dyke failures are reported for floods lower than the design level due to insufficient maintenance and reduced stability. Although embankment dams obligatory require spillways for controlled flood release these structures are widely missing. The consequences of such flood release structures are analysed by comparing flood protection alternatives - with and without a spillway - as well as by considering a dyke breach scenario. Based on a case study in an Austrian municipality the alternatives were evaluated by hydrologic and hydrodynamic modelling. Numerous hydrographs, considering uncertainties in model parameters and in rainfall pattern, were generated for different return periods and provided an input for a coupled 1D/2D hydrodynamic model for the endangered region. Water depths for simulated inundation areas were linked to land use to estimate the damage potential and to assess the number of endangered people based on census data. The respective flood risk was assessed on a micro scale level. In the frame of vulnerability assessment exposed objects were identified, mapped, categorised and assessed by regionally adapted damage functions derived from local damage reports. The results indicate that the implementation of a spillway is effective and efficient in terms of reducing the number of people exposed to extreme floods and providing sufficient time for emergency measures, such as evacuation. Further, the justification of additional construction costs to implement spillways was clearly demonstrated by a reduced damage potential compared to uncontrolled dyke overtopping and hence, dyke breaching.

Keywords: flood, spillway, protection measures, dyke breach scenario, hydrodynamic modelling.

Introduction

Although substantial amounts of money were invested in flood mitigation in Europe the reported damages increased tremendously and continuously during the last decades (Munich Re, 2007). Referring to the database compiled by the Centre for Research on Epidemiology Disasters (www.em-dat.net) floods are the type of natural disasters that affected the highest number of people in the period of 1900-2008 world-wide. One of the main causes was the change in land use from agricultural utilization to industrial and residential areas in former flood plains (Kenyon et al., 2008; Neuhold & Nachtnebel, 2008; Schanze et al., 2009). Obviously, these modifications led to a remarkable increase of the damage potential (BMFLUW, 2009). During the past centuries partly contradicting state-of-the-art approaches, varying from river training and straightening to river restoration, were applied to cope with flood events. Traditional approaches of structural flood protection measures are nowadays increasingly replaced by flood management approaches (de Vried, 2005; Samuels et al., 2005). Recent flood experience, consideration of residual risk as well as the understanding of non achievable total safety supported the change to an integrated flood risk management approach (Nachtnebel & Faber, 2009). The aim of flood risk management is to protect flood prone areas up to a predefined design level by simultaneously minimizing the residual risk (overtopping, dyke failure, etc.).

Dyke failure events are a considerable threat to socio-economic and ecologic values. Their failure mechanisms need to be investigated to predict breach locations. For temporal and spatial breach development no distinct functional relationship has yet been found due to highly complex breaching mechanisms (Singh, 1996). In case of dyke failure, loss of lifes and economic damages have to be expected as consequences, depending on the inundation depth, flow velocity, early warning and exposure (Zagonjolli, 2007). To prevent dykes from failing due to overtopping the implementation of spillways proofed to be an adequate strategy (BMFLUW, 2006). The main function of a spillway is to protect the dyke itself during extreme events. Spillways help to avoid failure by releasing excess water – water beyond the design level – to the hinterland without endangering the protective structure. The hazards posed by inappropriate spillways might approach or even exceed damages that would have occurred under natural flood conditions without the existence of dykes (Haimes, 2009). Due to the controlled flooding of pre-selected areas catastrophic events can mostly be avoided and therefore, an increase of the reliability of flood mitigation measures can be achieved (Neuhold & Nachtnebel, 2008 a). Although considerable benefits are expected by implementing spillways to existing flood mitigation measures an obstacle in the frame of political decision making is predictable – regardless of the spillway location there will be complaints and resistance by people feeling disadvantaged.

The objectives of this paper are (1) to analyse the hydrodynamic consequences of implementing a spillway to an existing flood mitigation scheme, (2) to assess the overall flood risk on a micro scale level under special consideration of the number of people exposed, residential buildings and industrial sites and (3) to discuss the benefits for flood risk management and the resulting increase of the flood protection reliability due to the implementation of a spillway.

Methodology

The analyses focused on the Austrian municipality of Gleisdorf and an adjacent industrial park where numerous residential areas and industrial sites were exposed to inundations of the Raab River. After the implementation of flood mitigation measures in 1999 (including dykes, flood walls and a flood retention basin designed to resist a 100-years flood) several industrial firms were developed in the former flood plain accompanied by increasing residential areas. As a consequence the vulnerability of the hinterland has increased substantially.

Hazard Assessment

Hazard assessment was based on a hydrologic (COSERO) as well as a hydrodynamic (MIKE-FLOOD) model. Due to lack of gauge data, hydrographs (design flood scenarios of HQ_{30}, HQ_{100}, HQ_{300}, HQ_{1000} and HQ_{5000}) were generated by a semi-distributed precipitation-runoff model (Nachtnebel et al., 1993; Kling, 2002; Nachtnebel et al., 2005) to obtain plausible input data for the hydrodynamic model. The hydrodynamic processes in the project area were modelled by the coupled 1D/2D software MIKE FLOOD (DHI) including the river network with its bridges and weirs, the dykes, the bank vegetation, the flood retention basin and the floodplain topography. Water tables together with flow velocities were obtained for each grid element with a resolution of 10*10 m. The impact of bridges, gates, weirs and possible log jams were simulated by the 1D component of the package (MIKE 11) while the flow pattern in the hinterland was modelled by the 2D flow model (MIKE 21). The model setup considered three flood mitigation scheme alternatives referring to the existing flood protection scheme which comprises dykes, flood walls and a flood retention basin (alternative 1), the implementation of a spillway into the existing dyke (alternative 2) and the restricted development in the flood plain area by imposing a building ban (alternative 3).

Vulnerability Assessment

In the frame of vulnerability assessment socio-economic consequences due to flooding were analysed under special consideration of the number of people exposed, residential buildings and industrial sites. The resident's vulnerability by means of potential loss of life was assessed by analysing Austrian micro census data evaluated in 2001 and provided by Statistik Austria (2005 a, b). Within the assessment of monetary damages the data base from Nachtnebel et al. (2005) was enhanced by collecting further information about the objects within the case study area. Related to residential buildings this was done by refining the classification, mapping and evaluation of attributes of each single object. Emphasis was put on the attributes "year of construction", "level of equipment", "type of heating system" and "building area". With respect to industrial sites monetary flood consequences, considering direct losses and added value losses, were assessed by interviewing chief operating officers, including an informative meeting. Using this information, damage functions for 20 of the most important enterprises as well as for residential buildings were derived on a micro scale level.

Risk Assessment

Flood risk emerges from the interaction of hazard and vulnerability (Merz et al., 2010). By applying a micro scale flood risk assessment procedure (BUWAL 1999 a, b; Neuhold & Nachtnebel 2008a, Neuhold & Nachtnebel 2008b, Neuhold et al., 2009) the overall flood risk was analysed considering economic criteria as well as intangible aspects such as the number of directly endangered people. Therefore, simulated inundation areas, water depths and flow velocities (hazard assessment) were linked to potentially exposed residents and buildings (vulnerability assessment). This was executed by a GIS to estimate the number of people exposed and the damage potential of the overall flood prone area.

Results

An overview of scenario and alternative based results (Tab. 9) shows that in case of dyke overtopping people are exposed to floods, regardless of the implementation of a spillway. Flood risk management strategies represented by alternatives 2 and 3 demonstrate a considerable potential in increasing the effectiveness of state-of-the-art flood protection measures (alternative 1).

Tab. 9: Overview of scenario and alternative related results. First count represents the number of affected buildings, the count in brackets represents the number of people exposed. No count means that no (reliable) data was available

Scenario	alternative 1	alternative 2	alternative 3	dyke breach	no protection
HQ_{30}					170
HQ_{100}	1		1		196
HQ_{300}	80 (254)	41 (53)	71	276	437 (1072)
HQ_{1000}	218 (635)	235 (647)	187	277	
HQ_{5000}	330 (645)		291	331 (840)	

Fig. 28 outlines the effectiveness of a spillway for flood events above the design level. The exposure to floods with a return period of 300 years has been estimated at 254 persons for the current state (alternative 1). Considering the implementation of a spillway to the hydrodynamic numeric model (alternative 2) in total 53 habitants have been assessed as being flood exposed. The simulation results of a 300-years flood for alternative 2 proofed that a densely populated area was simulated free of flooding compared to alternative 1. Therefore, the persons at risk in residential houses could be reduced from 254 to 53 (status of 2001). Obviously, the risk for residents and possible human fatalities can be reduced by about 80%. The effect of spillways decreases with increasing flood discharge and expanding inundation areas. In case of a 1000-years flood event no more positive effect could be assessed – 647 residents (with implemented spillway) and 635 persons (without spillway) had been characterised as exposed. This reversal from a clearly positive to a slightly negative consequence on the number of people exposed can emerge from two reasons: (1) uncertainty due to census data and (2) a change of spatio-temporal flood inundation characteristics. The census data had been delivered as cumulative data sets (with a grid resolution of 250 m²) due to data privacy obligations. Therefore, counts within grid cells going below pre-defined limits of buildings or residents were not included in total numbers depicted. The second reason is the obvious change in flood characteristics due to the implementation of a spillway. The positive effects for the 300-years flood scenario, where residential areas were calculated as flood free, were negatively compensated by earlier water release to the hinterland due to a lowered spillway dyke crest.

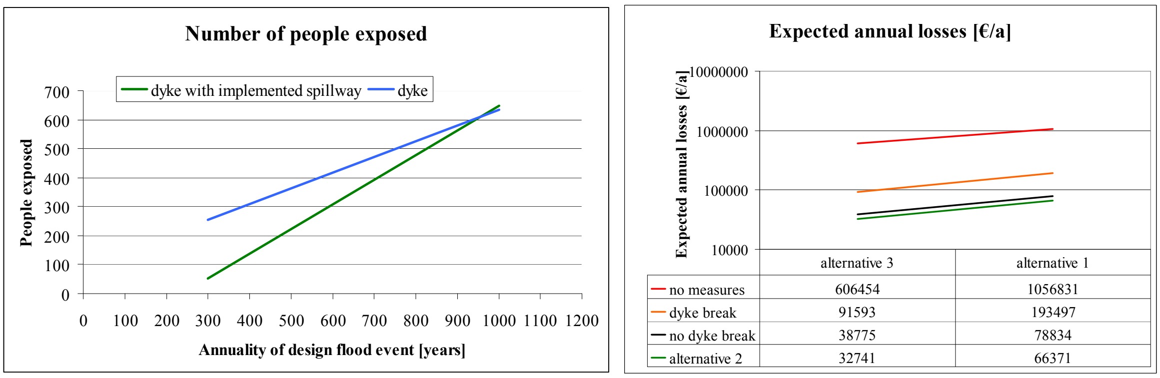

Fig. 28: Number of people exposed related to a 300-years and 1000-years flood (left). Expected annual losses considering alternative 1 (dyke break and no dyke break), alternative 2 (implemented spillway) and alternative 3 (imposed building ban)

The analysis of potential economic losses by means of expected annual losses showed a remarkable increase during the past decade, triggered by hinterland development (roughly 50%). The implementation of a spillway would reduce the expected losses by 10 to 15%. The assessments of dyke break scenarios lead to tremendous increase of the calculated damages (200,000 €/a) in comparison to risk assessment approaches, without dyke break scenarios (80,000 €/a). If no mitigation measures would have been implemented, the expected annual losses would have been dramatically higher (approx. 1Mio €/a). The benefit-cost analysis indicates that the efficiency of the implemented structural measures dyke, flood wall and flood retention basin could be tremendously improved if construction works in the former flood prone area would have been banned. Furthermore, the implementation of a spillway would lead to an increase of effectiveness and reliability, because dyke failures can be avoided and uncontrollable overtopping would be very unlikely.

Conclusions

This study presented a flood risk assessment methodology considering the number of people exposed to floods and economic losses for residential building and medium scale industrial sites. A micro scale risk assessment for the municipality of Gleisdorf was conducted where besides hydrological and hydrodynamic modelling several attributes were utilized to establish damage functions for single objects in the flood prone area. Based on this information the benefits from implementing spillways to existing dykes were assessed.

The risk assessment clearly showed that a combination of all considered alternatives would be the most effective flood risk management strategy. The simulation results of a 300-years flood for alternative 2 indicated no flooding for a densely populated area compared to alternative 1. Further, the number of persons at risk in residential houses could be reduced from 254 to 53 (status of 2001), whereas the census data had been delivered as cumulative data sets due to data privacy obligations. Therefore, counts within grid cells going below pre-defined limits of buildings or residents were not included in total numbers depicted which are obviously, subjected to uncertainty. Further, the positive effect decreases with increasing return periods of flooding and will be negatively compensated by a 1000-years flood event.

Considering the development during the past 10 years the increase of vulnerability is represented by remarkably higher expected annual losses. If this increase of vulnerability would have been avoided by imposing a building ban after the implementation of the protection scheme, the overall flood risk could have been reduced tremendously. The results indicate that the implementation of a spillway is effective and efficient in terms of reducing the number of people exposed to extreme floods (up to recurrence intervals of approximately 1000 years) and providing sufficient time for emergency measures, such as evacuation. Further, the justification for additional construction costs to implement spillways was clearly offset by a reduced damage potential compared to uncontrolled dyke overtopping and hence, dyke breaching.

References:

BMFLUW (2006): Freibord – Überströmstrecken: Leitfaden zur Festlegung des erforderlichen Freibords anhand projektspezifischer Rahmenbedingungen einschließlich der Kriterien für die Anordnung von Überströmstrecken. Fassung 2006. www.lebensministerium.at

BMFLUW (2009): Flood Risk II: Vertiefung und Vernetzung zukunftsweisender Umsetzungsstrategien zum integrierten Hochwassermanagement, Endbericht. www.lebensministerium.at

BUWAL (1999 a): Risikoanalyse bei gravitativen Naturgefahren – Methode. Umwelt-Materialien Nr. 107/I, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft

BUWAL (1999 b): Risikoanalyse bei gravitativen Naturgefahren – Fallbeispiele und Daten. Umwelt-Materialien Nr. 107/II, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft

De Vried, H. (2005): State of the art in flood management research, Proc. Of the 3rd International Symposium on flood defence, Nijmegen, the Netherlands.

Faber (2006): Flood risk analysis: residual risk and uncertainties in an Austrian context. Dissertation. Institute of Water Management, Hydrology and Hydraulic Engineering, Vienna: BOKU

Haimes, Y.Y. (2009): Risk modelling, assessment and management, Wiley series in systems engineering and management, 3rd edition

Kenyon, W., Hill, G., Shannon, P. 2008: Scoping the role of agriculture in sustainable flood management Land Use Policy, Volume 25, Issue 3, Pages 351-360

Kling H. 2002. Development of tools for a semi-distributed runoff model. Master thesis, Institute of Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Applied Life Sciences, Vienna, Austria.

Merz, B., Hall, J., Disse, M. & Schumann, A. (2010): Fluvial flood risk management in a changing world. Nat. Hazards Earth Syst. Sci., 10, 509-527

Munich Re (2007): Edition Wissen, Zwischen Hoch und Tief, Wetterrisiken in Mitteleuropa

Nachtnebel et. al (2005): Risikoanalyse des bestehenden Hochwasserschutzes Stadt Gleisdorf und Umgebung. River Basin Agenda, Wien: IWHW, BOKU

Nachtnebel H.P., Baumung S., Lettl W. (1993). Abflussprognosemodell für das Einzugsgebiet der Enns und Steyr (in German). Report, Institute of Water Management, Hydology and Hydraulic Engineering, University of Natural Resources and Applied Life Sciences Vienna, Austria.

Nachtnebel, H.P. & Faber R. (2009): Assessment and management of flood risks in Austria, Structure and Infrastructure Engineering, 5:4, 333-339

Neuhold, C., Stanzel, P., and Nachtnebel, H. P. (2009): Incorporating river morphological changes to flood risk assessment: uncertainties, methodology and application. Natural Hazards and Earth System Sciences, 9, 789-799; ISSN 1561-8633

Neuhold, C.; Nachtnebel, H.P. (2008 a): Flood risk assessment in an Austrian municipality comprising the evaluation of effectiveness and efficiency of flood mitigation measures. In: Taylor & Francis Group, London, UK, Flood Risk Management-Research and Practise, S 135; ISBN: 978-0-415-48507-4

Neuhold, C.; Nachtnebel, H.P. (2008 b): Detailed residual risk assessment in an Austrian municipality. In:European Geosciences Union, Volume 10, 2008, EGU General Assembly 2008, 14.04.2008-18.04.2008, Wien, ISSN 1029-7006

Samuals, P., Klijn, F. & Dijkman, J. (2005): River flood risk management policies in different parts of the world: Synsthesis of spezial session by NCR, Proc. Of the 3rd International Symposium on Flood Defence, Nijmegen, the Netherlands.

Schanze, J., Hutter, G., Harris, T., Koeniger, P., Kuhlicke, C., Meyer, V., Nachtnebel. H.P., Neuhold, C., Olfert, A., Parker, D., Penning-Rowsell E. and Schildt A. 2008. Systematisation, Evaluation and Context Conditions of Structural and Non-Structural Measures for Flood Risk Reduction. FLOODERA joint report, published by ERA-NET CRUE, London.

Singh, V.P. (1996): Dam brach modelling technology, Kluwer Academic Pub.

Statistik Austria (2005 a): Ein Blick auf die Gemeinde http://www.statistik.at/blickgem/gemList.do?bdl=6

Statistik Austria (2005 b): Leistungs- und Strukturstat. http://www.statistik.at/unternehmen/lse3_05.pdf

Zagonjolli, M. (2007): Dam break modelling, risk assessment and uncertainty analysis for flood mitigation, dissertation, Delft University of Technology.

Results and conclusions

Uncertainty analysis

Neuhold et al. (2009) provide results describing the variability and uncertainty related to the processes hydrology, hydrodynamics and sediment transport as well as risk assessment based on a multi-scenario approach. In the frame of this survey risk assessment was adapted by substituting the scenario approach (a few normatively defined design floods) by a multi-scenario approach by means of variation of input hydrographs and sediment load. Due to the incorporation of the impacts of hydrological and morphological processes on water surface tables, a refined hazard assessment approach is provided which was quantitatively applied. Vulnerability analyses and damage estimation tools were improved methodologically by interrelating the overtopping probability, the variability of inundation depth and a damage function to obtain a damage-probability relationship. Therefore, uncertainty and sensitivity are implicitly comprised in the probability distribution function of the expected damage.

The proposed concept was applied to an Austrian case study (River Ill), where numerous flood and associated sediment transport scenarios were considered, simulated and illustrated for the main river stem. The calculated morphological changes during floods provided a basis to estimate the variability of possible water surface levels and inundation. The associated epistemic uncertainty of results obtained by design-flood-based procedures – scenario approach – is emphasized by the overtopping probability caused by 138 considered scenarios. Alongside the River Ill settlements and utilisations are mainly protected by dykes and natural barriers with an estimated flood safety up to a recurrence interval of 100 years. The calculated overtopping probability of 12.27 % indicates that 7.4 km are not protected against floods caused by 100-year rainfall events which had not been previously identified as such. Referring to the results of the hydrological input variation, it has to be distinguished, that considered discharges resulting from 100-year rainfall events lead to as much as 160 % of the applied design value discharge (normative 100-year flood event) for the gauge furthest downstream. Analysing scenarios by means of sediment input variation obtained by an observed 100-year flood event in the year 2005 the overtopping probability equals 1.59 % for the entire reach. Nevertheless, at 40 cross sections dykes or barriers are overtopped and therefore most likely to break.

Regarding the magnitude of bed elevation changes, the influence of sediment input variation was found to be much higher than the influence of discharge input variations. Consequently, the derivation of sediment input functions appears to be the most important task wherever the incorporation of sediment transport calculations or estimations are applicable. In this context scarce data availability seems to be the restricting factor. Therefore, an enhancement of sediment gauges as well as the volumetric survey of accumulations, especially after flood events, is desirable. By means of an extended data base the derivation of sediment input functions as well as calibration and validation of sediment transport models would be more feasible and should be adaptable to further river types and scales.

Environmental flood risk assessment

Neuhold & Nachtnebel (2010a), Neuhold & Nachtnebel (2009) and Laner et al. (2008) developed a qualitative approach to assess flood risk associated with waste disposals on the basis of Austrian case studies. Further, an outline of data source related uncertainty and its influence of flood risk assessment accuracy is given. By means of hydrodynamic simulations, flood impacts on the disposal sites and emission impacts on protected goods were assessed based on four parameters: (1) spatio-temporal flood characteristics, susceptibility to erosion due to (2) flow velocity and (3) shear stress as well as (4) emission behaviour due to water saturation of the waste body. The probability of inundation, the hydrodynamic impacts on considered waste disposal sites and the expected consequences to the environment by means of potential emissions of hazardous substances were linked. Derived risk categories from “minor risk” to “serious risk” were used to express flood risk to environmental goods like groundwater bodies, nature reserves, recreation areas, etc.

Roughly, one third of considered sites in Austria showed a remarkable long term risk for humans and the environment. Considerable sources of uncertainty were identified by the (1) accuracy of data sets describing attributes and locations of waste disposals, (2) reliability of the hazard assessment tool HORA due to the neglect of protection measures, (3) scarce topographic data (4) a lack of documented historical flood events for calibration and validation purposes and (5) a lack of information related to possible emissions.

Economic flood risk assessment

Neuhold & Nachtnebel (2008) and Schanze et al. (2008) aimed to contribute to the development of a methodology to evaluate the effectiveness and efficiency of structural and non structural flood mitigation measures. Micro scale flood risk assessment was conducted where besides hydrological and hydrodynamic modelling a large quantity of socio-economic attributes and data sets were utilized to establish a damage function for each single object in the flood prone area. An analysis of several flood protection alternatives including structural and non structural measures by estimating their effectiveness (degree to which objectives are achieved and the extent to which targeted problems are resolved; WebFinance, 2010) and efficiency (comparison of what is actually produced or performed with what can be achieved with the same consumption of resources; WebFinance, 2010) was carried out. The overall construction costs, the object related damage functions and the land use data provided the input for cost-effectiveness as well as benefit-cost analysis.

One main focus of the case study was to revise damage functions of published data derived from ex-post and ex-ante flood damages. Based on a refined micro scale flood risk assessment approach the vulnerability of residential buildings and industrial sites was analysed. Detailed mapping, micro census data, analysed questionnaires and conducted interviews with chief operating officers, provided reliable results. The results indicated that the effectiveness and efficiency of non structural and structural protection and mitigation measures are within the same range. Spatial planning (imposing a building ban) as well as adapting existing flood protection schemes (implementing a spillway) proofed to be highly effective and efficient.

Neuhold & Nachtnebel (2008) further aimed to analyse the consequences of hinterland development with respect to flood vulnerability and flood risk. Vulnerability assessment referred to two temporal stages of land use development (1) the status prior to the implementation of flood protection measures and (2) after a decade of development within the former flood plain. Considering the development in 10 years the increase of the vulnerability is represented by remarkably higher expected annual losses triggered by land development.

Individual flood risk assessment

Neuhold & Nachtnebel (2010b) conducted a micro scale risk assessment to (1) analyse the hydrodynamic consequences of implementing a spillway to an existing flood protection scheme, to assess (2) the overall flood risk and related uncertainties under special consideration of the number of people exposed and (3) to discuss the benefits for flood risk management and the resulting increase of the flood protection reliability.

The effectiveness of a spillway for flood events above the design level (HQ_{100}) was of special interest. Given a 300 years flood an exposure of 254 people was estimated for the current state. Considering the implementation of a spillway in total 53 habitants have been assessed as flood exposed for the same scenario. Therefore, the individual flood risk can be reduced remarkably due to the adaptation of existing dyke structures. Within the case study area the effect of spillways decreases with increasing flood discharge and expanding inundation areas. In case of a 1000-years flood event no more positive effect could be assessed – 647 residents (with implemented spillway) and 635 persons (without spillway) had been characterised as flood exposed. This reversal from a clearly positive to a slightly negative consequence on the number of people exposed can emerge from two reasons: (1) uncertainty due to census data and (2) a change of spatio-temporal flood inundation characteristics. The census data had been delivered as aggregated data sets due to data privacy obligations. Therefore, counts within grid cells going below pre-defined limits of buildings or residents were not included in total numbers depicted. The second reason is the obvious change in flood characteristics due to the implementation of a spillway. The positive effects for the 300-years flood scenario, where some residential areas were calculated as flood free, were negatively compensated by earlier water release to the hinterland due to a lowered spillway dyke crest.

The justification to implement spillways was clearly offset by a reduced damage potential compared to uncontrolled dyke overtopping and subsequent, dyke breaching. Further, a spillway would lead to an increase of the reliability of the protection scheme, because dyke failures can be avoided and uncontrollable overtopping would be very unlikely. Although considerable benefits are expected by implementing spillways to existing flood protection schemes, an obstacle in the frame of political decision making is predictable: regardless of the spillway location, there will be complaints by people feeling disadvantaged.

Research questions

Based on presented results and conclusions, posed research questions (see: section "objectives and thematic outline") are answered as follows:

1. *How does the incorporation of additional processes - compared to the state of the art - influence flood risk assessment results?*

Obviously, uncertainty increases by including supplemental processes to flood risk assessment methodologies. At the same time, the consideration enables the possibility to identify process related uncertainty. Referring to state of the art flood risk assessment approaches mostly, the variability in relevant processes (hydrology, hydrodynamics) or the processes themselves (sediment transport) are generally neglected. By incorporating this information to flood risk assessment the basis of decision-making for risk management changes which could have significant implications on past decisions.

2. *How does the incorporation of additional data sources influence the flood risk assessment accuracy?*

The accuracy of risk assessment is highly dependent on data availability and data reliability resulting in the choice of qualitative or quantitative assessment procedures. Scarce data allows the qualitative identification of utilisations and regions at risk whereas an increase in data accuracy (topographical data, simulation results and vulnerability data) enables the calculation of expected losses. Within damage assessment typically two approaches are applied (1) the object related damage estimation [€ per flooded building] and (2) the specific damage estimation [€ per flooded m²] which often lead to totally different results. The incorporation of additional data sources such as detailed building mapping, census data, questionnaires, interviews etc. showed a remarkable reduction of differences between the two estimation approaches from one order of magnitude to a difference of lower than 50% and therefore, to a considerably higher assessment accuracy.

3. *What kinds of revisions are needed for flood risk assessment concepts to reduce epistemic uncertainty?*

Hazard Assessment: To obtain more reliable results, a multi-scenario approach should be applied instead of analysing a few normatively defined design floods. The variation of input hydrographs and sediment loads leads to a more realistic estimation of possible water tables related to specific recurrence intervals. This will provide a probability distribution function of inundation by means of water depth and flow velocity.

Environmental flood risk assessment: The revision of approaches outlined scarce data sources referring to topographic data, emission data and exposure data. Therefore, only qualitative risk assessment is applicable. Hence, a high demand on selective data source refinement was identified to enable the reduction of epistemic uncertainty.

Economic flood risk assessment: Remarkable improvement can be achieved on a micro scale data processing level (single object). A large quantity of socio-economic attributes and data sets can potentially be accessed and utilized to establish damage functions for each single object in flood prone areas. Related to residential buildings emphasis needs to be put on the attributes “year of construction”, “level of equipment”, “type of heating system” and “building area”. With respect to industrial sites monetary flood consequences, considering direct losses and added value losses, are assessable by interviewing chief operating officers, including an informative meeting.

Individual flood risk assessment: Consequences due to flooding are typically analysed under special consideration of the number of people exposed. The resident’s vulnerability is usually assessed by analysing census data which are typically delivered as aggregated data sets due to data privacy obligations. Therefore, the potential of improving the data reliability to assess the number of people exposed is limited and can only be done by interviewing flood prone residents.

Revised flood risk assessment: Due to the proposed supplemental steps of a revised methodological approach less uncertain results can be expected. However, much more time and resources will be needed to conduct studies based on highly detailed information. Therefore, this revised flood risk assessment concept is only appropriately applicable on detailed studies or rivers where relevant and reliable data is available.

Curriculum vitae

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Languages:

German (native language), English (fluent), French (moderate)

Professional experience:

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Research associate at the Institute of Water Management, Hydrology and Hydraulic Engineering at the University of Natural Resources and Life Sciences, Vienna

Main research: flood risk assessment, flood risk management, uncertainty, hydrodynamics, sediment transport

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Office Oberhofer, Vienna

Project aspects: flood protection, hydrodynamics

1997-2005

Various part-time employments

Education:

2006-2010

Doctoral studies of Land and Water Management and Engineering at the University of Natural Resources and Applied Life Sciences, Vienna

Participation at numerous international scientific congresses

1997-2005

Diploma studies of Land and Water Management and Engineering at the University of Natural Resources and Applied Life Sciences, Vienna

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Elementary and secondary school

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Publications

Journal articles

Neuhold, C. & Nachtnebel, H.P. (2010): Assessing flood risk associated with waste disposals: methodology, application and uncertainties. Nat Hazards DOI 10.1007/s11069-010-9575-9

Neuhold, C., Stanzel, P. & Nachtnebel, H.P. (2009): Incorporating river morphological changes to flood risk assessment: uncertainties, methodology and application. Natural Hazards and Earth System Sciences, 9, 789-799; ISSN 1561-8633

Chapter in collected volumes

Aubrecht, C., Freire,S., Neuhold, C., Curtis, A. & Steinnocher, K. (2010): Introducing a temporal component in spatial vulnerability analysis. In: Routledge Publications, Spatial Assessment and Analysis of Vulnerability; Taylor & Francis

Conference proceeding papers

Neuhold, C. & Nachtnebel, H.P. (2010): Reducing life-threatening conditions during extreme flood events: Benefits from implementing spillways to dykes. In: GRF Davos, IDRC Davos 2010 Proceedings [IDRC Davos, Davos, Switzerland, 30.05.2010-03.06.2010]

Neuhold, C. & Nachtnebel H.P. (2009): A qualitative approach to assess flood risk associated with landfills. In: Van Gelder, Proske & Vrijling, 7th International Probabilistic Workshop, 343-357; ISBN: 978-3-00-025048-4 [7th International Probabilistic Workshop, Delft, The Netherlands, NOV 25-26, 2009]

Laner, D., Fellner, J., Brunner, P.H., Neuhold, C. & Kolesar, C. (2008): Environmental Relevance of Flooded MSW Landfills in Austria. In: ISWA/WMRAS, ISWA/WMRAS World Congress 2008 - East meets Waste, Singapore Nov 3-6, 2008 [ISWA/WMRAS World Congress 2008 - East meets Waste, Singapore, NOV 3-6, 2008]

Neuhold, C. & Nachtnebel H.P. (2008): Flood risk assessment in an Austrian municipality comprising the evaluation of effectiveness an efficiency of flood mitigation measures. In: Taylor & Francis Group, London, UK, Flood Risk Management - Research and Practice, S 135; ISBN: 978-0-415-48507-4 [FLOODrisk2008, Keble College, Oxford, UK, 30.09.2008-02.10.2008]

Schanze, J., Hutter, G., Penning-Rowsell, E., Nachtnebel, H.P., Meyer, V., Königer, P., Neuhold, C., Harris, T., Kuhlicke, C. & Olfert, A. (2008): Evaluation of Effectiveness and Efficiency of non-structural measures in Flood Risk Management. , Proceedings of the 4th International Symposium on Flood Defence, 4, 10-ff [Managing Flood Risk, Reliability and Vulnerability-4th International Symposium on Flood Defence, Toronto, May 6-8, 2008]

Schanze, J., Hutter, G., Penning-Rowsell, E., Parker, D., Nachtnebel, H.P., Neuhold, C., Meyer, V. & Königer, P. (2008): Flood risk management strategies in European Member States considering structural and non-structural measures. In: Taylor & Francis Group, London, UK, Flood Risk Management - Research and Practice, S 138; ISBN: 978-0-415-48507-4 [FLOODrisk2008, Keble College, Oxford, UK, 30.09.2008-02.10.2008]

Conference proceeding abstracts

Neuhold, C., Stanzel, P. & Nachtnebel H.P. (2010): Integrating new aspects to flood risk assessment. [IDRiM 2010 - 1st Annual Conference of the International Society for Integrated Disaster Risk Management, Vienna, AUSTRIA, Sept 1-4, 2010]

Neuhold, C., Stanzel, P. & Nachtnebel, H.P. (2010): Analysing uncertainties associated with flood hazard assessment. In: EGU, Vol. 12, EGU2010-10255-1, 2010 [EGU General Assembly 2010, Vienna, Austria, 02.05.2010-07.05.2010]

Neuhold, C. & Nachtnebel H.P. (2008): Detailed residual risk assessment in an Austrian municipality. In: European Geosciences Union, Volume 10, 2008, EGU General Assembly 2008, EGU General Assembly 2008, 14.04.2008-18.04.2008, Wien, 10; ISSN 1029-7006 [EGU General Assembly 2008, Wien, 14.04.2008-18.04.2008]

Neuhold, C., Stanzel, P. & Nachtnebel H.P. (2007): Modelling morphological changes during floods utilised as impact on flood risk assessment.. In: European Geosciences Union, Geophysical Research Abstracts, Volume 9, 2007, EGU General Assembly, 15.04.2007-20.04.2007, Wien [EGU General Assembly, Wien, 15.04.2007-20.04.2007]

Stanzel, P., Neuhold, C. & Nachtnebel, H. P. (2007): Estimation of design floods for ungauged basins in an alpine watershed. In: European Geosicences Union, Geophysical Research Abstracts, Volume 9, 2007, EGU General Assembly, 15-20 April 2007, Wien [EGU General Assembly, Wien, 15-20 April 2007]

Research reports

Nachtnebel, H.P., Neuhold, C., Oberleitner, F. & Schraml, C. (2010): Umsetzungsstudie - Wasserwirtschaftliche Entwicklung in Überflutungsgebieten. Amt der Oberösterreichischen Landesregierung - Wasserwirtschaftliches Planungsorgan

Nachtnebel, H.P., Holzmann, H., Neuhold, C., Haberl, U., Kahl, B., & Bichler, A. (2009): GEDES: Gefährdung durch Deponien und Altablagerungen im Hochwasserfall - Risikoanalyse und Minimierung - Teilbericht 2 . Förderung durch das Bundesministerium für Verkehr, Innovation und Technologie und die österreichische Forschungsförderungsgesellschaft im Rahmen des Sicherheitsforschungsprogramms KIRAS

Nachtnebel, H.P. & Neuhold, C. (2008): Schutzwasserbauliche Bestandserhebung Ill - AP5: Hydraulik/Geschiebe/Schwebstoffe . Amt der Vorarlberger Landesregierung, 164

Nachtnebel, H.P., Müller, B., Neuhold, C., Oberleitner, F. & Schraml, C. (2008): Wasserwirtschaftliche Entwicklung in Überflutungsgebieten. Amt der Oberösterreichischen Landesregierung - Wasserwirtschaftliches Planungsorgan

Schanze, J., Hutter, G., Harries, T., Holzmann, H., Koeniger, P., Kuhlicke, C., Meyer, V., Nachtnebel, H.P., Neuhold, C., Olfert, A., Parker, D., Penning-Rowsell, E., Schildt, A. & Werritty, A. (2008): Systematisation, evaluation and context conditions of structural and non-structural measures for flood risk reduction. ERA-NET CRUE funding initiative, 131

Miscellaneous

Neuhold, C. (2007): Handling of fuzzy risk in decision making. Paper im Rahmen der Lehrveranstaltung "Environmental Risk Analyses and Mangement"

Nachtnebel, H.P., Fürst, J., Gamperling, C., Habersack, H., Holzmann, H., Leroch, K., Neuhold, C. & Schuster, G. (2007): Hydrologie und Flussgebietsmanagement LVA-Nr. 816.101.

Neuhold, C. (2005): Eigendynamische Entwicklung der Oberen Drau am Beispiel Kleblach-Lind. Diplomarbeit am Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau der Universität für Bodenkultur, 133