

Assessing flood risk associated with waste disposals: methodology, application and uncertainties

C. Neuhold · H. P. Nachtnebel

Received: 18 January 2010 / Accepted: 23 June 2010 / Published online: 14 August 2010
© Springer Science+Business Media B.V. 2010

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 and recreation areas. A screening of 1,064 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.

C. Neuhold (✉) · H. P. Nachtnebel

Department for Water, Atmosphere and Environment, Institute of Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Applied Life Sciences, Muthgasse 18, 1190 Vienna, Austria
e-mail: clemens.neuhold@boku.ac.at

Keywords Environmental flood risk assessment · Uncertainties · Waste disposal · Austria · Hydrodynamic modelling

1 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 and recreation areas by means of potential contamination. The study considered municipal solid waste (MSW) landfills and old waste deposits within the federal territory of Austria (Fig. 1). The inventory of landfill sites in Austria is based on information provided by the Austrian Federal Waste Management Plan (Krammer et al. 1992; BMFLUW 2006a), several waste management reports published by federal as well as local authorities and the Austrian Federal Environment Agency (AFEA 2008a). The considered inventory of landfills in Austria comprises of 1,064 locations, with 103 sites characterized as controlled landfills (black crosses) and 961 sites identified as old deposits (red dots) with overall volumes of more than 25,000 m³ (AFEA 2008a).

Maintenance and decomposition durations for waste disposals are assessed to 200–500 years depending on waste composition, climatic conditions and applied assessment methodologies (Ehrig and Krümpelbeck 2001; Stegmann and Heyer 1995, Belevi and

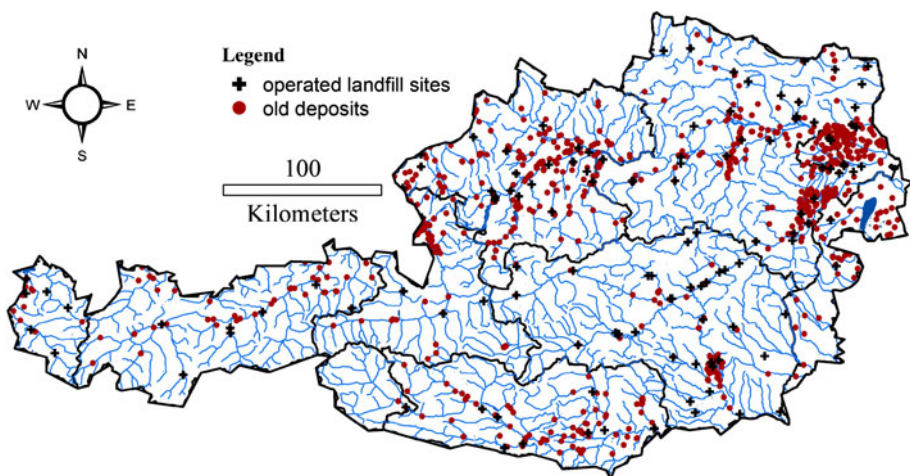


Fig. 1 Considered sites of MSW landfills and old waste deposits in Austria (AFEA 2008a, BMFLUW 2007)

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 mobilization of pollutants, since the presence of water enhances decomposition and transport processes (Christensen et al. 1996; Bogner and Spokas 1993; Klink and Ham 1982). Additionally, water saturation of waste disposals may lead to mechanical stability losses (Blight and 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 and 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 and 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 as follows:

- to identify flood-exposed waste disposal sites in Austria
- to conduct 3 case studies to quantify possible impacts on inundated waste disposal sites by analyzing 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

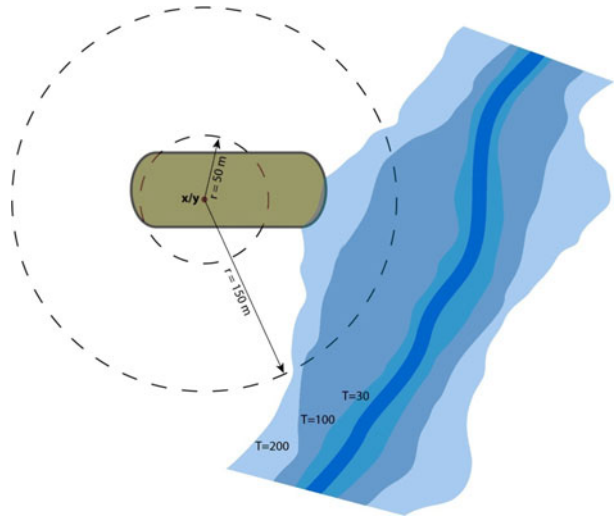
2 Methodology

2.1 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 2006b; 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. 2). Substantial uncertainties arise due to the applied inaccurate digital elevation model and generally disregarded technical flood mitigation measures within HORA (BMFLUW 2006b) as well as neglected river morphological processes like sediment transport (Neuhold et al. 2009).

The distances of waste disposal sites, represented by a pair of x/y point coordinates, to scenario-based inundation lines (HQ₃₀, HQ₁₀₀ and HQ₂₀₀) 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. 2). 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 proved 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.

Fig. 2 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 2006b) and site information (AFEA 2008a)



2.2 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 2008a), 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. 3), which were investigated in detail and will be discussed in Sects. 3 and 4.

2.2.1 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, 130,000 m³ waste disposal volume, land filling after 1980, no flood protection).

2.2.2 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 land filling heavily affected the ground water body as

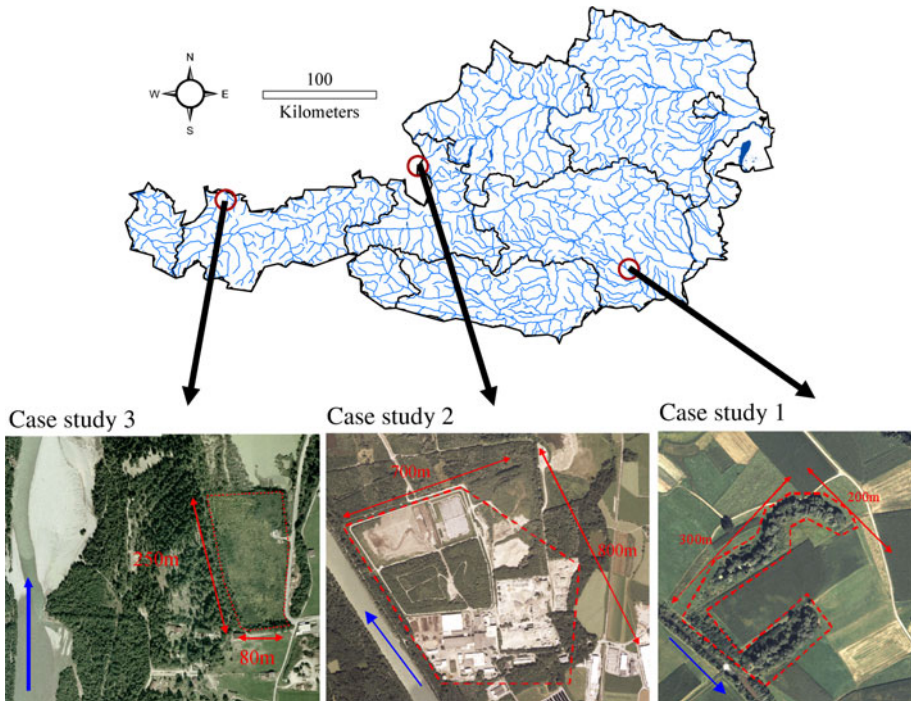


Fig. 3 Considered case study sites to quantify the possible impacts on waste disposal bodies on a micro-scale level (Nachtnebel et al. 2009; BMFLUW 2007)

no base seal was implemented prior to the restoration of the landfill site in 2008. The disposal volume was estimated at 130,000 m³ and comprises of domestic dump, construction waste, bulky waste, etc. The site was operated from 1976 to 1993 and showed no sufficient flood protection prior to the restoration.

2.2.3 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.

2.3 Hydrologic scenarios and hydrodynamic modelling

Three hydrologic scenarios following national and international guidelines for flood risk assessment (BMFLUW 2008a; EU 2007; Messner et al. 2007, Merz 2006) were considered: (1) HQ₃₀, (2) HQ₁₀₀ and (3) HQ₃₀₀. 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 (Fig. 3). 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 and 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 and Steffler 2002).

2.4 Landfill leaching scenarios

Emissions during flood events were estimated based on four substance release scenarios (Laner et al. 2008a, 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).

2.5 Flood risk evaluation matrix (FREM)

A flood risk evaluation matrix (FREM) including a colour scheme (Fig. 4) 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 (HQ₃₀, HQ₁₀₀ and HQ₃₀₀). Minor risk was defined for landfill sites where solely boundary areas are inundated. Moderate risk (inundation up to 50%) and serious risk (50–100% inundated) have 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 as follows: (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 and 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

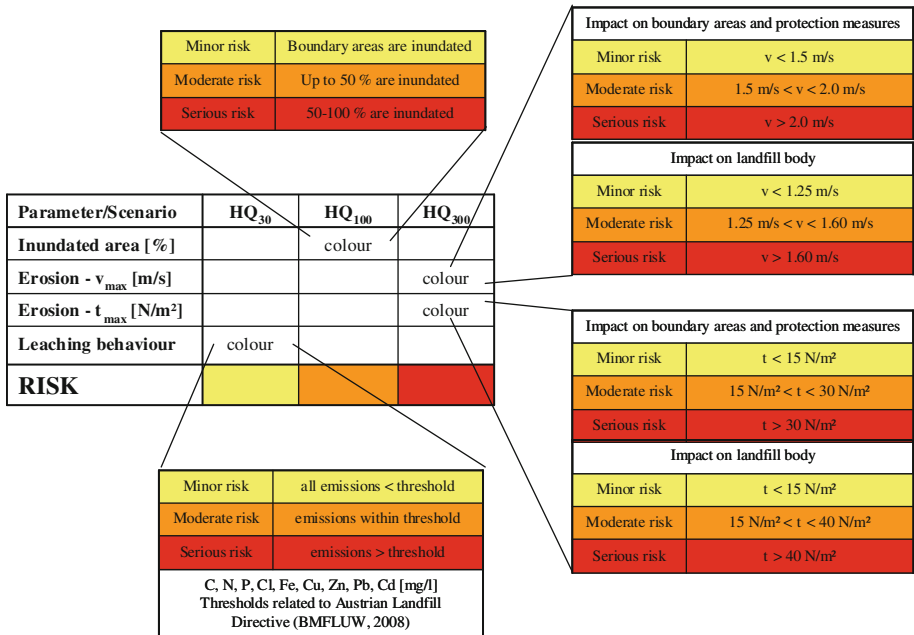


Fig. 4 The Flood Risk Evaluation Matrix (FREM), description of input parameters and threshold levels

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 that is able to dissolve substances during a flood event (Nachtnebel et al. 2009):

$$V_d = \left(\frac{A_v}{A_h} \times v_{\text{mean}} \right) \times b_A \times h_{\text{mean}} \times t \tag{1}$$

V_d water volume available for dissolving substances [m^3/s], A_v area of landfill where flow velocities >0 [m^2], A_h area of landfill where water depth is >0 [m^2], 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.

3 Application of the qualitative approach

The results of case study 1 will be presented in detail (Table 1) 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 and will be discussed in Sect. 4.

Table 1 Evaluation parameters utilized as input to the FLEM, grouped into hydrologic scenarios (columns)

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 $h > 0$ [m ²]	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 $v > 0$ [m ²]	43300	48400	53300
percentage of total area [%]	67.9	75.9	83.5
Evaluation parameter shear stress (τ)			
maximum [N/m ²]	50.32	48.74	50.57
mean [N/m ²]	3.13	2.83	1.38
affected disposal area with $\tau > 0$ [m ²]	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

Grey-shaded fields were compared to pre-defined threshold levels

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 130,000 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 utilizing 10 × 10 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 (HQ₃₀), 410 m³/s (HQ₁₀₀) and 480 m³/s (HQ₃₀₀). The results show inundation of the waste deposit and the overall hinterland. Hence, broad distribution of hazardous emissions has to be expected.

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 categorized as “serious risk” (Table 2). 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 HQ₃₀ and “moderate risk” for the scenarios HQ₁₀₀ and HQ₃₀₀. 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 HQ₃₀ and HQ₁₀₀ as well as to low mean shear stress values, the evaluation parameter shear stress led to a categorization of “minor risk” due to a 30 years flood and a 100 years flood. The calculations for a HQ₃₀₀ yielded a substantial increase of the affected disposal area where 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 (HQ₃₀) and minor/moderate for HQ₁₀₀ and HQ₃₀₀. 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 HQ₃₀₀.

Table 2 Simulation results of case study 1 including associated risk-related colours

Evaluation parameter	HQ ₃₀	HQ ₁₀₀	HQ ₃₀₀
Inundation [%]			
Erosion - v _{max} [m/s]			
Erosion - τ _{max} [N/m ²]			
Leaching behaviour			
Overall environmental risk			

yellow minor risk, *yellow/orange* minor to major risk, *orange* major risk, *orange/red* major to serious risk, *red* serious risk

4 Discussion and conclusions

4.1 Exposure to floods

One hundred and three controlled MSW landfills and 961 old waste deposits with at least 25,000 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 are exposed to flooding with respect to HORA (BMFLUW 2006b). 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 2008b). 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 have 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.

4.2 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.

4.3 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 landfilling 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 2008a)—a single document (AFEA 2008b) reported the falseness of coordinates and the category (old waste deposit) without implementation to the GIS database, which was provided (AFEA 2008a). 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 2006b) 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 utilized 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 was 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 that 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 flow 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.

Acknowledgments The authors want to show their gratitude to the federal governments of Salzburg and Tirol who provided the model setups for case study 2 and case study 3.

References

- AFEA (2008a) Austrian federal environment agency—Umweltbundesamt, GIS data supply. <http://www.umweltbundesamt.at/umweltschutz/altlasten/>
- AFEA (2008b) 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* 5:483–499
- Belevi H, Baccini P (1989) Long-term behaviour of municipal solid waste landfills. *Waste Manage Res* 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) River 2D, 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 GE, Fourie A (2005) Catastrophe revisited—disastrous flow failures of mine and municipal solid waste. *Geotech Geol Eng* 23:219–248
- BMFLUW (1996) Bundesgesetzblatt für die Republik Österreich, 186. Verordnung: Allgemeine Begrenzung von Abwasseremissionen in Fließgewässer und öffentliche Kanalisationen (AAEV). Wien
- BMFLUW (2006a) Federal waste management plan 2006. Federal Ministry of Agriculture and Forestry, Environment and Water Management, Vienna, p 320
- BMFLUW (2006b) Hochwasserrisikozonierung Austria—HORA, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft. www.hochwasserrisiko.at
- BMFLUW (2007) Digital hydrologic atlas Austria. <http://www.boku.ac.at/iwhw/ha0/>
- BMFLUW (2008a) Kosten-Nutzen-Untersuchung im Schutzwasserbau: Richtlinie, impressum.lebensministerium.at/filemanager/download/26589/
- BMFLUW (2008b) Austrian Landfill Directive. Verordnung über die Ablagerung von Abfällen. <http://www.lebensministerium.at/article/articleview/26629/1/6969/>
- BMFLUW (2009) Flood risk II, Vertiefung und Vernetzung zukunftsweisender Umsetzungsstrategien zum integrierten Hochwassermanagement, Synthesebericht
- Bogner J, Spokas K (1993) Landfill CH₄: rates, fates, and role in global carbon cycle. *Chemosphere* 26:369–386
- BUWAL (1999) Risikoanalyse bei gravitativen Naturgefahren—Methode. Umwelt-Materialien Nr. 107/I, Naturgefahren: Bern: Bundesamt für Umwelt, Wald und Landschaft
- Christensen TH, Kjeldsen P, Lindhardt B (1996) Gas-generating processes in landfills. In: Christensen TH (ed) Landfilling of waste: biogas. E&FN Spon, London, pp 27–44
- Döberl G, Huber R, Fellner J, Cencic O, Brunner PH (2002) Neue Strategien zur Nachsorge von Deponien und zur Sanierung von Altlasten (Projekt STRANDEZA). Abteilung Abfallwirtschaft und Stoffhaushalt. Technische Universität Wien, Wien, p 267
- Ehrig HJ, Krümpelbeck I (2001) The emission behaviour of old landfills in the aftercare phase. In: Christensen TH, Cossu R, Stegmann, R (eds) Proceedings Sardinia 2001, eighth 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
- 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, p 184
- Hydrotec (2008) Das 2D Strömungsmodell Hydro_AS-2D, Hydrotec Ingenieurgesellschaft. <http://www2.hydrotec.de/unternehmen/hydrothemen/hydro-as-2d/>
- Klink RE, Ham RK (1982) Effects of moisture movement on methane production in solid waste landfill samples. *Resources and Conservation* 8:29–41
- 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
- Krammer HJ, Domenig M, Striedner J, Vogel G (1992) Materialien zum Bundesabfallwirtschaftsplan (BAWP), Band 3: Kommunale Abfälle. Bundesministerium für Umwelt Jugend und Familie, Wien, p 180
- Laner D, Fellner L, Brunner PH (2008a) Gefährdung durch Deponien und Altablagerungen im Hochwasserfall—Risiko und Analyse (GEDES), Dokumentation zum Arbeitspaket 1. Zwischenbericht TU-Wien IWA, Wien, p 54

- Laner D, Fellner J, Brunner PH, 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
- Laner D, Fellner J, Brunner PH (2009) Flooding of municipal solid waste landfills—a long-term environmental hazard? *Sci Total Environ* 407(12):3674–3680
- Lange G, Lechner K (1993) *Gewässerregelung & Gewässerpflege—Naturnahe Ausbau und Unterhaltung von Fließgewässern*. Verlag Paul Parey, 3. Auflage, Hamburg
- Merz B (2006) *Hochwasserrisiken—Grenzen und Möglichkeiten der Risikoabschätzung*, E. Schweizerbart'sche Verlagsbuchhandlung, Nägele 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 HP, 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 HP, 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 HP (2009) Incorporation river morphological changes to flood risk assessment: uncertainties, methodology and application. *Natural Hazards and Earth System Sciences* 9:789–799
- Stegmann R, Heyer KU (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* 322:3–20
- Zhang Y (2006) *Technical report no. NCCHE-TR-2006-03, CCHE-GUI—graphical users interface for NCCHE Model, user's manual—version 3.0 NCCHE*. The University of Mississippi, Oxford
- 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, Oxford