Targeted Design and Integrated Evaluation of Land Use Alternatives for Sustainable Brownfield Redevelopment

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ABSTRACT

In the last 50 years the conversion of greenfield land to settlement and traffic areas in Germany has greatly increased. Over the last several years the average land consumption has exceeded 115 ha per day – a trend which can not be sustained on the long run. While new residential and industrial areas are being built on ever decreasing green space, approximately 140,000 ha of previously used land in Germany lie idle today. Reusing this land could thus play a key role in the reduction of land consumption. But many of these areas are characterized by little available data and by a presumably contaminated subsurface due to previous industrial use. The resulting fear that extensive investigation efforts, costly cleanup, and long-winded stakeholder negotiations may impede redevelopment of these so-called brownfield sites leads to the fact that many brownfields remain undeveloped to date.

It is generally recognized that successful brownfield revitalization (BR) strategies need to optimize the trade-off between the partly conflicting goals of maximizing both economic revenues and sustainable development while minimizing the expenditures for the revitalization. The evaluation of these complex interdisciplinary interrelations for large numbers of redevelopment options calls for computer-based decision support systems (DSS). However, recent reviews report a lack in DSS which provide an adequate integrated assessment of planning alternatives at early stages of the redevelopment process when land use planning is still flexible but data availability is limited.

Aiming to close this gap, this thesis describes the development of a DSS that supports the interdisciplinary evaluation of BR alternatives. It includes the development and integration of methods for the estimation of (i) subsurface remediation and site preparation costs, (ii) the expected economic value including the quantification of perceived economic risks, and (iii) the spatially explicit quantification of the future land use's contribution to a sustainable development. In three studies these methods are applied for the assessment of BR options in terms of the spatial allocation of different land use types at a model site. The iterative re-planning of these planning options is facilitated by the evaluation and visualization of the interdisciplinary consequences to spatial land use planning, whereby the focus is increasingly set on standardized and spatially explicit evaluation procedures. The results suggest that on the one hand BR is not automatically in line with sustainable development, and that on the other hand additional contributions to sustainability are not intrinsically tied to increased costs. The targeted identification of beneficial planning alternatives improves the basis for stakeholder discussions at early development stages. Thereby, decision making processes for sustainable BR can be initiated and streamlined. As a conclusion from the studies, key needs for future research are identified with respect to the single disciplines and to their integration.

KURZFASSUNG

Im Laufe der letzten 50 Jahre ist der Zuwachs an Siedlungs- und Verkehrsflächen in Deutschland stark angestiegen. Seit 1992 fielen im Schnitt täglich 115 ha Grünflächen und Ackerland diesem sogenannt Flächenverbrauch zum Opfer, während derzeit in Deutschland ungefähr 140,000 ha vormals genutzter Flächen brach liegen. Die erneute Nutzung dieser Flächen könnte über Jahre hinweg einen entscheidenden Beitrag zur Reduzierung des Flächenverbrauchs leisten. Häufig stehen diesem so genannten Flächenrecycling jedoch die mit Altlasten verbundenen Risiken – z.B. erhöhte Kosten und Verzögerungen der Nachnutzung – sowie das Negativimage von Brachflächen im Wege. Angesichts der Vielzahl der beteiligten Akteure aus unterschiedlichen Interessensgruppen scheitert die Wiedernutzung häufig an mangelnder Kommunikation und Kompromissbereitschaft.

So genannte Entscheidungs-Unterstützungs-Systeme (engl. decision support systems, DSS) können die Analyse und Diskussion der komplexen Sachlage auf Brachflächen fördern und dadurch Entscheidungsprozesse bei der Planung geeigneter Nutzungskonzepte entscheidend erleichtern. Aktuellen Studien zufolge mangelt es jedoch an geeigneten Werkzeugen, welche bereits früh im Planungsprozess – also bei größtmöglichem Planungsspielraum und gleichzeitig geringer Datenlage – eine interdisziplinäre Bewertung der ökonomischen, ökologischen und sozio-ökonomischen Konsequenzen von Landnutzungsoptionen auf Brachflächen ermöglichen.

In der vorliegenden Arbeit wird die Entwicklung und Anwendung eines solchen Systems beschrieben. Die darin implementierten Methoden integrieren neu entwickelte Ansätze für die frühzeitige und räumlich differenzierte Quantifizierung (i) der Kosten der Altlastensanierung, (ii) des zu erwartenden Marktwerts der Fläche unter Berücksichtigung der am Markt wahrgenommenen Risiken, und (iii) des Beitrags der Nachnutzung zu einer nachhaltigen Siedlungsentwicklung. In drei Studien an einem Modellstandort werden die Methoden mit einem zunehmenden Fokus auf standardisierte Bewertung angewandt und weiterentwickelt. Die vergleichende Bewertung von Planungsalternativen, der vereinfachte deterministische Entwurf vorteilhafter Landnutzung sowie die automatische räumliche Bewertung der Nachhaltigkeit von Nutzungsentwürfen unterstützen dabei die interdisziplinäre Planung. Die Ergebnisse am Modellstandort lassen darauf schließen, dass zwar nicht jede Wiedernutzung von Brachflächen automatisch nachhaltig ist, dass sich aber nachhaltige und ökonomisch attraktive Nachnutzung keinesfalls ausschließen. Abschließend wird der abgeleitete Entwicklungsbedarf sowohl für die einzelnen Bewertungsmethoden aus den unterschiedlichen Disziplinen als auch für deren interdisziplinäre Integration skizziert.

TABLE OF CONTENTS

LIST OF FIGURES 1

LIST OF TABLES 3

INTRODUCTION.. 5

CHAPTER 1: Designing sustainable and economically attractive brownfield revitalization options using an integrated assessment model.................. 11

- 1.1 INTRODUCTION.. 12
  - 1.1.1 Brownfield revitalization.. 12
  - 1.1.2 Necessity for appropriate decision support systems.................... 13
  - 1.1.3 Objectives... 14
- 1.2 DESCRIPTION OF METHODS 14
  - 1.2.1 Data Requirements 14
  - 1.2.2 Conflict Analysis.. 16
  - 1.2.3 Estimation of Costs for Site Preparation 16
  - 1.2.4 Market value estimation and mercantile value reduction (MVR)19
  - 1.2.5 Sustainability assessment 21
- 1.3 CASE STUDY 24
  - 1.3.1 Description of model site... 24
  - 1.3.2 Characterization of land use types and definition of redevelopment options 25
- 1.4 RESULTS AND DISCUSSION 27
  - 1.4.1 Evaluation of redevelopment options.. 27
  - 1.4.2 Discussion... 30
- 1.5 CONCLUSIONS.. 31
- SUPPLEMENTARY DATA: Case study model input data and their sources33

CHAPTER 2: Integrated planning and spatial evaluation of megasite remediation and reuse options 35

- 2.1 INTRODUCTION.. 36
- 2.2 METHODS... 37

2.2.1 Conflict analysis....38
2.2.2 Estimation of Costs for Subsurface Remediation and Deconstruction of Derelict Buildings....39
2.2.3 Market value assessment: location quality and risk rebate....41
2.2.4 Monetary Assessment: Summary....42
2.2.5 Sustainability Evaluation and Integrated Assessment....43
2.3 CASE STUDY....44
2.3.1 Site Description....44
2.3.2 Monetary Assessment and U^{max}....45
2.3.3 Sustainability Evaluation and Integrated Assessment....52
2.4 CONCLUSIONS....54
APPENDIX: List of variables....56
CHAPTER 3: Systematic improvement of sustainable brownfields redevelopment by automated quantitative spatial assessment of sustainability indicators....57
3.1 INTRODUCTION AND OBJECTIVES....58
3.2 DESCRIPTION OF METHODS....60
3.2.1 Prerequisites....60
3.2.2 Definition of algorithmic assessment scheme....60
3.3 CASE STUDY....63
3.3.1 Description of study site, previous work and setup of analyses....63
3.3.2 Transfer of the indicator set into an algorithmic evaluation scheme 65
3.3.3 Implementation....65
3.3.4 RESULTS....68
3.4 DISCUSSION....76
3.5 CONCLUSIONS....77
CONCLUSIONS....79
BIBLIOGRAPHY....87
ACKNOWLEDGEMENTS....105

LIST OF FIGURES

Figure I: Schematic illustration of the integrated assessment of the consequences of land use planning (modified after SAFIRA II brochure 2011)………..…………………………………………………………………..8

Figure 1.1: Case study site data: Information about groundwater regime and subsurface contamination, existing buildings, state roads, and water bodies, as a basis for subdivision into 12 planning units ("land patches"). 24

Figure 1.2: Definition of land use options A through H by allocating distinct land use types on the 12 planning units. 26

Figure 1.3: Model site's sustainability factor E_{tot} versus market value of analysed land use options.. 31

Figure 2.1: Case study site with the division into planning units (PUs) and the suspected contamination in soil (PAH) and groundwater (TCE). [m.a.s.l.]: meters above sea level. 45

Figure 2.2:: Exceedance maps showing the conflicts between the existing contaminant concentration in groundwater (two contaminants: TCE and PCE) and soil (one contaminant group: PAH) and the maximum acceptable concentration levels of three different land use types.. 47

Figure 2.3:: Costs for remediation of subsurface contaminations (R), which would be required in order to enable three different uniform land uses on the site......... 48

Figure 2.4: Estimated location quality (Q) as correction factor for reference land values for three different uniform land uses. Planning units (PUs) discussed in the text are labeled. 49

Figure 2.5: Summary of the monetary assessment results assuming uniform land use: land value per square meter ($L_{R,A}$) after subtraction of the anticipated land use specific soil and groundwater remediation costs. 50

Figure 2.6: Results of monetary optimization. Maximum land values [€/m^2] (map 1) are achieved by economically optimal allocation of land use types U^{max} (map 2). $\Delta L_{R,A}$ reflects the costs that an alteration of U^{max} would cause for each planning unit (PU) (map 3). PUs discussed in the text are labeled...................... 51

Figure 2.7: The degree of suitability E of three different land use types in terms of sustainable development, assuming uniform land use. 53

Figure 2.8: Three suggested initial planning scenarios based on monetary optimization (map 1), a first re-planning step U^{MOD1} guided by economic appraisal, $L_{R,A}$ (map 2), and a second re-planning step U^{MOD2} guided by sustainability evaluation (map 3) (compare Figure 2.6 and Figure 2.7)............... 54

Figure 3.1: The process of defining spatial indicator evalution algorithms, as followed in this work, and its "traditional" alternative, the manual evaluation of indicators (far right). Grey areas require input by stakeholders and experts......... 62

Figure 3.2: The case study site, subdivided into planning units, and the site-specific spatial data relevant for the evaluation of the sustainability indicators. .. 63

Figure 3.3: (a) Planning units (PUs) of the case study site with indices. (b) Distributions of individual PUs' suitability values E_{PU} for uniform residential land use, and (c) with commercial use in PU 0 (first of 27 planning alternatives in sequence 1.1). 70

Figure 3.4: Change in suitability values E_{tot} caused by the allocation of a complementary land use type to individual PUs as a function of the PU area...... 71

Figure 3.5: (a) E_{tot} for land use options with an increasing fraction of commercial land use on an otherwise residentially used site. (b) and (c): Maps of sequences W-E and E-W, left to right, top to bottom. Dark shaded PUs represent commercial land use. 72

Figure 3.6: The variations in E_{tot} that are caused by changed boundary conditions in the discussed sequences of planning options, separated by the five relevant indicators. Mind the different scales. Sch.: three planning options from Schädler et al. (2011b) 75

LIST OF TABLES

Table 1.1: Required input data for the integrated assessment model.................. 15

Table 1.2: Empirical uncertainty in remediation costs as a function of investigation/information levels (Kerth and Griendt, 2000), and the resulting “time” factors for estimation of MVR as evaluated by Bartke and Schwarze (2009b).. 21

Table 1.3: Sustainability first and second level goals, and representative indicators used for assessment. Evaluation by “TRUE/FALSE” statements translates into integer value pairs (TRUE: first value, FALSE: second value). “n”: no relevance with respect to the given land use type (i.e. “0/0”).. 22

Table 1.4: Considered land use types and their properties.................................. 26

Table 1.5: Results of the integrated analysis of redevelopment options.............. 28

Table 2.1: Unit price values for work steps of contaminated soil remediation. Source: LUA NRW (2005)... 40

Table 2.2: Characterization of three land use types with respect to economic and ecological assessment. 46

Table 2.3: Estimation of contaminated subsurface volumes that require remediation and resulting remediation costs for three different land use types.... 46

Table 2.4: Results of the evaluation of uniform land use types and of the preliminary optimum land use option U^{max}... 51

Table 2.5: Comparison of three suggested initial planning options (Figure 2.8) as re-evaluated on the basis of site characteristics and land-use interdependencies. 54

Table 3.1: Scheme for the evaluation of sustainability indicators. Grey shaded indicators are considered spatially constant in this case study. Framed indicators are re-evaluated for different assumptions in a sensitivity and a scenario analysis. W: Indicator weight. SD: the spatial domain considered for the evaluation which can be either R (the region), A (the area of the site), or a logic combination of the two.. 66

Table 3.2: Results of the evaluation of the benefits from one complementarily used planning unit (PU) on an otherwise uniformly used site. The PU with the highest E_{tot} value in each column is highlighted. A: PU area in hectares [ha]. PU Index: the PU that the complementary use type is allocated to. 69

Table 3.3: The change in each sequence's mean $\bar{E}$ value that is created by a lack of local amenities (indicator #14) and primary school (indicator #15). 73

Table 3.4: The change in mean $\bar{E}$ values caused by a hypothetical change in boundary conditions, broken down by the five indicators which contribute to the change in results. 74

INTRODUCTION

Within the last three decades, the world's population has increased at a rate of about ~80 million persons per year, or about 150 persons per minute (United Nations Secretariat, 2010). At the same time, the average use of land per person has been increasing due to a growing consumption of energy, food and industrial products, and due to a rising demand in habitable space (e.g., Nellemann et al., 2009). The result is a world-wide increase in human land use activities which are also termed "land consumption". Among the regionally varying consequences of this trend are the loss of native habitats, the degradation of the quality and a decreasing quantity of available fresh water resources, a loss of ecosystems' services as well as effects on regional climate and air quality (e.g., Foley et al., 2005). The following, numbers from Germany shall exemplify recent trends in land consumption. Similar trends can be observed across Europe and world-wide.

In Germany, within the last 50 years the loss of open space has increased to a level that was never reached before in German history and that is highest among all European countries. In the period 1992 through 2010, on average 115 ha of greenfields per day were converted into building ground. Peak average values reached 131 ha/day in the years 1998 through 2000 and 2004 and since then have been slightly decreasing (FSO – German Federal Statistical Office, 2010a). Rather than depending on the actual size of the population, the increasing land consumption is attributed mainly to changes in the land use per capita: the average net dwelling area per capita increased from 15 m^2 per person in 1950 to now 43 m^2 per person in Germany (FSO – German Federal Statistical Office, 2010b). Additionally, modern peri-urban residential areas tend to be by a factor of ~3 less densely populated than typical inner-urban areas and thus require more space. The urging need to slow down this trend, as expressed by responsible parties of hundreds of German cities already in the year 2000 (DIFU, 2000), led the German government to establish a goal of reducing land consumption to 30 ha per day by the year 2020 (Bundesregierung, 2002). Since then, this so-called "30-ha-goal" has been repeatedly revisited in a number of reports, among others by the German Council for Sustainable Development (CSD, 2004) and the German Federal Government (Bundesregierung, 2008). But although land consumption has decreased to an average of 95 ha/day until 2008 (FSO – German Federal Statistical Office, 2010b), lowering this present value to 30 ha within less than ten years from now remains an extremely ambitious aim.

At the same time, the amount of fallow land has been increasing by about 10 ha per day in Germany. Today, these abandoned areas make up about 140,000 ha of land in Germany, an area about three times the size of Lake Constance, or about five times the total land consumption of the year 2008 (FEA – German Federal Environmental Agency, 2005). The numbers suggest that the reuse of fallow land could provide a major contribution to the targeted reduction in land consumption for years or even decades. While benefitting from beneficial locations and already existing infrastructure of abandoned sites in many cases (FEA – German Federal Environmental Agency, 2005), the reuse of abandoned land could additionally enhance a sustainable urban and regional development because a reduced land consumption typically leads to a reduction in habitat endangerment, in the cost for mobility and for maintenance of infrastructure and in the deterioration of air, soils and water resources (e.g., Bardos et al., 2000; Nuissl and Schroeter-Schlaack, 2009). Thus, the desirability of revitalizing derelict sites is gaining more and more political and market credence (Adams et al. 2010; Dixon 2006; Schulze Baing 2010).

But in many cases, abandoned industrial or military sites, also termed "brownfields", are characterized by soils and groundwater that are contaminated by the legacy of the sites' previous uses. The United States Environmental Protection Agency USEPA, the European CABERNET project and the Canadian National Round Table on the Environment and the Economy NRTEE similarly define brownfields as sites that are degraded by a real or perceived subsurface contamination and can therefore not be re-used without an intervention (CABERNET, 2005; NRTEE, 2003; USEPA, 2002). This intervention, i.e., the investigation of the brownfield site and, where necessary, the remediation of its contamination, can be both time-consuming and extremely costly. Moreover, it is highly uncertain how large the costs exactly are. For example, estimates for the costs of remediating all European brownfields range from approximately € 28 billion (European Commission, 2006) to values as high as € 100 billion (EEA, 2000). What makes things worse is that even after the complete remediation of a brownfield, the negative headlines associated with the site and the perceived risk of remaining contamination both can lead to a reduction in the site's reputation, a so-called stigma (Mundy, 1992; Patchin, 1991), which reduces the value and marketability of former brownfields. These complexities require trade-offs to be made by the involved stakeholders, which typically come from different backgrounds and represent potentially conflicting interests:

1. Town planners aim towards a sustainable reuse in terms of local or regionally specific social or socio-economic goals.
2. From an ecological point of view, the risks to human health and the environment are in the focus, the aim being the reduction of these risks to the widest possible extent.
3. Investors tend to maximize their economic benefits by minimizing expenditures and maximizing revenues.

The resulting fear that extensive investigation efforts, intricate stakeholder negotiations and time-consuming and costly cleanup may outrun any market interest leads to the above-described fact that many brownfields remain undeveloped to date. Given the significant economic, ecological and socio-economic advantages of brownfield redevelopment and a number of success-stories at already redeveloped sites suggest that beneficial land use alternatives may exist for a large fraction of today's brownfield sites (FEA, 2005). The challenge remains to identify these alternatives, and to make the involved stakeholders act in concert in order to achieve the required trade-offs.

Whether and how the land use on a redeveloped brownfield is sustainable and at the same time economically attractive depends on a large number of factors. First of all, there are the site's properties such as existing plants, buildings and infrastructure, and the type and severity of existing subsurface contamination. Secondly there is the land use in the site's vicinity and the region's market environment. These aspects will strongly determine which land use types are best suited for the site's reuse. Where exactly these land use types should best be allocated on the site in order to minimize required remediation efforts, maximize market value and enhance beneficial socio-economic effects will be influenced by the site-specific spatial features, and additionally depends on the interrelations with respect to optimal land use planning between the different land use types themselves (e.g., Rossi-Hansberg, 2004). The consideration of this multi-faceted spatial data and the evaluation and comparison of more than some very few planning alternatives on the search for beneficial compromises quickly becomes inconveniently cumbersome if performed manually. That is where computer-based spatial decision support systems (sDSS) become helpful or may even be essential. They make use of geographical information systems (GIS) in order to provide capacity for the display and evaluation of spatial data, thereby strongly facilitating decision making (Densham and Goodchild, 1989; Malczewski, 2006; Ascough et al., 2008).

Besides the management of complex data for the identification of beneficial BR options, it has been repeatedly agreed on in literature related to the brownfield context that the initiation of a successful BR project requires a vision of future land use that is shared among the stakeholders of the brownfield site (Adair et al., 2000; Prato, 2007). But despite a wide consensus that BR requires decision support systems, and that adequate DSS would need to integrate the economic, ecological and sustainability concerns of the mentioned stakeholders, recent literature reports a lack of DSS which conveniently fulfil this requirement. The two main deficits that were identified are (i) a missing consideration of sustainability aspects besides the comparatively well established evaluation of economic and ecologic planning consequences (e.g., Brüggemann et al., 2005; Doick et al., 2009; Hassan, 2004; Jakeman et al., 2008), and (ii) the management of comparably complex data in a way that fosters communication among stakeholders (e.g., Agostini et al., 2007; Agostini and Vega, 2007; Bardos et al., 2001; Carlon et al., 2007; Tam and Byer, 2002).

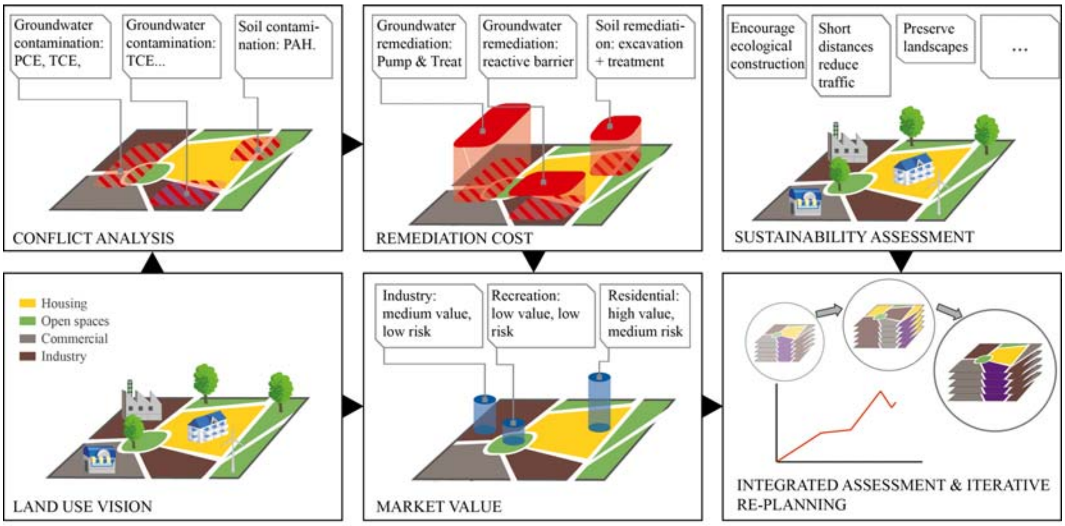

Figure I: Schematic illustration of the integrated assessment of the consequences of land use planning (modified after SAFIRA II brochure 2011).

Therefore, the motivation of this work is twofold.

1. To develop and integrate methods for the evaluation of economic, ecological and sustainability aspects in the assessment of brownfield redevelopment planning alternatives.
2. To implement the developed methods in user-friendly software that supports stakeholders from different backgrounds in decision making already at early stages of the decision process.

The first motivation, i.e. the interdisciplinary method development and integration, along with the demonstration of the methods at a case study site, is reflected by the following three chapters of this work which are reproduced from three scientific publications. Figure I represents a simplified scheme of the interrelations between the different aspects that these studies are based on. This scheme is followed throughout this work, with an increasing focus on standardized methods for a targeted design of beneficial planning alternatives.

Chapter 1: This chapter summarizes the existing need for decision support in the context of brownfield redevelopment projects. It provides novel methods for the estimation of sustainability aspects of land use planning, for the appraisal of the market value and the quantification of perceived economic risks, and for the adaption of existing models for a land-use-specific estimation of costs for soil and groundwater remediation. Based on these methods, an integrated evaluation of land use alternatives is described. In a case study, the developed methods support the iterative re-planning of manually defined land use options in a trial and error approach which is implicitly guided by previously evaluated options.

Chapter 2: Based on the methods described in the first chapter, Chapter 2 provides a framework of algorithms for the targeted design of near optimal land use options. This method replaces the iterative trial and error approach from Chapter 1 by a standardized method. Evaluating uniform use of the site for different land use types and thereby neglecting these use types' spatial interdependencies, a simplified preliminary optimum planning alternative is generated along with a map-based support for the iterative re-planning.

Chapter 3: Whereas in the first two chapters the assessment of sustainability is described as a stakeholder-based evaluation of sustainability indicators, in Chapter 3 this assessment is transferred into an automated process. In a case study this process is explored for the spatially explicit evaluation of a large number of planning alternatives under varying assumptions. This study provides additional insights into sustainable land use planning on the model site. This work enables the application of genetic algorithms in the integrated optimization of BR options that is described by Morio et al. (2011).

The second motivation, i.e., the implementation of the developed methods in user-friendly DSS, although not reflected in these three publications, has been closely linked to the method development. The product of this work, the SAFIRA II Megasite Management Toolsuite (MMT[1]) provides user-friendly implementation of most of the methods used in these studies and has greatly facilitated the data generation for the manuscripts. More importantly, the demonstration of the implemented methods within the scope of a number of workshops provided additional feedback from practitioners and stakeholders which complements the scientific feedback and provides important conclusions to this thesis.

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[1] Further information and downloads: http://www.safira-mmt.de/

CHAPTER 1

Designing sustainable and economically attractive brownfield revitalization options using an integrated assessment model[2]

Abstract

We describe the development of an integrated assessment model which evaluates redevelopment options of large contaminated brownfields and we present the application of the model in a case study. Aiming to support efficient and sustainable revitalization and communication between stakeholders, the presented assessment model integrates three pinnacles of brownfield revitalization: (i) subsurface remediation and site preparation costs, (ii) market-oriented economic appraisal, and (iii) the expected contribution of planned future land use to sustainable community and regional development. For the assessment, focus is set on the early stage of the brownfield redevelopment process, which is characterized by limited data availability and by flexibility in land use planning and development scope. At this stage, revealing the consequences of adjustments and alterations in planning options can foster efficiency in communication between the involved parties and thereby facilitates the brownfield revitalization process. Results from the case study application indicate that the integrated assessment provides help in the identification of land use options beneficial in both a sustainable and an economical sense. For the study site it is shown on one hand that brownfield redevelopment is not automatically in line with sustainable regional development, and on the other hand it is demonstrated that additional contributions to sustainability are not intrinsically tied to increased costs.

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[2] Reproduced from: Schädler, S., Morio, M., Bartke, S., Rohr-Zänker, R., Finkel, M., 2011. Designing sustainable and economically attractive brownfield revitalization options using an integrated assessment model. Journal of Environmental Management 92(3),827 – 837. DOI:10.1016/j.jenvman.2010.10.026. Copyright 2010 Elsevier.

1.1 INTRODUCTION

1.1.1 Brownfield revitalization

Different definitions in both Europe and the US similarly describe brownfield sites as abandoned or underused properties, for which intervention is required to ensure beneficial reuse because of the real or suspected presence of hazardous substances, pollutants or contaminants (CABERNET, 2005; USEPA, 2002). The health and economic threats of Brownfields as well as the challenges and potential of their reuse are recognized world-wide and international literature describes concerns related to brownfields e.g. in Africa (e.g., Haylamicheal and Dalvie, 2009; Kaufman et al., 2005), Asia (e.g. Cao and Guan, 2007; Zhang and Wong, 2007), Australia (e.g., Apostolidis and Hutton, 2006; Toms et al., 2008), and Canada (e.g., DeSousa, 2001; NRTEE, 2003). Estimated costs for restoration of large brownfield sites in the US range from $100 billion (USEPA, 2003) to over $650 billion (NRTEE, 2003) and for the European Union amount to almost €100 billion (EEA, 2000).

When brownfields are especially large in terms of area, prominence, relevance, seriousness, regional significance, complexity of contamination and of stakeholder networks, they are typically referred to as megasites in more recent literature (Agostini et al., 2007; Bardos, 2004). The revitalization process of such sites may be complicated e.g. by extensive investigation efforts, intricate negotiation among stakeholders with potentially differing interests, large uncertainties, and time-consuming and costly cleanup that may outrun any market interest by far (Bardos, 2004; NRTEE, 2003). The consequence of this is that many of the most complex brownfields to date remain undeveloped.

On the other hand, successful brownfield revitalization can benefit from the typically prominent location of the sites and of already existing infrastructure and it can drastically enhance sustainable regional development (Bardos et al., 2000) by contributing to a reduction of land consumption and urban sprawl. Large sites additionally provide developers with a wide scope of planning for the design of future land use options, i.e. the use types considered and their allocation on the site. Only if this freedom is exploited in order to optimally trade-off between the partly conflicting goals of maximizing land value (i.e. realization of valuable land use types), minimizing remediation costs (i.e. by optimal definition and allocation of land use types with respect to exposure to contaminants), and at the same time contributing to a sustainable urban and regional development, revitalization of large brownfields can be successful (DeSousa, 2006).

1.1.2 Necessity for appropriate decision support systems

The concept of spatial decision support systems (sDSS) evolved from the need to make decisions based on quantitative and qualitative spatial data in geographic information systems (GIS) (Densham and Goodchild, 1989). Interest in sDSS research has been continuously increasing (Malczewski, 2006) and so has their use for comparative analysis of environmental management alternatives (Ascough et al., 2008), when the high uncertainty associated with forecasting consequences to future actions (Walker et al., 2003) could otherwise result in inaction or improper action like excessive data collection (Reichert and Borsuk, 2005; Smit and Smit, 2003; Wang and McTernan, 2002).

A wide variety of methods to date deal with one or a number of aspects of brownfield revitalization such as risk assessment (e.g., Carlon et al., 2008; Semenzin et al., 2006; Strenge and Chamberlain, 1995), policy analysis (e.g., Linkov et al., 2006), optimization of remediation (e.g., Ahlfeld et al., 1995; Buerger et al., 2007; Wang and McTernan, 2002), remediation cost assessment (e.g., Kaufman et al., 2005), general success factors for brownfield redevelopment (e.g., Lange and McNeil, 2004; Nijkamp et al., 2002), infrastructure redevelopment (Attoh-Okine and Gibbons, 2001), urban planning and site prioritization under budget constraints (e.g., Alvarez-Guerra et al., 2009; Stevens et al., 2007) and mediation of negotiation (Sounderpandian et al., 2005).

Despite the variety of models, several authors have recently described additional need for DSS for contaminated land reuse, which integrate the manifold relevant topics into one system and manage the complicated balance between complexity of information and transparency of results (e.g., Agostini et al., 2007; Agostini and Vega, 2007; Bardos et al., 2001; Tam and Byer, 2002), and that provide guidance to stakeholders while analyzing the huge number of factors that influence optimal future land use on large contaminated sites (Carlon et al., 2007). In particular further development of DSS that integrate an assessment of sustainability has been claimed (Hassan, 2004). Although several definitions of sustainability criteria are described in literature, as well as models to assess the sustainability of land use options (e.g., Wedding and Crawford-Brown, 2007; Zavadskas and Antucheviciene, 2006), most DSS today still do not integrate such assessments. This is explained by the topic’s abstract notion (Esty et al., 2005), its multidimensionality (Doick et al., 2009; Jakeman et al., 2008), and a perceived lack of transparency and objectivity.

1.1.3 Objectives

The objective of this work was to provide an integrated assessment model, which is based on the use of screening level data and serves as a spatial decision and communication support system for the comparative evaluation of alternative brownfield redevelopment options. The following key factors (modified from Tam and Byer, 2002) were considered in this sDSS:

1. Examine alternative clean up goals.
2. Examine alternative site use options.
3. Examine the social, economic, and ecological sustainability of land use alternatives.
4. Estimate all of the economic implications, including clean-up costs, liability, and site use benefits.
5. Examine uncertainties.
6. Be computationally feasible and accessible to stakeholders.
7. Generate results that are understandable to stakeholders (not only to experts in the respective fields).

By encouraging stakeholders to communicate their different expectations towards brownfield redevelopment, the model is meant to promote concerted, constructive and site-specific compromises, thereby fostering the optimal exploitation of the sites' physical planning scope which enables successful revitalization. The focus of this paper is the description of the framework of methods that underlie the integrated assessment, as well as the discussion of results from their application to a case study site.

1.2 DESCRIPTION OF METHODS

1.2.1 Data Requirements

The proposed integrated assessment requires a set of general site-specific data and subsurface conditions including aquifer geometry, properties and contamination (Table 1.1). In addition to this, the redevelopment options of the site need to be specified in terms of land use maps (i.e., the spatial allocation of defined land use types on the site). Redevelopment options that shall be assessed may stem from proposals made by the local authority's planning board or from the investor's plans, but can also be the result of stakeholder discussions and/or iterative re-planning guided by the results of an assessment model as is presented herein. The description of the redevelopment options is complemented by a set of parameters that characterize the particular land use types being considered.

Table 1.1: Required input data for the integrated assessment model.

		Spatial data	**Non-spatial data**
Site-specific	Location and extent of site	x	
	Digital Elevation Model	x	
	Depth and thickness of contamination in soil and groundwater	x	
	Aquifer top and bottom	x	
	Hydraulic conductivity	x	
	Distribution of contaminant(s)	x	
	Contaminant properties		x
	Unit cost data for remediation		x
	General conditions of the site (social, economic, ecological)	x	x
Option-specific	Reference values for price of clean land		x
	Compliance criteria for contaminant concentration		x
	Planned allocation land use options	x	
	Buildings to be deconstructed		x
	Information on site features, attributes, and attractions		x

The parameter set is composed of reference values for the price of clean land in order to reflect the land use-specific potential revenues from revitalising the site, and compliance criteria for contaminant concentration in soil and groundwater. These compliance criteria define levels of environmental quality, which need to be achieved in order to permit the planned future use of the site. Levels may be defined using human health risk assessment methods (e.g., Marsland et al., 1999; Strenge and Chamberlain, 1995; USEPA, 1991) or based on regulatory remediation goals (Rügner et al., 2006), and they should always be established in cooperation with local authorities in order to achieve the commensurate and reasonable levels required by law (Begley, 1996). For the sustainability assessment and market value appraisal further information needs to be gathered about the (non-)existence of several key features, attributes and attractions of the site (assuming the redevelopment option under consideration has been implemented) and the surrounding region.

1.2.2 Conflict Analysis

The conflict analysis is comprised of a set of GIS-based procedures which identify those regions on the site that will require remediation given the information on the distribution of contaminants, as well as on the map of compliance criteria attributed to each specific redevelopment option. The resulting raster maps of exceedance factors for each contaminant of concern indicate areas and magnitudes of conflicts and serve as an input for the estimation of soil and groundwater remediation costs.

In addition, conflicts can be assessed under the assumption that the entire site is uniformly used. This enables planners to identify land use type allocations which are free of conflicts and thus do not require remediation. These supplementary conflict maps provide insight into the opportunities offered when future land use is optimally allocated and give valuable support for an iterative re-planning of land use options.

1.2.3 Estimation of Costs for Site Preparation

The cost estimation model covers (i) groundwater remediation costs and (ii) soil remediation costs, which from the real estate appraisers' point of view are among the most influential cost factors to affect investors' decisions on the redevelopment of brownfield sites (e.g., Dotzour, 2002; Healy and Healy, 1992), as well as (iii) costs related to the deconstruction of buildings. Costs of other and more specific site preparation activities that may be required (e.g., demolition of subsurface infrastructure, asbestos disposal, etc.) are not considered due to the simplicity of this model.

1.2.3.1 Groundwater Remediation Costs

Costs for groundwater remediation are estimated using two models: (i) a model to calculate costs of remedial activities on site that are necessary to resolve conflicts between planned land use and the contamination situation, and (ii) a model to estimate costs of additional measures in order to avoid unacceptable risks to neighbours. Such measures may be necessary if the contaminant flux across site boundaries is expected even after revitalization has taken place, e.g. because contamination on site is partly or entirely left in place due to insensitive land use and associated compliance criteria. In this case costs for plume containment along the concerned site boundary are considered.

Model I estimates the land use related costs for groundwater clean-up, C_{GW} [€], based on the volume of contaminated groundwater and the respective magnitude of exceedance factors as calculated previously in the conflict analysis. Based on this, costs are calculated with an empirical method following Bonnenberg et al. (1992) who designed and validated the method for a quick and convenient evaluation of a large number of sites without explicit differentiation between remediation techniques. The method only requires little detail in input data for the estimation of groundwater remediation costs: spatial information about top and bottom of the contamination (yielding the contaminated volume V [m^3]) as well as about the type and level of contamination. For a map of exceedance factors that contains n conflicting cells, groundwater clean-up costs C_{GW} [€] are summed up as follows:

$$C_{GW} = \sum_{i=1}^{n} C_{u,GW} V_i f_{D,i} f_{K,i} f_{L,i} n_{eff}$$ **Eqn. 1.1**

where $C_{u,GW}$ [€ m^{-3}] are standard unit costs of contaminated groundwater clean-up, n_{eff} is the effective porosity of the contaminated aquifer volume [%], and f_D [-], f_K [-] and f_L [-] are spatially variant factors considering the severity of the contamination in terms of depth (shallow, medium, deep), contaminant group and degree of contamination (low, medium, high and non-aqueous phase), respectively.

Additional costs for plume containment along the site boundaries are calculated using model II in terms of a screening level estimation based on the contaminant flux across site boundaries. A permeable reactive barrier (PRB) filled with zero-valent iron is taken as a reference plume containment technology for chlorinated hydrocarbons (see case study below). Investment costs C_I [€] for containment of each contaminant plume are estimated following the cost functions introduced by Buerger et al. (2003) and are based on an approximate calculation of required PRB dimensions.

$$C_I = \underbrace{w\, S_{het,1}\, m_{Aq}\, T}_{V_B} (C_{RM}\, f + C_E (1-f)) + C_S$$ **Eqn. 1.2**

The required PRB volume V_B [m^3] is represented by the width w [m] of the contaminant plume, corrected for the safety factor $S_{het,1}$ [-] that accounts for flow direction variability (Benner et al., 2001, Elder et al., 2002), the aquifer thickness m_{aq} [m], and the thickness of the reactive barrier T [m]. The latter is defined by $T = K_f\, n_{eff}\, I\, S_{het,2}\, t_c$, where multiplication of the hydraulic conductivity K_f [m s^{-1}], the hydraulic gradient I [-], and the effective porosity n_{eff} [-] yields the groundwater flow velocity in the barrier. The safety factor $S_{het,2}$ [-] accounts for variations in this flow velocity due to aquifer heterogeneities (Benner et al., 2001, Elder et al., 2002), and t_c [s] is the necessary contact time $t_c = \log(c_0 / c_{target})\, \lambda$ between the contaminant and the reactive material, which depends on the actual concentration c_0 [µgl^{-1}], the compliance value i.e. accepted maximum concentration c_{target} [µgl^{-1}], as well as on the contaminant's degradation rate constant λ [s^{-1}]. C_E [€ m^{-3}] and C_{RM} [€ m^{-3}] represent unit costs per volume of earthworks and reactive material (here: zero-valent iron), respectively. Where the barrier thickness T equals values smaller than the technically achievable thickness T_{min}, the dimensionless factor $f = T_{min}/T$ corrects the actual physical thickness of the barrier and the amount of reactive material. Otherwise f equals 1. C_S [€] represents site mobilization costs.

In order to account for deactivation of zero-valent iron during PRB operation, these investment costs are applied again as reactivation costs after regular periods during the required total operation time and discounted to present value costs (see e.g., Lemser and Tillmann, 1997).

It should be noted that literature values are available for many of the above mentioned parameters as shown in the supplementary data. These can be used for a screening-level assessment if site-specific data is not available.

1.2.3.2 Soil remediation costs

The model for estimating soil remediation costs C_s follows the framework KONUS commissioned by the German Federal Environmental Agency (UBA, 1995). Cost estimates are calculated based on contaminated soil volume V_{cont} [m^3] and technology-specific unit costs $C_{U,k}$ [€]:

$$C_s = V_{cont}\, \min\left(C_{U,k}\right), \quad k \in \left\{ i : A\left(M_i\right) \geq th_A \times A\left(M_j\right) \forall i, j \in \left\{1, \ldots, n_M\right\}\right\}$$
$$\text{with} \quad A\left(M_i\right) = \sum_{l=1}^{n_c} \left(a_c\, a_A\, a_D\, a_{Kf}\right)_l \qquad \textbf{Eqn. 1.3}$$

For each of the n_M remediation methods M considered (here $n_M = 12$), the method's technical appropriateness $A(M_i)$ for the prevailing mixture of a number of n_c contaminants is determined by specific suitability values a_c, a_A, a_D and a_{Kf}, which depend on the contaminants present, size of the contaminated area, depth of the contamination and on the aquifer's hydraulic conductivity, respectively. Only those remediation methods are considered which show a sum of suitability values that is above a certain threshold fraction th_A of the best of all methods. Among those, the least costly method is chosen for the cost estimation. Similar to the approach described by Kaufman et al. (2005), the model considers 11 typical contaminant groups which are described by specific properties concerning mobility and oral and respiratory toxicity.

1.2.3.3 Building deconstruction costs

The calculation model for building deconstruction costs *BDC* [€] is adapted from UBA (1995). The cost calculation is based on gross cubic space *V* [m^3] of the buildings and a set of refining factors:

$$BDC = \sum_{i=1}^{n} (f_U f_W f_S f_H C_u V)_i \qquad \textbf{Eqn. 1.4}$$

where f_U [-], f_W [-], f_S, [-] and f_H [-] represent empirical cost-driving factors for the kind of use, the wall thickness, slab thickness and the height of each of a total number of n buildings, respectively. C_u [€ m^{-3}] is the unit cost which again depends on the type of building, as well as on gross cubic space categories for each building.

1.2.4 Market value estimation and mercantile value reduction (MVR)

Although it is theoretically possible to derive the value of brownfield sites in a comparative purchase price analysis of (previously) contaminated sites which have been sold, the necessary market data of comparable transactions is often not available in practice. Therefore, the market value of a contaminated property is traditionally estimated using a residual value approach, in which expected costs for site preparation are subtracted from the value of a comparable uncontaminated site (Adair et al., 2001, Rinaldi, 1991). However, due to perceived remaining risks, revitalized brownfields are usually prized considerably below this value, as has been described in literature within the last three decades (cf. Bell, 1999; Jackson, 2001; Mundy, 1992; Patchin, 1988; Syms and Weber, 2003). In order to correctly account for these value reductions, our model uses two steps to assess the site's market value. In a first step a so-called theoretical land value $V_{L,theor}$ of cleared land is estimated in a residual value approach by subtracting site preparation costs from the reference value of a comparable but clean real estate. The latter is obtained using reference land values per square meter of distinguished land use types (e.g. GSD, 2010). Costs for soil and groundwater remediation and deconstruction of buildings are subtracted from the $V_{L,theor}$ in order to obtain the preliminary land value $V_{L,pre}$.

In a second step, a mercantile value reduction (MVR) is applied (equation 1.5). MVR is a scoring method proposed by Bartke and Schwarze (2009b) with the scope of reducing the contradictions frequently found between existing risks and those perceived by marketers (Patchin, 1991; Mundy, 1992). The concept is based on an international real estate literature survey and a poll of German appraisal experts and it represents a market value markdown (here: a reduction of $V_{L,pre}$) caused by perceived uncertainties regarding rehabilitation, risk of future liability claims, investment risks, utilization risks, as well as stigma and marketability risks. The method quantifies a risk rebate based on (i) local site characteristics, (ii) the information level of the site's redevelopment costs, and (iii) the ability to pass on the monetary risk to others.

Following the concept of Bartke and Schwarze (2009b), a set of local site characteristics (e.g. "Poor demarcation of (suspected) contamination", "Great media attention for contamination risk") are key determinants of the value reduction of a brownfield site as derived from a literature analysis (e.g. Jackson, 2002; Kleiber and Simon, 2007). These key characteristics are specified during a site evaluation by the stakeholders' input U. The average value diminution level m_i [-], as well as the respective weights $w_{S,i}$ [-] of each key local characteristic are median values from the aforementioned expert poll, and thus represent extensive empirical knowledge from previous revitalization projects. Evaluation of the sum of local characteristics results in a relative value reduction F_L between 5% and 30%, which is subsequently adjusted for the factors "time" F_T and "risk" F_R.

$$MVR = V_{L,pre} \underbrace{\sum_{i=1}^{15}\left(m_i(U)\, w_{S_i}\right)}_{F_L} \times \underbrace{\sum_{T_i=1}^{2} w_{Ti} - 1}_{F_T} \times F_R \qquad \textbf{Eqn. 1.5}$$

The informational factor "time" F_T , which is determined by the weights w_{T1} and w_{T2}, reflects the fact that MVR drops over time (i) before site rehabilitation due to increasing availability of detailed information about remediation costs from site investigation (Table 1.2), and (ii) after site rehabilitation as remaining stigma of the previously contaminated site diminishes over time. Finally, the "risk" factor F_R corrects for the fact that, depending on the market situation, potential risks could be passed on from the sellers to the buyers of a site, thus decreasing the value reduction. The MVR risk factor F_R takes values between zero (for acute shortage and great demand in a booming market) and one (big oversupply of similar properties), and will equal 0.5 in a balanced market.

The site's market value is obtained by subtracting MVR from the preliminary land value only where $V_{L,pre}$ is positive. Otherwise both MVR and the market value are set to zero.

Table 1.2: Empirical uncertainty in remediation costs as a function of investigation/information levels (Kerth and Griendt, 2000), and the resulting "time" factors for estimation of MVR as evaluated by Bartke and Schwarze (2009b).

Information level	No study	Historical investigation	Phase 1 investigation	Phase 2 investigation	Phase III investigation	Remediation Plan	Remediation completed
Lower limit	10 %	20 %	50 %	70 %	80 %	85 %	100 %
Upper limit	280 %	260 %	200 %	160 %	140 %	130 %	100 %
Resulting factor "time"	1.45	1.4	1.25	1.15	1.1	1.08	1.0

1.2.5 Sustainability assessment

The sustainability assessment method evaluates the compatibility of land use types and specific future planning options with the goal of sustainable urban development in terms of the principles of the Agenda 21 (ICLEI, 1994; United Nations, 1992) and the three fundamental dimensions of ecological, social and economic sustainability. Within this general framework the focus was set on the main areas of local governments' planning policies (see e.g. pilot projects of sustainable urban development in Germany: Deutsche Umwelthilfe, 2004; Fuhrich, 2004; ICLEI, 2004; Teichert, 2000), which are reflected by five first level goals (i) sustainable land management, (ii) preservation of nature and landscape, (iii) preservation of resources and reduction of emissions by intelligent mobility management, (iv) high quality residential environment, and (v) strengthening of municipal economy. These goals are represented by a set of indicators, as is common practice in international sustainability evaluations (e.g., Esty et al., 2005; Hansen, 2009; Shmelev and Rodríguez-Labajos, 2009), especially on larger scales with comparably limited data density, where a convenient comparison of results and promotion of further detailed stakeholder discussion is achievable only by simplification. The assessment method, namely the anticipation of effects of different types of land use on a specific site and its vicinity, made it necessary to develop new indicators since most of the commonly applied indicators of sustainable urban development (a) are used for ex post comparisons but not for predictive assessments (Singh et al., 2009) and (b) are not focused on specific characteristics of a brownfield site's allocation.

Table 1.3: Sustainability first and second level goals, and representative indicators used for assessment. Evaluation by "TRUE/FALSE" statements translates into integer value pairs (TRUE: first value, FALSE: second value). "n": no relevance with respect to the given land use type (i.e. "0/0").

	Weighting (%)	I. Residentital	II Local Services	III. Recreational	IV. Trade/ Industries	V. Emitting industries	VI. large-space business centres	VII. Monofunctional facilities w/ large open spaces
1. SUSTAINABLE LAND MANAGEMENT								
1.1: Realization of short distances by complementing land uses								
1.1.1 Residential Areas in the surrounding area	10	n	+1/-1	+1/0	+1/0	n	n	n
1.1.2 Green spaces in the surrounding area	10	+1/0	n	n	n	n	n	n
1.1.3 Local supplies within walking distance	10	+1/0	n	n	n	n	n	n
1.1.4 Neighbouring uses are strongly emitting	20	-1/0	n	-1/0	n	n	n	-1/0
1.2: Prevention from additional soil sealing								
1.2.1 Site contains <40% sealed soil	10	n	n	+1/-1	-1/0	-1/0	-1/0	+1/-1
1.3: Support for urban inner development								
1.3.1 Site location within urban area	40	+1/-1	+1/-1	n	+1/-1	n	n	n
2. PRESERVATION OF NATURE AND LANDSCAPE								
2.1: Preservation of sites important for urban ecology								
2.1.1 Site is part of a local habitat	40	-1/0	-1/0	n	-1/0	-1/0	-1/0	-1/0
2.1.2 High value tree or plant populations	20	n	n	n	n	-1/0	-1/0	n
2.2: Conservation of natural reserves								
2.2.1 Direct vicinity to nature reserve	40	-1/0	n	n	n	-1/0	-1/0	n
3. RESOURCE-CONSERVING & EMISSION-REDUCING MOBILITY MANAGEMENT								
3.1: Preventing overburdening of local road system								
3.1.1 Low capacity of access roads	30	n	n	n	-1/0	-1/0	-1/0	-1/0
3.2: Reduction of individual car use								
3.2.1 Good access to public transport	40	+1/-1	+1/-1	+1/0	+1/-1	n	+1/-1	+1/-1
3.3: Protection of residents from transport emissions								
3.3.1 Access to clearway	20	n	n	n	n	+1/-1	+1/-1	n
3.4: Support for non-motorized mobility								
3.4.1 Good accessibility for bikers	10	+1/-1	+1/-1	+1/-1	+1/-1	+1/0	+1/0	+1/0
4. HIGH QUALITY RESIDENTIAL ENVIRONMENT								
4.1: Good local supplies								
4.1.1 Local amenities in walking distance	10	+1/-1	n	n	+1/0	n	n	n
4.1.2 Primary school in walking distance	10	+1/-1	n	n	n	n	n	n
4.2: Preservation and development of local recreational space								
4.2.1 Great impact on recreational areas	20	-1/0	-1/0	n	-1/0	-1/0	-1/0	-1/0
4.3: Preservation and upscaling of historic cityscape								
4.3.1 Historically relevant buildings	10	+1/0	n	-1/0	+1/0	-1/0	-1/0	+1/0
4.3.2 Great influence on cityscape	10	n	n	+1/0	n	-1/0	-1/0	n
4.4: Minimizing land use conflicts								
4.4.1 Neighbouring uses sensitive to immissions	40	n	n	n	n	-1/0	-1/0	n
5. STRENGTHENING OF LOCAL ECONOMY								
5.1: Small burden for local budget by investment/follow-up costs related to local infrastructure								
5.1.1 Good supply and disposal infrastructure	20	+1/-1	+1/-1	n	+1/-1	+1/-1	+1/-1	+1/-1
5.2: Small burden for local budget related to site remediation								
5.2.1 Site strongly contaminated	30	-1/0	-1/0	-1/0	n	n	n	-1/0
5.3: Enhancement of local attractiveness by innovative businesses								
5.3.1 Site suitable for innovative industries	30	n	n	n	+1/0	n	n	n
5.4: Preservation of business location								
5.4.1 adjacent enterprises w/ precarious sense of security	20	-1/0	n	n	n	n	n	n
maximum positive score: $P_{+,max}$ = f(weights)		160	120	80	170	50	90	90
maximum negative score: $P_{-,max}$ = f(weights)		-300	-210	-80	-210	-260	-300	-210

The resulting 22 indicators (Table 1.3) are related to forms of settlement and land use and describe qualitative and quantitative features of a site and its vicinity. The existence or absence of these features is used to express whether and how a specific land use option will either foster or contradict the goals of sustainable urban development. For each spatial planning unit and attributed land use type, it is evaluated whether the descriptive statements of the individual indicators *k* are applicable or not. This evaluation is done based on spatial data created according to regional maps, aerial photographs data from (historical) site investigations and stakeholder knowledge. The resulting Boolean (TRUE/FALSE) answers translate into integer values (Table 1.3) which are multiplied with the individual weight for each indicator k to obtain a positive or negative actual score p_k^+ and p_k^-. The degree of suitability *E* is then calculated according to

$$E = \left(\frac{\sum_{k=1}^{22} p_k^+}{P_{\max}^+} \times 100 \right) - \left(\frac{\sum_{k=1}^{22} p_k^-}{P_{\max}^-} \times 100 \right) \qquad \textbf{Eqn. 1.6}$$

where $P_{\max}^+$ $(P_{\max}^-)$ represent the positive (negative) boundary for each land use type which is obtained by calculating the sum over each indicator's maximum (minimum) possible score (Table 1.3).

Case-study-specific default weights were applied for each indicator. These weights represent the state of scientific discussion about the relative importance of each respective goal and indicator for sustainable urban development in this specific context of the case study site. This setup may be changed by the evaluating experts to improve the representation of specific local conditions.

To evaluate specific redevelopment alternatives that consist of a number of n_P different planning units, equation (1.6) is evaluated separately for each planning unit *i*. The results for each planning unit are then weighted by the fraction of the area of the planning unit $A_{P,i}$ and the total site area A_S, and summed up into one resulting value E_{tot} for the entire site as shown in equation (1.7).

$$E_{tot} = \sum_{i=1}^{n_P} E_i \frac{A_{P,i}}{A_S} \qquad \textbf{Eqn. 1.7}$$

This evaluation allows for a convenient and direct comparison of different site redevelopment options with respect to their contribution to sustainable development. Further details on the methodology are given in Müller and Rohr-Zänker (2009).

1.3 CASE STUDY

1.3.1 Description of model site

The model site is a former military site situated on the outskirts of the city of Potsdam near Berlin, Germany (see Figure 1.1). The site with an area of approximately 113 ha was used by German and Russian armed forces until 1945 and 1991, respectively. The operation of gas stations and a dry cleaning facility has led to vast contamination dominated by chlorinated solvents, which affect an aquifer with a thickness of ~5 m. The depth of the water table is ~2 m to ~6 m below ground surface. Contaminated groundwater flows from the site towards two lakes, nature reserves, local recreation areas and other potential receptors. The surrounding areas contain businesses and industry as well as residential areas.

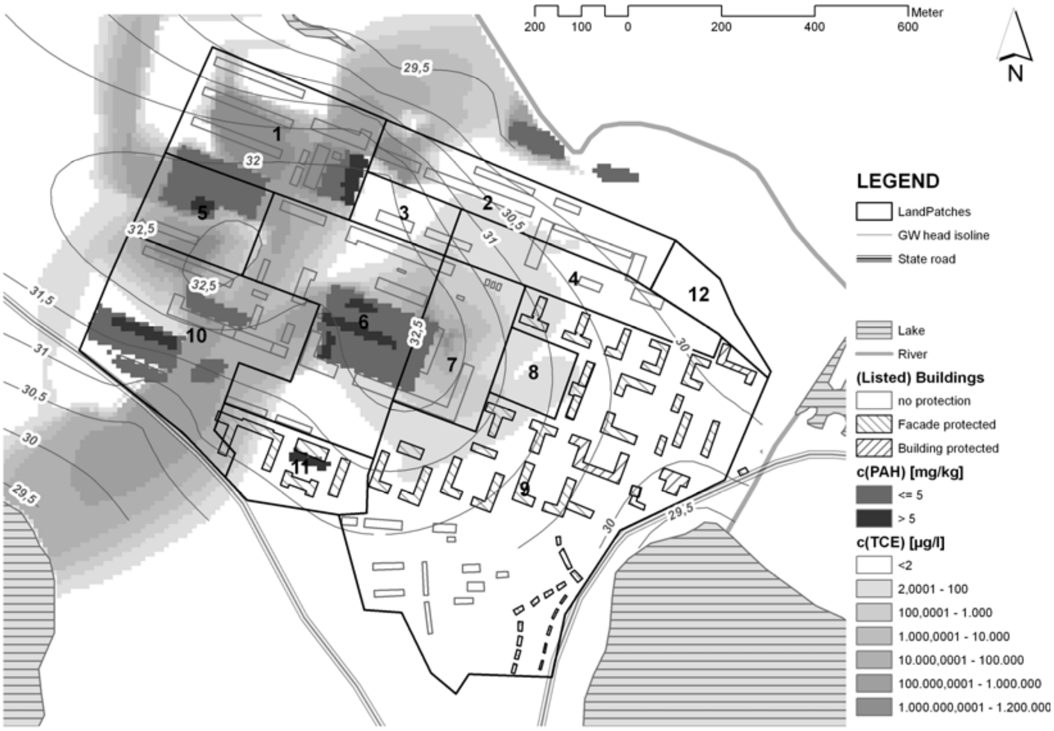

Figure 1.1: Case study site data: Information about groundwater regime and subsurface contamination, existing buildings, state roads, and water bodies, as a basis for subdivision into 12 planning units ("land patches").

The site contains both listed historical buildings and economically worthless buildings constructed after 1945. Since 1992, the site has been investigated several times by various groups of consultants and researchers. More detailed site and data descriptions are given in Morio et al. (2008) and Rein et al. (2011).

The input data used for this case study is based on information from a detailed expert report about a site inspection in 1996 and on data from two groundwater investigation campaigns, conducted in 2000 and 2001 (with 24 sampled wells), and in 2007 (direct push investigation with 123 measurement points). According to this data, the contamination at the site is dominated by three priority contaminants/contaminant groups, i.e., TCE and PCE in the groundwater and PAHs in the soil. Please note that information about soil contamination is uncertain and limited to the delineation of potentially contaminated areas.

In order to conceive a set of basic redevelopment options, the site was subdivided into 12 planning units (i.e. land patches, compare Figure 1.1). In this study the definition of planning unit boundaries is based on spatial features of the site such as distribution of contamination, existing buildings (some of which are partially or entirely listed as protected monuments), proximity to state roads, environmentally protected areas in close vicinity to the site, infrastructure and neighbouring recreational areas.

1.3.2 Characterization of land use types and definition of redevelopment options

For the definition of redevelopment options, the following exemplary land use types were considered: “housing area” (HA), “trade/industries” (TI), “recreational” (RE), “no use” (NU), and “high tech industry” (HT) as a special type of “trade and industry”. Sensitivities with respect to tolerable exposure to contaminants are reflected by specific remediation standards assigned to each land use type. Corresponding concentration threshold values are shown in Table 1.4. Absence of target values for the “no use” type indicates that no conflicts will be considered in relevant areas as no risk is anticipated due to restricted access.

For evaluating sustainability, the land use types considered here were further characterized as follows: (1) neither land use types “Trade/Industry” nor “High Tech Industry” are strongly emitting, (2) the close surrounding area is not populated (corresponds to today’s situation but may not remain true in future), and (3) “Housing area” includes local supplies, but not the building of an additional school (compare sustainability indicator 4.1.2).

Table 1.4: Considered land use types and their properties

		TI, HT	HA	RE	NU
Compliance criteria:	TCE [µg/l]	100	10	60	n.a.
	PCE [µg/l]	100	10	60	n.a.
	PAH [mg/kg]	10	2	4	n.a.
Reference Land Value RLV [€/m^2]		40	95	10	0
Site preparation [% RLV]		75	80	50	0

Based on these land use types a total of 10 different redevelopment options were defined as shown in Figure 1.2. Option A is based on stakeholder discussions; options A' to H are additionally drafted for comparison in order to exemplify possible benefits and drawbacks of alternative redevelopment plans. Each option comprises one or more land use type in different fractions, which are assigned to the 12 planning units.

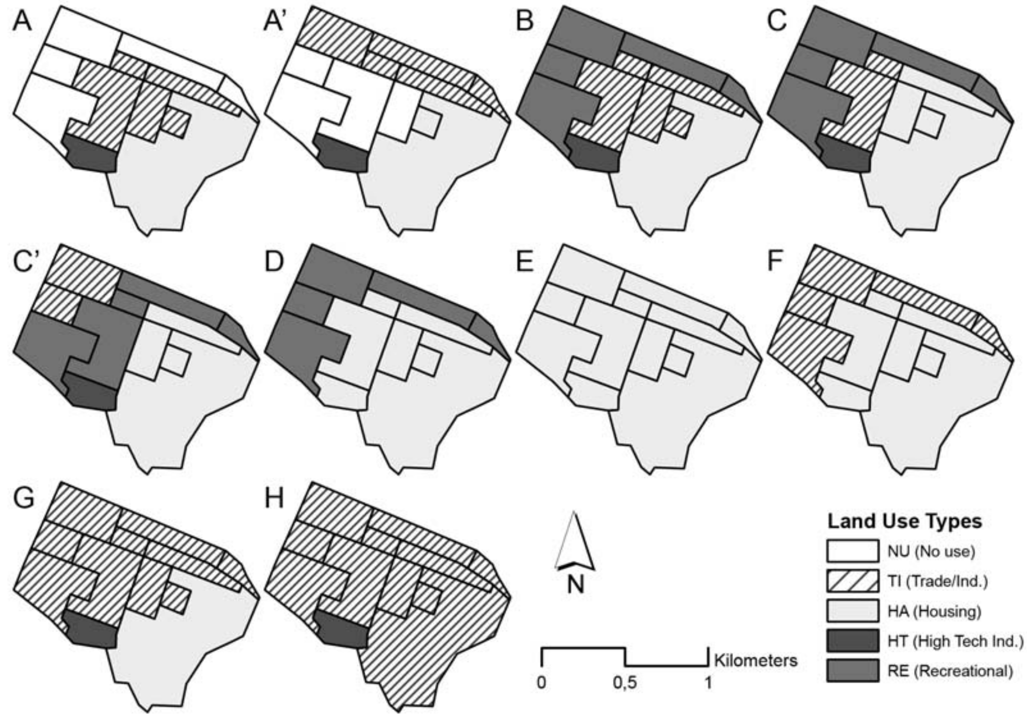

Figure 1.2: Definition of land use options A through H by allocating distinct land use types on the 12 planning units.

As a simplification, costs for the deconstruction of buildings are assumed to be constant through all land use options, i.e., all buildings except for the listed ones are deconstructed. Further specification requires additional methods for appraisal of buildings as well as spatially explicit deconstruction cost estimation, both of which require detailed data beyond the screening level sought here.

The planning horizon for discounting was set to 50 years, with a relevant PRB reactivation period of 10 years and an annual discount rate of 5 %. All further assumptions as well as literature values that were taken as input data for the assessment model are listed in the Supplementary Information.

1.4 RESULTS AND DISCUSSION

1.4.1 Evaluation of redevelopment options

We first evaluated redevelopment option A, which is the result of stakeholder discussions. The intention of option A was to avoid costly remediation on the site by restricting access to the most severely contaminated areas in the western part of the site: “no use” (NU) is assigned to the respective land patches and the contamination is left in place. Therefore, in these areas, costs will be incurred for measures to sufficiently reduce the risk to neighbours affected by the chlorinated solvent plumes emitted from the site. In the Eastern part of the site, valuable residential areas are allocated on mainly uncontaminated land with a high number of listed buildings and good access to two state roads (patch 9). A trade and industry area conveniently separates the residential area from the highly contaminated western parts of the site and ensures a good sustainability rating as will be discussed below. Conflicts between land use and existing contamination in groundwater are completely avoided in this option, and only a small volume of soil in patch 6 shows contamination above the limit concentration for use type “TI”. Only the costs for the deconstruction of derelict buildings lead to a significant decrease of the theoretical land value, and after a mercantile value reduction of about 0.6 million €, the remaining market value is positive. The combination of complementary land use, good accessibility, and the non-relevance of those parts of the site that remain unused, leads to an overall slightly positive sustainability rating (compare Table 1.5).

Option A’ results from searching for a redevelopment option with fractions of land use types that are similar to the ones in option A. A re-allocation of land use was sought that minimizes conflicts between existing contamination and land use-specific subsurface quality requirements. The consequences are decreased costs for both soil remediation and plume containment. Hence, the market value increases to 2.9 million €. However, at the same time the sustainability rating of option A’ is significantly lower than in option A (A’ ranking 9th out of ten as compared to A ranking 2nd). This is due to the anticipated increase in motorized transport resulting from the fact that in option A’ trade and industry have been reallocated onto land use patches that are not easily accessible by public or non-motorized transport (sustainability indicators 3.2.1 and 3.4.1).

Table 1.5: Results of the integrated analysis of redevelopment options.

Land Use Option Land Use Type [ha]	**A**	**A'**	**B**	**C**	**C'**	**D**	**E**	**F**	**G**	**H**
Housing Area (HA)	40	42	40	54	54	76	114	76	40	0
Trade/Industry (TI)	31	28	31	17	15	0	0	38	69	109
High Tech Industry (HT)	5	5	5	5	5	0	0	0	5	5
Recreational (RE)	0	0	38	38	40	38	0	0	0	0
„no use“ (NU)	38	39	0	0	0	0	0	0	0	0
Economic Evaluation [Mio €]										
$V_{L,theor}$	8.7	8.7	8.9	9.8	9.8	11.5	16.7	14.1	11.4	8.8
BDC	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
GW[1] remediation costs	0.0	0.0	0.8	0.8	0.8	0.9	0.9	0.9	0.7	0.7
Soil remediation costs	0.9	0.6	7.2	7.8	8.2	10.6	10.6	5.2	1.8	1.8
Costs for reducing risks to neighbours	0.5	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Preliminary land value	3.1	3.6	-3.2	-2.9	-3.3	-4.2	1.0	3.9	4.7	2.1
MVR	0.6	0.6	0	0	0	0	0.2	0.7	0.9	0.4
Market value[2]	**2.6**	**2.9**	**(-3.2)**	**(-2.9)**	**(-3.3)**	**(-4.2)**	**0.8**	**3.2**	**3.9**	**1.7**
Sustainability Evaluation [%]										
Housing Area	17	17	17	4	4	4	-13	7	11	-
Trade/Industry	8	-35	8	8	8	-	-	2	8	-4
High Tech Industry	30	30	30	30	30	-	-	30	30	30
Recreational	-	-	0	0	0	0	-	-	-	-
Sustainability Rating E_{tot}	**9.4**	**-7.1**	**9.4**	**5.3**	**5.3**	**2.7**	**-13**	**6.6**	**10.1**	**-2.3**
Sustainability Ranking	2	9	2	5	5	7	10	4	1	8

[1] GW: groundwater.

[2] negative market values are shown in brackets - in practice they would be set to zero.

The use pattern in option B is similar to option A with the only difference being the "no use" planning units from option A replaced by recreational areas. The underlying idea is to better support the principle of reusing land and to minimize land consumption, and to consider "no use" areas only where extreme remediation costs make an economically feasible land use impossible. One consequence is that in this option the compliance criteria ensure a total remaining TCE flux below the limit flux, so that no additional cost for the reduction of risks to neighbours is added. However, to enable the sensitive land use in the strongly contaminated north-western part of the site, cleanup of the vast soil contamination is now required which makes the costs for remediation exceed the preliminary land value in option B: the resulting market value would be negative and in practice it is set to zero: The sustainability rating in option B equals that of option A: the only change in land use, i.e., the change from no use to recreational use, does not affect the rating, as the recreational use is rated neutrally.

Options C, C', D and E represent the goal to raise market value by a stepwise increase of the spatial fraction of residential use (being the most valuable among the defined land use types here, see Table 1.4). Starting with the placement of additional housing in low contaminated areas, its fraction was increased from 48% (options C and C') to 67% (option D) and eventually to 100% (option E). Despite a considerable increase in the theoretical land value $V_{L,theor}$ (9.8 million € for options C and C', 11.5 million € for option E, and 16.7 million € for option F), resulting market values are much lower compared to the value of options A and A'. This is due to a disproportionately high increase in remediation costs that diminish the market value strongly (as was shown before for option B).

Remediation costs of options D and E differ only marginally (estimates for both options are approx. 10.6 million €). The replacement of recreation by housing areas and associated changes in compliance criteria (Table 1.4) only very slightly alter the conflicts that need to be resolved by remediation. This is due to the fact that levels of existing contamination are well above the remedial targets throughout the site. Therefore, option E, having the highest of all possible land values $V_{L,theor}$, results in a distinctly higher market value than option D. A clear drawback, however, is a strongly negative sustainability rating (ranked 10th and thus worst of all options considered), which can be attributed to the location of the site on the outskirts of the city Potsdam: a homogeneous i.e. pure residential use is not rated sustainable because distances to existing public facilities in the city of Potsdam and its surroundings are too large (compare indicators 1.1.3, 1.3.1, 3.2.1, 3.4.1, and 5.1.1). Contrary to this, redevelopment options involving a mixture of residential areas, recreational areas and trade and industry that inherently form a sustainable unit (i.e. a well functioning quarter) are rated more sustainable. The poor rating for option E thus reflects the fact that this option lacks the positive aspects of mixing complementary land use types.

Design of the mixed use options F and G reflects the findings of the previously discussed options: The mixing of trade/industry and residential areas in different ratios yield very good results with respect to market value as well as sustainability rating. Bad effects identified before are most widely avoided, as well as required soil remediation, which is reduced to a minimum by smart land use allocations on the patches.

Considering the slight improvement in assessment results that was achieved by increasing the fraction of trade/industry from option F to option G, consequently a pure trade and industry option H was investigated. However, because remediation costs cannot be further reduced when compared to option G, and as the sustainability rating is distinctly worse due to the uniform use, this is not a favourable option.

1.4.2 Discussion

The integrated assessment of revitalization options enables stakeholders to identify and explain strengths and weaknesses in particular options and to systematically improve land use planning on brownfields by comparing alternative options. The quick comparison at screening level enables assessment of consequences to adjustments of land use allocation plans or land use characteristics such as clean-up goals or reference land values. In this way, the model helps to identify potentially valuable revitalization options on the basis of one common data set, and supports discussions on possible adjustments in order to achieve optimal redevelopment solutions.

In the evaluation presented herein, site redevelopment options F and G can be seen as the result of a learning process that was encouraged by the integrated assessment model, where positive aspects learned during the evaluation of previous options, like a mix of complementary uses (e.g. Evans and Foord, 2007), were applied in an iterative improvement.

The sustainability assessment results of this case study show two major aspects of sustainable brownfield revitalization: While they underline the statement by Eisen (1999) that it is wrong to suspect all brownfield redevelopment to be inherently sustainable, more importantly it is shown that sustainable land use options are not necessarily economically unfavourable. Figure 1.3 compares the sustainability rating of the redevelopment options with their market value after remediation with no correlation seen between results of the economic and sustainability assessment for the options considered here. Hence, the preconception that sustainability is intrinsically costly, which would result in a negative correlation between the two results, cannot be supported by this data. For the subset of economically qualified options having a positive market value (A, E, G, H), even a positive correlation between market value and sustainability can be observed. The best options among the given set of 10 candidates are most valuable in terms of both money and sustainability. The results of the evaluation would thus promote that these options, A, F, and G are worthy of further refinement and a more detailed investigation.

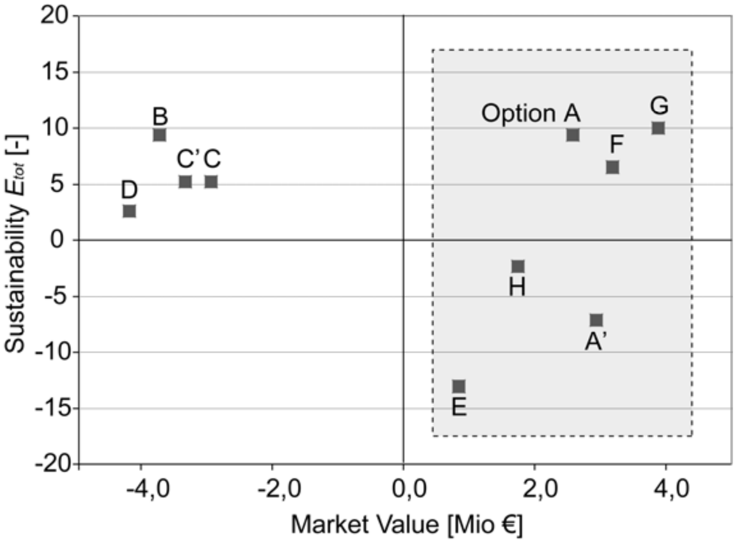

Figure 1.3: Model site's sustainability factor E_{tot} versus market value of analysed land use options.

1.5 CONCLUSIONS

The intention in developing an integrated assessment model for brownfield revitalization options was to obtain a screening level sDSS which reveals the economic and social consequences of alternative redevelopment plans on large contaminated sites. The aim was to foster communication among stakeholders particularly in early phases of a redevelopment project. Due to the integration of remediation cost estimation, mercantile value reduction, and evaluation of sustainability with respect to regional development, the model proves helpful especially for contaminated sites in urban areas.

The integrated assessment model consequently employs only simplified methods that require relatively little input data. Obviously, refining these methods and implementing the assessment of further aspects of the revitalization process could extend the applicability of the sDSS to later project stages when accumulated data and information allow for the use of more sophisticated methods. Further model development may include, among other issues, a sustainability evaluation with a site-specific (local) definition of sustainability by stakeholder involvement (e.g., Curtis et al., 2005; Hartmuth et al., 2008) addressing additional issues such as sustainable remediation and green building (e.g., Wedding and Crawford-Brown, 2008), and differentiation between technological remediation scenarios.

SUPPLEMENTARY DATA: Case study model input data and their sources

Parameter	Unit	Value	Comment	Source
GW remediation cost model 1				
f_d	-	{1.0, 1.2, 1.5}	GW depth dependent	Bonnenberg et al. (1992)(4)
f_k	-	2.5	for cont. Group CHC(1)	Bonnenberg et al. (1992)(4)
f_l	-	{1.0, 1.5, 3.0}	concentration-dependent	Bonnenberg et al. (1992)(4)
$K_{u,GW}$	€/m^3	2	validation parameter	Bonnenberg et al. (1992)(4)
GW remediation cost model 2				
Discount interest rate	%	5	-	Lemser and Tillmann, 1997(8)
PRB Operation time	years	50	-	Lemser and Tillmann, 1997(8)
PRB Reactivation interval	years	10	-	Lemser and Tillmann, 1997(8)
$S_{het,1}$	-	1.3	typical range: 1…2	Benner et al., 2001(3), Elder et al., 2002(6)
$S_{het,2}$	-	5	typical range: 2…10	Benner et al., 2001(3), Elder et al., 2002(6)
λ	s^{-1}	0.07	-	Gavaskar et al. 1999(7)
K_S	€	60.000	-	Buerger et al., 2003(5)
K_E	€/m^3	14	-	Buerger et al., 2003(5)
K_{RM}	€/m^3	350	-	Buerger et al., 2003(5)
T_{min}	m	0.3	-	These authors
CHC limit flux	g/d	20	-	BBodSchV, 1998(2)
Soil remediation cost model				
a_c, a_D, a_A, a_{Kf}	-	{0, …, 4}	integer suitability values	UBA, 1995(9)
K_U	€/t €/m^2	{45, …, 150} {130, …, 300}	technique-specific	UBA, 1995(9)
th_A	%	80		These authors
Cost model for deconstruction of buildings				
f_U	-	{0.9, 1.0,1.2}	dep. on buildings' use	UBA, 1995(9)
f_W	-	1.0 1.2	wall thickness ≤ 0.24m wall thickness > 0.24m	UBA, 1995(9)
f_S	-	1.0 1.1	slab thickness ≤ 0.24m slab thickness > 0.24m	UBA, 1995(9)
f_H	-	1.0 1.1	height ≤ 15m height > 15m	UBA, 1995(9)
C_U	€/m^3	{8, 9, 10, 12 14}	per gross cubic space, dep. on construction type	UBA, 1995(9)

(1) CHC: chlorinated hydrocarbons

(2) BBodSchV, 1998. German Federal Soil Protection Ordinance.

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CHAPTER 2

Integrated planning and spatial evaluation of megasite remediation and reuse options[3]

Abstract

Redevelopment of large contaminated brownfields (megasites) is often hampered by a lack of communication and harmonization among diverse stakeholders with potentially conflicting interests. Decision support is required to provide integrative yet transparent evaluation of often complex spatial information to stakeholders with different areas of expertise. It is considered crucial for successful redevelopment to identify a shared vision of how the respective contaminated site could be remediated and redeveloped. We describe a framework of assessment methods and models that analyzes and visualizes site- and land use-specific spatial information at the screening level with the aim to support the derivation of recommendable land use layouts and to initiate further and more detailed planning. The framework integrates a GIS-based identification of areas to be remediated, an estimation of associated clean-up costs, a spatially explicit market value appraisal, and an assessment of the planned future land use's contribution to sustainable urban and regional development. Case study results show that derived options are potentially favorable in both a sustainability and an economic sense and that iterative re-planning is facilitated by the evaluation and visualization of economic, ecological and socio-economic aspects. The framework supports an efficient early judgment about whether and how abandoned land may be assigned a sustainable and marketable land use.

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[3] Reproduced from: Schädler, S., Morio, M., Bartke, S., Finkel, M., 2011. Integrated planning and spatial evaluation of megasite remediation and reuse options. Journal of Contaminant Hydrology, in press. doi:10.1016/j.jconhyd.2011.03.003. Copyright 2010 Elsevier.

2.1 INTRODUCTION

Brownfields, as defined by USEPA (2002) and CABERNET (2005), represent both a world-wide health and economic threat (e.g., Apostolidis and Hutton, 2006; Cao and Guan, 2007; DeSousa, 2001; Haylamicheal and Dalvie, 2009; Kaufman et al., 2005; Toms et al., 2008) and a valuable resource of land, of which the (re-)use is seen as an important accompanying strategy to achieve a reduction of land consumption (e.g., BMBF, 2004; Commission of the European Communities, 2006; DETR, 2000).

Due to their often complex subsurface contamination, the aggregate cost for restoring all large brownfields in the US may exceed $650 billion (NRTEE, 2003; USEPA, 2003) and may be as high as €100 billion in the EU (EEA, 2000). Revitalization of especially large, complex and prominent brownfields, so called megasites, is additionally hampered by a huge number of influencing factors. One of these factors typically is the large number of stakeholders with different areas of expertise and potentially differing interests (Agostini et al., 2007; Bardos, 2004). These individual interests and societal needs will determine the future use of megasites, which in turn will determine the requirements regarding the soil and groundwater remediation choices to be made. Today it is widely accepted that successful brownfield redevelopment can only be achieved in an adaptive manner (Linkov et al., 2006) that optimizes the trade-off between economically prized remediation scenarios and maximized economic benefit within a socio-economic framework ensuring sustainable urban and regional development (e.g., DeSousa, 2006).

A shared and clear vision of how a site could be remediated and redeveloped is considered to be a critical entry point for this adaptive approach as well as for the required stakeholder discussions (e.g., Adair et al., 2000; Prato, 2007). The identification of such a vision is often stated as the most important starting point of regeneration projects (e.g., Bardos, 2004), because the planning iterations that emerge from it enable stakeholders to challenge current assumptions, broaden their perspectives and merge their concepts (Duinker and Greig, 2007), thereby guiding them towards beneficial compromises between their potentially differing interests.

Although the comparative analysis of environmental management options is increasingly aided by spatial and environmental decision support systems (sDSS and eDSS) (Ascough et al., 2008; Malczewski, 2006), recent research articles and reviews describe and explain a lack of integrative DSS that conveniently manage complex spatial information, provide transparent results, and integrate socio-economic sustainability assessments to promote the above-mentioned compromises (e.g., Agostini et al., 2007; Agostini and Vega, 2007; Bardos et al., 2001; Gregory and Slovic, 1997; Hassan, 2004; Jakeman et al., 2008; Tam and

Byer, 2002). Additionally, existing methods have in common that they require a redevelopment scenario (i.e. a definite description of planned future use) as an input for evaluation and can therefore aid the decision making process only after an initial vision has been provided. That holds true for integrative evaluation methods (e.g., Carlon et al., 2007; Schädler et al., 2011; Wedding and Crawford-Brown, 2007), but also for methods that evaluate only a specific aspect such as human health risk (e.g., IEM, 2005; McKnight et al., 2010; Whelan et al., 1999) or remediation cost (e.g., Bayer et al., 2005).

On this basis, we propose a method that summarizes and visualizes site- and land-use-specific data and clarifies the role that single aspects of both the prevailing conditions at the site and its possible future use will play with respect to (i) soil and groundwater (GW) remediation costs, (ii) market value, and (iii) the contribution to sustainable urban and regional development. As a final step, the method integrates this information in the design of a vision about how to use an abandoned site in the future. This vision is an initial land use option that may serve as input for the above-mentioned models and as a starting point for stakeholder discussions and for iterative re-planning and optimization. Thereby it may enhance the process of regeneration projects and foster the benefits that are associated with it, e.g. positive impacts on the regional economy and sustainable development, and the reduction of both land consumption and health risks to humans and the environment.

2.2 METHODS

The scope of this paper is to provide an initial land use layout based on site- and land-use-specific data. This is achieved by integrating different models for the spatial evaluation of economic, ecological and socio-economic aspects. Each of these aspects can in principle be evaluated by a number of different models described in the literature. As the selection of suitable models will strongly depend on the specific situation at the site and on the amount and quality of available data, the models described here can be considered exemplary. In contrast, the below described methodological strategy of combining these models for integrating the three fundamental dimensions of ecological, social and economic sustainability is considered compulsory. The existing planning scope for the redevelopment of large brownfields typically offers the possibility of a mixed future use of the site, i.e. the allocation of more than just a single land use type to the site's area. Physical planning of such a mixed land use layout has to consider not only the relationships between spatial site characteristics and certain land use types (e.g., the remediation that is required to reduce human health risks to a land-use-specific limit), but also the interdependencies between the different land use types themselves (e.g., greenways between residential and industrial areas). Given the scope of this work, the methods described in this section are applied prior to having the knowledge of a specific land use option. Consequently, interdependencies between different land use types are not considered in the creation of initial land use layouts. However, these interdependencies are finally accounted for in the concluding evaluation of the created layouts.

2.2.1 Conflict analysis

Realization of a future land use option on a contaminated site may require soil or GW cleanup activities. The particular remedial expenditure will depend both on (i) the actual extent, type and spatial distribution of subsurface contamination and on (ii) the planned future use. The use type will determine the pathways and frequency of exposure of human and ecological receptors to the risks posed by the contamination.

The conflict analysis is based on a geographical information system (GIS) and is used in order to identify cleanup requirements and provide input data for the estimation of remediation costs. The required inputs for this analysis are the following:

1. Spatial data on subsurface contamination: Typically this input has to be generated by interpretation and interpolation of scarce point data (e.g., Kitanidis and Shen, 1996). A method tailored to the needs of this conflict analysis is the flow-guided interpolation (FGI) (Morio et al., 2010).
2. Concentration threshold values: Values that are specific to the type of land use and to the contaminant can be used as provided by the responsible environmental authorities (e.g., LUA B, 2006). Otherwise, compliance criteria can be determined by conducting a site-specific risk assessment (e.g. ASTM, 2002; Strenge and Smith, 2006; USEPA, 1990, 1991, 2001).
3. Data on the planned future use, i.e. the spatial allocation of the different land use types considered. In a first step, uniform use scenarios are evaluated for each of the different land use types considered.

Given a number of m different land use types of interest and n_{soil} (n_{GW}) contaminants considered in soil and groundwater, two matrices[4] $\mathbf{T}_{soil}$ and $\mathbf{T}_{GW}$ are defined which contain the maximum acceptable concentrations for each

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[4] Bold upper case letters are used here to denote a matrix, whereas italic lower case letters with subscripts denote the respective matrix elements, e.g., matrix $\mathbf{B}$ may consist of elements b_{ij}.

contaminant and each land use type. Spatial distributions of each contaminant are expressed as raster data (*x* rows and *y* columns) and merged in the contaminant matrices $\mathbf{C}_{soil}$ and $\mathbf{C}_{GW}$.

A land use option **U** is defined by the allocation of land use types on a number of *p* planning units (PUs). Then, $\mathbf{U}_{ras}$ is the expression of this land use option on a raster with *x* rows and *y* columns, where every raster cell (*i,j*) whose centre is situated within planning unit *h* is attributed the same land use as *h*. Then, the contaminant matrix for every soil or GW contaminant *z* is compared to the compliance criteria of the land use option in order to produce the three-dimensional exceedance matrices $\mathbf{D}_{soil}$ and $\mathbf{D}_{GW}$ with their matrix elements d_{ijz}:

$$\mathbf{D}_{soil} : d_{ijz}^{soil} = c_{ijz}^{soil} / t_z(u_{ij}^{ras}) \qquad \textbf{Eqn. 2.1}$$

$$\mathbf{D}_{GW} : d_{ijz}^{GW} = c_{ijz}^{GW} / t_z(u_{ij}^{ras}) \qquad \textbf{Eqn. 2.2}$$

Thus, for every planning option, $n = n_{soil} + n_{GW}$ maps of contaminant-specific exceedance factors support the identification of areas of conflict ($d_{ijz} > 1$) for a given land use option. Considering m different uniform land use options, a number of $m \cdot n$ maps are generated in order to provide planning guidance.

In this way, areas are visualized on which the particular land use types can be allocated without creating a need for remediation. Furthermore, $\mathbf{D}_{soil}$ and $\mathbf{D}_{GW}$ serve as an input for the spatially differentiated estimation of remediation costs **R** for soil and GW. Costs are estimated for each raster cell (*i,j*) in which the exceedance d_{ijz} equals values >1 for any of the contaminants *z* considered.

2.2.2 Estimation of Costs for Subsurface Remediation and Deconstruction of Derelict Buildings

Three different models are proposed for estimating the cost of soil and groundwater remediation as well as the cost for deconstruction of derelict buildings. The low complexity of the models makes them fit the screening level data of the case study site. Where detailed data are missing, the models make use of empirical relations. Groundwater remediation costs $\mathbf{R}_{GW}$ are estimated based on contaminated volumes and empirical cost driving factors as described by Schädler et al. (2011a). For this work, soil remediation costs $\mathbf{R}_{soil}$ are estimated assuming that contaminated soil is excavated, transported off-site to a treatment plant, thermally treated, transported back, reinstalled and ameliorated before reuse. Cost estimates are based on regionally specific unit price values (Table 2.1), on the volume v_C of contaminated soil and on the surface area a_C which needs to be processed. v_C is determined from the land-use-specific relevant contamination depth and a_C. Describing the sum of the tabulated volume-based unit prices as b_V, and the area-based unit price as b_A, $\mathbf{R}_{soil}$ is derived as follows:

$$\mathbf{R}_{soil}\text{: } r_{ij}^{soil} = \begin{cases} v_C \cdot b_V + a_C \cdot b_A : d_{ijz} > 1 \\ \quad 0 \qquad : d_{ijz} \leq 1 \end{cases} \qquad \textbf{Eqn. 2.3}$$

The spatially explicit estimate of the total remediation cost R is then evaluated by summing up r_{ij}^{GW} and r_{ij}^{soil} for every raster cell (*i,j*) and serves as an intermediate result for the overall monetary evaluation as described below.

Table 2.1: Unit price values for work steps of contaminated soil remediation. Source: LUA NRW (2005).

	Relevant range for case study	Unit price	Unit
Excavation	- volume 1,001 – 10,000 m^3 - top soil, depth <1 m - no additional charges for special contaminants	10.0	[€/m^3]
Transport of cont. soil	- mass < 10,000 t - distance < 40 km	13.5	[€/t]
Off-site thermal treatment	- c(PAH) < 500 mg/kg - $c_W \leq 25$ % - < 60% w/w[1] fine grained material (< 0.063 mm)	49.5	[€/t]
Transport of decont. soil	- mass < 10,000 t - distance < 15 km	3.4	[€/t]
Re-installation	- volume < 10,000 m^3 - depth < 1 m	2.8	[€/m^3]
Soil amelioration	-	15.0	[€/m^2]

[1] [% w/w]: mass percentage.

For this study deconstruction of all buildings on the site is assumed with the exception of declared listed monuments. The costs for building deconstruction are calculated based on the buildings' gross cubic space as previously described in UBA (1995).

2.2.3 Market value assessment: location quality and risk rebate

The market value of a contaminated site is usually assessed in a residual value approach where expected remediation and site preparation costs are deducted from the market value of a comparable uncontaminated site (Sheard, 1992). In general, the economic value of a property is affected by a number of site features, three important ones being (i) the types of land use (e.g., Sayce et al., 2006), (ii) the location quality for the different land use types (e.g., Gelfand et al., 2004) and (iii) the perceived economic risks (e.g., Bartke and Schwarze, 2009a; Jackson, 2002).

The impact of the type of land use is assessed by referring to market data of comparable uncontaminated sites in the region of the brownfield to be appraised. The data can be obtained through a sales comparison analysis or as a so-called reference land value (here: **g**) in several jurisdictions. In Germany, the reference land value represents regional average values of properties based on recent purchase prices and is available from regional committees of valuation experts for different types of land use. Where the state of development of a site is not yet ready for use, so-called site preparation costs **s** have to be accounted for. They reflect the development costs, losses due to holding periods, planning, construction of infrastructure etc., and lead to a reduction of **g**. Typically these costs are obtained from a site-specific appraisal report. In the preliminary assessment described here, **s** is derived as introduced by Bartke and Schwarze (2009b). This simplified method estimates land values for a cleared site and consequently neglects edificial values.

The values of two identical but differently situated sites may strongly vary from one another depending on their locations. Consequently, location is often understood to be a key factor for real estate traders and investors (Sayce et al. 2006). For the assessment of the market value of a contaminated site, **g** is therefore corrected for location quality. Generally, location quality depends on socio-economic market conditions, neighborhood characteristics and infrastructural connectivity, e.g. the proximity to municipal services or to means of transportation (e.g. Gelfand et al., 2004), all of which may be influenced by interdependencies between different land use types.

The method for a preliminary estimation of location quality applied here is based on Bartke and Schwarze (2009a). Location quality is assessed per planning unit because it can vary over short distances (Clapp, 2003). The assessment results in a location quality matrix $\mathbf{Q}$ with one entry q_{hk} for each PU h and each land use type k. $\mathbf{Q}$ is determined by grading a set of weighted indicators. Grading is based on proximities with regard to physical features (e.g. public transport, schools, and complementary land use types), on statistics with regard to socio-economic macro- and micro-conditions (e.g. regional economy and demography) and on stakeholder knowledge regarding further indicators such as the reputation of the district. The result is a discount or surcharge factor that spatially corrects the reference land value g_k for each land use type k in every PU h. This correction yields $\mathbf{L}_A$, the matrix of location-corrected land values per square meter and **L**, the absolute values per PU given its surface area a_h.

$$\mathbf{L}_A : \; l_{hk}^{A} = g_k \cdot s_k \cdot q_{hk} \qquad \textbf{Eqn. 2.4}$$

$$\mathbf{L}: \; l_{hk} = l_{hk}^{A} \cdot a_h \qquad \textbf{Eqn. 2.5}$$

$\mathbf{L}_A$ is visualized by maps to depict the preference of individual PU with regard to the allocation of different land use types.

Brownfields are usually priced considerably below comparative land values because of economic uncertainties associated with their redevelopment (e.g., Adair et al. 2000; Jackson, 2002). Personal perception of these financial risks is strongly divergent among marketers, and so are the rebates applied. To avoid this divergence, in this study we follow the concept of Mercantile Value Reduction (MVR) (Bartke and Schwarze, 2009b). MVR provides transparent quantification of rebates and reflects the appraisal experts' view on uncertainties, which in its practical implications may be the most relevant one. As MVR was shown to be very sensitive to general site characteristics, but less so with respect to different land use options (Schädler et al., 2011a), it is evaluated only once and applied to the final monetary results in this work.

2.2.4 Monetary Assessment: Summary

Two steps are performed in order to summarize the monetary assessment. In the first step, the market value assessment and land use type specific remediation costs are combined into a matrix of maps depicting remaining land values for each individual land use type: $\mathbf{L}_R$. In order to produce this data, **R** as determined for each land use type k is transferred to costs per planning unit h by adding up r_{ij} of those raster cells which are situated within h. This planning unit specific cost value $\sum r_{ij}(h)$ is subtracted from the land value l_{hk}:

$$\mathbf{L}_R: \; l_{hk}^{R} = l_{hk} - \sum r_{ij}(h) \qquad \textbf{Eqn. 2.6}$$

In the second step, an approximation to the economically optimal spatial allocation of land use types is generated by selecting the land use type k in each planning unit h, which provides the maximal remaining land value $\mathbf{L}_{R,max}$:

$$\mathbf{L}_{R,max} : l_h^{R,\max} = \max(l_{hk}^R) \qquad \textbf{Eqn. 2.7}$$

As for **L**, also for $\mathbf{L}_R$ and $\mathbf{L}_{R,max}$ the area-normalized matrices $\mathbf{L}_{R,A}$ and $\mathbf{L}_{R,max,A}$ may be preferred for convenient visualization and further processing, especially where the surface areas of different PUs vary strongly.

The land use layout which corresponds to this maximization of $\mathbf{L}_R$, hereinafter denoted as $\mathbf{U}^{max}$, will not ordinarily represent the best option from a sustainability point of view and/or may not meet the needs of some of the stakeholders involved in the planning process. $\mathbf{U}^{max}$ is therefore considered to be an interim result. Two methods are proposed to aid the likely required re-planning: The first one is based on economic data, the second one on evaluation of sustainability (see next section).

The first planning iteration can be supported by analyzing, for each PU, how the economic optimum would be cut if a land use type other than the optimal one was allocated. In this way the matrix $\Delta\mathbf{L}_R$ is determined which contains maps of the reduction in land value that any variation to $\mathbf{U}^{max}$ would result in:

$$\Delta \mathrm{L}_\mathrm{R} : \Delta l_{hk}^R = l_h^{R,\max} - l_{hk}^R \qquad \textbf{Eqn. 2.8}$$

2.2.5 Sustainability Evaluation and Integrated Assessment

Crucial support for re-planning is provided by an indicator-based sustainability assessment (e.g., Fraser et al., 2006; Reed et al., 2006). The method used in this work is described in detail by Müller and Rohr-Zänker (2009). It evaluates the compatibility of future land use options with sustainable urban and regional development according to ICLEI (1994) and AGENDA 21 (United Nations, 1992), hereafter denoted as suitability for short. The three widely accepted fundamental dimensions of ecological, social and economic sustainability provide the framework for five sustainability goals of local governments' planning policies. The latter are represented by a set of 22 indicators with the aim of providing a clearly laid-out definition of sustainability and of enabling a quick comparative assessment of the general suitability of land use types with respect to spatial features of the site itself and its neighborhood.

Here, the degree of suitability is spatially evaluated on a normalized scale that ranges from 100% to -100% for the strongest possible positive and the strongest possible negative contribution to sustainable development, respectively (Müller and Rohr-Zänker, 2009; Schädler et al., 2011a). The suitability matrix **E** contains suitability values e_{hk} for each planning unit h and land use type k. The total suitability value of the site E_{tot} is determined by summing up the (PU-)area-weighted e_{hk} values over all PUs.

Visualization of **E** supports the identification of preference areas for each of the land use types. Due to interdependencies between different neighboring land use types, the indicator values are very likely to change once the evaluation of **E** is performed for mixed land use layouts. Therefore the evaluation of uniform land uses does not allow for inferences with respect to complementary land uses, and **E** has to be re-evaluated for specific mixed use options once they are envisioned.

As a final step, the described aspects are jointly analyzed in an iterative approach which (i) results in land use options that represent an integrated vision of how the site may be assigned a beneficial use, and (ii) builds a basis for further detailed evaluations considering ecological, economic and socio-economic aspects.

2.3 CASE STUDY

2.3.1 Site Description

A case study was performed for a former military site used by the German and Soviet armed forces until 1945 and 1991, respectively. This site is situated on the outskirts of the city of Potsdam near Berlin, Germany, and covers an area of approximately 1.1 km^2. According to data from a 1996 environmental expert report, groundwater contamination on the site was caused by the operation of gas stations and a dry cleaning facility and is dominated by trichloroethylene (TCE) and tetrachloroethylene (PCE). Two additional groundwater investigation campaigns with 24 sampled wells in the year 2000 and 2001 and a direct push investigation with 123 measurement points in the year 2007 revealed that an aquifer with a thickness of ~5 m and a water table ~2 m to ~6 m below ground surface is affected by at least six plumes with TCE concentrations up to its solubility limit (Rein et al. 2011). Based on these measurements, Morio et al. (2010) delineated groundwater contaminant plumes in a modeling study. Five of these plumes extend beyond the site boundary in the northern, western and southern directions towards a nature reserve, local recreation areas, two lakes and other potential receptors. Information about soil contamination is limited to the delineation of areas potentially contaminated by polycyclic aromatic hydrocarbons (PAHs). Close-by areas contain trade, industrial as well as residential zones.

2.3.2 Monetary Assessment and U^{max}

For the evaluation of spatial data on aquifer geometry and subsurface contamination, the chosen resolution of 10 m × 10 m divides the site into 11,360 raster cells. For land use planning, 27 planning units (PUs) were specified based on site-specific features as depicted in Figure 2.1. The integrated assessment was performed for three land use types, i.e., (1) residential areas, (2) recreational areas, and (3) trade and commercial areas, as defined by the attributes displayed in Table 2.2.

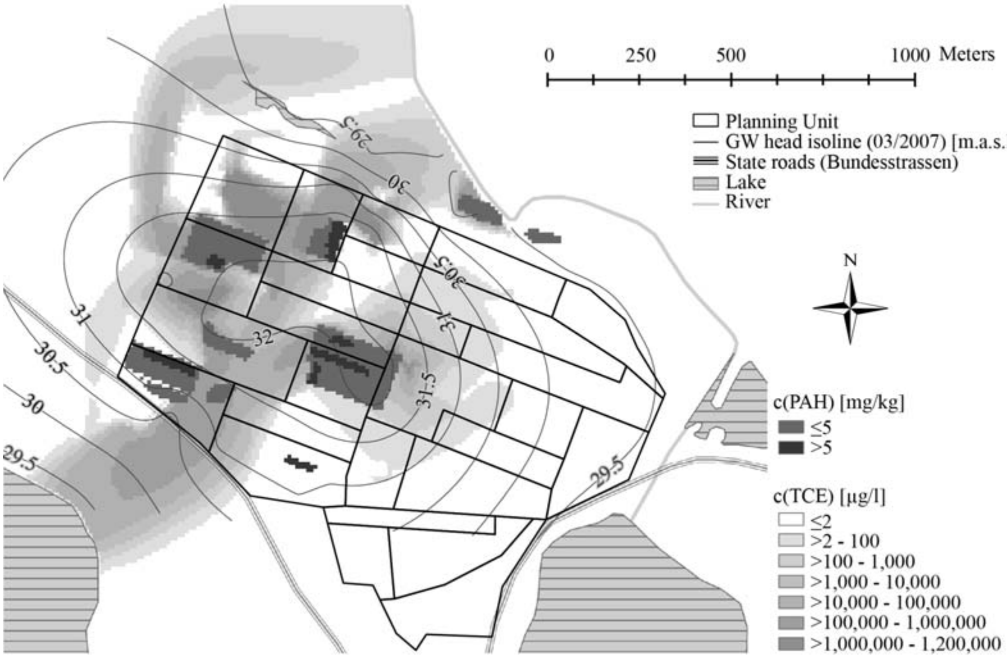

Figure 2.1: Case study site with the division into planning units (PUs) and the suspected contamination in soil (PAH) and groundwater (TCE). [m.a.s.l.]: meters above sea level.

The conflict analysis yields 9 maps of conflicts as depicted in Figure 2.2. Depending on the exceedance factor, conflicts are classified into “weak”, “moderate”, and “strong”, according to the classes, which are distinguished in the subsequently applied remediation cost estimation model to account for the severity of contamination as a major cost-driving empirical factor. Details on this classification are given in Schädler et al. (2011a).

Table 2.2: Characterization of three land use types with respect to economic and ecological assessment.

Land use type:		Residential	Recreational	Commercial
Compliance criteria:	TCE [µg/l] in GW[a]	10	60	100
	PCE [µg/l] in GW[a]	10	60	100
	PAH [mg/kg] in soil	2	4	10
	Rel. depth[b] [cm]	35	10	10
Reference land value g[c] [€/m²]		95	10	40
Estimated site preparation costs[d] [% g]		80	50	75

a GW: groundwater

b relevant depths for probing soil contaminations. Values based on a risk assessment considering oral and dermal contact (BBodSchV, 1999).

c value for cleared land obtained from committee of valuation experts (City of Potsdam, 2009).

d development costs (e.g. soil levelling and infrastructure), Bartke and Schwarze (2009a)

With respect to soil volumes to be remediated, the land use types differ from each other by more than one order of magnitude. While the entire area of suspected PAH contamination (98,000 m^2) would require cleanup in order to allow for either residential or recreational use to be realized, a future use as trade and commercial area would be possible with significantly less effort (16,300 m^2). These contaminated areas along with the use-type specific contamination depths result in estimated volumes of up to 34,000 m^3 of soil material requiring remediation (Table 2.3).

Table 2.3: Estimation of contaminated subsurface volumes that require remediation and resulting remediation costs for three different land use types.

Land Use type	Residential	Recreational	Trade/Commercial
Relevant soil volume [m³]	34,000	10,000	1,630
Relevant soil surface area [m²]	98,000	98,000	16,300
Soil remediation cost [million €]	6.0	2.8	0.5
Relevant GW volume [m³]	2,830,000	2,380,000	2,270,000
GW remediation cost [million €]	5.3	4.5	4.2
Sum [million €]	11.3	7.2	4.7

On the other hand, from Figure 2.2 it becomes clear that large areas exist on the site where no conflicts are to be expected independent of the planned land use. The differences between individual land use types with respect to this non-conflict area are limited mainly to the fringes of the TCE plumes, because TCE concentrations in groundwater within the major parts of the plumes are some orders of magnitude higher than the compliance criteria for all three land use types (Table 2.2). According to the conflict analysis and considering the spatial data on aquifer thickness and effective porosity, the estimated GW volumes that require remediation range from 2.3 million m^3 to 2.8 million m^3.

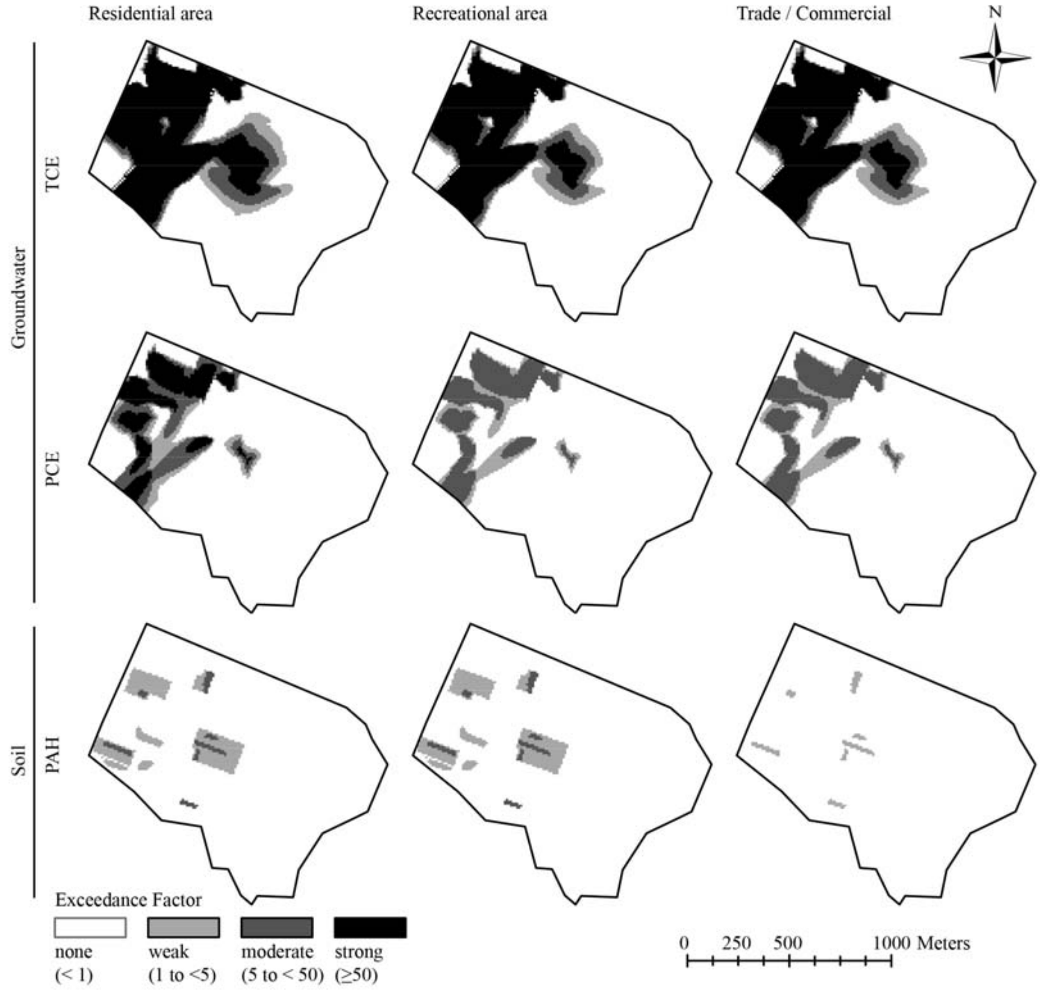

Figure 2.2: Exceedance maps showing the conflicts between the existing contaminant concentration in groundwater (two contaminants: TCE and PCE) and soil (one contaminant group: PAH) and the maximum acceptable concentration levels of three different land use types.

As remediation costs are mostly dependent on the relevant contaminated volumes, the patterns of the conflicting areas also appear in the maps of remediation costs (Figure 2.3). Despite the high chlorinated solvent concentrations and the strong exceedance of compliance criteria in GW, estimated remediation costs are most notably influenced by the soil remediation required for the realization of residential or recreational areas on the site: whereas the estimated cost for groundwater remediation vary from € 4.2 million in the least sensitive case (commercial use) to € 5.3 million for the most sensitive case (residential use), estimated cost for soil remediation range from € 0.5 million for commercial to € 6.0 million for residential use (cf. Table 2.3).

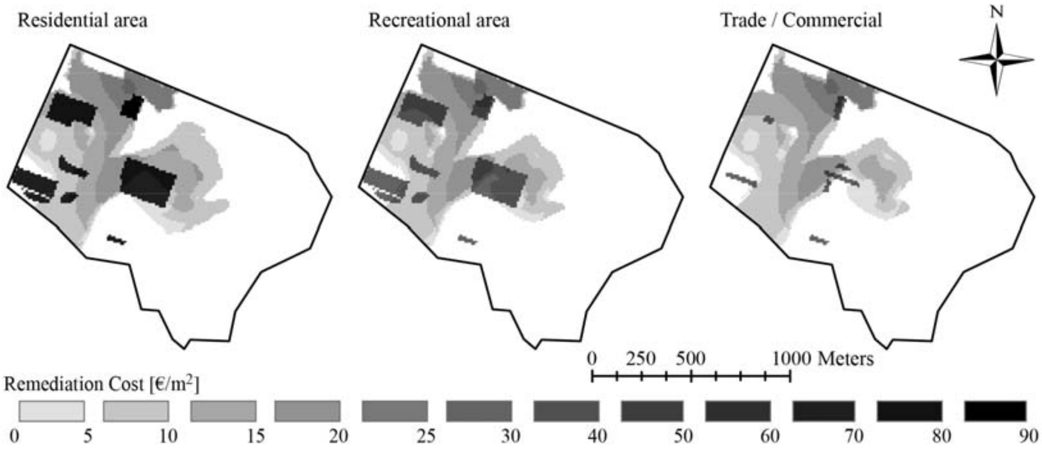

Figure 2.3: Costs for remediation of subsurface contaminations (R), which would be required in order to enable three different uniform land uses on the site.

Additional costs for the prevention of risks posed to neighbors by the PCE and TCE plumes in groundwater were not considered. Previous work (Schädler et al., 2011a) has shown that these risks (i.e., the contaminant fluxes across the site boundaries) are reduced below the regulatory limits given that groundwater is remediated in accordance to the compliance criteria of any of the land use types considered here. Where this is not the case, e.g., because of higher contaminant fluxes from the site or less sensitive land use types considered, an examination of the cost for additional measures along the site boundaries would be required. Schädler et al. (2011a) give an example for a suitable model to estimate the required dimensions of remediation or plume containment measures and the costs thereby incurred.

The evaluation of the site's market value is in general governed by the bad development condition of the site in its current status and its relatively large distance from the city center of Potsdam. Estimated location quality factors q_{hk} range from 0.75 for recreational use on PU 9 to 1.04 for residential use on PU 14 (Figure 2.4). Note that values greater than 1, which represent a surcharge on reference land value, were determined only for PU 14 and PU 21 for residential use. For all other PU and use types estimated values are at or below 100% representing a discount. Taking a look at the distribution of discounts, it can be seen that (i) they are on average biggest for recreation, less for commercial and minor for residential use and that (ii) those units which are less accessible due to their distance to the state roads (Figure 2.1) are of mediocre to bad location quality for any of the specified land use types. Comparatively high values for residential areas are due to the direct neighborhood of the site to natural recreation areas, the proximity to lakes, and to the distance to the origins of negative externalities such as industrial or commercial zones. These indicators are more important for residential use than, e.g., for a commercial use, because the location quality of the latter is dominated by other determinants such as proximity to transportation infrastructure.

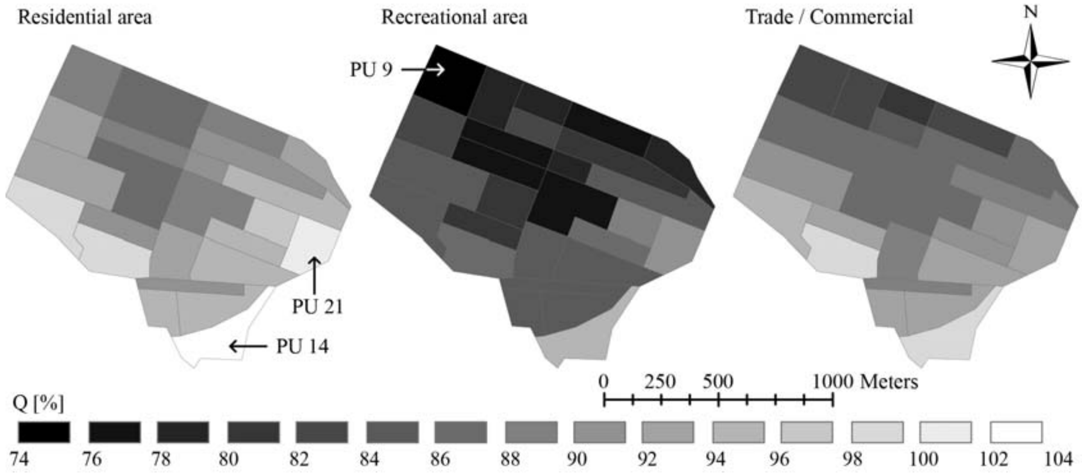

Figure 2.4: Estimated location quality (Q) as correction factor for reference land values for three different uniform land uses. Planning units (PUs) discussed in the text are labeled.

The assumed uniform recreational use is evaluated as the worst of the three options because the absence of neighboring residential and commercial areas results in a lack of demand for recreational use. This evaluation would be more positive in case of a mixed use land use. Given the interdependencies of the different land use types, combining residential, commercial and recreational uses indeed results in increased location qualities for recreational use (see below).

The display of the remaining land value matrix $\mathbf{L}_{R,A}$ in terms of one graph for each land use type (Figure 2.5) provides an overview of the monetary consequences of the assumed uniform use of the site. Having the highest reference land value

(Table 2.2), residential use is clearly ranked most beneficial from an economic point of view on those planning units that are not affected by contamination (i.e. non-conflict areas in SE' part of the site). Figure 2.5 shows that negative remaining land values l_R appear where remediation and site preparation costs exceed the land value l.

The economically optimal option is derived as a mixed use option by selecting the land use, which produces the highest land value for each PU. The resulting values of $\mathbf{L}_{R,max,A}$ are shown in Figure 2.6.1. Three PUs remain for which the optimal remaining land value is negative (in practice tantamount to a zero value) due to high remediation cost. The corresponding allocation $\mathbf{U}^{max}$ of land uses for which this optimum would be achieved is displayed in Figure 2.6.2. The land use allocation is largely dominated by residential areas. In areas exhibiting the highest contamination levels, trade and commercial areas are favored.

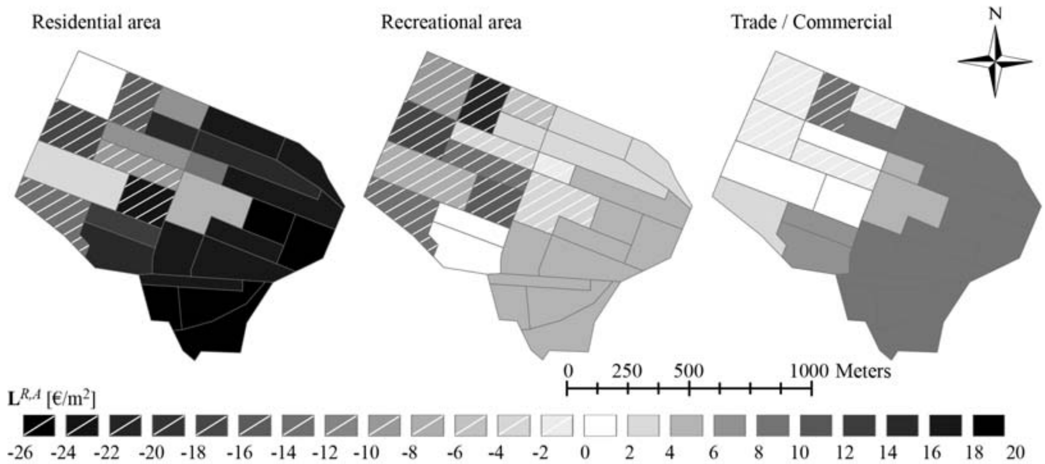

Figure 2.5: Summary of the monetary assessment results assuming uniform land use: land value per square meter ($\mathbf{L}_{R,A}$) after subtraction of the anticipated land use specific soil and groundwater remediation costs.

$\mathbf{U}^{max}$ is the result of an optimal trade-off between a high land value and low remediation expenditures as compared to the three uniform land uses. $\mathbf{U}^{max}$ represents a rather patchy land use layout which may not represent a realistic option for planners and would therefore require some adjustment. To exemplify how the $\Delta\mathbf{L}_{R,A}$ map (Figure 2.6.3) can be used to guide this adjustment, a modified layout $\mathbf{U}^{MOD1}$ is created from $\mathbf{U}^{max}$. At the north-western site boundary (PU 7 and PU 9) residential areas are inexpediently surrounded by trade and commerce. Figure 2.6.3 shows that changing the use of PU 7 and PU 9 to trade/commercial areas would result in comparably low $\Delta l_{R,A}$, i.e., little loss in land value (3.3 €/m^2 in PU 7 and 4.1 €/m^2 in PU 9, respectively) and may thus seem plausible. The evaluation results for $\mathbf{U}^{MOD1}$ are discussed below.

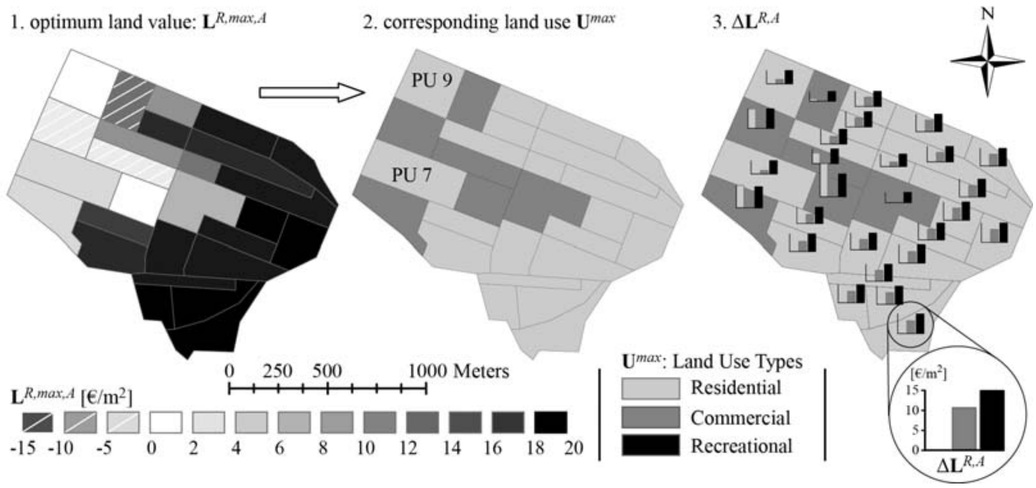

Figure 2.6: Results of monetary optimization. Maximum land values [€/m^2] (map 1) are achieved by economically optimal allocation of land use types U^{max} (map 2). $\Delta L_{R,A}$ reflects the costs that an alteration of U^{max} would cause for each planning unit (PU) (map 3). PUs discussed in the text are labeled.

Table 2.4: Results of the evaluation of uniform land use types and of the preliminary optimum land use option U^{max}.

	Residential	**Recreational**	**Commercial**	U^{max}
Land value [€]	20,147,000	5,676,000	10,180,000	17,782,000
Remediation cost [€]	11,290,000	7,232,000	4,705,000	6,034,000
Remaining land value [€]	8,856,000	-1,556,000	5,476,000	11,748,000
Building deconstruction cost [€]	4,124,000	4,124,000	4,124,000	4,124,000
Sub-total [€]	4,732,000	-5,680,000	1,352,000	7,624,000
Mercantile value reduction [€]	710,000	0	203,000	1,144,000
Market value [€]	4,022,000	(-5,681,000)[a]	1,149,000	6,480,000
E_{tot} [%][b]	4.4	5.5	32.0	11.8

[a] negative remaining land values are shown in brackets and would in practice be set to zero.

[b] E_{tot}: total suitability value in terms of sustainable development.

Table 2.4 shows the results of the monetary assessment of $\mathbf{U}^{max}$ including those parameters that were not determined in a spatially explicit manner, i.e., the costs for deconstruction of buildings (47 buildings with a total gross cubic space of

11,300 m^3) and a mercantile value reduction of about 15 % of the remaining difference which is deduced due to the perceived economic risks. The market value is positive for residential and commercial uses but negative (in practice: zero) for recreational use.

2.3.3 Sustainability Evaluation and Integrated Assessment

The sustainability evaluation of the three uniform site use scenarios (Figure 2.7) shows two main trends. First, those planning units, which are situated further north and thus closer to the adjacent nature reserve and more distant to the two state roads (Figure 2.1), seem to be poorly suited for reuse by any of the land use types considered here. Note that this pattern resembles the location quality assessment (Figure 2.4), which is an indication that on this site a land use that is sustainable in terms of the indicators introduced by Müller and Rohr-Zänker (2009) would be economically favorable as well. Eight PUs on the site (hatched areas in Figure 2.7) show negative suitability values for all three land use types. Following Müller and Rohr-Zänker (2009), this is an indication that a developmental use may not be recommendable in these units from a sustainability point of view.

A second trend that can be observed in Figure 2.7 is that recreational use seems to be preferable (among the use types considered) throughout the entire site. Among the factors that most strongly influence this result are (i) the site's direct vicinity to a nature reserve, (ii) its location outside of an urban area, and (iii) its insufficient supply and disposal infrastructure, which strongly diminish the suitability of both residential and commercial areas. Examples for factors that spatially vary on the site are the anticipated access to public transport, which improves the ratings of all three land use types if allocated close to the state roads, and the promotion of residential use where historically relevant buildings are present.

Correspondingly, evaluation of the total suitability value E_{tot} for a uniform use of the site results in only slightly positive suitability values of 4.4 % for residential and 5.5 % for commercial use while recreational use is rated with 32.0 % (Table 2.4). The mixed use in $\mathbf{U}^{max}$ ($E_{tot} = 11.8$ %) is rated better than its two constituting use types and shows that complementary land use can positively affect a site's contribution to sustainable development. As the latter is crucial for successful site revitalization, knowledge of the suitability matrix **E**, as visualized in Figure 2.7, finally needs to be integrated into the vision of a beneficial future land use. This integration is achieved by a second re-planning step based on the result of the first one, $\mathbf{U}^{MOD1}$ (Figure 2.8.2), where further improvement is sought by taking the sustainability assessment results into account.

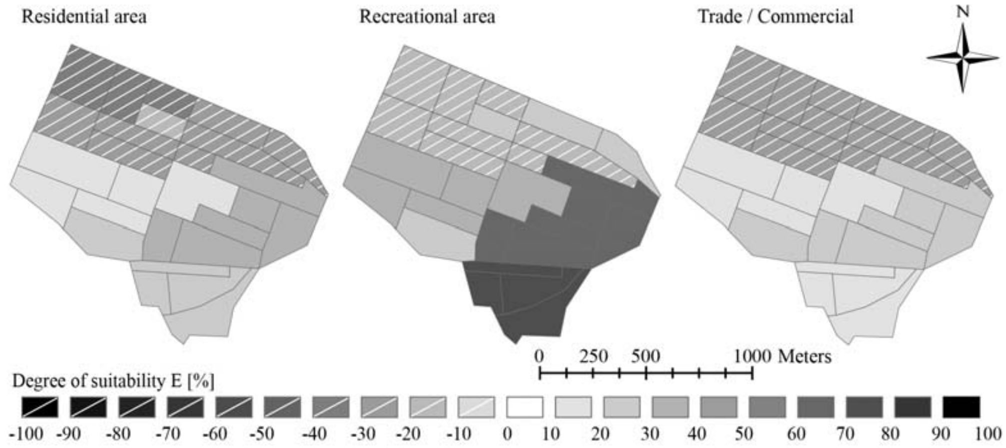

Figure 2.7: The degree of suitability E of three different land use types in terms of sustainable development, assuming uniform land use.

Given the distinct recommendation for recreational use and considering both (i) the poor suitability of the northern parts of the site in case of residential and commercial use, and (ii) the additional sustainability value that a mixed land use in $\mathbf{U}^{MOD1}$ provides, the layout $\mathbf{U}^{MOD2}$ is suggested here for improvement (Figure 2.8.3).

Finally, all three layouts, $\mathbf{U}^{max}$, $\mathbf{U}^{MOD1}$, and $\mathbf{U}^{MOD2}$ are re-evaluated. Results are summarized in Table 2.5. Please recall that this concluding evaluation includes the land use interdependencies for the location quality as well as for the sustainability evaluation. As $\mathbf{U}^{max}$ results from the economic optimization, obviously its remaining land value is higher than the two alternative layouts, $\mathbf{U}^{MOD1}$ and $\mathbf{U}^{MOD2}$. This difference is only slightly decreased by smaller mercantile value reduction in both these modified options. The reduction of the final estimated market value of the cleared sites due to the re-planning of $\mathbf{U}^{max}$ is about € 200,000 for option $\mathbf{U}^{MOD1}$ and about € 1.5 million for option $\mathbf{U}^{MOD2}$. However, both modified layouts show an increase in suitability with respect to sustainable regional development, as reflected by their suitability value E_{tot}. As could be expected, in particular the incorporation of the findings from the sustainability assessment in the second planning iteration yields a clear step-up.

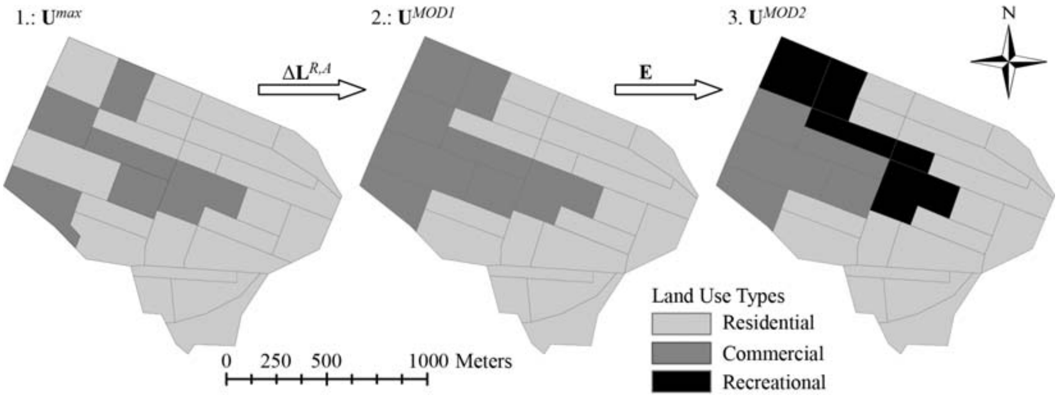

Figure 2.8: Three suggested initial planning scenarios based on monetary optimization (map 1), a first re-planning step U^{MOD1} guided by economic appraisal, $L_{R,A}$ (map 2), and a second re-planning step U^{MOD2} guided by sustainability evaluation (map 3) (compare Figure 2.6 and Figure 2.7).

The positive effect generated by a mixed land use with respect to the sustainability evaluation is again underlined by the very high rating of $\mathbf{U}^{MOD2}$ (cf. Table 2.4 and Table 2.5). Note that in both re-planning steps one may consider more than the few exemplary land use layouts discussed here.

Table 2.5: Comparison of three suggested initial planning options (Figure 2.8) as re-evaluated on the basis of site characteristics and land-use interdependencies.

	$\mathbf{U}^{max}$	$\mathbf{U}^{MOD1}$	$\mathbf{U}^{MOD2}$
Land value [€]	17,419,000	16,366,000	15,189,000
Remediation cost [€]	6,034,000	5,243,000	5,576,000
Remaining land value [€]	11,385,000	11,123,000	9,613,000
Building deconstruction cost [€]	4,124,000	4,124,000	4,124,000
Sub-total [€]	7,261,000	6,999,000	5,489,000
Mercantile value reduction [€]	1,089,000	1,050,000	823,000
Market value [€]	6,171,000	5,949,000	4,665,000
E_{tot} [%]	11.8	12.6	19.3

2.4 CONCLUSIONS

We provide an integrated planning and evaluation framework and show how it can be applied to provide an initial vision of brownfield reuse. The framework comprises methods that support planning iterations in order to render a purely economic-driven initial vision more convenient from a planning perspective and more valuable in terms of sustainable development. Spatial information is comprehensively analyzed and visualized to provide transparent assessment results for the identification of preferable planning options. This will facilitate discussions among stakeholders and is thought to also accentuate the advantages an integrated assessment of the consequences – specific to the realization of a certain reuse plan – will have with respect to economic, ecological and social issues. The proposed method integrates evaluation models which are tailored to a specific case study and may be less suited for sites with different hydrogeological settings, different kinds of contamination or a different context with respect to sustainability. An adaption or expansion of the evaluation models in order to provide applicability to different sites may be required and appears feasible within the proposed framework.

APPENDIX: List of variables

Name	Description	Dimensions	Unit
$\mathbf{A}$	Planning unit area vector	p	[m^2]
a_c	Contaminated area requiring soil remediation	-	[m^2]
$\mathbf{C}^{soil}$	Contaminant concentration matrix for soil	$x \times y \times n^{soil}$	[mg/kg]
$\mathbf{C}^{GW}$	Contaminant concentration matrix for groundwater	$x \times y \times n^{GW}$	[µg/l]
$\mathbf{D}^{soil}$	Conflict matrix for soil contaminants	$x \times y \times n^{soil}$	[-]
$\mathbf{D}^{GW}$	Conflict matrix for groundwater contaminants	$x \times y \times n^{GW}$	[-]
$\mathbf{E}$	Suitability matrix	$m \times p$	[%]
E_{tot}	Suitability value	-	[%]
$\mathbf{g}$	reference land value vector	m	[€/m^2]
H, i, j, k, z	Indices for planning unit, x-value, y-value, contaminant, and land use, respectively	-	[-]
$\mathbf{L}$, $\mathbf{L}^A$	Land value matrix (^{A}: area-normalized)	$p \times m$	[€], [€/m^2]
$\mathbf{L}^R$, $\mathbf{L}^{R,A}$	Remaining land value matrix (^{A}: area-normalized)	$m \times p$	[€], [€/m^2]
$\mathbf{L}^{R,max}$, $\mathbf{L}^{R,max,A}$	Maximum land value vector (^{A}: area-normalized)	p	[€], [€/m^2]
$\Delta\mathbf{L}^R$, $\Delta\mathbf{L}^{R,A}$	Difference to $\mathbf{L}^{R,max}$ (^{A}: area-normalized)	$m \times p$	[€], [€/m^2]
m	Number of land use types considered	-	[-]
N	Total number of contaminants considered	-	[-]
n^{soil}	Number of contaminants in soil considered	-	[-]
n^{GW}	Number of contaminants in groundwater considered	-	[-]
P	Number of planning units	-	[-]
$\mathbf{Q}$	Location quality matrix	$p \times m$	[-]
$\mathbf{R}$, $\mathbf{R}^A$	Remediation cost matrix (^{A}: area-normalized)	$x \times y$	[€]
$\mathbf{S}$	Site preparation cost vector	m	[%]
$\mathbf{T}^{soil}$	Compliance criteria matrix soil contaminants	$n^{soil} \times m$	[mg/kg]
$\mathbf{T}^{GW}$	Compliance criteria matrix groundwater contaminants	$n^{GW} \times m$	[µg/l]
$\mathbf{U}$, $\mathbf{U}^{ras}$	Land use matrix (^{ras}: raster-based)	$p\,/\,x \times y$	[-]
v_c	Contaminated soil volume requiring remediation	-	[m^3]
$\mathbf{x}$	Number of raster rows	-	[-]
$\mathbf{y}$	Number of raster columns	-	[-]

CHAPTER 3

Systematic improvement of sustainable brownfields redevelopment by automated quantitative spatial assessment of sustainability indicators[5]

Abstract

Contemporary land use planning is based on concise and well-defined project-specific evaluation methods from various scientific disciplines and, more recently, focuses on the integration of sustainability evaluation schemes. Many of these use sets of indicators to evaluate and quantify the sustainability of different planning options for given contexts. Typically, these indicator-based methods rely heavily on (expert) stakeholder input, which poses a challenge to integrating them into standardized and automated assessment tools. This is seen as one of the reasons why sustainability, despite being widely accepted as one of the most crucial aspects in any development, is often not considered on equal terms in decision making and planning compared to environmental risk and economic orientation. In this paper we propose a scheme to transfer site-specific sustainability definitions into automated quantitative and spatially explicit assessments which can be integrated into multidisciplinary spatial optimization algorithms. Using a case study site near Potsdam, Germany, this transfer for a site-specific indicator set for the evaluation of sustainable brownfield redevelopment is implemented with simple landscape metrics to evaluate typical spatial data and stakeholder knowledge. An automatic spatial evaluation of hundreds of systematically designed land use options is explored to provide a detailed understanding of the indicator-based evaluation of sustainable land use planning. The results suggest that an algorithmic spatially explicit evaluation of sustainability indicators significantly improves the applicability, comprehensiveness, reliability and, potentially, the acceptance of sustainability assessments.

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[5] Reproduced from: Schädler, S., Finkel, M., Bleicher, A., Morio, M., Gross, M., 2011. Systematic improvement of sustainable brownfields redevelopment by automated quantitative spatial assessment of sustainability indicators. Landscape and Urban Planning (submitted),

3.1 INTRODUCTION AND OBJECTIVES

Decisions in land use planning and environmental management in the last two decades have increasingly become based on the analysis of quantitative and qualitative spatial data in geographic information systems (GIS) (Ascough et al., 2008; Densham and Goodchild, 1989). To date, spatial decision support systems (sDSS) that partly rely on algorithmic and automated processes are typically used to perform such analyses (e.g., Malczewski, 2006). This is the case especially where the numbers of influential factors or planning options, or the uncertainty associated with the planning alternatives are large (e.g., Reichert and Borsuk, 2005; Walker et al., 2003).

The redevelopment of brownfields is a prominent context for such complex decision making. Brownfields are defined as abandoned or underused properties, the beneficial reuse of which will need intervention because of the real or suspected presence of hazardous substances, pollutants or contaminants (CABERNET, 2005; USEPA, 2002). Brownfield revitalization (BR) demands extensive efforts for the site investigation and remediation, as well as intricate negotiations among stakeholders with heterogeneous interests (Bardos, 2004). Summing up the estimates by different European and North American environmental agencies suggests that the cleanup expenditures for brownfields on a global scale may well exceed $1 trillion (EEA, 2000; NRTEE, 2003; USEPA, 2003). It is generally recognized that besides reducing long-term health risks by contaminants, increasing tax revenues and avoiding additional land consumption (Nuissl and Schroeter-Schlaack, 2009), BR has the potential to drastically enhance sustainable urban development (e.g., Bardos et al., 2000; DeSousa, 2008; Nijkamp et al., 2002), which in the broad sense of the Brundtland commission (WCED, 1987) addresses issues around the natural environment, natural resources, the maintenance of human wellbeing, and of economic growth.

One general finding from work on the concept of sustainable development in the last two decades is that sustainability needs to be understood as dependent on space and time, on the scale of both of the latter and on the actors involved (Bleicher and Gross, 2010; Olsson, 2009). Many efforts were undertaken to define precise goals of sustainable development and to derive indicators to measure the sustainability of any development in relation to its spatial, temporal and thematic context (e.g., Hartmuth et al., 2008; Singh et al., 2009). As a consequence, a multitude of tailored and context-specific indicator-based sustainability definitions exist to date, many of which allow for a quantification of sustainability (e.g., Pediaditi et al., 2010; Shmelev and Rodríguez-Labajos, 2009; Wedding and Crawford-Brown, 2007; Zavadskas and Antucheviciene, 2006).

Nevertheless, environmental risk and economic orientation still dominate decision making and the respective support systems in environmental management and land use planning. Whereas the expected economic and ecologic costs and benefits of environmental decisions are typically examined in great detail in the search for optimal remediation and redevelopment options (e.g., Bayer et al., 2005; Buerger et al., 2007, Carlon et al., 2008), while sustainability is often not considered on equal terms (e.g., Agostini and Vega, 2007; Ryan, 2011). This situation is attributed to the facts that the Brundtland definition of sustainable development itself is not quantifiable and that the manifold existing site-specific and sometimes elaborately operationalized sustainability definitions are based to a large extent on stakeholder input and are not readily integrated into automated or standardized evaluation methods (e.g., Jakeman et al., 2008; Pearson et al, 2010).

This paper outlines the process of transferring a set of existing indicator -based sustainability definitions into spatially explicit quantitative algorithms using so-called spatial metrics. The latter have been widely used to aid spatial analyses in many scientific fields. In landscape ecology for example, the current state of knowledge about relationships between landscape patterns and processes is to a wide extent based on spatial metrics (Antrop et al., 2009; McGarigal et al., 2009; O'Neill et al., 1988). Also urban modelers and social scientists make use of spatial metrics on larger scales; for example, in the analysis of land cover change by remote sensing (e.g., Geoghegan et al., 1998; Greenhill et al., 2003; Herold et al., 2005). Different sets of spatial metrics have been developed and extensive efforts have been made to classify these metrics, analyze correlations between them and define standard or baseline sets of spatial metrics related to holistic or sustainable planning (e.g., Antrop and Van Eetvelde, 2000; Botequilha-Leitão and Ahern, 2002; Golledge, 1995; Palmer, 2004).

The proposed transfer shall serve as an example of completely automated and spatially explicit evaluation of existing indicator sets. Besides allowing the implementation of sustainability assessments in integrated assessment and optimization algorithms, this should facilitate application, calibration, validation and further development of indicator-based evaluation schemes in physical planning. We demonstrate this transfer in a BR case study, where the automated evaluation of a given set of sustainability indicators is used in a systematic search for optimal land use alternatives (hereafter also termed redevelopment options). The latter are represented by the spatial allocation of specific land use types to different planning units (PU) on the study site. By delivering a more quantitative understanding of the previously reported advantages that mixed land use options have over uniform use (e.g., Matsuoka and Kaplan, 2008; Pauleit et al.; 2005), this case study aims at a pre-selection of sustainable reuse options, thereby streamlining the decision making processes in the early stage of a BR process (Beach, 1993; Prato, 2007).

3.2 DESCRIPTION OF METHODS

3.2.1 Prerequisites

For the transfer of sustainability definitions into an algorithmic and automated evaluation scheme, a contextualized definition of sustainable development is required as a starting point. This definition consists of (i) an indicator set which describes the context-specific definition of sustainable development and (ii) an aggregation scheme for these indicators. Both prerequisites can best be fulfilled by stakeholder involvement as described in previous work (e.g., Li et al., 2009, Raymond et al., 2010; Valencia-Sandoval et al., 2010).

The exact data requirements are context-specific. They reflect information queried by the indicator set but may become clear only after the definition of the algorithmic assessment scheme. In the case study described below the required information is based on the exact specification of land use types and on the positive and negative impacts that they have on one another and on the social, economic and ecologic features addressed by the indicator set. The latter include the spatial distribution of subsurface contamination, accessibility of local transport or amenities, local habitats, etc., all of those have different implications on the different land use types.

3.2.2 Definition of algorithmic assessment scheme

To obtain a quantitative assessment scheme, the existing context-specific set of indicators needs to be translated into a set of algorithms that describe the dependency of the indicators' values on digital data. Given an indicator set consisting of n single indicators Ind_z in terms of verbal descriptions of criteria for sustainable development in a given context and a range, Rg_z, of possible evaluation results, k_z, for each indicator. This range depends on the particular type of specification of the indicator, e.g., Boolean (possible answers for indicators formulated as a "TRUE/FALSE" question), certain value ranges (e.g., a percentage) or integer values (e.g. the number of occurrences of incidences or individuals in time and/or space). Each indicator's verbal description is then reformulated so that k_z can be determined automatically by an algorithmic evaluation involving a number m of sets of spatial data $\mathbf{D}_a$ ($a \in \{1, \ldots, m\}$). Evaluation of each Ind_z in a spatially explicit way, for example for every cell of a raster representation of the area of interest, results in a map $\mathbf{K}_z$ of indicator results.

$$Ind_z:\quad \mathbf{K}_z = \begin{pmatrix} k_{z,11} & \cdots & k_{z,1x} \\ \vdots & \ddots & \vdots \\ k_{z,y1} & \cdots & k_{z.yx} \end{pmatrix} = f_z\left(\mathbf{D}_1,\ldots,\mathbf{D}_m\right),\quad k_z \in Rg_z;\ z \in \{1,\ldots,n\}; \quad \textbf{Eqn. 3.1}$$

In equation 3.1 the function f_z indicates dependency on spatial features. We distinguish three different characteristics of spatial dependency, being

i. direct dependency on spatial features
ii. indirect dependency on spatial features
iii. spatial constancy/independency

A direct dependency on spatial features is given where f_z is described exclusively by spatial metrics and the respective spatial data set, e.g., where distance, presence, area, frequency of occurrence, etc., of particular features represented by $\mathbf{D}_a$ are evaluated. An example is the evaluation of an indicator called "Residential areas in the surrounding area" (indicator #1 in our case study) with a Boolean result. Given spatial data on residential areas $\mathbf{D_1}$, a linear search for the nearest neighbor among all occurrences of green spaces and a comparison of the nearest neighbor distance to an exact definition of "surrounding area", e.g. using a minimum threshold distance $thres_1$, yield map $\mathbf{K}_1$ (eqn. 3.2).

$$\mathbf{K}_1 = k_{1,ij} = \begin{cases} MINDIST(\mathbf{D}_1;(i,j)) \le thres_1 : \text{TRUE} \\ MINDIST(\mathbf{D}_1;(i,j)) > thres_1 : \text{ FALSE} \end{cases} \quad i \in \{1,\ldots,x\};\ j \in \{1,\ldots,y\}; \quad \textbf{Eqn. 3.2}$$

Here, the spatial dependency is evaluated by the sampling of the "surrounding area" and the spatial metric "distance".

An indirect dependency on spatial data is given when an indicator's evaluation depends on spatial data **D** that varies with different planning alternatives **A** but which is not inherent in the definition of **A**. Where **D** can be expressed as a function $g(\mathbf{A})$, the indicator evaluation is directly dependent on **D** and indirectly dependent on **A** via g.

$$Ind_z:\quad k_z(\mathbf{A}) = f_z\left(\mathbf{D}_z\right) = f_z\left(g_z(\mathbf{A})\right); \quad \textbf{Eqn. 3.3}$$

Indirect dependencies on spatial data can be solved by defining g or, when this is not possible, by additional assumptions that render the indicator directly dependent on either an invariable data set $\mathbf{D} \ne f(\mathbf{A})$ or **A** itself. Our case study contains examples for all these three approaches to indirect dependencies.

Where an indicator's spatial dependency does not result in any variation throughout the area of interest (e.g., because the relevant spatial features are located far beyond a given threshold distance), or where an attribute is uniformly distributed over the area of interest, the indicator value is spatially constant. Spatial constancy and spatial independence result in an indicator evaluation that does not depend on the sampled positions on the area of interest. Indicators for which this is the case can be simplified so that they do not contain any spatial queries.

$$Ind_i : \quad k_i \neq f(\mathbf{D}); \qquad \textbf{Eqn. 3.4}$$

The process of identifying the different cases of spatial (in)dependence, defining the resulting data requirements and necessary assumptions for a given set of indicators, as well as the possible relation of this process to the "traditional way" of stakeholder-based evaluation, are depicted in Figure 3.1. Stakeholders and sustainability experts have to be involved (grey areas in Figure 3.1) in order to accurately describe every indicator's dependencies as well as all underlying additional assumptions by algorithms and by digital (spatial) data, which makes the final step, the evaluation itself, independent of human input. On this basis, the (spatial) analysis and subsequent aggregation of indicator results can be conducted automatically for large numbers of physical planning options, as indicated by the circular arrow in Figure 3.1.

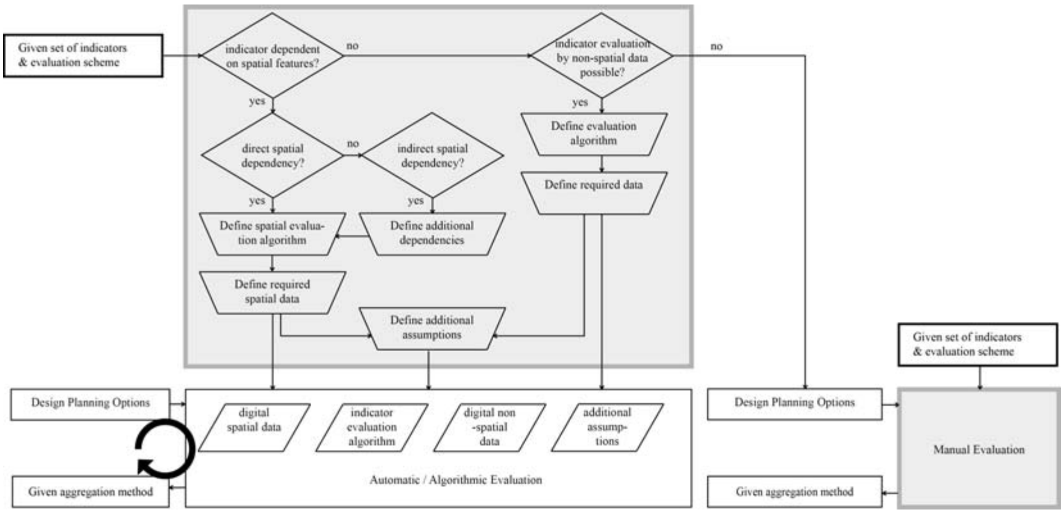

Figure 3.1: The process of defining spatial indicator evalution algorithms, as followed in this work, and its "traditional" alternative, the manual evaluation of indicators (far right). Grey areas require input by stakeholders and experts.

In the following analysis an example is presented for such a process and a subsequent application of an existing indicator-based sustainability evaluation scheme. The indicator set is transferred into algorithms which are then applied in a case study with the aim to support the identification of sustainable planning options for the redevelopment of a contaminated site near Potsdam, Germany.

3.3 CASE STUDY

3.3.1 Description of study site, previous work and setup of analyses

The model for this case study is a former military site situated in the outskirts of Potsdam, Germany, and covers an area of approximately 1.1 km^2. Soil and groundwater at the site are heavily contaminated (Morio et al., 2008; Rein et al., 2010). The wider surrounding area contains trades and industries as well as residential areas. Two likes are situated close-by and directly bordering the site is a nature reserve (see Figure 3.2).

Figure 3.2: The case study site, subdivided into planning units, and the site-specific spatial data relevant for the evaluation of the sustainability indicators.

For the case study site, a set of indicators for sustainable BR (see Table 3.1) and a respective aggregation scheme exist as a result of previous studies (Müller and Rohr-Zänker, 2009). The 23 indicators are based on criteria for urban development in Germany. They are verbally formulated as statements with the result of their evaluation being a Boolean True or False. In three aggregation steps, the associated positive or negative implications of the true or false statements on different land use types are first represented as tabulated integer values. These are then given different weights according to stakeholder-defined indicator relevance and summed up. Finally, normalization to a scale between -100 and +100 yields the so-called suitability value.

Schädler et al. (2011a, 2011b) describe a context-specific spatially explicit way for the application of this method by introducing different planning units (PU) on the site and assessing PU-specific suitability values (E_{PU}). A total suitability value E_{tot} is then built by summing up all E_{PU}, the latter being weighted by the PU surface area. E_{tot} will be used as a reference aggregate measure of sustainable development in the presented study.

Given 27 different PUs and considering 3 different land use types that complement each other with respect to a beneficially mixed land use (residential, commercial and recreational use), a total number of 3 to the power of 27 ($> 7\times10^{12}$) different land use options are possible on the study site. Out of these numerous planning alternatives, the two previous studies describe the evaluation of 13 options that resulted from stakeholder discussions.

Using the same setup of PUs and land use types, in the presented case study a large number of systematically designed land use options are assessed by an automated evaluation in order to gain a deeper understanding of the consequences with respect to sustainable development that can be expected from the beneficial mixing of different land use types in varying spatial allocations and under varying assumptions. The following four analyses aim to provide insights into various aspects of land use planning:

- Analysis 1 evaluates the benefit of a complementarily used PU on an otherwise uniformly used site, as well as the dependency of this benefit on the PU's spatial allocation.
- Analysis 2 identifies the areal fraction of complementary use types that delivers the greatest benefits.
- Analysis 3 quantifies the sensitivity of the results of Analyses 1 and 2 to the simplifying assumptions
- Analysis 4 explores how the results change in response to a hypothetical future change in the site's boundary conditions.

3.3.2 Transfer of the indicator set into an algorithmic evaluation scheme

The existing indicators are verbally formulated as statements, so that each indicator's evaluation yields a Boolean TRUE or FALSE result. In order to achieve an algorithmic indicator evaluation using automated analysis of digital data, these statements are reformulated by an algorithmic description of the spatial dependency of each indicator's evaluation on respective data. Table 3.1 shows a short form of the original indicator formulation, the translation into pseudo-code, and the description of the resulting data requirements.

Additionally, the verbal expression of the relevant spatial dimensions (e.g., "in walking distance" (indicator #14) or "good accessibility" (indicator #13)) have to be converted into an exact definition, e.g. into a threshold distance. For the sake of simplicity, all threshold distances are set to 500 meters. Use-type specific compliance criteria from Schädler et al. (2011a) were used as contaminant concentration limits. This defines the indirect dependency of indicator #21 ($thres_{21}$) on the planning alternative.

Further indirect spatial dependencies were avoided independent of the land use option by the addition of the following general assumptions: (i) Traffic on the future site will not increase to an extent that exceeds the access roads' capacities (k_{10} = FALSE). (ii) Local amenities will be available in walking distance to any residentially or commercially used PU and primary schools will be available in walking distance to any residentially used PU ($k_{14} = k_{15}$ = TRUE). (iii) Public transport access is given at two invariable positions at the site boundaries (#11) (see Figure 3.2).

12 indicators were considered spatially constant and 11 indicators' evaluations depend on the spatial data defined in Table 3.1.

3.3.3 Implementation

The indicator evaluation was implemented in VisualBasic code, using GIS functionalities from the open source project MapWindows (www.mapwindow.org) for spatial queries such as the evaluation of distances or neighborhoods. Existing site data from previous investigations, as well as stakeholder expertise, are represented by ESRI ascii grid files. All land use options for this study are represented by systematically generated ESRI polygon shape files describing the allocation of land use types on the PUs.

Table 3.1: Scheme for the evaluation of sustainability indicators. Grey shaded indicators are considered spatially constant in this case study. Framed indicators are re-evaluated for different assumptions in a sensitivity and a scenario analysis. W: Indicator weight. SD: the spatial domain considered for the evaluation which can be either R (the region), A (the area of the site), or a logic combination of the two.

Indicator: number and description	**W [%]**	**SD**	**Evaluation algorithm/results for PU *x***	**Required Input data**
1 Residential areas in the surrounding area	2	R	If $\mathit{MINDIST}(\mathrm{A}_{\mathrm{res}}; \mathrm{x}) < \mathit{thres}_1$ then $k_{1,x}$ = TRUE; Else $k_{1,x}$ = FALSE	Land use data **A**
2 Green spaces in the surrounding area	2	R	k_2 = TRUE	Land use data **A**
3 Commercial areas within walking distance	2	R	If $\mathit{MINDIST}(\mathrm{A}_{\mathrm{comm}}; \mathrm{x}) < \mathit{thres}_3$ then $k_{3,x}$ = TRUE Else $k_{3,x}$ = FALSE	Land use data **A**
4 Neighboring uses strongly emitting	4	R	If PU TOUCHES $\mathrm{A}_{\mathrm{emitting}}$ then k_4 = TRUE; Else k_4 = FALSE	Land use data **A**
5 Site contains >40% sealed soil	2	A	k_5 = FALSE	Stakeholder input
6 Site location within urban area	8	R-A	k_6 = FALSE	Regional maps
7 Site is part of a local habitat	8	A	k_7 = FALSE	Stakeholder input
8 High value tree/plant population	4	A	k_8 = FALSE	Plant data **P**/add. Assumption
9 Direct vicinity to nature reserve	8	R	If PU TOUCHES N then k_9 = TRUE else k_9 = FALSE	Nature reserve extent **N**
10 Low capacity of access roads	6	R	k_{10} = FALSE	Stakeholder input
11 Good access to public transport	8	R	If $\mathit{MINDIST}(\mathrm{T}; x) < \mathit{thres}_{11}$ then $k_{11,x}$ = TRUE; Else $k_{11,x}$ = FALSE	Public transport data **T**

Table 3.1, continued: Scheme for the evaluation of sustainability indicators. Grey shaded indicators are considered spatially constant in this case study. Framed indicators are re-evaluated for different assumptions in a sensitivity and a scenario analysis. W: Indicator weight. SD: the spatial domain considered for the evaluation which can be either R (the region), A (the area of the site), or a logic combination of the two.

Indicator: number and description	W [%]	SD	Evaluation algorithm/results for PU x	Required Input data
12 Good access to clearway	4	R	k_{12} = TRUE	Regional maps
13 Good accessibility for bikers	2	R	If $MINDIST(B, x) < thres_{13}$ then $k_{13,x}$ = TRUE; Else $k_{13,x}$ = FALSE	Map of bike paths **B**, aerial photos
14 Local amenities in walking distance	2	R	If a_x = “residential” or a_x = “commercial” then $k_{14,x}$ = TRUE; Else $k_{14,x}$ = FALSE	Land use data **A**/ add. assumptions
15 Primary school in walking distance	2	R	If a_x = “residential” then $k_{15,x}$ = TRUE Else $k_{15,x}$ = FALSE	Land use data **A**/ add. assumptions
16 Great impact on recreational areas	4	A	k_{16} = FALSE	Stakeholder input
17 Historically relevant buildings	2	A	If B = 1 then k_{17} = TRUE	Buildings data **B**
18 Great influence on cityscape	2	A	k_{18} = FALSE	Stakeholder input
19 Neighboring uses sensitive to immissions	8	R	If x *TOUCHES* A_{sens} then $k_{18,x}$ = TRUE; Else $k_{18,x}$ = FALSE	Land use data
20 Good supply and disposal infrastructure	4	A	k_{20} = FALSE	Stakeholder input
21 Area strongly contaminated	6	A	If $D_x > thres_{21}$ then $k_{21,x}$ = TRUE Else $k_{21,x}$ = FALSE	Subsurface contamination **D**
22 Site suitable for innovative industries	6	A	k_{22} = TRUE	Stakeholder input
23 Adjacent enterprises susceptible to new industries	4	R	k_{23} = FALSE	Stakeholder input

3.3.4 RESULTS

3.3.4.1 Analysis 1: Uniform site use with varying allocation of one complementarily used planning unit

In order to provide a better understanding of the potential benefit from mixing complementary land use types, this first analysis evaluates how much one PU of a complementary land use contributes to the site's sustainability in terms of suitability E_{tot}. Further it is analyzed how this contribution depends on the allocation of the complementary use type. To achieve this E_{tot} is evaluated for different sequences of planning alternatives, which are defined by successively allocating a complementary use type to single PUs (each PU once) in the following ways:

- Sequence 1.1: Residential use, one PU commercial use
- Sequence 1.2: Residential use, one PU recreational green space
- Sequence 1.3: Commercial use, one PU residential use
- Sequence 1.4: Commercial use, one PU recreational green space

The benefit of the complementarily used PU is quantified as the difference in E_{tot} that it creates as compared to the respective uniform site use. The calculation of E_{tot} for different uniform uses of the site shows that a uniform residential use ($E_{tot} = 7.9$) would be preferable if compared to a commercial use ($E_{tot} = 3.9$) (Table 3.2: "uniform reference use"). These E_{tot} values stem from a range of heterogeneously distributed E_{PU} values. Figure 3.3 illustrates this distribution, as well as the benefits within the threshold distance of the complementarily used PU 0.

Using the uniform residential use as a reference and changing one PU (3.7 % of the site's total surface area on average) to a commercial use (sequence 1.1) increases E_{tot} by about +5 although uniform residential use is rated more beneficial than uniform commercial use on this site. It plays an important role for the overall benefit where on the site the complementary land use is allocated (Table 2). The resulting change in E_{tot} values ranges from +2.9 to +6.2 when compared to the reference uniform use. The results furthermore show that the PUs with the most beneficial contribution to sustainability are not inherently the ones with the largest area, although every PU's contribution to the site's overall E_{tot} value is weighted by the PU's surface area. Whereas allocation of commercial use in sequences 1.1 and 1.3 is most beneficial in the site's very central part (best PUs #9, #10, #11, #16), the recreational green areas have their strongest impact in the southeastern parts (PUs #3, #13, #20, #21, #22, #23) in both sequences 1.2 and 1.4.

Table 3.2: Results of the evaluation of the benefits from one complementarily used planning unit (PU) on an otherwise uniformly used site. The PU with the highest E_{tot} value in each column is highlighted. A: PU area in hectares [ha]. PU Index: the PU that the complementary use type is allocated to.

		Sequence 1.1			Sequence 1.2			Sequence 1.3			Sequence 1.4		
Reference use type		Residential			Residential			Commercial			Commercial		
Complementary use type		Commercial			Recreational			Residential			Recreational		
PU Index	A [ha]	E_{tot} [-]	ΔE [-]	rel. ΔE [ha^{-1}]	E_{tot} [-]	ΔE [-]	rel. ΔE [ha^{-1}]	E_{tot} [-]	ΔE [-]	rel. ΔE [ha^{-1}]	E_{tot} [-]	ΔE [-]	rel. ΔE [ha^{-1}]
Uniform reference use		7.9			7.9			3.9			3.9		
0	4.2	12.7	4.8	1.2	10.1	2.2	0.5	8.6	4.7	1.1	5.7	1.8	0.4
1	4.1	13.5	5.5	1.4	8.6	0.7	0.2	9.5	5.6	1.4	4.3	0.4	0.1
2	5.7	13.3	5.4	1.0	9.4	1.5	0.3	9.1	5.2	0.9	4.8	0.9	0.2
3	4.5	12.0	4.1	0.9	10.2	2.3	0.5	8.6	4.7	1.0	6.1	2.2	0.5
4	4.9	11.8	3.9	0.8	8.7	0.8	0.2	8.0	4.0	0.8	4.4	0.5	0.1
5	4.4	11.7	3.8	0.9	9.1	1.2	0.3	7.5	3.6	0.8	4.6	0.7	0.2
6	7.8	13.2	5.3	0.7	10.0	2.1	0.3	9.0	5.1	0.7	5.1	1.2	0.2
7	4.0	13.1	5.2	1.3	9.0	1.1	0.3	8.2	4.3	1.1	4.3	0.4	0.1
8	5.9	12.2	4.3	0.7	9.5	1.6	0.3	7.1	3.2	0.6	4.5	0.5	0.1
9	6.7	14.1	6.2	0.9	9.7	1.8	0.3	9.8	5.9	0.9	5.0	1.0	0.2
10	3.4	13.7	5.8	1.7	8.8	0.9	0.3	9.4	5.5	1.6	4.4	0.5	0.2
11	3.9	13.9	6.0	1.5	8.9	1.0	0.3	9.6	5.7	1.4	4.5	0.6	0.2
12	5.6	12.8	4.9	0.9	10.8	2.9	0.5	9.5	5.6	1.0	6.7	2.7	0.5
13	5.2	11.2	3.3	0.6	10.5	2.6	0.5	8.0	4.1	0.8	6.4	2.5	0.5
14	2.4	12.8	4.9	2.0	8.9	1.0	0.4	9.1	5.2	2.1	4.9	1.0	0.4
15	3.6	13.1	5.2	1.5	8.5	0.6	0.2	9.1	5.2	1.5	4.2	0.3	0.1
16	1.6	**14.1**	**6.2**	3.8	8.2	0.3	0.2	**9.9**	**6.0**	3.6	4.1	0.2	0.1
17	5.5	13.5	5.6	1.0	8.8	0.9	0.2	9.7	5.8	1.0	4.4	0.5	0.1
18	3.1	12.4	4.5	1.5	9.5	1.5	0.5	8.7	4.8	1.6	5.4	1.5	0.5
19	3.1	13.0	5.1	1.7	9.5	1.6	0.5	9.3	5.4	1.7	5.4	1.5	0.5
20	4.4	10.8	2.9	0.7	10.1	2.2	0.5	7.5	3.6	0.8	6.0	2.1	0.5
21	3.3	13.5	5.6	1.7	9.6	1.7	0.5	9.8	5.9	1.8	**9.8**	**5.9**	1.8
22	5.8	12.8	4.9	0.8	**10.9**	**3.0**	0.5	9.6	5.7	1.0	9.6	5.7	1.0
23	2.3	12.5	4.5	2.0	9.0	1.1	0.5	8.6	4.7	2.1	8.6	4.7	2.1
24	2.6	11.9	4.0	1.6	9.2	1.3	0.5	8.2	4.3	1.7	5.2	1.2	0.5
25	2.7	13.0	5.1	1.9	8.7	0.7	0.3	8.3	4.4	1.6	4.2	0.2	0.1
26	3.0	11.9	4.0	1.3	9.5	1.6	0.5	7.7	3.8	1.3	5.2	1.3	0.4
	MAX	14.1	6.2	3.8	10.9	3.0	0.5	9.9	6.0	3.6	9.8	5.9	2.1
	MIN	10.8	2.9	0.6	8.2	0.3	0.2	7.1	3.2	0.6	4.1	0.2	0.1
	Mean	12.8	4.9	1.3	9.4	1.5	0.4	8.8	4.9	1.3	5.5	1.6	0.4

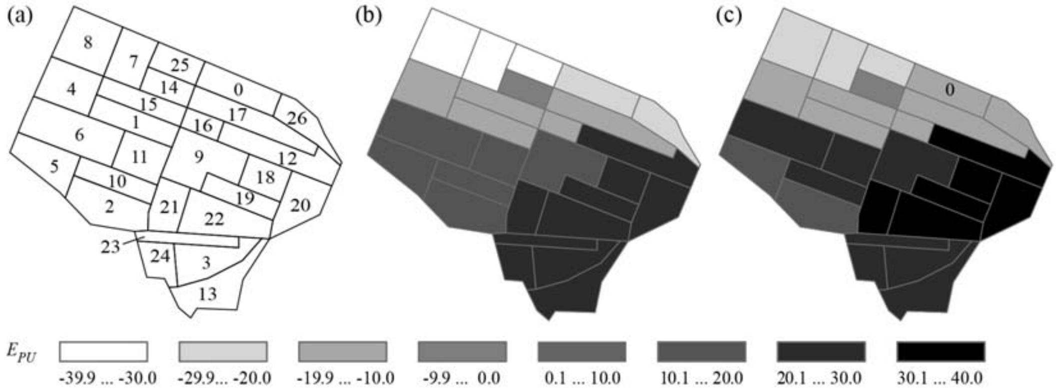

Figure 3.3: (a) Planning units (PUs) of the case study site with indices. (b) Distributions of individual PUs' suitability values E_{PU} for uniform residential land use, and (c) with commercial use in PU 0 (first of 27 planning alternatives in sequence 1.1).

Mainly, this is due to the existence of the nature reserve along the northern boundary of the site, and by the contamination in the central and northwestern part of the site. Here, the suitability for residential use is decreased to a bigger extent than for commercial use by indicator #21. Thus, rather than surface area alone, the precise location of land use types has a strong influence on the suitability value. This is confirmed by evaluating the relative change in E_{tot} per area of the complementarily used PU that provoked the change as plotted in Figure 3.4.

Only very weak correlations exist between a PU's area and its influence on E_{tot} when a complementary land use is allocated on it. The correlation is highest for sequence 1.2 (R^2 = 0.29), reflecting the fact that recreational areas are very favorable on this site and suggesting that their pure amount on this otherwise residentially used site is of relatively greater importance than for the other land use types. The relevant indicators which describe this beneficial complementation of different land use types are indicators #1 through #4.

The spatial evaluation of the indicator results by threshold distances explains the importance of the PU's location. A PU in the centre of the site lies within the specified threshold distance for all other PUs and has therefore a stronger (positive or negative) influence than PUs situated along the site boundaries.

Analysis 1 shows that a small fraction of a complementary land use can strongly enhance the sustainability of a site's redevelopment options, and this effect is increased if it is conveniently allocated. From these results the question arises how much of an areal fraction of a complementary land use type would yield the highest benefits, which leads to analysis 2.

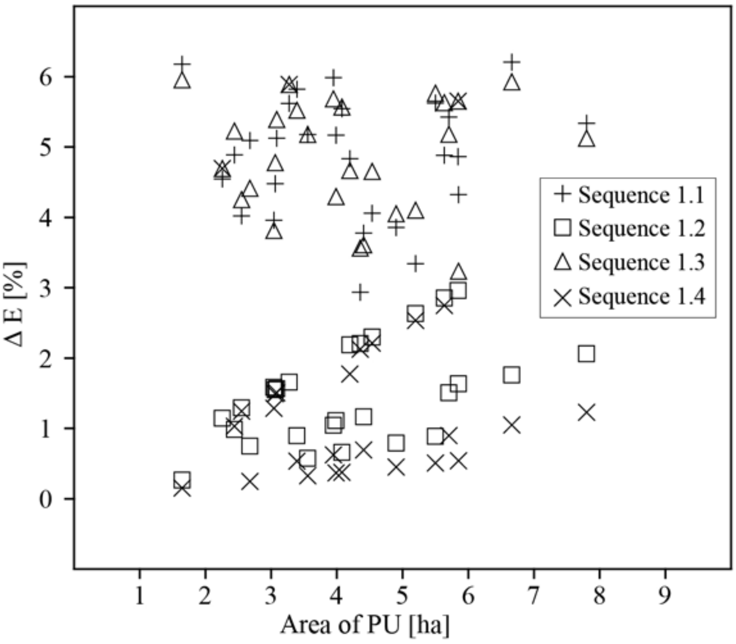

Figure 3.4: Change in suitability values E_{tot} caused by the allocation of a complementary land use type to individual PUs as a function of the PU area.

3.3.4.2 Analysis 2: Sequential increase of land use fractions

This second analysis examines the effects of increasing the fraction of commercially used land on an otherwise uniformly used residential site. From the many possibilities of spatial allocations, two sequences are chosen: one which increases the fractions of commercial use starting from the northwestern part of the site (sequence 2.1: "W-E") and the second with the allocation of commercial use starting in the Northeast corner (sequence 2.2: "E-W"). In both cases the commercially used PUs are interconnected so that one single commercial area is "growing" on the site. The main reasons for choosing these sequences are (i) the creation of land use options where both commercial and residential areas are conveniently clustered and (ii) the various impacts that the different regions had in Analysis 1 (sequence 1.1), most strongly seen in the south-eastern parts. As a result, E_{tot} values for "E-W" and "W-E" are expected to strongly differ from each other. The sequences of planning and the evaluation results for the two sequences are shown in Figure 3.5.

As already observed in the first analysis, both curves share the aspect that they strongly increase from both sides, with the first addition of a complementary land use to the uniform reference uses (at 0 % and 100 % commercial area, respectively). As the fraction of commercial use increases both curves quickly level off. As anticipated, E_{tot} values are higher for the W-E sequence than for the E-W sequence. The difference is small for near-uniform land use, and exceeds 3 for similar fractions of residential and commercial use. Thus, E_{tot} depends on the areal fraction of complementary land use especially when this fraction is small. When two use types are present in similar fractions, the site-specific spatial dependence and the land use type interdependencies strongly influence E_{tot} and convenient planning becomes more complex and more important. Analysis 2 confirms that, although commercial areas are less favorable than residential areas on this model site, a mix of the two land use types results in higher E_{tot} values than uniform residential use.

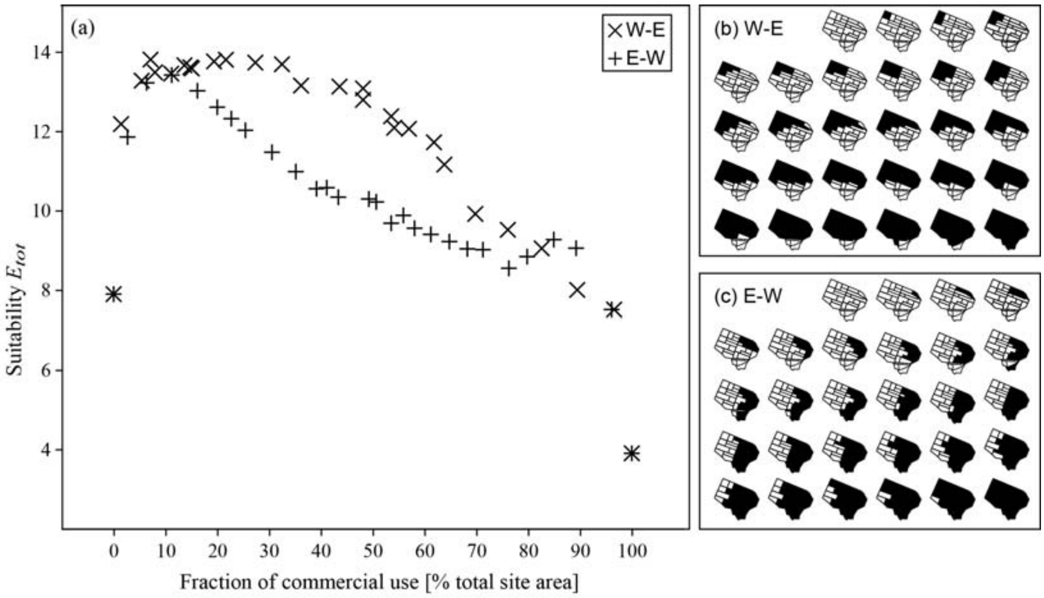

Figure 3.5: (a) E_{tot} for land use options with an increasing fraction of commercial land use on an otherwise residentially used site. (b) and (c): Maps of sequences W-E and E-W, left to right, top to bottom. Dark shaded PUs represent commercial land use.

3.3.4.3 Analysis 3: Sensitivity to simplifying assumptions

Analyses 1 and 2 show how a spatially explicit and algorithmic indicator evaluation provides some understanding of the response of this particular indicator set and aggregation scheme to variations in spatial planning. Several assumptions were introduced in order to transfer the indicator set into an automatic evaluation scheme. Here, the sensitivity of the evaluation results to a change in two of these assumptions is analyzed. Besides reconsidering all planning options of the previous sequences, this analysis is extended to three beneficially mixed land use options that were identified in a previous study (Schädler et al., 2011b). These options are characterized by residential areas in the entire eastern part, with varying fractions of commercial and recreational use in the west, and are rated by $E_{tot} = 14.0$, 14.3 and 17.6, respectively, under the assumptions defined above.

Table 3.3: The change in each sequence's mean $\bar{E}$ value that is created by a lack of local amenities (indicator #14) and primary school (indicator #15).

Analysis	Sequence	n options	$\bar{E}$ (Base Case)	Change by lack of - Local amenities $\Delta\bar{E}$	- Primary school $\Delta\bar{E}$
#1	1.1	27	12.8	-9.4	-9.2
	1.2	27	9.4	-9.2	-9.2
	1.3	27	8.8	-6.0	-0.4
	1.4	27	5.5	-5.7	0.0
#2	W-E	26	12.2	-7.6	-4.4
	E-W	26	10.5	-7.8	-5.0
Schädler et al. (2011b)	-	3	15.3	-7.9	-6.3
	Total	163	9.9	-7.5	-7.4

The assumptions in Analyses 1 and 2 were that local amenities and a primary school are available in walking distance to any residentially used PU (indicators #14 and #15 are evaluated TRUE throughout the study area). In order to check the consequences of future planning falling short of this requirement, all options are re-evaluated with the result of indicators #14 and #15 set to FALSE. For the sake of brevity, Table 3.3 shows the aggregated mean $\bar{E}$ of all E_{tot} values per sequence.

In total, an average decrease in E_{tot} of 7.5 is caused by the lack of local amenities and of 7.4 due to a lack of primary schools in walking distance to residential areas. The variations in the results are stronger for the planning options of analysis 2 because of the stronger variation in land use fractions in the evaluated options (results not shown). The main difference between the indicators' influence on E_{tot} is that indicator #15 (primary schools) is relevant for the residential use type only and therefore hardly relevant and irrelevant in sequences 1.3 and 1.4, respectively, whereas indicator #14 (local amenities) is relevant for both the residential and the commercial land use.

3.3.4.4 Analysis 4: Hypothetical future change in the site’s boundary conditions

In order to further demonstrate the extended applicability of the chosen indicator set by the automated assessment, all six sequences’ options and the three additional options from Schädler et al. (2011b) are re-evaluated based on the assumptions from Analysis 1 and the new assumption that the entire area surrounding the model site, except for the nature reserve, is used for residential purposes. The corresponding change in the respective spatial data can be creatively explored as it simulates different hypothetical scenarios such as a future urban sprawl of the neighboring city of Potsdam, or an inner development case where an otherwise identical brownfield site is located within the city. The assumed change in the site’s surroundings affects the evaluation results of the following six indicators from Table 3.1:

- Indicator #1: New residential areas, which are independent of the planning options, are present in the surrounding area of some of the PUs.
- Indicator #2: As recreational green spaces are partly replaced by residential areas, the distance to green spaces increases for some of the PUs.
- Indicator #6: The site is located within the urban area (k_6 = TRUE).
- Indicator #10: The capacity of the access roads is low due to higher assumed population density of the area (k_{10} = TRUE).
- Indicator #20: A good supply and disposal infrastructure is assumed to exist along with the surrounding residential areas (k_{20} = TRUE).

Table 3.4: The change in mean $\bar{E}$ values caused by a hypothetical change in boundary conditions, broken down by the five indicators which contribute to the change in results.

Options investigated		$\bar{E}$ (Base Case)	Ind. #1 $\Delta\bar{E}$	Ind. #2 $\Delta\bar{E}$	Ind. #6 $\Delta\bar{E}$	Ind. #10 $\Delta\bar{E}$	Ind. #20 $\Delta\bar{E}$	$\sum\Delta\bar{E}$	$\bar{E}$(result)
Analysis	Sequence								
1	1.1	12.8	0.0	-2.8	38.5	-0.5	19.2	54.5	67.2
	1.2	9.4	0.0	-0.5	36.9	0.0	18.5	54.8	64.2
	1.3	8.8	1.2	-0.1	42.4	-13.8	21.2	50.9	59.7
	1.4	5.5	5.5	0.0	41.1	-13.8	20.6	53.5	58.9
2	W-E	12.2	0.4	-1.9	40.6	-7.7	20.3	51.7	63.9
	E-W	10.5	0.3	-1.7	40.4	-6.9	20.2	52.3	62.7
Schädler et al. (2011b)	-	15.3	0.0	-1.5	37.1	-4.0	18.5	50.2	65.5
Total	Mean		1.3	-1.1	38.9	-6.7	19.5		

The results of the re-evaluation, separated by each indicator's contribution to the change in mean E_{tot}, are shown in Table 3.4. Obviously, all 163 mixed land use options (see Table 3.3) would generally benefit from the hypothetical residential land use in the surrounding area. On average, E_{tot} rises by a $\Delta\bar{E}$ of 53.6 as compared to the base case. The indicators contribute with very different fractions and variability to this change in sustainability.

These different contributions can best be seen in Figure 3.6 (note the different y-axis scales). The increase in E_{tot} is driven mainly by two spatially independent and site-wide relevant indicators, namely the site's location within the urban area (indicator #6) and the assumed presence of a good supply and disposal infrastructure (indicator #20). The benefits of residential areas in the surroundings (indicator #1) are hardly relevant, whereas the now lacking green spaces (indicator #2) notably downgrade the results. The negative change in E_{tot} that is caused by the lower capacity of the access roads (indicator #10) becomes most relevant for the large fractions commercial use found in the planning options of sequences 1.3 and 1.4.

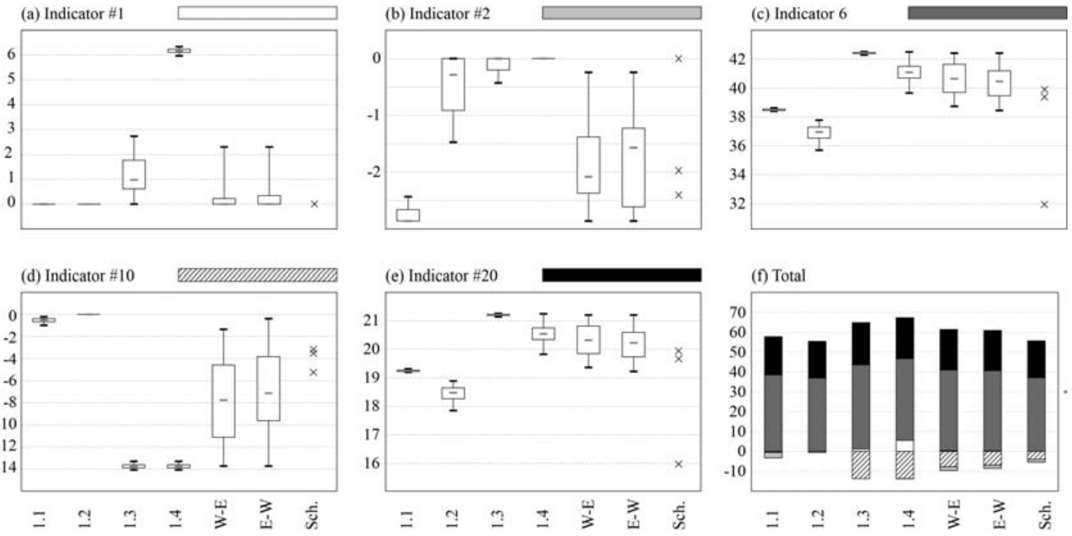

Figure 3.6: The variations in E_{tot} that are caused by changed boundary conditions in the discussed sequences of planning options, separated by the five relevant indicators. Mind the different scales. Sch.: three planning options from Schädler et al. (2011b)

Within each sequence in analysis 1, the variation between the land use options is primarily of a spatial nature (i.e., same features allocated on varying positions). Because indicators #6, #10 and #20 are not evaluated in a spatially explicit manner, the variations in E_{tot} that are caused by these indicators exclusively stem from the different surface areas with which the planning units contribute to the site's overall result. Hence, for analysis 1 the variations caused by these indicators are smallest as shown in Figure 3.6. Therefore, where the site's condition or the "status" of the entire site affects the analysis results, the spatial variations of planning on the site become less relevant.

Figure 3.6 furthermore shows identical patterns for indicators #6 and #20, although on different absolute scales. By definition in the aggregation scheme, these indicators do not distinguish between the residential and the commercial use type and are different only by their respective indicator weights (Müller and Rohr-Zänker, 2009). Figure 3.6 (f) depicts each indicator's contribution to the total change in E_{tot}.

3.4 DISCUSSION

The results of this case study have different implications with respect to the understanding (1) of the specific indicator evaluation scheme and its responses to different variations in input data and parameters, (2) of sustainable urban and regional planning on the case study site, and (3) of the potential benefit that the application of a transfer of indicator systems into automated assessments could have for indicator-based evaluation schemes in general.

(1) With regard to the understanding of the indicator evaluation scheme, the case study demonstrates that the transfer of the set of indicators into a spatially explicit evaluation scheme allows for a more detailed and deepened analysis than was possible with a manual indicator evaluation. New aspects of sustainable development can be assessed. One example is the determination of the most beneficial fractions of different land use types in mixed land use options. The additionally introduced transfer parameters such as threshold distances or chosen spatial metrics would obviously require site-specific calibration in order to make the results of such transferred sustainability assessments reliable. One major benefit of the standardized and automated assessment is that it facilitates such calibration and validation not only of the transfer parameters but also of parameters that were originally present in the indicator scheme, such as the indicator weightings, which in this case study showed to be of great importance.

(2) For a sustainable re-use of the presented case study site, the specific spatial allocation of land use types shows to be less relevant in comparison to assumptions that potentially affect the entire site or wide parts of its surrounding. This was exemplified by a general presence or lack of schools or local amenities in Analysis 3. When hypothesizing that the site was situated within an urban area

a strong increase in suitability values for virtually all investigated re-use options is observed. This clearly underlines the potential benefits of inner urban development. Nevertheless, the consideration of complex spatial dependencies is demonstrated to be crucial for successful planning. The effect is largest where given assumptions result in redevelopment options with low suitability values, and where only small fractions of land use types are to provide a beneficial complementation.

(3) Regarding the general implications of the proposed approach, the presented case gives an impression of the potential information that can be gained by using algorithmic spatially explicit evaluation of indicator-based sustainability assessment schemes. The results of Analyses 1 and 2 shows valuable insights that the automated evaluation provides with respect to convenient allocation and fractionation of different land use types. The results furthermore show how susceptible the expected sustainability of land use options is to underlying assumptions and (spatial) data. The automated assessment allows for the exploration of targeted variations in these assumptions and specifically designed data sets in sensitivity analyses, scenario analyses and hypothesis testing. Two considerations shall underline the huge potential for additional knowledge that could be provided by automatic and spatially explicit indicator evaluation: The repeated evaluation of 163 specifically designed mixed and two uniform land use options on 27 PU and under various different assumptions in this study each of 23 indicators had to be evaluated over 35,000 times. This task is by far too laborious if human evaluation was involved in every step. Still, only 4.7×10^{-7} % of all possibilities of this simple setup of 27 PUs and 3 land use types were evaluated. This emphasizes the huge potential in additional knowledge that can be provided by an automatic evaluation scheme. At the same time, with only 11 out of these 23 indicators being spatially variable, our case study contains a comparably low fraction of spatially varying indicators. Within context of land use planning, the majority of sustainability indicators may actually have a spatial component and consequently their evaluation should be performed in a spatially explicit way. Therefore the relevance and potential benefits of automated and spatially explicit sustainability evaluations may be much stronger than can be concluded from the results presented here.

3.5 CONCLUSIONS

The goal of sustainable urban and regional development has already been articulated in various studies decades ago, underlining that the revitalization of brownfields has the potential to strongly contribute to sustainable development. Nevertheless, operationalization of sustainability goals remains a challenge and to date only few instruments exist that allow the assessment of the quality of brownfield redevelopment in terms of sustainability. This article illustrates how the traditional stakeholder-based evaluation of existing indicator schemes can be transferred into an automated and standardized evaluation process that allows the spatially explicit consideration of sustainability issues within interdisciplinary spatial evaluation and optimization of land planning alternatives. This paper presents a framework that defines and describes an algorithmic (re-)formulation of indicator-based sustainability evaluation methods in a transparent and reproducible way. The implementation of the framework was applied to a field site in the city of Potsdam, Germany, where a set of regional and site-specific indicators proposed by Müller & Rohr-Zänker (2009) was explored in four systematic analyses of 165 different land use options under varying assumptions. This case study emphasizes the importance of spatially explicit sustainability evaluations and serves as proof of concept for the constructive use of previously established sets of sustainability indicators in an automated evaluation of a large number of planning alternatives.

Spatially explicit algorithmic schemes for the evaluation of sustainability indicators may be applicable to a range of different indicator sets found in the literature, and to various physical planning contexts such as habitat planning or water quality management. Their application could strongly improve not only the understanding of the consequences of physical planning decisions to sustainable development but also the quality and convenience of development, testing and validation of indicator sets and parameters for their respective evaluation schemes. Furthermore, it could enable the convenient consideration of sustainability issues within an integrated planning and for spatial optimization of land use options which in existing approaches is not present to date.

To be sure, due to the known limitations inherent in the representation of complex systems by simplified models and limited data (e.g., Walz et al., 2007), neither of these advantages can replace a detailed and expert-based evaluation of sustainability measures. They may, however, strongly improve the basis for transparent and stakeholder friendly discussions at early development stages. The presented method can streamline the pre-choice screening of beneficial and sustainable planning options and contribute to a strong improvement of the acceptance, applicability, transparency and comprehensibility of indicator-based sustainability evaluation schemes. Thereby it can facilitate complex decision making processes on our way towards sustainable brownfield development.

CONCLUSIONS

The identification of beneficial redevelopment options for brownfields during early planning stages is considered crucial for the initiation of successful redevelopment projects. This requires an integrated evaluation of planning alternatives, as well as the communication of the interdisciplinary evaluation results to stakeholders from different backgrounds. A reported lack in decision support systems (DSS) that adequately fulfil these requirements has been the motivation for this work. Within the previous chapters new methods were introduced that support the identification of redevelopment options that are beneficial in terms of the trade-off between low remediation costs, high expected market values and positive contribution to a sustainable development: Chapter 1 described the evaluation of 10 different land use options that are designed in an iterative "trial and error" planning process. Chapter 2 illustrated the targeted design of near-optimal planning alternatives in a deterministic way, and Chapter 3 illustrated the exploration of an entirely automated evaluation process for the evaluation of the sustainability of hundreds of planning alternatives. The major conclusions from these studies are summarized in the following.

- The development and application of an integrated assessment model for brownfield revitalization options reveal economic, ecologic and social consequences of alternative redevelopment plans on a large contaminated site. By consequently employing only simplified methods that require relatively little input data the integrated assessment provides screening-level decision support and can foster communication among stakeholders particularly in early phases of a redevelopment project (Chapter 1).
- Neglecting either one of the three main aspects, (i) the cost for subsurface remediation, (ii) the economic value less the perceived economic risk, and (iii) the sustainability of the future land use, in the case study leads to non-optimal land use plans, whereas an increased understanding of all three aspects results in land use options that are rated best in terms of economic value and in terms of sustainability (Chapter 1).
- In Chapters 1 it is confirmed that the redevelopment of brownfields is not intrinsically sustainable. It is also shown that sustainable BR options are not necessarily less favourable from an economic point of view.
- By an additional framework for the integrated evaluation of uniform land use options, as proposed in Chapter 2, the methods introduced in Chapter 1 can be used in order to directly determine near optimal allocations of distinct land use types. The described framework comprises methods that (i) provide an initial vision of beneficial brownfield reuse and that (ii) support planning iterations in order to render a purely economic-driven initial land use vision more convenient from a planning perspective and more valuable in terms of sustainable development. For the case study site, this deterministic approach

showed better results than the stakeholder-based trial and error iterations in the previous study.

- The traditional stakeholder-based evaluation of existing sustainability indicator schemes can be transferred into an automated and standardized evaluation process which enables the spatially explicit consideration of sustainability issues in an interdisciplinary optimization of spatial land use planning (Chapter 3). This work forms the basis for the optimization studies described by Morio et al. (2011).
- Chapter 3 has further emphasized the importance of spatially explicit sustainability evaluations and serves as a proof of concept on how a previously established set of sustainability indicators can be constructively used to evaluate a large number of planning alternatives by making the indicators amenable to an automated spatial evaluation scheme.
- It is common to the three chapters of this thesis that they aim at an integration of models for the evaluation of economic, ecological and sustainability aspects of brownfield redevelopment planning. As is stated in Chapter 2, within each of these three topics there are a multitude of aspects to be considered in a given redevelopment process. Every single one of these aspects can in principle be evaluated by a number of methods. Obviously the outcomes and the conclusions from an integrated assessment likely vary with the chosen models. This is exemplified by a comparison of different simplistic methods for remediation cost estimation by Schädler et al. (2007).
  The methods described in this thesis therefore have to be considered exemplary. They may have to be adapted (e.g., refined, expanded) or replaced by different methods in order to ensure applicability at different sites or later project stages, as will be suggested in more detail below. What is promoted in this work is that the three fundamental dimensions of ecological, social and economic sustainability should be considered and communicated among the stakeholders of any brownfield redevelopment project.

As mentioned in the introduction, this work was accompanied by the development of decision support software, the so-called SAFIRA II Megasite Management Toolsuite (MMT) which provides user-friendly implementation of most of the methods described in the previous chapters. To date, MMT modules enable the creation of BR options in terms of land use maps, the analysis of conflicts between existing contamination and planned land use, the pre-selection of suitable remediation options, the estimation of remediation cost by different estimating algorithms, the appraisal of the site's market value including a correction for MVR and location quality, an entire framework for the evaluation of sustainability, and an integrated spatial optimization of BR options based on genetic algorithms. Besides facilitating the data generation for this work, the tool provided hands-on experience of the developed methods to practitioners and stakeholders, i.e. to the target audience of this development. This enabled valuable direct feedback with respect to the relevance and applicability of the developed methods outside the scientific community. This feedback suggests that the tool (i.e., the SAFIRA II MMT) and the implemented methods provide a convenient representation of the complexities that are relevant during early stages of a brownfield redevelopment process. However, owed to the focus on interdisciplinary integration within this work, many aspects of brownfield redevelopment have been considered only in little detail here, and others have been entirely neglected. Future work should therefore cover the following topics.

1. *Case studies and calibration of methods*: The application of the SAFIRA II MMT to additional case study sites will further demonstrate both the methods' applicability and their limitations. The case studies will also provide a wider context to the partly abstract results of previous evaluations. As an example, the results of the sustainability evaluation, the so-called suitability values (E_{tot}), will gain significance from comparing them to previously evaluated sites. Also, case studies at already developed sites with known remediation cost and market value should provide data for the calibration of the models. This is especially true for the described remediation cost models and their unit cost basis, for the novel quantification of the sustainability assessment (section 1.2.5), and for the market value appraisal with its new concepts of MVR (section 1.2.4) and quantitative correction for location quality (section 2.2.3). At the time of writing, one additional case study in Radeberg, Germany, is being worked on and a number of additional sites for potential case studies are under discussion within the context of the TIMBRE EU project until June 2014.
2. *Dissemination*: Introducing the tool to a large number of users from the target audience increases the possibility of receiving vital feedback with respect to the practicability of the tool and the underlying ideas.
   The widespread dissemination of these concepts is aimed at by the development of web-based decision support within the scope of the TIMBRE EU project until June 2014.
3. *Remediation technologies*: The empirical estimates on remediation costs introduced in Chapters 1 and 2 of this thesis are only partly technology-specific and can therefore not consider comparison and selection of suitable remediation technologies. To date, the SAFIRA II MMT cost estimation module provides an evaluation and comparison of three different technologies for the containment of chlorinated solvent plumes[6]. MMT also contains an

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[6] Schädler, S., Finkel, M., SAFIRA II Megasite Management System (MMS): Schadenstypbezogene Kostenermittlung. Project report 07/2011, 26pp.

implementation of the PRESTO tool[7] developed in the WELCOME EU project which allows for a determination of suitable remediation technologies and which has not been discussed within this thesis. Considering a screening of suitable remediation technologies for the given conditions at brownfield site in combination with a cost estimating method for these technologies, would open a range of interesting scientific topics such as (i) the planning of realistic remediation scenarios from the spatially varying suitability of different technologies, (ii) the consideration of different technology combinations to enhance their effectiveness, especially with regard to multiple contaminants, and (iii) the estimation of the time needed until a site is adequately remediated for the intended future use (see item no. 4 below).

4. *Remediation/redevelopment timeframes*: The consideration of specific soil and groundwater remediation technologies should also be expanded with respect to the expected time that is required for remediation, i.e. the time until a certain future land use is actually possible. This in turn has implications on the preference of methods (e.g., Bayer & Finkel, 2006) and on the economic appraisal of the site and the preference of land use planning alternatives. A method for the preliminary assessment of remediation times has recently been described by McKnight & Finkel (2007). Using this or a similar method for a rough estimate of remediation timeframes would make land use planning decisions more robust and would furthermore bring into play the topic of possible interim land use (see item no. 5 below).
5. *Interim land use*: Land use alternatives as described in the previous chapters were considered static in time. This twofold simplification neglects both the economic consequences of a delay in the site's reuse due to the time required for adequate remediation and the possibility for additional benefits from a less sensitive interim land use.

   One very interesting aspect within this topic is an interim use for energy crops: Fast-growing trees such as willow or poplar could not only be used for the generation of renewable energy, but also for the screening of the subsurface contamination ("phytoscreening", e.g., Holm & Rotard, 2011; Larsen et al., 2008) and for the remediation of the latter ("phytoremediation", e.g., Schnoor et al., 1995; Salt et al., 1995; Salt et al., 1998). This combination appears logical and topical. Given current German incentives for small bioenergy plants (< 20 MW), medium sized brownfields between 5 ha and 20 ha could be suitable for pilot projects (Dr. Daniela Thrän, personal communication, February 2011).

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[7] Schädler, S., Morio, M., Finkel, M., SAFIRA II Megasite Management System (MMS): MMT-PRESTO: Werkzeug zur Vorauswahl von Sanierungsmaßnahmen. Project report 11/2009, 38pp.

6. *Uncertainty of the results*: The uncertainty of the economic evaluation, which includes the aspect of uncertainty of the remediation cost estimation, is accounted for in this work via the so-called Mercantile Value Reduction (MVR) as described in Chapter 1 (section 1.2.4). The empirical concept of MVR attributes an economic discount to the manifold uncertainties involved in the planning and appraisal of the redevelopment process. MVR leads to a reduction of the estimated market value with the result that the market value itself contains no uncertainty margin. This reflects the appraisal expert's view, which in its practical implication may be the most relevant one. However, MVR has some intrinsic weaknesses which could be improved at least with respect to the consideration of uncertain remediation costs. Rather than an empirical average discount MVR (or a similar concept) should consider a more detailed evaluation of uncertainty as exemplified by Weber (1997). The MMT to date contains a Probabilistic Conflict Analysis[8] and a respective cost estimation tool[9]. Both require a statistically relevant number of equiprobable contaminant distributions and thereby shift the complexity towards the input data generation. Alternatively, an examination of the uncertainties could be based on the work of McMahon et al. (2001) using a Monte Carlo Analysis, or by an expansion of the more sophisticated method described by Bolster et al. (2009) which in absence of the relevant data can be based on expert opinion. More generally, Aerts et al. (2003) and Ascough et al. (2008) summarize important issues to be addressed with respect to the consideration of various aspects of uncertainty in environmental decision making.
7. *Input data*: Previous work on the SAFIRA II MMT has considered the relevant input data a given prerequisite for the application of the tool and the underlying methods. This excludes the scientifically interesting topics of site investigation and data interpretation. Especially at early project stages, quantitative data about a site's contamination is typically sparse and first estimates on the contamination may additionally have to be based on soft data like information from stakeholders or on semi-quantitative data (e.g., from plant screenings). Incorporating such data into a DSS has the potential of decreasing the uncertainty in the evaluation results, as previously suggested (e.g., Crumbling et al., 2001). An improved economic evaluation could then perform a data-worth analysis, i.e., it could consider the trade-off between a reduction in the uncertainty of the evaluation results and the cost for additional

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[8] Morio, M., Finkel, M., 2011. SAFIRA II Megasite Management System (MMS): Megasite Management Toolsuite (MMT): Probabilistische Konfliktanalyse. Project report 01/2011, 14pp.

[9] Schädler, S., Finkel, M., SAFIRA II Megasite Management System (MMS): Schadenstypbezogene Kostenermittlung. Project report 07/2011, 26pp.

site investigation (e.g., Cirpka et al., 2004; James & Gorelick, 1994; Taylor et al., 2004).

8. *Improved Sustainability Assessment*: The sustainability evaluation scheme that has been described in this thesis allows for an automated spatially explicit quantification of sustainability. The disadvantage of this method is that it is based on a fixed set of sustainability indicators and on predefined land use types. Thereby it contradicts the widespread consensus in sustainability research that sustainability needs to be specifically defined for every project by involvement of the stakeholders (e.g., Reed et al., 2006). Besides the described method, the MMT contains a framework which allows groups of stakeholders to set up their own specific definition of sustainability[10]. However, in contrast to the first method, this framework to date lacks the possibility for a spatially explicit evaluation of sustainability indicators. It would be desirable to combine the advantages of both methods by providing a tool that allows for the application of the methods described in Chapter 3 to stakeholder-defined indicator sets. Thereby, indicator sets may adequately reflect locally specific sustainability issues and at the same time enable the consideration of sustainability within spatial optimization algorithms.
9. *Sustainability: predefinition of land use types*: The sustainability assessment used in Chapters 1 through 3 is based on predefined land use types with anticipated properties and impacts on their surrounding. Thereby this assessment relies on today's conception of these land use types without considering or even promoting their potentially positive future evolvement. Rather than that, for a more detailed evaluation land use types would need to be defined for every redevelopment process just as the sustainability indicators themselves.

This work aimed at an improvement of the interdisciplinary decision support for brownfields redevelopment. The development of new concepts for the integration of three scientific fields was focusing on basic consideration of (i) the cost for remediation of a given subsurface contamination, (ii) the valuation of contaminated land and (iii) the sustainability of urban and regional land use planning. The developed concepts set a strong focus on the reduction of complexity in favour of comprehensibility to stakeholders. Thereby the limitations that are inherent in any representation of complex systems by simplified models

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[10] Schädler, S., Morio, M., Bartke, S., Bleicher, A., Finkel, M., 2009. SAFIRA II Megasite Management System (MMS): Beschreibung der in die MM Toolsuite integrierten Methoden. Project report 12/2009, 61pp.

and limited data are particularly relevant in this study. This implies that neither of the described methods can replace a detailed and expert-based evaluation of planning alternatives. This research shall provide a basis for the initiation and the streamlining of interdisciplinary decision making processes and thereby improve sustainable brownfield development.

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