Dissertation

A GEOSPATIAL PERSPECTIVE ON POPULATION EXPOSURE AND SOCIAL VULNERABILITY IN DISASTER RISK RESEARCH

Demonstrating the importance of spatial and temporal scale and thematic context

eingereicht zum Zwecke der Erlangung des akademischen Grades eines
Doktors der Naturwissenschaften
der Technischen Universität Wien, Fakultät für Mathematik und Geoinformation
von

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Doctoral Thesis

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submitted in satisfaction of the requirements for the academic degree of
Doctor in Natural Sciences
of the Vienna University of Technology, Faculty of Mathematics and Geoinformation
by

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Vienna, Austria, 11 October 2013

Declaration

[German] Hiermit erkläre ich, dass ich diese Arbeit selbständig verfasst habe und sie für keinen anderweitigen akademischen Titel eingereicht wurde. Sämtliche verwendete Quellen und Hilfsmittel wurden vollständig angegeben, sowie diejenigen Stellen der Arbeit, einschließlich Tabellen, Karten und Abbildungen, die anderen Werken oder dem Internet im Wortlaut oder dem Sinn nach entnommen sind, unter Angabe der Quelle als Entlehnung kenntlich gemacht. Alle persönlichen Ansichten in dieser Dissertation sind meine eigenen und entsprechen nicht notwendigerweise jenen von unterstützenden Institutionen.

I declare that all the material presented in this thesis is my own work and has not been written, entirely or partly, by any other person and that it has not been submitted for any other academic award. Work done in collaboration with, or with the assistance of others, is indicated as such. I also declare that any external information used, including texts, tables, maps, and figures, are cited accordingly if they are used literally or analogously. Any views expressed in this dissertation are my own and do not necessarily match those of any supporting or funding institution.

Vienna, September 2013

Large parts of the present work have already been incorporated in peer-reviewed journal papers and reports – respective references and citations are given at the beginning of corresponding (sub)chapters. This work was realized based on the expertise built up in the context of several research projects working at the AIT Austrian Institute of Technology and during various international visiting research stays as well as further international research collaborations. In direct relation to this dissertation, these are as follows. A complete list is attached in the resume section at the end.

Related research projects at AIT Austrian Institute of Technology:

- <u>CRISMA</u>: Modeling crisis management for improved action and preparedness
  Since 2012: 7th Framework Programme, European Union
- <u>geoland|2</u>: Operational Monitoring Services for our Changing Environment
  2008 – 2012: 7th Framework Programme, European Union
- <u>GMSM (I & II)</u>: Global Monitoring of Soil Moisture for Water Hazards Assessment
  2008 – 2012: Austrian Space Applications Programme VI/VII
- <u>EO-NatHaz</u>: Assessment of Natural Hazard Damage Potential and Risk Exposure with Earth Observation
  2007 – 2008: Austrian Space Applications Programme IV

Related research stays:

- <u>The World Bank</u> / Urban and Disaster Risk Management Unit
  2013 (Jul – Sep): Washington, DC, USA
- <u>Global Facility for Disaster Reduction and Recovery</u> / GFDRR Labs
  2012 (Jun – Sep): Washington, DC, USA
- <u>University of Southern California</u> / Spatial Sciences Institute
  2010 (Aug): Los Angeles, CA, USA
- <u>Columbia University</u> / CIESIN (Center for International Earth Science Information Network) & <u>NASA</u> / SEDAC (Socioeconomic Data and Applications Center)
  2009 (Jul – Sep): Palisades, NY, USA
- <u>NOAA</u> (National Oceanic and Atmospheric Administration) / NGDC (National Geophysical Data Center)
  2007 (Jul – Sep), 2008 (Jul), 2009 (Sep – Oct): Boulder, CO, USA

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The process of writing this thesis has been a long journey for me and over the years there have been many situations and people that influenced me in some way and helped shaping that journey with or without being aware of it. This also includes my friends and in particular my parents and family who I want to thank for their unconditional support. I want to specifically highlight a couple of key persons and also say thank you to all the ones who are not listed individually here.

Despite spending the last time not physically in Vienna any more, it has surely been my affiliation to the AIT Austrian Institute of Technology that basically set the ground for all that has come. Klaus Steinnocher has been advising and fostering me from the very beginning of my scientific career and we have successfully progressed what we started already years ago during my Masters studies. You have been much more than a colleague, advisor, or personal mentor. Thanks for supporting all my interests and activities in almost every possible and impossible sense! I am aware that it may not have been all that easy 'guiding' me 'through' all the walls that I tried to pull down in spirit of idealism. Thank you! Also our core research group at AIT has been immensely helpful and inspiring in many ways throughout my time in Vienna. I specifically want to say thanks in that regard to Mario Köstl and Jan Peters-Anders who always helped finding a path to solution in the GIS-universe when needed.

My decision to pursue my PhD studies at Vienna University of Technology was driven by the motivation to move towards an even more integrative perspective to GIScience and spatial data handling including building up improved expertise in varying remote sensing aspects. In achieving that objective I want to say thank you to my official supervisor Wolfgang Wagner for accepting me as his PhD candidate and guiding me remotely through my process of personal and scientific development. Thanks for being open to different perspectives and for always strengthening my appreciation of scientific values!

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This thesis would not look the way it does without my strong international involvement and the contacts made and experiences gained. Throughout the years I have been working with many brilliant people who shaped the way I am thinking and operating not only in scientific terms – be it at NOAA, at Columbia University, at the University of Southern California, or at the World Bank. At this point I want to refer back to the very beginning and say thank you to Chris Elvidge from NOAA-NGDC for truly amplifying my interests in global issues to be tackled with spatial analysis and for further stimulating my aspirations to 'get out' and get strongly involved and interconnected in the international scientific community.

Along those lines I also want to account for the dozens of conference visits during those years – thanks to AIT support – which offered me the chance to extend my horizon in many aspects, with science and its application just among them. At one of those trips I met Sérgio Freire who – after first attracting my attention by discussing my presentation in his typical lively way – turned out to become the most amazing colleague, my best friend, and eventually best man. Many parts of this thesis would have gone in different directions without our countless after-hour-studies and discussions. Thanks buddy for everything!

Coming to an end, I want to address these lines to my wonderful wife Dilek who inspires me in every single aspect of my life and through her amazing dedication always brings out the very best of me. With also bringing in your thematic expertise your input and review have been crucial for the outcome of this thesis. Thank you for all your support and motivation, and above all thank you for being the sunshine, joy, and melody of my life canım aşkım!

“Life is what we make of it. Travel is the traveler.

What we see isn't what we see but what we are.”

Fernando Pessoa, The Book of Disquiet

Abstract

In the context of disaster risk management and in particular for improving preparedness and mitigation of potential impacts of hazardous events both in the short- and long-term, information on socio-economic characteristics including aspects of situation-specific human exposure and vulnerability is considered vital. This thesis elaborates on multi-level geospatial information and modeling approaches from global to local scales that can serve to build up inventories for people involved in disaster risk management related areas. Concepts and applications related to the *human exposure* and *social vulnerability* domain as well as inherent *space-time-dynamics* aspects are addressed by illustrating the varying dimensions and *contextual implications*. Newly developed methods are highlighted and evaluated that can be applied to assess population exposure to natural hazards, ranging from global and continental-scale population disaggregation approaches to high resolution functional urban system models. Going one step further, the integration of social structure and the development of aggregative social vulnerability indicators eventually enable the differentiation of situation-specific risk patterns. Hazard domains addressed in this context include earthquakes, tsunamis, coastal flooding, and heat stress amongst others.

With disaster risk management being considered "*an inherently spatial problem*" (Goodchild, 2005) this thesis particularly aims at investigating root causes of threats and impacts on society and therefore also the dynamics and variability of the decisive underlying internal societal structures and risk-shaping characteristics, i.e. "*how and why […] vulnerability […] and its inherent characteristics […] change from place to place and over time*" (Cutter et al., 2002). The dedicated research emphasis and strategic guideline is in that context built upon the necessity of applying *scale- and level-specific geospatial data* and information with proper accounting for the *action-specific thematic context* and application in various stages of integrated disaster risk management.

Kurzfassung [in German]

Informationen zu sozioökonomischen Charakteristika sozialer Systeme einschließlich ihrer situationsspezifischen Gefährdung und Vulnerabilität werden im Rahmen von Katastrophen- und Risikomanagement und insbesondere zur Verbesserung von Vorsorge- und Schadensbegrenzungsmaßnahmen sowohl im kurz- als auch langfristigen Kontext als unerlässlich erachtet. Die vorliegende Dissertation beschäftigt sich ausführlich mit komplexen mehr-dimensionalen räumlichen Geoinformations- und Modellierungsansätzen von der globalen zur lokalen Ebene, die helfen können, integrativen Informationsgewinn zu erlangen und kontext-spezifische Datenbanken zur Unterstützung von Entscheidungsträgern im Naturgefahren- und Katastrophenmanagement und damit verwandten Bereichen aufzubauen. Konzepte und Anwendungen im Kontext von *Gefährdung und Vulnerabilität sozialer Systems* sowie inhärente Aspekte zur *Raum-Zeit-Dynamik* und den unterschiedlichen Dimensionen und *kontext-spezifischen Implikationen* werden im Detail diskutiert. Neu entwickelte Methoden zur Abschätzung des Gefährdungsgrads von Bevölkerung im Naturgefahrenkontext werden hervorgehoben und bewertet, wobei die Palette von globalen und kontinentalen Bevölkerungsdisaggregationsansätzen zu hochaufgelösten funktionalen Stadtmodellen reicht. Eine Stufe höher hinsichtlich der thematischen Komplexität beschäftigt sich die Dissertation mit der Integration von sozialer Struktur und der diesbezüglichen Entwicklung aggregativer Indikatoren zur sozialen Vulnerabilität, die letztendlich eine Unterscheidung situationsspezifischer Risikomuster ermöglicht. Naturgefahrentypen, die in diesem Zusammenhang behandelt werden, sind unter anderem Erdbeben, Tsunamis, Überschwemmungen von Küstengebieten, und Hitzestress.

Vor dem Hintergrund, dass Naturgefahren- und Katastrophenmanagement als „*inhärent räumliches Problem*“ beschrieben wird (Goodchild, 2005), setzt sich die vorliegende Dissertation speziell zum Ziel, Ursachen von Bedrohungen und Auswirkungen auf die

Gesellschaft und in diesem Zusammenhang auch die Dynamik und Variabilität der entscheidenden zugrundeliegenden gesellschaftlichen Strukturen und risikoformenden Eigenschaften zu untersuchen, d.h. „*wie und warum […] Vulnerabilität […] und seine inhärenten Merkmale […] sich von Ort zu Ort und im Laufe der Zeit ändern*“ (Cutter et al., 2002). Forschungsschwerpunkt und strategische Richtlinie der vorliegenden Dissertation beziehen sich in diesem Kontext auf die Notwendigkeit der Anwendung *skalen- und dimensionsspezifischer raumbezogener Daten* und Informationen unter ordnungsgemäßer Berücksichtigung des *situationsspezifischen thematischen Kontexts* der jeweiligen Implementation in verschiedenen Phasen des integrativen Katastrophen- und Risikomanagements.

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List of Acronyms

AAG	Association of American Geographers
ACS	American Community Survey
AIT	Austrian Institute of Technology
ALS	Airborne Laserscanning
API	Application Programming Interface
ASOS	Automated Surface Observing System
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATUS	American Time Use Survey
CAPRA	Disaster Risk Information Platform for Probabilistic Risk Assessment
CC	Climate Change
CDC	(U.S.) Centers for Disease Control and Prevention
CIAT	International Center for Tropical Agriculture
CIESIN	Center for International Earth Science Information Network (Columbia University)
CLC	CORINE Land Cover
CLM	Climate Local Model
CORINE	Coordination of Information on the Environment
CRISMA	Crisis Management for Improved Action and Preparedness (EU-FP7 Project)
DC	(Washington) District of Columbia
DKRZ	Deutsches Klimarechenzentrum (German Climate Computing Center)
DMSP	Defense Meteorological Satellite Program
DPRI	Disaster Prevention Research Institute (Kyoto University)
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
EC	European Commission
EEA	European Environment Agency
EFTA	European Free Trade Association

EGM	EuroGlobalMap
EM-DAT	Emergency Events Database
EO	Earth Observation
EPA	(U.S.) Environmental Protection Agency
EQ	Earthquake
ERM	EuroRegionalMap
ETM+	(Landsat) Enhanced Thematic Mapper
EU	European Union
FAO	(U.N.) Food and Agriculture Programme
FEMA	(U.S.) Federal Emergency Management Agency
GAR	Global Assessment Report
GDP	Gross Domestic Product
GED4GEM	Global Exposure Database for Global Earthquake Model
GEM	Global Earthquake Model
GEOSS	Global Earth Observation System of Systems
GHCN	Global Historical Climatology Network
GI	Geo(graphic) Information
GI4DM	Geo-Information for Disaster Management
GIS	Geographic Information System(s)/Science
GIT	Geoinformation technology
GMES	Global Monitoring for Environment and Security
GPS	Global Positioning System
GPW	Gridded Population of the World
GRID	(UNEP) Global Resource Information Database
GRUMP	Global Rural-Urban Mapping Project
HETUS	Harmonized European Time Use Survey
HR	High Resolution
HSI	Heat Stress Index
HSRI	Heat Stress Risk Index
HSVI	Heat Stress Vulnerability Index
HWF	Heat Wave Frequency

ICA	International Cartographic Association
IDNDR	International Decade for Natural Disaster Reduction
IDRiM	Integrated Disaster Risk Management
INSPIRE	Infrastructure for Spatial Information in the European Community
IPCC	Intergovernmental Panel on Climate Change
ISDR	(U.N.) International Strategy for Disaster Reduction
ISPRS	International Society for Photogrammetry and Remote Sensing
LAU	Local Administrative Unit
LBSN	Location-Based Social Networks
LECZ	Low Elevation Coastal Zone
LMA	Lisbon Metropolitan Area
LULC	Land Use/Land Cover
LS	LandScan
LSS	Location Sharing Services
MAUP	Modifiable Areal Unit Problem
MMI	Modified Mercalli Intensity
MOVE	Methods for the Improvement of Vulnerability Assessment in Europe (EU-FP7 Project)
NASA	National Aeronautics and Space Administration
nDSM	normalized Digital Surface Model
NCDC	(U.S. NOAA) National Climatic Data Center
NCR	(U.S.) National Capital Region
NDVI	Normalized Difference Vegetation Index
NGA	(U.S.) National Geospatial Agency
NGO	Non-Governmental Organization
NH	Natural Hazards
NLCD	(USGS) National Land Cover Database
NLDAS	North America Land Data Assimilation System
NOAA	(U.S.) National Oceanic and Atmospheric Administration
NRC	(U.S.) National Research Council
NUTS	Nomenclature of Units for Territorial Statistics

NWS	(U.S. NOAA) National Weather Service
OBIA	Object Based Image Analysis
OECD	Organisation for Economic Co-operation and Development
OLS	Operational Linescan System
ORNL	Oak Ridge National Laboratory
OSM	Open Street Map
PEPPER	Pre-Event Planning for Post-Event Recovery
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PROTAML	Regional Plan for Territorial Management for the Lisbon Metropolitan Area
SAFER	Seismic eArly warning For EuRope
SAHIE	Small Area Health Insurance Estimates
SEDAC	Socio-Economic Data and Application Center (NASA)
SHELDUS	Spatial Hazard Event and Losses Database for the US
SRTM	Shuttle Radar Topography Mission
TIGER	Topologically Integrated Geographic Encoding and Referencing
UN	United Nations
UNEP	U.N. Environment Programme
urbanAPI	(Interactive Analysis, Simulation and Visualisation Tools for) Urban Agile Policy Implementation (EU-FP7 Project)
US	United States (of America)
USGS	U.S. Geological Survey
VGI	Volunteered Geographic Information
VHR	Very High Resolution
VHSR	Very High Spatial Resolution
WALTPS	West Africa Long Term Perspective Study
WDPA	World Database on Protected Areas

1 Introduction and context[1]

1.1 Background

This study is set in an interdisciplinary scientific framework, drawing upon a basic background in geography and geoinformation science (GI Science) and accounting for the detailed and explicit expertise of integrating geospatial information and technology in an applied research context built up during the work and studies at the AIT Austrian Institute of Technology and collaborative research with the Vienna University of Technology as well as other national and international partners. Already dealing with issues of spatial and functional modeling of population patterns in urban environments prior to the presented doctoral studies (Aubrecht, 2007), the main idea was to move on further along those lines and set the thematic context and focus to one of today's crucial topics and "*grand challenges*" (NSTC, 2005; Ambrose, 2008) for both the scientific world and the general public, i.e. dealing with assessment, analysis, and management of natural disasters (Wisner et al., 2004; Baas et al., 2008; UNISDR, 2011) as well as identifying and evaluating options for enhancing related resilience of social systems (e.g., Adger, 2000; Folke, 2006; Manyena, 2006; Olson, 2011). This is seen in particular in the context of investigating root causes of threats and impacts on society and therefore also with regard to the dynamics and variability of the decisive underlying internal societal structures and risk-shaping characteristics, i.e. "*how and why […]vulnerability change[s] from place to place and over time*" (Cutter et al., 2002; van Westen, 2012).

[1] Parts of this introductory section refer to Aubrecht et al. (2013a)

1.2 Geospatial and temporal dimensions and scale domains in disaster risk research

While it is understood that even small disturbances may cause dramatic social consequences to an inherently vulnerable system (Adger, 2006), today's policies in a dynamic environment of constant change on a global scale aim to manage coping and adaptive capacities rather than to follow prior aspirations to control and limit change in assumedly stable systems (Gallopín, 2006; Smit and Wandel, 2006). The observed increase in the number, frequency, and severity of weather extremes and associated catastrophic events (Birkmann, 2006a) such as the 2010 Haiti Earthquake, the 2011 Tohoku Earthquake and Tsunami and entailed nuclear disaster, and the most recent 2012 Superstorm Sandy hitting the Eastern United States has boosted the public awareness of hazards and threats exposure and inherent vulnerabilities of modern society. Risk patterns and related damage potentials and impact characteristics are subject to constant change due to the interaction of environmental and societal developments.

"Disaster management is an inherently spatial problem"

(Quote by Michael F. Goodchild, 2005)

Geographic Information Systems (GIS) and the later promoted field of GI Science (Goodchild, 1992; Longley et al., 2010) and related technologies including airborne and satellite remote sensing techniques have long been considered crucial in disaster monitoring and risk and emergency management (Alexander, 1991; Johnson, 1992; Rengers et al., 1992; Cova, 1999; NRC, 2006). The United Nations' proclamation of the 1990s as the International Decade for Natural Disaster Reduction (IDNDR) (UN, 1987) attracted increased attention in the scientific research community regarding the development of improved methods and more effective models for risk reduction measures. Already in the early 1970s the UN had created an authorized Disaster Relief Office (UNDRO) in order to "*promote the study, prevention, control and prediction of natural disasters*" and to "*assist in providing advice to governments on pre-disaster planning*" (UNISDR, 2013a). Technological advancements in the field of geoinformation technologies (GIT) including improved geospatial data processing and analysis methods based on GIS, remote sensing, and enhanced global positioning systems (GPS), in line with the setup of the IDNDR-succeeding United Nations International Strategy for Disaster Reduction (UNISDR), eventually resulted in a strong promotion of an integrated and applied perspective on GI Science in disaster risk research (Chen et al., 2003; Abdalla and Li, 2010; Altan et al., 2010; Herold and Sawada, 2012).

Locational aspects have since then increasingly been seen essential in the aim of building disaster resilient communities through coordinated international action by promoting increased situational risk awareness as an integral component of sustainable development (e.g., Mileti, 1999; UNISDR, 2001; Godschalk, 2003, Maskrey, 2011). With disasters and disaster management being an "*inherently spatial*" problem (Goodchild, 2005; Curtis and Mills, 2009), geographic information and related technologies applied for data interpretation and information dissemination can provide insight and decision support in all aspects of integrated disaster risk management (DRM) and offer the basis for estimating and mapping risk, for determining damage potentials and impacted areas, for evacuation planning, for resource distribution during recovery, and for risk communication to involved stakeholders (Goodchild, 2006; Maglia-Norgren, 2009; Manfré et al., 2012; van Westen, 2012; Piper, 2013).

Figure 1: Mapping and communicating risks (cartoon from Natural Hazards Observer, 05/2006).

The term disaster is usually not used until severe impacts on social systems including human beings and associated assets are caused, i.e. a catastrophe unfolds when an extreme event exceeds a community's ability to cope with that event's impacts. A more broad perspective going beyond the social scope might include wide-scale impacts on ecosystems, particularly related to substantial environmental pollution such as oil spills and toxic chemical release.

"Warn the right people in the right place at the right time"

(Quote by Steven D. Ambrose, 2008)

The assessment of spatial and temporal dimensions is an essential part within integrated disaster risk management, but has so far often been neglected in respective academic efforts (Egner & Pott, 2010; Müller-Mahn, 2013). Understanding the spatial patterns of hazardous events as well as the geographic limits of their potential impacts and how they develop over time is essential particularly when combined with information on human beings and social systems in general, i.e. for both risk reduction measures prior to an event and follow-up response and recovery efforts. With "*each phase [i.e., pre-/post-event] [being] geographically related to where people, places, and things are spatially located*" (Gunes and Kovel, 2000), the effective use of GIT offers huge potential to significantly enhance the entire disaster management process (van Westen, 2012).

Applications and challenges that GI Science, related tools and methods are able to tackle in that regard include e.g. the representation, analysis, and cognition of geographic information, as well as associated dynamics and uncertainties (Cutter, 2003). Recent improvements in information and model interoperability as well as inter-accessibility (Goodchild, 2005) through new data sharing, crowdsourcing, and integration initiatives (Havlik et al., 2011; Meier, 2012; Norheim-Hagtun and Meier, 2010) add to this agenda.

"Everything that happens,

happens somewhere in space and time"

(Quote by Michael Wegener; from Goodchild, 2005)

This statement on space and time might seem very much self-evident. However, it is exactly that implicitness to our understanding of the processes of our world that shows and underlines its critical importance. Goodchild (2005) outlines that "*the location of an event establishes its context*". He further argues that "*space and time appear explicitly*" in any type of process models. Responding to public and policy interests driven by change, already in the very early days of GIS (early 1970s) researchers were increasingly attempting to analyze geographical processes, i.e. developing statistically and mathematically models to try and find ways for modeling the evolution of spatial patterns through time (Wilson, 1972; Cliff & Ord, 1975). The theoretical framework in that regard was grounded in the social sciences and social geography in particular, i.e. studying the effects of space and time in human spatial activity (e.g., time-space prisms and related domain constraints by Hägerstrand, 1970). Efforts to apply space-time concepts to the GI Science domain have become more and more prominent in the following decades (e.g., Hooper & Hewings, 1981; Goodchild et al., 1993; Hornsby & Egenhofer, 2000; Peuquet, 2002; Batty, 2005a; Miller, 2005).

> ***"The application of GIS […] raises the fundamental concern about the 'proper' scale of analysis"***
>
> *(Quote by Luc Anselin, 1999)*

The parameter 'scale', both in spatial and temporal dimensions, has been identified as key indicator to set the framework for consistently organizing information for literally any kind of assessment, and particularly relevant in a disaster risk context (Rengers et al., 1992; Birkmann and von Teichman, 2010; Fekete et al., 2010). Different scale concepts and definitions across disciplines including remote sensing and spatial modeling have been comprehensively discussed in the literature (e.g., Jenerette & Wu, 2000; Wu & Li, 2009). There is a general need for holistic multi- and cross-scale as well as dynamic and process-oriented considerations in both spatial and temporal contexts (Kasperson et al., 2001; Cash et al., 2006). In disaster risk and vulnerability related studies it has been documented that different approaches are demanded either (1) integrating cross-scale dynamics – and thus working at multiple scales – or (2) rather reducing complexity by focusing at one scale or level (Fekete et al., 2010). Spatial analysis and modeling "*provide the basis for data integration, or [consistent] conversion of data collected at one spatial scale and temporal dimension to other scales and dimensions*" (Anselin, 1999). The application of geoinformation technology and spatial analysis tools enable the acquisition and processing of data for any scale and level, but it also highlights the fundamental issue about identifying the 'proper' scale of analysis as was stressed almost 15 years ago.

> ***"The identification of the appropriate types of scale (spatial, temporal) and the type of nesting of phenomena (single-level, multi-level, cross-level) should be a prior step to conceptualization."***
>
> *(Quote by Alexander Fekete, 2010)*

The *spatial scale* of assessment in a disaster risk research and management perspective is most relevant in terms of the level of spatial detail and the spatial extent (Goodchild, 2001). Approaches can vary from analyzing the global picture to identification of regional and local-level conditions which strongly affects the scale-dependent data sources' context-specific applicability and usability (Aubrecht et al., 2013b). The *temporal scale* can e.g. relate to the analyses' and actions' points in time with regard to the course of a certain (potentially disastrous) event, i.e. pre-event vs. post-event assessment in all its long- and short-term variations. Time scales can in that context range from decades (climate change adaptation) to days (early-warning and immediate response actions) (Goodchild, 2010). For example in post-event emergency management applications almost always "*the need for speed*" is stressed, i.e. in particular fast immediate response bearing the greatest chance of saving lives (Goodchild, 2008a). Furthermore, the temporal scale is essential when looking at certain characteristics of elements at risk (Kakhandiki and Shah, 1998). Besides inherent short-term temporally variable characteristics or 'micro-level components' of exposure to potential hazardous events whose variations can be spatio-temporally traced and tracked, e.g. related to human mobility patterns in the diurnal cycle (Goodchild, 2008b; Freire, 2010), those patterns also evolve in the medium and long term ('macro-level dynamics') (Fekete et al., 2010). Furthermore, with ongoing social, economic and built-environment changes including often unplanned and uncontrolled urban growth and rapid urbanization, more people tend to live in high-hazard areas than ever before, also including associated assets and corresponding monetary values (Baas et al., 2008; Aubrecht et al., 2012a; Hewitt, 2013).

Earth Observation (EO) technology and derived geographical information have great potential to monitor and represent spatially explicit phenomena, in particular related to built-up areas and related structural elements at risk (e.g., Schneiderbauer, 2013), therefore supporting exposure and vulnerability analysis as well as impact assessment and many other aspects of disaster risk modeling and management (Davidson, 2013). With regard to the space-time characteristics of spatially-explicit information including EO-based data sources and specifically its capacities as potential input for geospatial analysis in a disaster risk context, scale issues are intertwined with inherent resolution aspects, i.e. the trade-off between possible spatial and temporal resolution of a data set compilation has to be considered (e.g., Quattrochi & Goodchild, 1997; Lillesand et al., 2008). Referring to the raster data domain, very high spatial resolution (VHSR) imagery in the sub-meter range is readily available and can be applied for hazard and disaster related phenomena detection. However, the higher the spatial resolution the more ‘focused’ is the view or ‘perspective’ of a sensor and consequently its spatial coverage which results in longer revisit periods, i.e. lower temporal resolution (see fig. 2). This inevitable compromise in terms of choosing the best-suited input data underlines the essential case of ‘scale’ in GI-related research and applications and extends the quest for identification of the ‘proper’ scale to the *necessity of identifying the ‘proper, feasible, and applicable’ scale of analysis*. With regard to remote sensing data it should be added that some satellite systems have the capability to tilt their sensors and thus image the same area several times during different satellite overpasses. For analyses with only short time ranges this might indeed allow to overcome the dichotomy of high spatial and temporal resolution and compile an optimal data set with regard to both domains. Also, sets of identically-constructed sensors flying in just marginally temporally-shifted orbits offer this short-interval time-stamp capability, e.g. the Disaster Monitoring Constellation (Stephens et al., 2008). Furthermore, some satellites (e.g., Formosat-2) operate in special orbits designed for high resolution change detection (Liu et al., 2013).

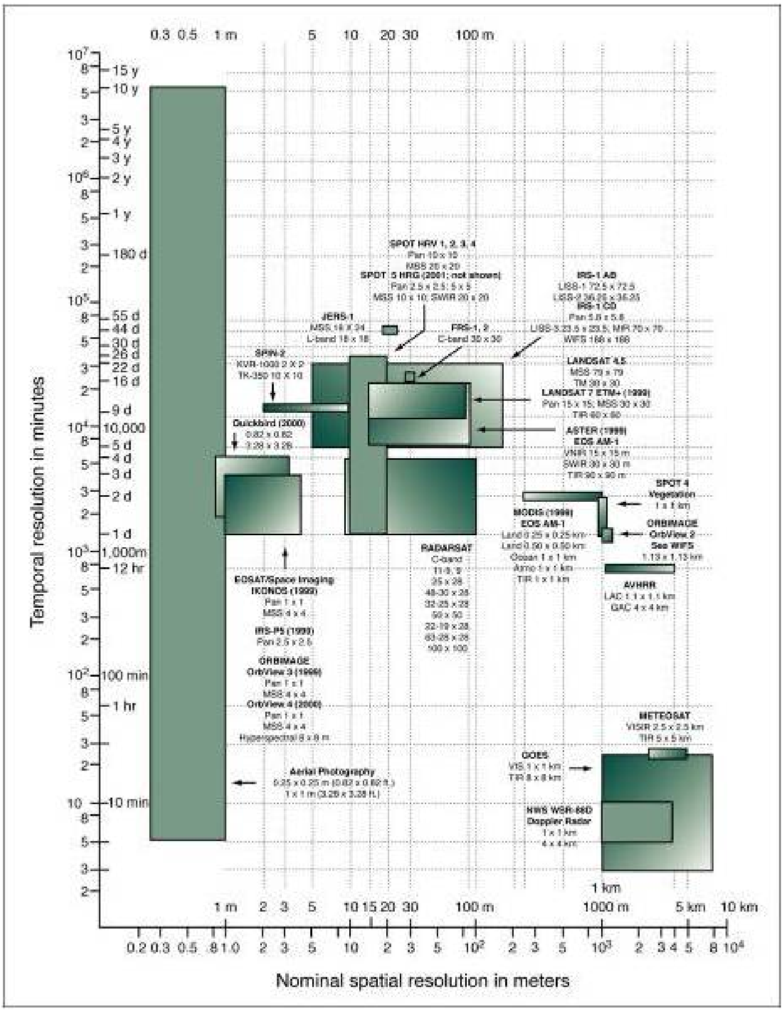


Figure 2: Spatial and temporal characteristics of commonly used remote sensing systems and their sensors (from Longley et al., 2010; originally based on Jensen & Cowen, 1999).

Both spatial and temporal aspects in DRM relate to perceptions, coping capacities and strategies of affected people and communities (e.g., NRC, 2006), to intangible and indirect economic losses, and to communication and education networks. In addition to partially addressed aspects of such variations there is neither a uniform and well-accepted technique, nor a method or standard available to assess spatio-temporal aspects within its multifaceted nature. In terms of the technical-methodological coupled framework issues in Temporal GIS have been addressed by applying various approaches such as layer-based Sequential Snapshot models (Armstrong, 1988), Space-Time composite (Langran & Chrisman, 1988) and Space-Time Cube models (Langran, 1992), Event-based data models (Peuquet & Duan, 1995), or integrative versions thereof (Raza et al., 1998). However, in the field of disaster risk research different approaches and disciplines often remain in their corner and interdisciplinary approaches are still rare.

> ***"After many years, we are finally able to examine data in full spatio-temporal perspective"***
>
> *(Quote by Michael F. Goodchild, 2008a)*

Recently, methodological and theoretical advances with regard to issues of space-time integration have increasingly been incorporated in modeling and analysis aspects of natural hazards and risk research (Zerger and Smith, 2003; Dobson, 2007; Aubrecht et al., 2013d; Fuchs & Keiler, 2013). The increasingly popular organization of symposia such as the Association of American Geographers' (AAG) '*Symposium on Space-Time Integration in Geography and GIScience*', workshops on '*Persistent problems in geographical visualization*' by the International Society for Photogrammetry and Remote Sensing (ISPRS) and the International Cartographic Association (ICA), as well as sessions at the conference series GI4DM (*Geo-Information for Disaster Management*) confirm and emphasize this trend. Fig. 3 exemplarily illustrates dominant words in scientific abstracts highlighting the relevance of aspects such as 'space', 'location', 'time', 'temporal', 'dynamic', 'spatio-temporal' in current research.

Figure 3: A word cloud of submitted abstracts (visualization based on word frequency) indicating topics covered during a workshop of the ICA Commission on GeoVisualization in Paris in 2011 (available at http://www.casa.ucl.ac.uk/geoviz/, accessed 30 September 2013).

Already more than a decade ago "*the development of new forms of 'local' or 'context-dependent' spatial analytical methods*" was promoted as the way to move forward in GI Science, focusing on "*exceptions to the general trend represented by the more traditional 'global' methods*" (Fotheringham, 2000). 'Context' has since then prominently been highlighted as great emphasis in spatial thinking in general (Goodchild, 2008a). Also, choosing the 'proper' contextual scale of analysis has long been identified as the "*essential part of the design of scientific inquiry [in the spatial sciences]*" (Anselin, 1999). Fig. 4 shows schematic illustrations of the spatial and temporal scale domains as well as putting the contextual understanding of scale in relation to that in terms of a 'knowledge domain' as introduced by Cash et al. (2006). In a disaster risk and sustainable development context 'functional scale' has been introduced as yet another domain and challenge, referring to institutional and organizational mismatches in addressing risks and implementing disaster risk reduction measures (Birkmann and von Teichman, 2010).

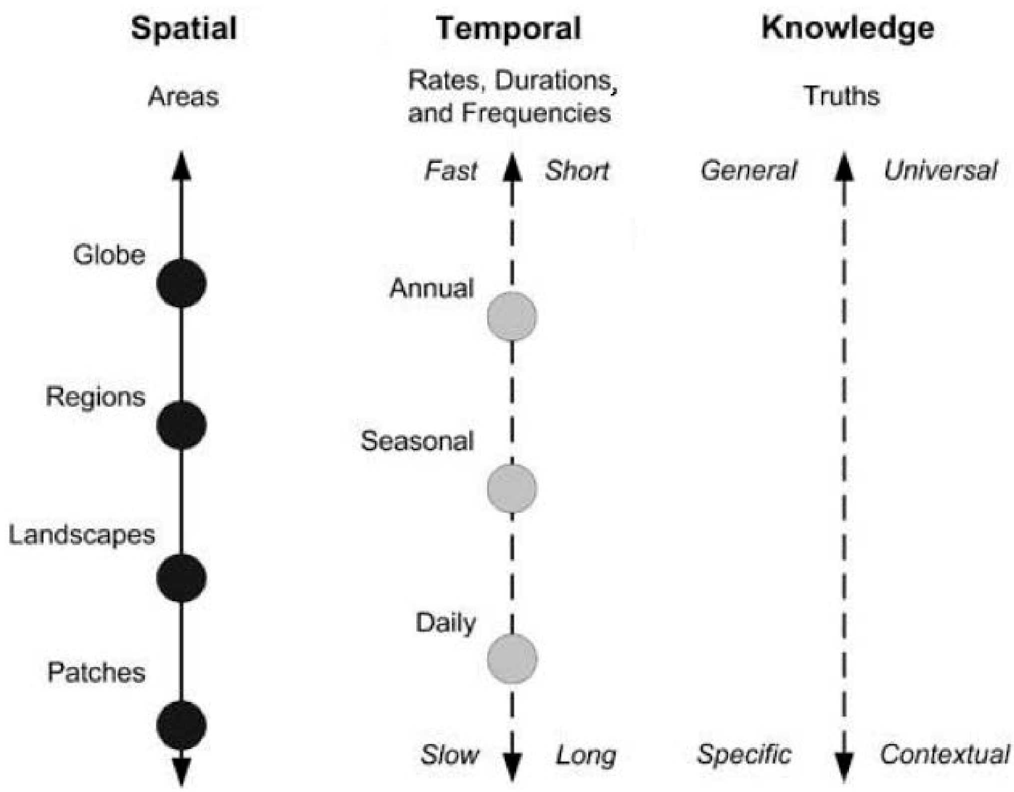


Figure 4: Schematic illustrations of selected scale domains (after Cash et al., 2006).

1.3 Objectives and structure

Drawing upon these conceptual theories and applied research guiding strategies outlined above as well as considering improved and increasingly sophisticated state-of-the-art spatio-temporal modeling capabilities, *the still common use of uniform geodata unaware of scale, level, and context of assessment in disaster risk research is obsolete*. This served as main motivation for this thesis and the dedicated research emphasis and strategic guideline is therefore built upon *the necessity of applying scale- and level-specific geospatial data and information with proper accounting for the action-specific thematic context and application domain* (i.e., thereby following research needs of the future outlined by Goodchild, 2010) in various stages of integrated disaster risk management, focusing particularly on aspects of exposure, vulnerability, and risk assessment.

While spatial patterns of exposure are basically evolving on all temporal scales and are often subject to fast changes such as daily or weekly variation (e.g., Freire and Aubrecht, 2012), vulnerability alterations usually rather occur in the longer term such as changes in regional population or economic characteristics (e.g., ageing, poverty). Referring to the third scale domain outlined above, vulnerability is critically context-dependent (Brooks et al., 2005) and variable patterns of vulnerability eventually determine where and when a mere natural event potentially turns into a disaster (Wehrli et al., 2010).

> ***"The case for Geographic Information and Technology in disaster management is clear and undisputed"***
>
> *(Quote by Michael F. Goodchild, 2006)*

Building upon these guiding principles of spatial, temporal, and contextual scale domains, the development and application of geospatial analysis methods in disaster risk research are key aspects of the presented study. First, the framework for this work is set by explaining and sort of 'revisiting' the concept of Integrated Disaster Risk Management and its various stages in the pre- and post-event phase of a disastrous event (chapter 2). Commonly accepted definitions and state-of-the art approaches are presented and conceptual research trends are identified.

In the further steps the focus is on the application perspective of population exposure (chapter 3) and then moves on to inherent vulnerability characteristics as well as risk in the end (chapter 4). At all stages the spatial and temporal aspects serve as cornerstones for the setup of this thesis, e.g. coarse to local scale in terms of the spatial domain and short-term daily variation to climate change with regard to the temporal domain. The thesis is concluded with an extensive discussion on applicability of the presented and newly developed approaches as well as an outlook to potential improvements for disaster risk management and current ongoing developments and initiatives specifically addressing exposure and vulnerability issues on multiple scale levels (chapter 5).

One aspect that should still be highlighted here in the introductory section refers to the appreciation of the concept of *spatial modeling* per se and specifically in a disaster risk context. The term ‘model’ is widely used in this thesis considering different aspects and in varying contexts. In order to avoid misinterpretation and confusion it should be made clear that a ‘*model*’ can never be understood appropriately as a singular one-level entity. It is a combination of data, scale and context domains as outlined above, processing and analysis methods applied, and last but not least the user who implements the model and takes subjective decisions regarding its setup. A model is always a *simplified description of reality* whereby it is important to understand that it is mostly not essential to approximate reality as closely as possible but rather to focus on the context-relevant aspects and even leave out unnecessary content in order to emphasize key features. In this thesis particular focus lies on spatio-temporal models describing dynamic processes in a spatial backbone framework as e.g. illustrated by Bolstad (2012). A geospatial GIS-based approach can be considered a model generator in itself in the sense that it offers scenarios to best reproduce a specific aspect of reality that needs to be governed in some way. Integrative spatio-temporal modeling offers a toolset needed for risk analysis, impact assessment, and other facets of disaster management. One key point of this thesis therefore lies in its scale- and domain-consistent elaboration on context-oriented integrated model implementations.

2 Integrated Disaster Risk Management[2]

In this section the most relevant terminology in the context of this thesis showing the state-of-the-art common understanding in disaster risk research as well as the corresponding conceptual management framework is presented. The focus is thereby on the *concept of risk* and its influencing components, i.e. besides the initial *hazard* aspects in particular the factors of *exposure* and *vulnerability* that sort of shape and determine risk and associated potential impacts from a social perspective. As outlined in the introduction, the UN proclamation of the 1990s as the International Decade for Natural Disaster Reduction (IDNDR) – in the U.S. also referred to as the International Decade for Natural *Hazard* Reduction (Mitchell, 1988) – attracted increased attention in the scientific community regarding the development of improved methods and more effective models for risk reduction. It also promoted further research on conceptual approaches to disaster risk management (DRM), leading to a more common acceptance across disciplines regarding the important influences of socio-economic factors on the extent and impacts of natural disasters (Blaikie et al., 1994; Quarantelli, 1995; Cutter, 1996), inter-connected with the (geo)-physical hazardous 'triggering' processes that had previously attracted predominant attention in terms of research on disaster impact determination (Ball, 1979; Quarantelli, 1982; de Blij, 1994). It was acknowledged by then, that disaster analyses "*need to become more sophisticated and multi-disciplinary and must take account of several forms of context within which developments take place*" (Alexander, 1997). Despite all these efforts or maybe rather *because* of this increasingly interdisciplinary nature of that field of research, there has been ongoing intense debate and limited agreement on the exact topical terminology (Hewitt, 1995; Wisner et al., 2004; Schneiderbauer, 2007) which is still widely the case today.

[2] Parts of this section refer to Aubrecht et al. (2012a, 2013ad)

2.1 Relevant terminology on disaster risk

In an attempt to identify, assemble, and define accepted relevant terms in the field of disaster risk management the UN Office for Disaster Risk Reduction set up the '*UNISDR Terminology on Disaster Risk Reduction*' (UNISDR, 2009). The main idea was to promote a common understanding and consistent usage of conceptual approaches in disaster risk research, also aiming to assist disaster risk reduction (DRR) efforts across multi-stakeholder levels. This effort had been requested at the 2005 World Conference on Disaster Reduction and in the follow-up '*Hyogo Framework for Action 2005-2015*' that highlighted the need to "*update and widely disseminate international standard terminology related to disaster risk reduction […] for use in program and institutions development, operations, research, training curricula and public information programs*" as a key activity in information management and exchange (UNISDR, 2007). The UNISDR terminology is commonly used as basic source to guide common understanding for European Union disaster risk related projects, such as most recently for the compilation of a glossary for the EU-FP7 project CRISMA[3] '*Modeling crisis management for improved action and preparedness*' (Aubrecht et al., 2012b).

Figure 5: Understanding/defining 'disasters' (cartoon from Natural Hazards Observer, 03/2004).

[3] More information available at http://www.crismaproject.eu/ (accessed 30 September 2013)

In most aspects the UNISDR terminology is in line with the understanding of terms applied in this thesis. There is however a multitude of varying details in the perception of these concepts which have been elaborated on for decades by disaster researchers. In the following some of the most relevant concepts are presented and discussed.

Defining and conceptualizing the term 'disaster'

As outlined earlier on, the term *disaster* is not used until severe impacts on social systems, including human beings (loss of life) and associated assets (destruction of property) are caused (e.g., Johnson et al., 2006). This view was already promoted in the early stages of the last century (e.g., Queen and Mann, 1925; Carr, 1932) and is still seen as the key aspect in current commonly accepted definitions such as the one cited below, which additionally highlights the affected social system's event-specific exceeded coping capacity. The latter – e.g. also identified as criterion in the EM-DAT terminology (CRED, 2013) and earlier on already in the 1988 U.S. Robert T. Stafford Disaster Relief and Emergency Assistance Act (FEMA, 2007) – in fact adds the domain of (social) vulnerability to the disaster concept, as it describes the disaster-specific characteristics of a system in terms of its limited "*ability to face and manage adverse conditions […] using available skills and resources*" (UNISDR, 2009).

<< Disaster >> (according to UNISDR, 2009):

"*A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources. Disasters are often described as a result of the combination of: the exposure to a hazard; the conditions of vulnerability that are present; and insufficient capacity or measures to reduce or cope with the potential negative consequences. Disaster impacts may include loss of life, injury, disease and other negative effects on human physical, mental and social well-being, together with damage to property, destruction of assets, loss of services, social and economic disruption and environmental degradation.*"

The notion of a '*natural*' disaster implies that it is triggered by a '*natural*' hazardous event. However, the impacts that eventually justify the label 'disaster' are largely a product of different socio-economic conditions (World Bank, 2010), which brings up the understanding that disasters are at least to some extent "*socially constructed*" (Quarantelli, 1995; Cannon, 2008). While that social science dominated perspective might be considered too narrow in some aspects, it remains without doubt that disasters are "*a complex mix of natural hazards and human actions*" (Wisner et al., 2004) with social constraints and framework conditions influencing strongly the way how hazards affect people and communities (White, 1978).

In addition to the basic qualitative acknowledgment on accepting social aspects as significant influencing factors in determining disaster impacts, the question came up how to identify and possibly define disasters in quantitative terms (e.g., Foster, 1976; Burton et al., 1978). Alexander (1997) provides a list of elements that have been used for that purpose; including the number of deaths, the value of damage and losses, the impact upon the social system, as well as geophysical factors. Despite being found vastly simplistic (NRC, 2006) such thresholds have still been applied until today, particularly in the setup of disaster event databases such as the open-access EM-DAT[4] (CRED, 2013) and SHELDUS (Gall et al., 2009) or the private-domain NatCatSERVICE (Munich Re, 2012) and Sigma (Swiss Re: Bevere et al., 2012) which are heavily drawn upon in order to identify and visualize potential trends (see fig. 6-8).

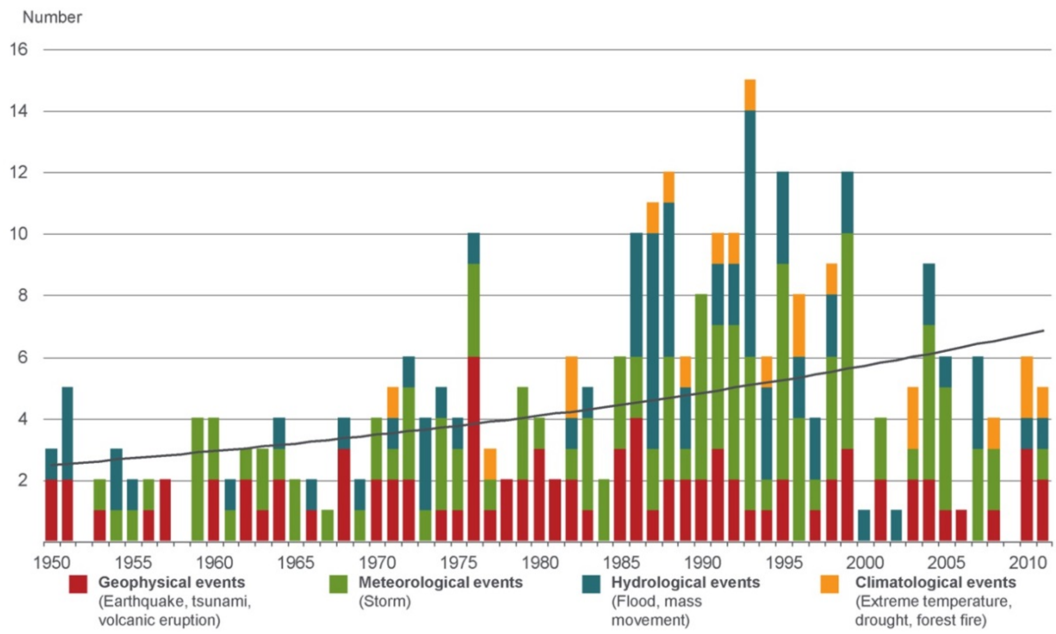


Figure 6: Great natural disasters worldwide 1950-2011, Number of events with trend recorded in NatCatSERVICE (from Munich Re, 2012).

[4] See criteria and thresholds at http://www.emdat.be/criteria-and-definition (accessed 30 September 2013).

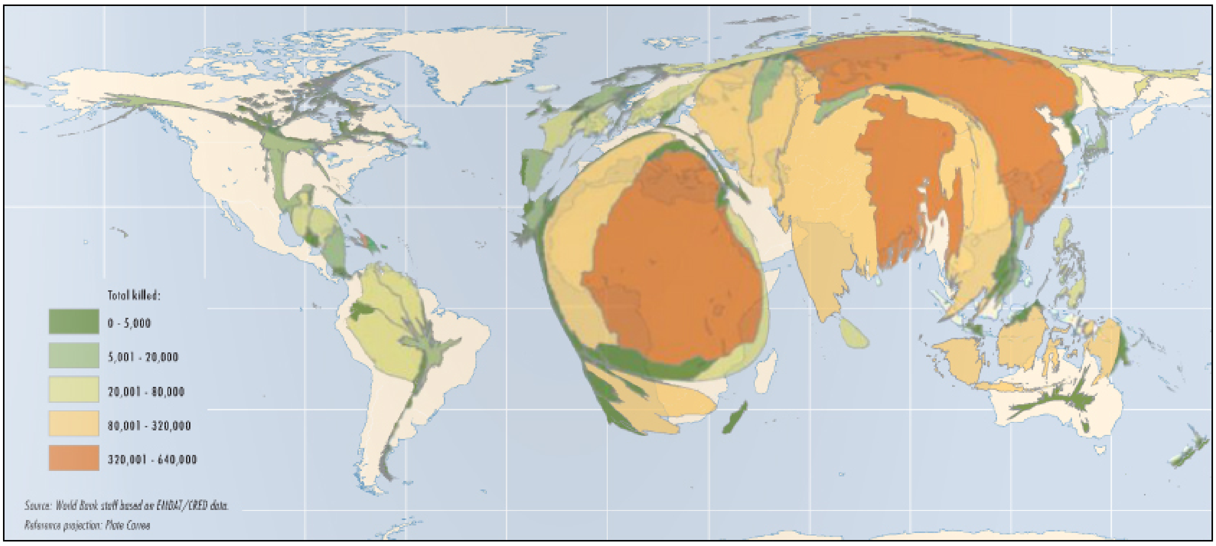


Figure 7: Areas reflect cumulative deaths from disasters for 1970 to 2010. Selection and identification of disaster events based on EM-DAT (from World Bank, 2010).

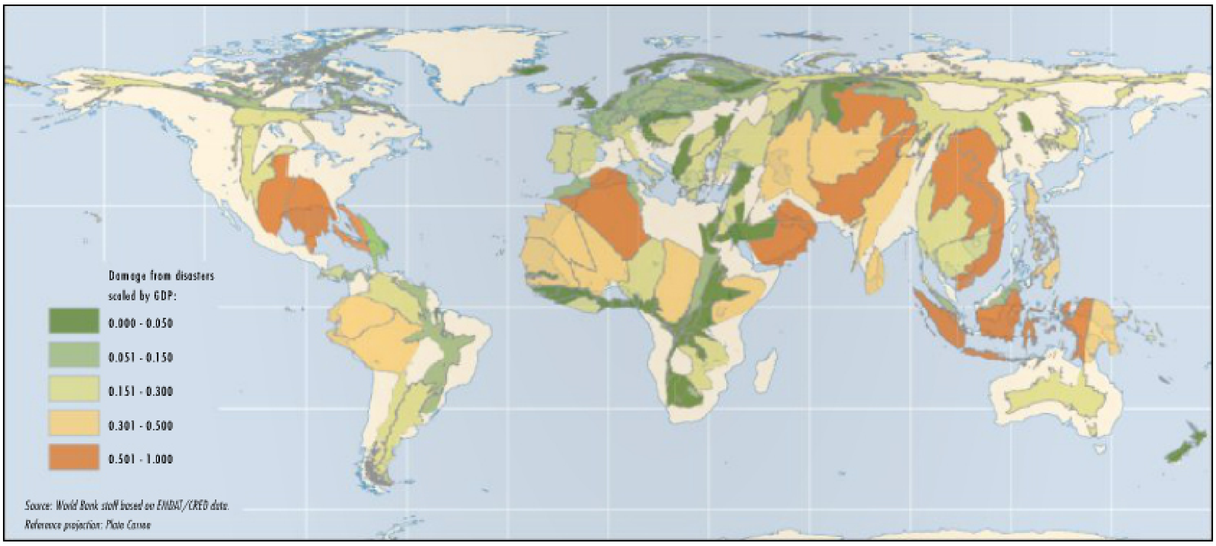


Figure 8: Areas reflect cumulative damage from disasters scaled by GDP for 1970 to 2008. Selection and identification of disaster events based on EM-DAT (from World Bank, 2010).

Figure 6 illustrates EM-DAT records in terms of the annual trend in the absolute number of disaster events. Figures 7-8 visualize the characteristics of these selected events on a map, highlighting the locational discrepancy between number of deaths and economic damage on a global scale, i.e. poor regions of the world accounting for the majority of disaster deaths whereas damage costs are reported disproportionally high in middle-income countries.

Moving on towards the concept of 'risk'

While the definition of the term *disaster* has already been quite multi-faceted, in particular since its introduction into systematic social science research (Quarantelli, 1995; NRC, 2006) in the 1950s (e.g., Killian, 1954; Moore, 1956; Fritz and Williams, 1957), the scientific discussion gets even more controversial or rather 'conceptually diverse' when it comes to the underlying fundamental concepts of *(disaster) risk* and *vulnerability*. Particularly the understanding of the latter differs considerably between the natural hazards and the climate change research communities (Wisner et al., 2004; Adger, 2006; Birkmann, 2006a).

In order to get a grasp on *risk* as a central concept in integrated disaster risk management including its various aspects and influencing factors, a few terms need to be clarified before. Risk analysis as an integral part of DRM is composed of *hazard* and *vulnerability* assessment and before going into details risk can therefore be preliminary understood as the interaction of these main individual components (referring to the 'pressure and release model' of Blaikie et al., 1994) – i.e., natural (physical) and human (behavioral) factors (e.g., Pelling et al., 2004; Merz et al., 2010; Eiser et al., 2012). Both aspects are highly sensitive to spatial and temporal variation (Cutter, 2003; Wisner et al., 2004; Aubrecht et al., 2012a). Root causes of extreme events and in that sense initiating risk factors have been identified and mapped with increasing accuracy (Faulkner and Ball, 2007) which, however, concerns in particular specific environmental aspects, i.e. mostly the hazard part.

'Hazard' as the main initial stress component of risk

A *hazard* in its' broad sense is a "*dangerous phenomenon, substance, human activity or condition*" (UNISDR, 2009) that *may* cause adverse impacts on a social (e.g, loss of life, injury or other health impacts, property damage, social and economic services disruption) or environmental (e.g., ecological damages) system (e.g., Pelling et al., 2004; Du and Pan, 2007; Birkmann et al., 2013; Dewan, 2013). Following that perspective this includes threatening events and conditions of natural origin (e.g., geological, meteorological, hydrological, oceanic, biological sources) as well as man-made or human-induced (e.g. related to technological and industrial aspects as well as terrorist attacks) and so called socio-natural hazards (i.e., "*induced or aggravated by a combination of extreme natural events and human interventions in nature*") (Garatwa and Bollin, 2002). In the context of the presented study, the focus is on *natural hazards* (as defined below). Anyway, it remains an issue of open debate whether for example increased hazardous environmental conditions attributable to climate change (e.g., heat waves) should be considered of pure natural or rather 'socio-natural' origin, bearing in mind the significant human influence on patterns of climate change. This point should, however, not influence the basic discrimination of environment-related and directly man-caused characteristics in the hazard classification terminology.

> **<< Natural hazard >>** (according to UNISDR, 2009):
>
> "*Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.*
> *Natural hazards are a sub-set of all hazards. The term is used to describe actual hazard events as well as the latent hazard conditions that may give rise to future events. Natural hazard events can be characterized by their magnitude or intensity, speed of onset, duration, and area of extent…*"

The understanding of the term hazard promoted here includes both actual threatening events as well as latent hazardous conditions (i.e., given probability of occurrence) that may initiate future *potentially* damaging events (UNISDR, 2009; CRED, 2013). Most aspects of hazard investigations have a spatial component where both Earth Observation data and terrestrial surveys provide essential information for delineation of potentially affected areas and monitoring environmental conditions (Aubrecht et al., 2011a). In addition to that *spatial aspect* (areal extent) and the *overall dimension* of the hazard (in terms of its magnitude and intensity) also the *temporal component* is essential in hazard assessments. In particular this refers to the duration of a hazardous event as well as to the speed of onset. For example, earthquakes are characterized by very short onset and short durations, whereas heat waves and droughts as well as flood events usually imply a certain lead time in their development and are also slow to fade away. In some cases hazards may be coupled to produce cascading events (Aubrecht et al., 2013c) which may eventually even incur the highest fraction of total damage (Korup, 2010); as floods caused by a hurricane (e.g., Rygel et al., 2006), earthquakes leading to landslides (e.g., Chang et al., 2007), a volcanic eruption resulting in lava flows, lahars, and ash fallout (e.g., Zuccaro and Gregorio, 2013), or wildfires initiated by electrical failures due to earthquake-damaged power infrastructure (e.g., Osaragi, 2013). The variable 'temporal spacing' describes the sequence of events in that regard (Burton et al., 1993).

The mere incidence of a 'hazard event' does not necessarily cause negative effects (Garatwa and Bollin, 2002) and is in fact often considered beneficial in helping to maintain "*the Earth's dynamic equilibrium*" (Schwab et al., 2007). For example, wildfires are an important factor for ecosystem stability and biodiversity while recurring flooding often benefits riparian forests and agricultural areas through nutrient supply and sedimentation. Natural hazard events turn into natural disasters when they affect human or economic systems that cannot withstand their impact (Annan, 2003; Deichmann et al., 2011). Risk can therefore merely be considered "*the probability of a hazard contributing to a potential disaster*" (Stenchion, 1997). It is at this point that the complex and dynamic dimensions of *vulnerability* come into play, being defined as the degree of susceptibility to harm from stresses associated with environmental and social change (Adger, 2006) as well as influenced by a set of interrelating input factors including exposure and sensitivity, initial coping capacity, robustness and response of a system (Füssel, 2007; Cutter et al., 2008).

'Exposure' referring to the spatial aspect of risk

Considering all these factors and their interactive relations, the first-mentioned preliminary understanding of risk as a function of hazard and vulnerability is extended by the variable *exposure* – a concept of major significance and sort of entry point for the applications presented in this thesis. In particular with regard to risk hotspots mapping (Dilley et al., 2005), strong emphasis is put on that parameter as the integrating spatial factor that sets the context and brings together the physical event characteristics and human aspects of risk. Before going into further details, *natural disaster risk* as regarding "*potential disaster losses*" (UNISDR, 2009) is therefore now seen as being determined by the three major components: (1) hazard characteristics, (2) exposure, and (3) vulnerability (Kron, 2002; Peduzzi et al., 2005; Gwilliam et al., 2006; Tomlinson et al., 2011; UNISDR, 2011) – a conceptual approach also referred to as the "*risk triangle*" (Crichton, 1999) (fig. 9). If any of these three elements increases or decreases, then risk increases or decreases respectively (Kelman, 2003).

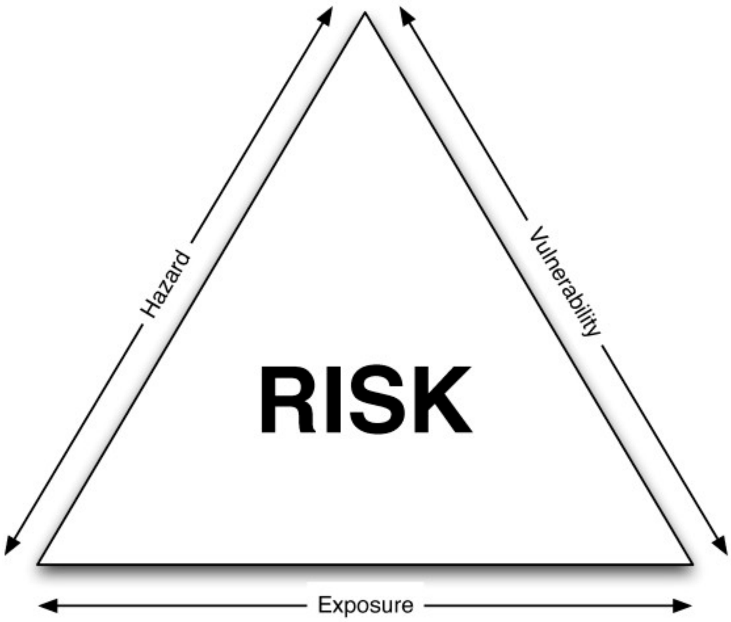


Figure 9: Crichton's Risk Triangle (from Tomlinson et al., 2011; based on Crichton, 1999).

Accordingly, if any one component is zero, then there is no risk (Peduzzi et al., 2009) – this refers back to the notion of a disaster only establishing itself in the interplay of the hazardous physical phenomenon and its respective social context. Disaster risk is often difficult to quantify, but can be assessed and mapped by integrating the spatio-temporal patterns of prevailing hazards and socio-economic development (UNISDR, 2009).

The additional spatially-integrative variable exposure can actually be seen as an extract from the conceptually more broad appreciation of vulnerability (Kron, 2002) as it was described before. It is used in defining the area potentially affected by a hazardous event (hazard-prone area) and identifying the *elements at risk* located in that area that are subject to potential losses or that may suffer damage due to the hazard impact (UNISDR, 2009; Ehrlich and Tenerelli, 2013; van Westen, 2012). Being defined in rather general terms, both physical and socio-economic elements at risk may be exposed. These usually include people and associated assets or artifacts (Peduzzi et al., 2005; Birkmann et al., 2013) such as property and infrastructure or economic goods (Bollin et al., 2003; Birkmann, 2006b; NRC, 2006; Gunasekera et al., 2013).

<< Exposure >> (according to UNISDR, 2009):

"*People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses.*
Measures of exposure can include the number of people or types of assets in an area. These can be combined with the specific vulnerability of the exposed elements to any particular hazard to estimate the quantitative risks associated with that hazard in the area of interest."

Asset exposure is reported to have been rapidly increasing (especially in low- and middle-income countries) due to population and economic growth as well as urbanization and is considered a major factor in increased disaster risk (NRC, 2006; UNISDR, 2011). Accurate exposure estimation and quantification in that context is a key component of spatially-explicit catastrophe loss modeling, one element of effective risk analysis and emergency management (Chen et al., 2004; NRC, 2007).

In terms of temporal aspects the spatial distribution of population is highly dynamic and time-dependent particularly in metropolitan areas due to human activities and mobility (daytime working population vs. nighttime residential population, seasonal cycles, etc.). Besides this short-term temporally variable characteristics of human exposure (McPherson et al., 2006; Ahola et al., 2007; Freire and Aubrecht, 2012), exposure patterns also evolve in the long term. With ongoing social, economic, and built-environment changes, more people tend to live in highly hazardous areas than ever before (World Bank, 2010). If produced at appropriate spatial and temporal scales, updated and detailed mapping of population and other elements at risk and particularly recognizing their variability in hazard-specific exposure is the first step preceding vulnerability and risk assessment and provides important decision support for proactive emergency planning (Cutter and Finch, 2008) and practically every phase of disaster management (Sutton et al., 2003; Freire, 2010; Aubrecht et al., 2011a).

Being yet another 'conceptually diverse' term, *exposure* is often used in an overlapping way with vulnerability (UNISDR, 2009); in the disaster risk community usually considered as separate concept next to that (Blaikie et al., 1994; Davidson and Shaw, 1997; Bollin et al., 2003; Schneiderbauer, 2007; Peduzzi et al., 2009; Kappes et al., 2012), sometimes even standing as sort of substitute for vulnerability (Krellenberg et al., 2013), in other cases as one – '*external*' (Chambers, 1989; Bohle, 2001) – aspect or part of vulnerability (Turner et al., 2003; White et al., 2004; McEntire et al., 2010), or in interconnected conceptual form as main influencing and determining factor of vulnerability (NRC, 2006; Bründl et al., 2009; Schmidt et al., 2011; Strunz et al., 2011). In particular in the research communities that are driven by geospatial data concerns, mostly a strong emphasis is given to exposure as an objectively and externally detectable factor (e.g., in remote sensing imagery), therefore considering it as unique feature or parameter (Deichmann et al., 2011; Dell'Acqua et al., 2013; Geiß and Taubenböck, 2013). Even though this often applies mainly to the *physical* dimension of exposure (Ehrlich and Tenerelli, 2013), i.e. buildings and infrastructure, it also matches with the author's general understanding and appreciation of that term – extending to the *social* dimension (Aubrecht et al., 2011ab, 2013b; Freire and Aubrecht, 2012) – and thus with the applied approach in this thesis.

'Vulnerability' shaping risk in terms of the susceptibility of potentially affected elements

In any case, the factors exposure and *vulnerability* are very closely interlinked and remain inseparable (Blaikie et al., 1994), even if they are seen as two distinct concepts. For example, in a disaster scenario where evacuation measures are evaluated, high population density in a potentially affected area – i.e., high population exposure – indirectly implies higher specific vulnerability (due to limited or reduced possible evacuation speed), before even considering the inherent characteristics of the affected population groups (Freire et al., 2013). As outlined in the introduction – and again putting the focus on the spatio-temporal and locational impact in the conceptual understanding – vulnerability is critically context-dependent (Brooks et al., 2005), dynamic, and scale-dependent (Vogel and O'Brien, 2004). Variable patterns of vulnerability eventually determine where and when a hazardous event of any kind potentially turns into a disaster (Wehrli et al., 2010; Aubrecht et al., 2011b; Dewan, 2013). Societal aspects and vulnerability in that regard are considered as greater contributing factors to disaster risk than the mere occurrence of hazards (Uitto, 1998; Alexander, 2006; Hewitt, 2013).

To achieve an integrated approach in assessing various drivers and components of risk, the concept of vulnerability has evolved in recent years and decades out of the social sciences to cover the 'lack' next to the hazard component (Chambers, 1989; Adger and Kelly, 1999; Pelling, 2004; Schneiderbauer and Ehrlich, 2004; Douglas, 2007). Accurately assessing and measuring vulnerability in space and time has increasingly been considered a starting point and key step towards effective risk reduction and the promotion of a culture of disaster resilience (Birkmann, 2006b). The concept of vulnerability as a descriptor of the status of a society or community with respect to its susceptibility to an imposed hazard or threat and its corresponding coping capacity (Cardona, 2004; Hilhorst and Bankoff, 2004) is deeply rooted in a multidisciplinary research effort (Turner et al., 2003; Adger, 2006; Birkmann, 2006b) and comprises various dimensions such as environmental, physical, social, economic, cultural and institutional (UNISDR, 2009; Alexander et al., 2011; Papathoma-Köhle et al., 2011).

> **Vulnerability** (UNISDR, 2009):
>
> "*The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.*
> *There are many aspects of vulnerability, arising from various physical, social, economic, and environmental factors. […] Vulnerability varies significantly within a community and over time. This definition identifies vulnerability as a characteristic of the element of interest (community, system or asset) which is independent of its exposure. However, in common use the word is often used more broadly to include the element's exposure.*"

A central objective of each vulnerability assessment is to provide indications where (i.e., overlapping with exposure analysis), how and why people might be affected by a certain threat and should provide decision- and policy-makers with essential information to target their responses adequately (Aubrecht et al., 2010a). Vulnerability of people and physical assets are closely linked as, for example, injury or mortality are often caused indirectly, for instance by collapsing buildings (Deichmann et al., 2011).

While certain characteristics such as the general quality of construction of buildings are sort of generic contributors to vulnerability, some other parameters are strongly hazard-dependent. With regard to relevant population characteristics, for example, short-onset earthquake and tsunami hazards imply a very different set of adaptation and coping requirements (e.g., related to possible evacuation speed) than rather slowly building up heat waves (e.g., access to air condition, pre-existing medical constraints particularly in terms of cardiovascular issues) or associated drought conditions (e.g., water provision access) (Alexander et al., 2011).

Despite extensive research efforts in recent years (reviews in Adger, 2006; Birkmann, 2006a; Kumpulainen, 2006; Villagrán de León, 2006; Fuchs, 2009) still no universally accepted definition of vulnerability exists (Birkmann et al., 2013). The term has become rather vague and abused running the "*danger of losing its analytical value*" (Cannon, 2008), and a gap prevails in particular between climate change and DRR research communities. There are multiple studies available giving overviews on existing definitions of vulnerability (Green, 2004; Schneiderbauer and Ehrlich, 2004; Birkmann, 2006b; Thywissen, 2006).

While the one cited above is rather widely accepted in the disaster risk domain – when it comes to the assessment and reduction of climate induced hazards, different research and policy communities representing climate change adaptation, environmental management and poverty reduction have taken up the discussion (Thomalla et al., 2006). A consensus on a more integrative approach has not yet been achieved (Hufschmidt, 2011) and even within the climate change community divergent notions of vulnerability exist (Kelly and Adger, 2000).

For example, the prominent 'end point' definition sees vulnerability as the residual of climate change impacts attenuated by adaptation (i.e., the remaining potential adverse consequences that are not targeted through adaptation) – thus putting vulnerability as the final determining factor in any stress or impact appraisal (Klein and Nicholls, 1999; IPCC, 2001). In contrast, the 'starting point' interpretation views vulnerability as "*a general characteristic of societies generated by different social and economic factors and processes*" (Bogardi et al., 2005). Vulnerability and adaptive capacity in that context are interpreted as two separate but closely interdependent aspects. In the 'end point' view adaptive capacity determines the extent of vulnerability, whereas in the 'starting point' view vulnerability determines the way in which adaptive measures must be targeted.

In the disaster risk community adaptive as well as coping and other dimensions of capacity are generally understood to be major determining factors for vulnerability – in particular social vulnerability (Blaikie et al., 1994; Cutter et al., 2003) – in terms of defining the lack or limited level of resilience that shapes overall vulnerability of a social system. The concept of *resilience* is heavily discussed as well (Klein et al., 2003; Manyena, 2006; Olson, 2011). It is hereby understood as "*the ability of a system […] exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner…*" and is determined by "*the degree to which the [system] has the necessary resources and is capable of organizing itself both prior to and during times of need*" (UNISDR, 2009).

Yet another perspective on vulnerability considers it as an overarching concept – a 'focal point' (Kelly and Adger, 2000) – defining it in terms of "*the exposure to stress and crises, the capacity to cope with stress, and the consequences of stress and the related risk of slow recovery*" (Watts and Bohle, 1993). Related holistic approaches to understanding risk and vulnerability were later also promoted by Cardona (1999, 2004) and Carreño et al. (2007).

This brings us back to the controversial position of exposure in the vulnerability framework – as a distinctly detectable and identifiable but yet inseparable component, shaping in particular the spatial and temporal characteristics of disaster risk. Bogardi and Birkmann (2004) proposed a model attempting to transform the disaster risk community understanding of risk into an approach that is more linked with the vulnerability model of the climate change community ('BBC model'), i.e. continuing to define risk in terms of external hazards and internal vulnerabilities, but incorporating or at least partially relating the aspects of coping capacities and exposure within multi-dimensional vulnerability (see also Birkmann, 2006a).

Following up on that, figure 10 illustrates the various dimensions of vulnerability and the interrelation with spatial and temporal aspects of exposure in a coupled socio-natural system framework as most recently defined in the MOVE project (Alexander et al., 2011; Birkmann et al., 2013), eventually determining risk patterns and risk management options.

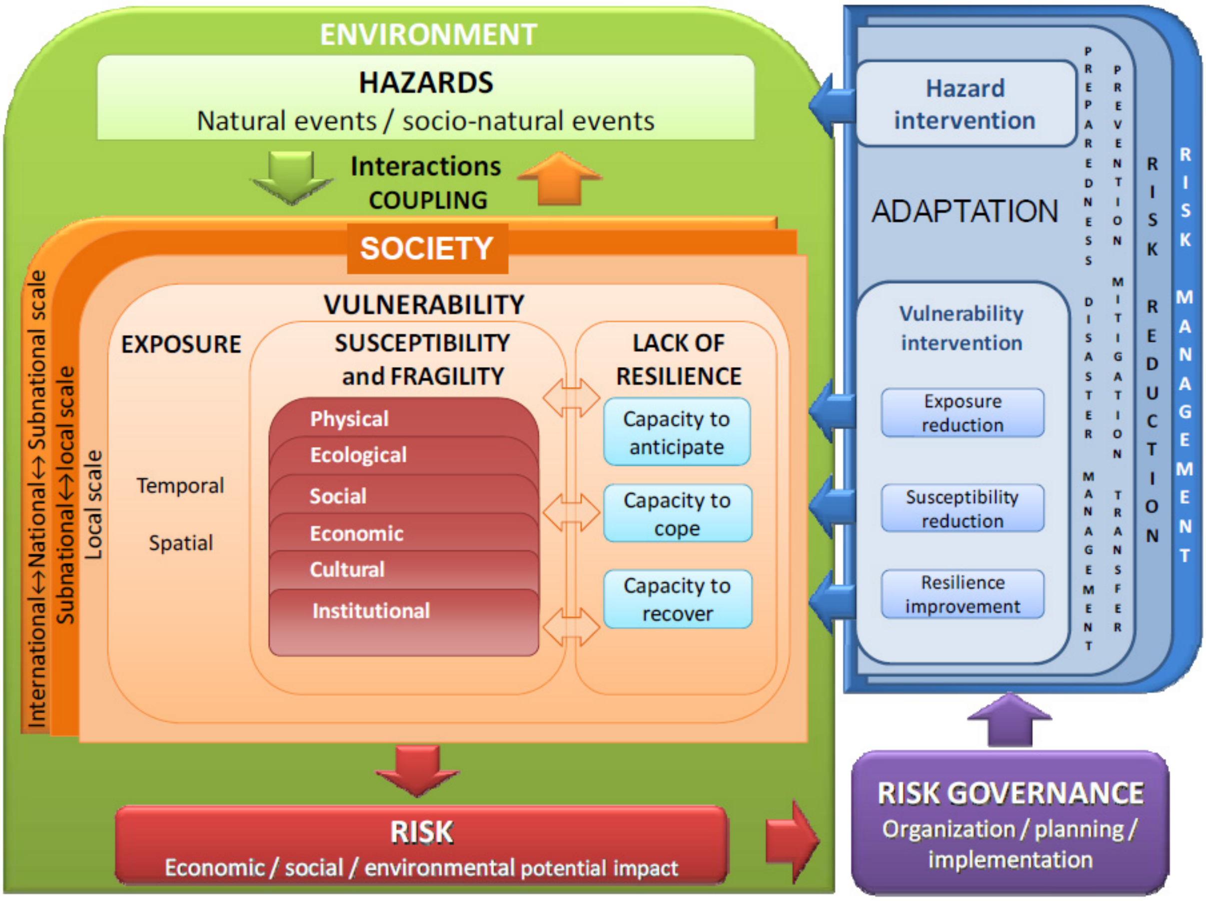


Figure 10: The MOVE Framework (from Alexander et al., 2011; Birkmann et al., 2013).

That MOVE framework in many aspects can serve as conceptual basis for the approaches presented in this thesis. Besides highlighting the different dimensions of vulnerability – whereby the social component is considered most relevant – it also refers to the multiple possible scales of analysis ranging from the local to the global or 'intercontinental' level. Risk is eventually illustrated as a result from underlying hazardous conditions initiated in a certain environmental setting (therefore referring mainly to natural hazards) that 'materializes' when these conditions affect a societal system (the system becoming exposed). Risk in the sense of Crichton's previously described 'Risk Triangle' is in that context understood to be shaped by inherent vulnerability and resilience characteristics and can eventually be managed or 'governed' by implementing certain adaptation measures on both the hazard and the vulnerability components.

2.2 The cycle as conceptual framework for disaster risk management

Following the elaborations on disaster risk and its individual components and driving factors, the conceptual understanding of *integrated disaster risk management* sets the framework for applied research and effective implementation of risk reduction and impact mitigation measures. With disaster risk management (DRM) thus encompassing the concept of disaster risk reduction (DRR), the main aim is to lessen or – if possible – even to eliminate risks and adverse impacts of hazardous events (Garatwa and Bollin, 2002; Ammann, 2009; Birkmann et al., 2013) by systematically using available resources to address all potential aspects prior to (prevention, mitigation, preparedness), during, and in the aftermath of (response, recovery, rehabilitation) an event (UNISDR, 2009). Different types of hazards such as hurricanes, tsunamis, floods, earthquakes and fires feature individual characteristics and require adapted actions and analysis methods in all stages – greatly facilitated by the application of GIS in all its facets (Radke et al., 2000).

> **Disaster risk management** (UNISDR, 2009):
>
> "*The systematic process of using administrative directives, […] and operational skills and capacities to implement strategies, policies and improved coping capacities in order to lessen the adverse impacts of hazards and the possibility of disaster.*
> *[…] Disaster risk management aims to avoid, lessen or transfer the adverse effects of hazards through activities and measures for prevention, mitigation and preparedness.*"

DRM has widely been regarded as a cyclic multi-stage concept (Johnson, 1992; Mileti, 1999; Alexander, 2003; Menon and Sahay, 2006; Schneiderbauer, 2007; Khan et al., 2008; Warfield, 2009; Abdalla and Li, 2010), ideally starting with (1) risk analysis, followed by (2) mitigation efforts to minimize the impacts of future events, and eventually rounded off by (3) a response and recovery phase after disaster strikes (Aubrecht et al., 2010a). Referring to the PEPPER (pre-event planning for post-event recovery) approach first addressed in the late 1980s (Spangle, 1987; NRC, 2006), the cycle illustrates the phrase '*after a disaster is before the next disaster*' and thus explains the varying focus during different (overlapping) phases before, during and after a catastrophic event occurs (fig. 11).

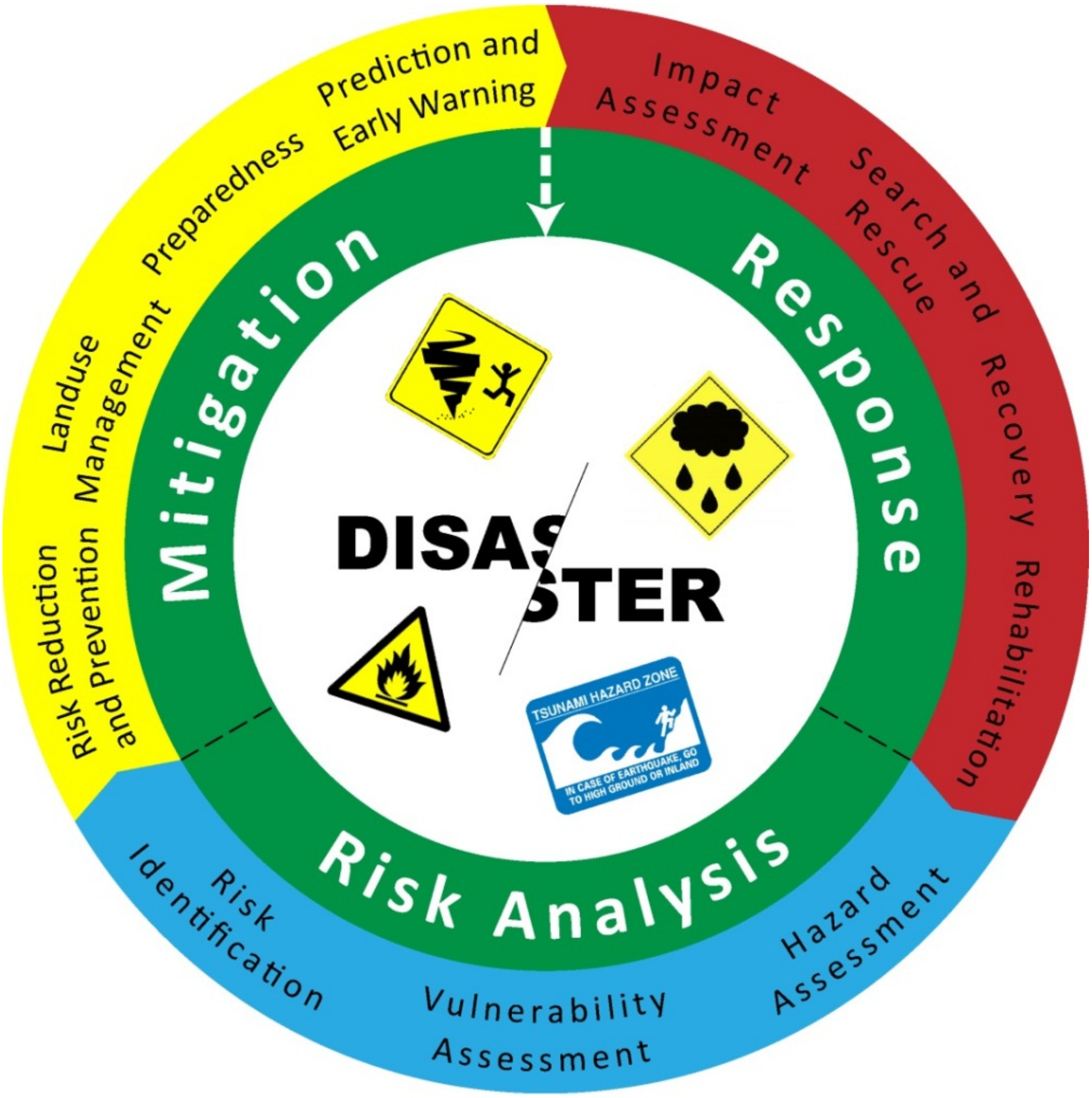


Figure 11: Personal view on the cyclic concept of disaster risk management with its continuous interconnected and interrelated pre- and post-event stages.

There is no commonly accepted version of that cyclic concept; the pre-event phase is for example often split in two distinct stages of longer-term mitigation and short-term preparedness, while a similar temporal approach is applied for the post-event phase distinguishing short-term response and long-term recovery. Recently, the DRM framework has been conceptualized as continuum with fluid transitions between pre-, during-, and post-disaster phases (Baas et al., 2010; Piper, 2013).

'Risk analysis' as the preferred starting point in a cyclic conceptual DRM framework

In a DRM context *risk analyses* are required that integrate multifaceted hazards and risk drivers for estimation of potential losses associated with social systems (Amendola et al., 2008). In response to the outcome of these assessments identified systemic vulnerabilities have to be addressed and potentially reduced and along these lines resilience has to be built up and strengthened (Baas et al., 2008; Olson, 2011) – all again concerning not only the predisposition and susceptibility of a social system to a hazardous event but also its response capacities in case risk materializes and emergency occurs.

Addressing such issues obviously also requires a set of strategic and often political and legislative decisions, particularly in terms of determining '*how safe is safe enough*' (Fischhoff et al., 1978; Derby and Keeney, 1981), i.e., setting optimal safety levels and promoting levels of '*acceptable*' and '*tolerable*' risk (Kasperson, 1983; Fischhoff, 1994; Voortman et al., 2001; see fig. 11) – such as the popular '100-year design event' approach in flood risk management (Godber, 2002).

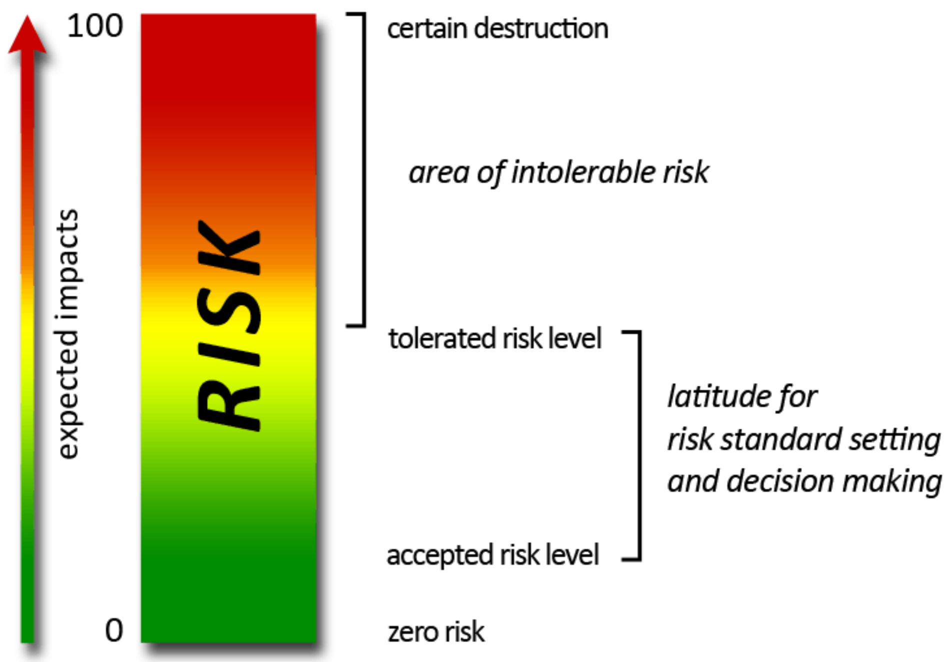


Figure 12: Schema for risk levels and decision making (adapted from Kasperson, 1983).

Public *risk perception* – mostly on an irrational level (Ropeik, 2010) – plays an important role in that regard (Slovic, 1987; Eiser, 2004; Siegrist et al., 2005; Zhai, 2006), being on the one hand strongly influenced and sometimes distorted by such decisions (due to trust in the communicated feeling of total safety) and on the other hand often itself affecting and even driving public decision making (particular in times of recovery after a major disaster when impact impressions are still mentally available) (Renn, 1998). At the same time the way risks are perceived is also a major contributing factor to the vulnerability and resilience of a social system facing latent hazard conditions (in terms of its public awareness and related anticipated response level) (Aubrecht et al., 2009a; Deeming, 2013).

The pre-event phase being characterized by long- and short-term 'mitigation' actions

Mitigating impacts of disasters includes interventions made in advance of an event to prevent or reduce the potential for physical harm and social disruption (NRC, 2006) and therefore starts with risk reduction and prevention measures. The adverse impacts of hazardous events mostly cannot be prevented or avoided fully, but their scale and severity can be substantially lessened by various strategies and actions (UNISDR, 2009).

Land use planning and management plays an important role at this stage (Kötter, 2003; NRC, 2006) (e.g., environmental policies, 'smart growth', discouraging settlement in hazard zones), as well as general preparedness both in terms of social and economic activities (e.g., increasing public awareness as well as governmental and professional response capacities) and infrastructural measures (e.g., construction of key installations in hazard-prone areas, consideration of service routes). In particular the latter is often publicly considered as risk prevention, but residual risks resulting from pre-defined hazard-specific construction dimensions always remain (e.g., an individual flood event exceeding dam design capacity).

Prediction and early warning prior to the next hazard event form the final part of this stage (Mileti, 1999). Spatial analysis and GIS in general offer powerful tools to support decision making in a mitigation context. Following the assessment of spatial and temporal aspects of hazards, exposed elements at risk and associated vulnerabilities, the identification of geographical trends and patterns of risk forms the basis for directing mitigation measures. In addition to basic mapping services, GIS capabilities in that regard include database and inventory creation, sensitivity and cost-benefit analysis, scenario analysis, and decision matrix, based on geoprocessing and spatial statistics methods (Menon and Sahay, 2006).

The post-event phase being characterized by long- and short-term 'response' measures

The post-disaster *response* phase includes initial impact assessment (damage and losses) and accordingly coordinated search and rescue efforts as well as emergency services during or immediately after an event, followed by recovery and rehabilitation. Recovery is sometimes also considered a distinct phase, separated from initial short-term response actions that are also referred to as disaster relief (UNISDR, 2009; Abdalla and Li, 2010). Recovery then is understood more in the long-term, e.g. in terms of restoration of services and living conditions, reconstruction, and general rehabilitation (NRC, 2006).

While EO data and remote sensing in particular serve as the main source for situation monitoring and impact assessment, GIS is especially strongly applied in terms of information access provision and dissemination (Mills, 2008), as well as logistics and spatial planning activities for sustainable rehabilitation. Making use of the heightened public awareness and engagement after a disaster, recovery actions can afford a valuable opportunity for sustainable development and implementation of DRR measures for future events (according to the 'building back better' principle; Berke et al., 1993; Baas et al., 2008; Kirk, 2008; UNISDR, 2011). This, again, is based on updated risk analysis processes where risks are revaluated and new sources identified.

Conceptual advancement from a cyclic to a conic or spiral perspective

Following the ambition to reduce risks and become better prepared and therefore continually improve overall DRM, the cyclic perspective has been sort of conceptually unrolled in recent years as it was considered to misleadingly convey a feeling of ending up back in disaster after phases of response to an event and preparation for the next event (Stewart, 2005).

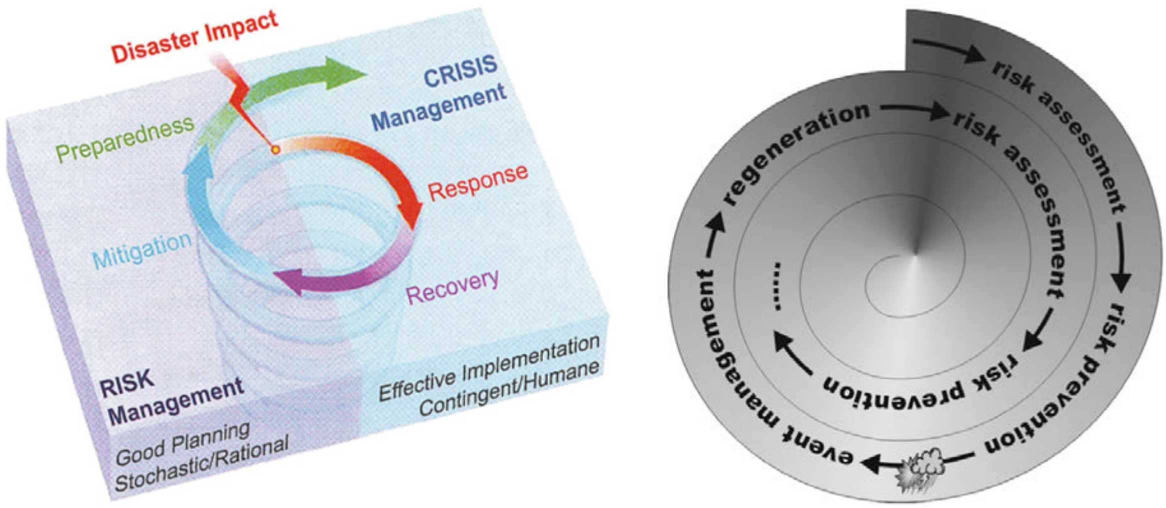


Figure 13: Adaptation of the cyclic concept of disaster risk management to a spiral (left; Kyoto University-DPRI, 2009) or conic (right; Kipfer et al., 2006) perspective.

A spiral or conic approach has been adopted (Kienholz et al., 2004; Kipfer et al., 2006; Kyoto University-DPRI, 2009), illustrating the continuous performance improvements in management practices (good planning and effective implementation) which ideally result in reduced impacts of future events (fig. 13). As it is however impossible to achieve zero risk, the residual risks prevent the DRM spiral from reaching the top of the cone (Kipfer, 2005) and thus conceptually keep the spiral on the loop (Aubrecht et al., 2011c).

Certainly not always DRM is improved, particularly in marginalized societies disaster events potentially break down the entire organizational structure making them even more prone to catastrophic impacts from following events. From a conceptual point of view, that would imply even a widening of the spiral structure, with the residual risk level in fact aligning with maximal damage potentials due to lack of risk reduction actions.

Both mitigation and response actions do not just affect the current situation immediately before or after a disaster, but should ultimately also aim at reducing overall future risk in the long-term (NRC, 2006). This is obvious for the mitigation phase, but not less important for the response phase, where well-organized search and rescue actions and also coordinated recovery and rehabilitation support can dramatically reduce overall impacts and set the stage for sustainable future developments.

Seeing this in an ex ante perspective, such measures primarily aiming at the immediate pre- and post-event phase of a disaster can also be considered as attempts to reduce overall vulnerability of the affected system (referring to strengthened coping and adaptive capacities). Vulnerability can therefore also be regarded as a time-dependent function of mitigation and response measures (Aubrecht et al., 2012a).

Furthermore, the concept of vulnerability itself introduces a significant temporal aspect into DRM. Disparities in the socio-economic structure of a society shape coping capacities and overall vulnerability of local communities and result in uneven impact of a catastrophic event (Finch et al., 2010). Particular aspects of social vulnerability, such as varying patterns of health vulnerability, result in spatial variation in the speed of neighborhood recovery with the most socially vulnerable being the slowest (Plyer, 2010). It becomes evident that all the different DRM phases are highly interconnected and influence each other in many ways.

Continual improvement and shifting focus in risk management strategies

With regard to a sustainable approach to handling risk, emphasis is placed on the continual improvement in risk management (Purdy, 2010), considering learning from past experiences and anticipating relevant future developments (OECD, 2004; NRC, 2006; Turoff et al., 2009). Increased awareness of the public and of public authorities as a result of a disastrous event can be valuable input and stimulus for pre-disaster planning regarding the next event, and also lead to more sustainable recovery and rehabilitation (Berke et al., 1993). There is, however, often a vast discrepancy between the levels of knowledge acquired through analysis of past disasters and actual implementation actions for future events (Donahue and Tuohy, 2006; Scanlon, 2013) (fig. 14).

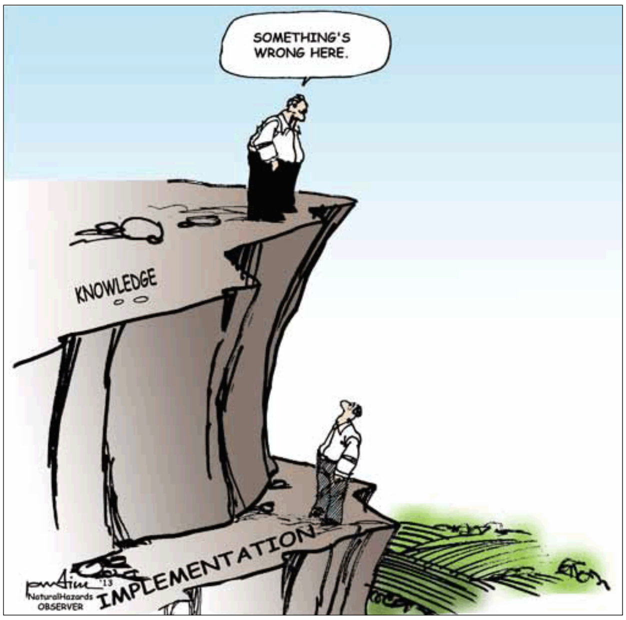


Figure 14: The discrepancy between the levels of knowledge acquired through past-disaster analysis and implementation actions for future events (cartoon from Natural Hazards Observer, 01/2013).

Public attention quickly decreases even after major disasters, which is tightly linked to dipping media response after the initial peak coverage in the emergency stage (fig. 15). This is relevant not only in terms of changing public awareness and associated patterns of public risk perception. Public attention also causes a strong relationship between media exposure and funding. Another challenge for DRM is therefore to maintain attention and interest in that regard, in particular as the majority of accessed finances are in fact needed for recovery in the longer term (Khan et al., 2008; Piper, 2013; Taubenböck and Strunz, 2013).

With the development of future situations being to a high degree uncertain, in the past most efforts were reactive in nature (NRC, 2006) and focused on the post-disaster phase without considering lessons learnt from past events, thus remaining in a vicious cycle where the next disaster was going to cause the same effects or worse (van Westen, 2012). In recent years, a paradigm shift from a *reactive* approach of focusing attention on immediate emergency response to *proactive*, anticipatory, and therefore much more sustainable DRR and DRM by strengthening prevention, mitigation, and preparedness, has been promoted in the disaster risk community (e.g., Annan, 1999; Garatwa and Bollin, 2002; Baas et al., 2008) and is also positioned in the '*Hyogo Framework for Action 2005-2015*' report (UNISDR, 2007).

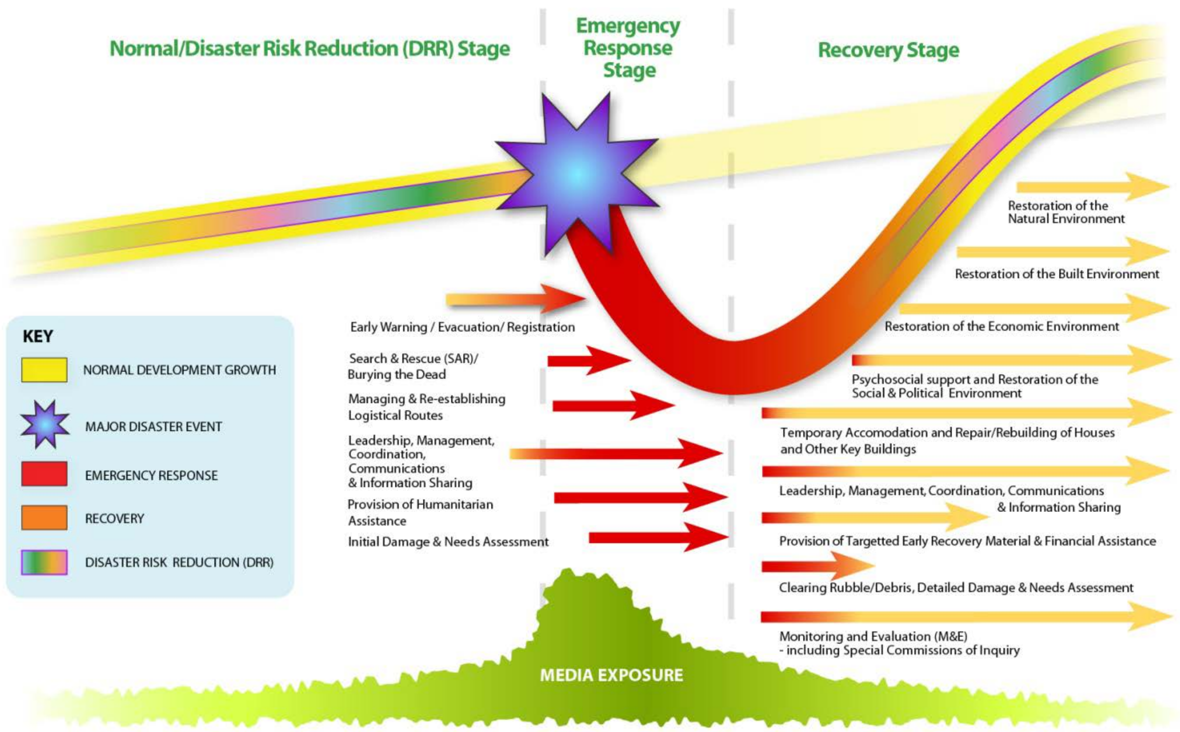


Figure 15: Phases of disaster risk management in the context of effects of emergency response and disaster risk reduction on socio-economic development (modified from Piper, 2013).

As an intermediate step in that process of attitude change, first, more attention has been given to short-term disaster preparedness through the development of sophisticated early warning systems and comprehensive evacuation planning. To further foster the ambition of a ‘preventive risk culture’ eventually more emphasis is put on the longer-term pre-disaster stage, particularly focusing on prevention and preparedness.

The ultimate goal of DRM in that context is to fully prevent disaster events when possible, to reduce impacts of individual events and eventually only reach the response phase for extreme events with very low frequency. Fig. 16 illustrates that paradigm shift, highlighting the changing focus while turning from a reactive to a preventive approach.

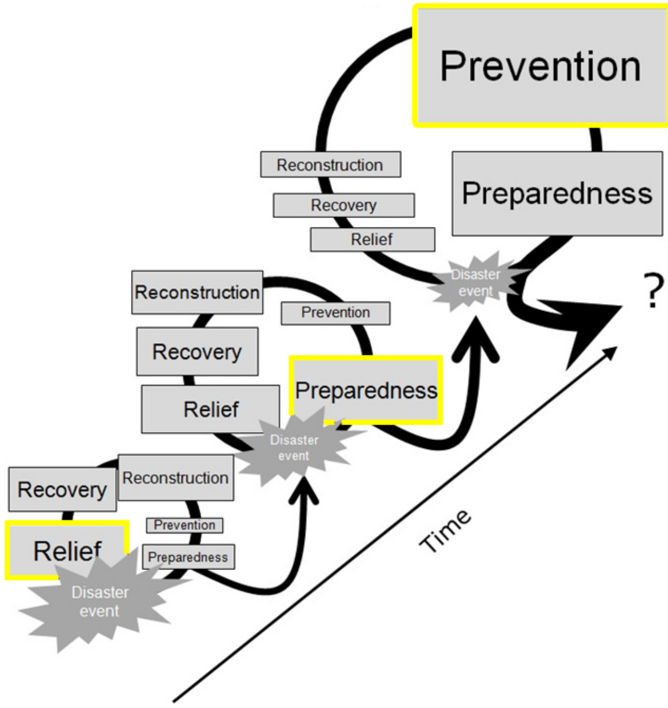


Figure 16: Shift of focus in DRM towards a culture of prevention (modified from van Westen, 2012).

Forward-looking risk governance

Despite these theoretical and conceptual advancements, the growing scale and frequency of disaster situations in recent years have shown a lack of adequate foresight and strategic planning (Linstone and Turoff, 2011), with responses to major disasters still seeming to be very short-term reactions with very limited integration into long-term mitigation and recovery plans (van de Walle and Turoff, 2008). Employing forward-looking activities and participatory risk assessment (Ikeda et al., 2008; Kemp, 2008; van Aalst et al., 2008) involving multiple stakeholders (NRC, 2006; Crandall and Spillan, 2010) including professionals, local authorities, the private sector, and the people living in the exposed areas in collaborative activities (Montague, 2004; EC, 2010) is particularly relevant in this long-term risk reduction context. Envisioning future developments and integrating past findings as well as current characteristics helps trying to minimize potential impacts before disasters occur.

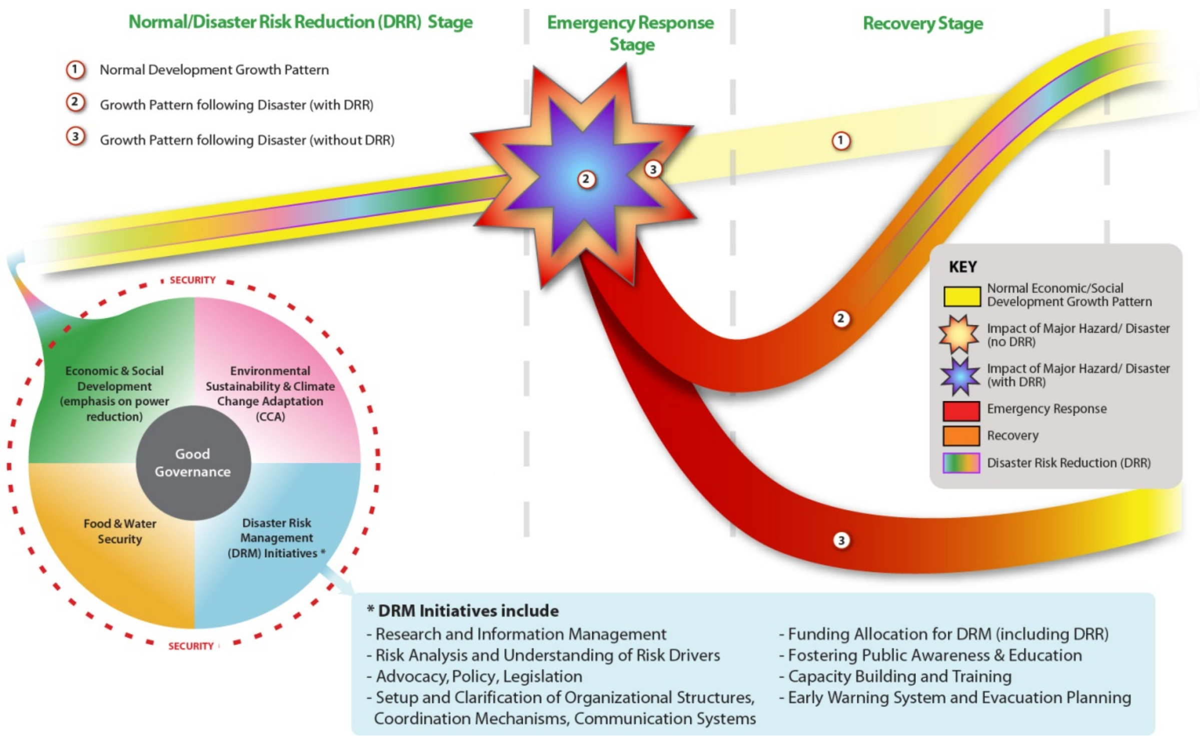


Figure 17: The effects of improved disaster risk reduction on impact and recovery pace in the context of promoting a more sustainable disaster risk management (modified from Piper, 2013).

The need for multi-perspective and comprehensively forward-looking risk governance for DRM is evident in that regard (NRC, 2006; Renn, 2008; van Westen, 2012; Aubrecht et al., 2013e). To guarantee sustainability this must exceed basic DRR actions (UCB-NHRAIC, 2001; von Lubitz et al., 2008) and encompass a much broader perspective including fostering overall economic and social development (with an emphasis on poverty reduction), food and water security (with regard to minimizing conflict potentials), as well as environmental sustainability and proactive climate change adaptation (NRC, 2006; Piper, 2013).

Fig. 17 illustrates in that context how effective DRR in a ‘good governance’ setting influences the course of disasters both in terms of the (reduced) immediate scale of impact and in terms of (fast) system recovery. If DRR measures are not applied successfully, reactive policies may increase long-term vulnerability of affected populations (Ingram et al., 2006) or social systems might even collapse and never be able to return to pre-event functionality again.

3 Population exposure implementation: Spatial and temporal aspects[5]

In the context of disaster risk management and particularly for exposure and impact assessments the quality of available input data both in terms of spatial and thematic accuracy and reliability is one of the most important factors. Census data available in heterogeneous spatial reference units are considered the standard information input for assessing potentially affected people, e.g. in case of an emergency. However, there is a strong demand for population data that are independent from enumeration and administrative areas. Raster representations meet this demand but are not yet available globally in both spatial and thematic consistency. Re-allocating aggregated population counts from administrative areas to a regular grid requires areal interpolation methods such as dasymetric mapping. This technique utilizes ancillary data to disaggregate coarse population data to areas where it is effectively present, at a finer resolution (Aubrecht et al., 2009b). Land Use/Land Cover (LULC) maps are often used as a basis for the disaggregation and reallocation process in that regard (Eicher and Brewer, 2001; Mennis and Hultgren, 2006; Langford, 2007).

Information on functional relationships in urban and suburban environments as well as high-level population distribution information are often not quickly available in case of emergency and cannot be immediately produced with high accuracy.

[5] Parts of this section refer to Aubrecht et al. (2009b, 2010bc, 2011ad, 2012acd, 2013b) as well as Freire and Aubrecht (2010, 2011, 2012)

3.1 Coarse-scale approaches

For applications dealing with population exposure on a supra-regional level, rather coarse-scale raster data on population patterns are mostly well suited, but for sub-regional analyses representations on higher spatial resolution are required, i.e. fine-scale population grids which eventually go down to basic building level. After elaborating on coarse-scale approaches in the following, local-scale approaches will be the focus of chapter 3.2.

3.1.1 Different concepts on global and continental level

For an overview of broad-scale approaches to population distribution modeling, Balk et al. (2006) presented a list of datasets all focusing on representing resident population based on the highest resolution input data available. The first and least complex dataset is the *Gridded Population of the World (GPW)* (SEDAC-CIESIN, 2013) representing the residence-based spatial distribution of human populations consistently across the globe to facilitate cross-national and sub-national analysis. 'The Global Demography Project' (Tobler et al., 1995, 1997) can be considered the first major effort in that regard. That first version of GPW illustrating population estimates for the year 1994 at 5' x 5' resolution was a precursor for the subsequent series of approaches to consistently map population on a global scale. Earlier population modeling efforts and data characteristics prior to GPW are described by Clarke and Rhind (1992) and Deichmann (1996a).

The current third edition of that broad-scale data product (GPWv3) aims at providing a spatially disaggregated population layer that is compatible with datasets from social, economic, and geoscience fields (CIESIN and CIAT, 2005). The output shows the distribution of human population converted from national or sub-national spatial units (usually administrative) of varying resolutions, to a series of geo-referenced grids at a resolution of 2.5 arc-minutes (Deichmann et al., 2001). GPWv3 incorporates a number of improvements to the two prior iterations of GPW (Balk and Yetman, 2004). Input administrative data have been improved for nearly all of the 232 countries included in the dataset (i.e. the number of administrative units has increased three-fold since GPWv2 and twenty-fold since GPWv1) (compare table 1) and slight modifications have been made to the processing (Balk et al., 2010). Additionally, the input data years have been updated for over two-thirds of the countries. Population data estimates are available for the period 1990-2015 by quinquennial years with projections for 2005, 2010, and 2015 produced in collaboration with the UN Food and Agriculture Programme (FAO) as 'GPW: Future Estimates' (Balk et al., 2005a). Fig. 18 shows a comparison of GPWv3 and selected global scale datasets on earthquake hazard patterns. Being designed at similar level of detail, such data sets can be spatially overlaid and jointly analyzed to derive preliminary population exposure estimations.

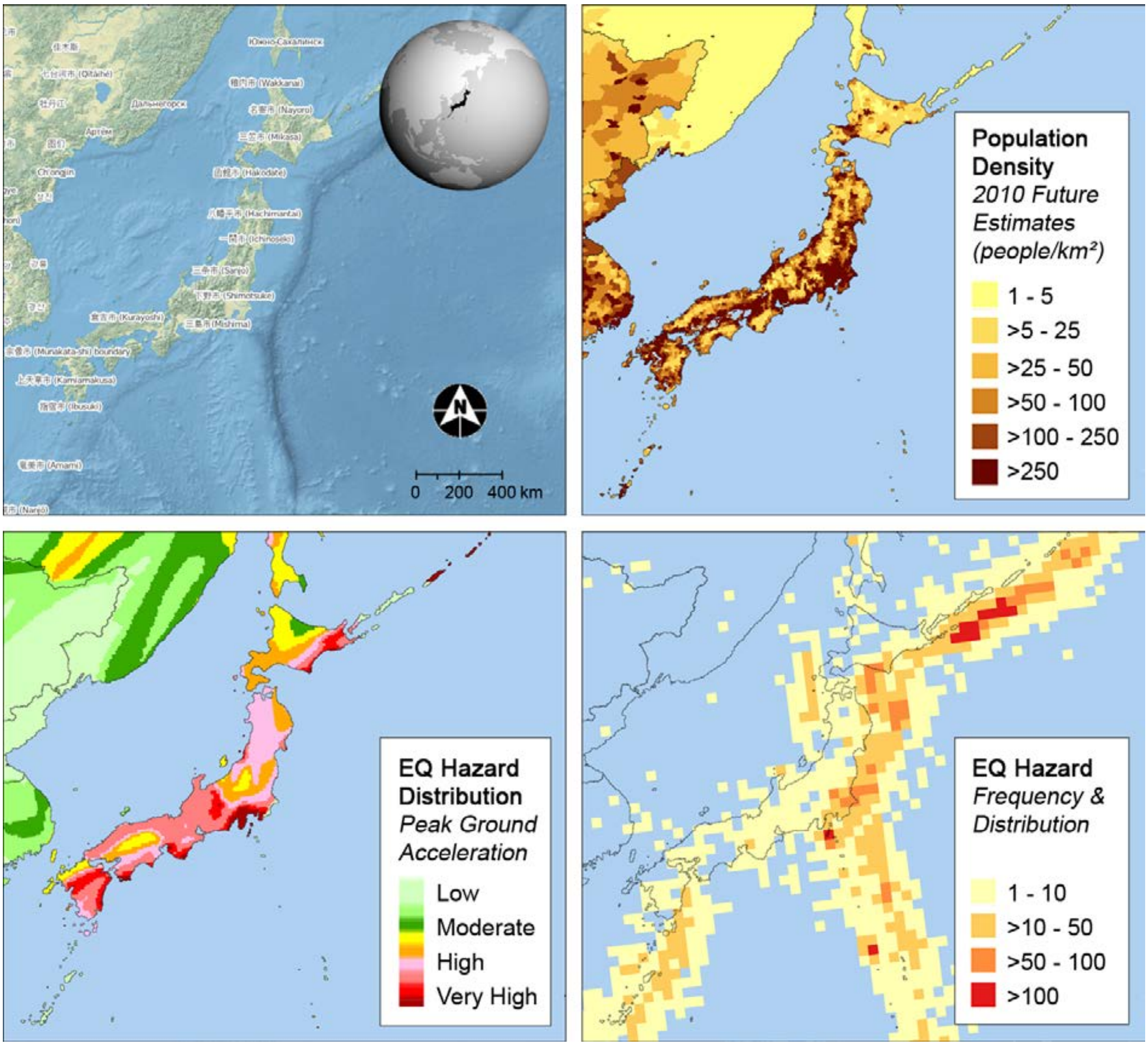


Figure 18: Comparison of global-scale population density (GPWv3) and EQ hazard pattern data for Japan (Source: SEDAC-CIESIN, 2013). OpenStreetMap is provided on the top left for orientation.

The *Global Rural-Urban Mapping Project (GRUMP)* provides a new suite of data products that add rural-urban specification to GPWv3 by combining census data with satellite data, hence featuring an increased level of complexity (Balk et al., 2005b). This project emerged out of a need for researchers to be able to distinguish population spatially by urban and rural areas (Montgomery et al., 2003). There is however no single definition of what makes an area 'urban'. Balk (2009) points out the UN World Urbanization Prospects (UN, 2006) which identifies each country's definition of the term 'urban' where criteria include a variety of population size or density thresholds associated with administrative areas, capital cities, and combinations thereof. The urban-rural mask that is eventually used for weighted reallocation (see fig. 19) is developed partly based on DMSP nighttime lights data (showing areas artificially lit at night) as well as other supplementary data such as buffered settlement centroids (where night lights are not sufficiently bright) (SEDAC-CIESIN, 2013).

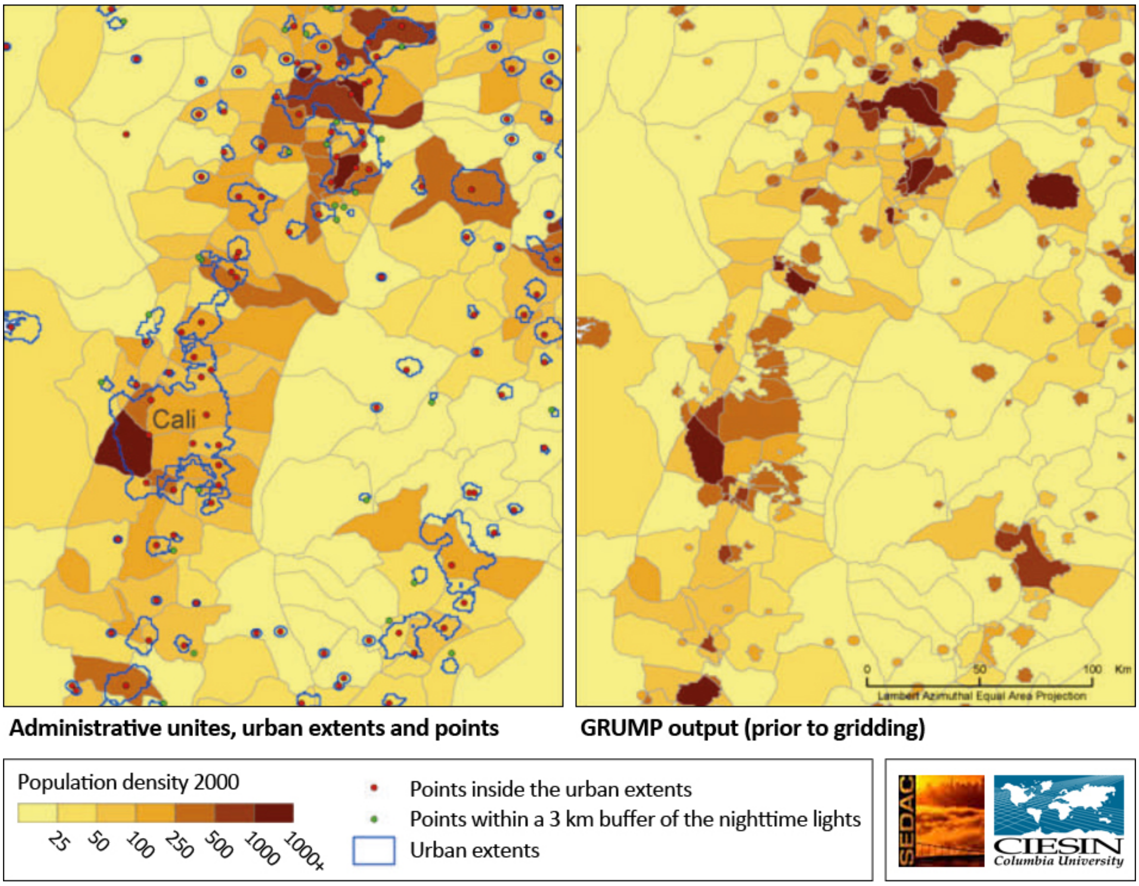


Figure 19: Demonstration of the urban reallocation for an area near Cali, Colombia; left shows GPWv3 gridding basis, right shows GRUMPv1 gridding basis (modified from Balk et al., 2010).

More details on the methodology as well as related constraints and shortcomings are provided by Balk et al. (2010). The central data product resulting from GRUMP (current status: Version 1, GRUMPv1) is a 'Gridded Population of the World with Urban Reallocation' in which spatial and population data of both administrative units and urban extents are gridded at a resolution of 30 arc-seconds (corresponding to approximately 1 km at the equator; i.e. 25-fold higher resolution compared to GPW). In addition GRUMPv1 also provides the urban extents data that are used for the urban-rural reallocation.

Comparison of the Gridded Population Products GPW (all versions) and GRUMPv1					
Summary information	**GPW *v1***	**GPW *v2***	**GPW *v3***	**GPW *fe***	**GRUMP *v1***
Publication year	1995	2000	2005	2005	2011
Years of estimation	1994	1990, 1995	1990, 1995, 2000	2005, 2010, 2015	1990, 1995, 2000
Number of input units (sub-national geographic units)	19,000	127,000	~ 400,000	~ 400,000	~ 8,000,000
Data and Map Products *Grid datasets are available in bil, ascii, and zipped ArcInfo workspace formats*					
Grid resolution	2.5 arc-min	2.5 arc-min	2.5 arc-min 1/4 deg 1/2 deg 1 deg	2.5 arc-min	30 arc-sec
Population grid	Country Continent World	Country Continent World	Country Continent World	Country Continent World	- Continent World
Population density grid	Country Continent World	Country Continent World	Country Continent World	Country Continent World	- Continent World
Land area grid	Country Continent World	Country Continent World	Country Continent World		- Continent World
Urban extents grid					Country Continent World

Table 1: Comparison of the CIESIN Gridded Population data products showing the development and expansion of GPW and the follow-up GRUMP over time (SEDAC-CIESIN, 2013).

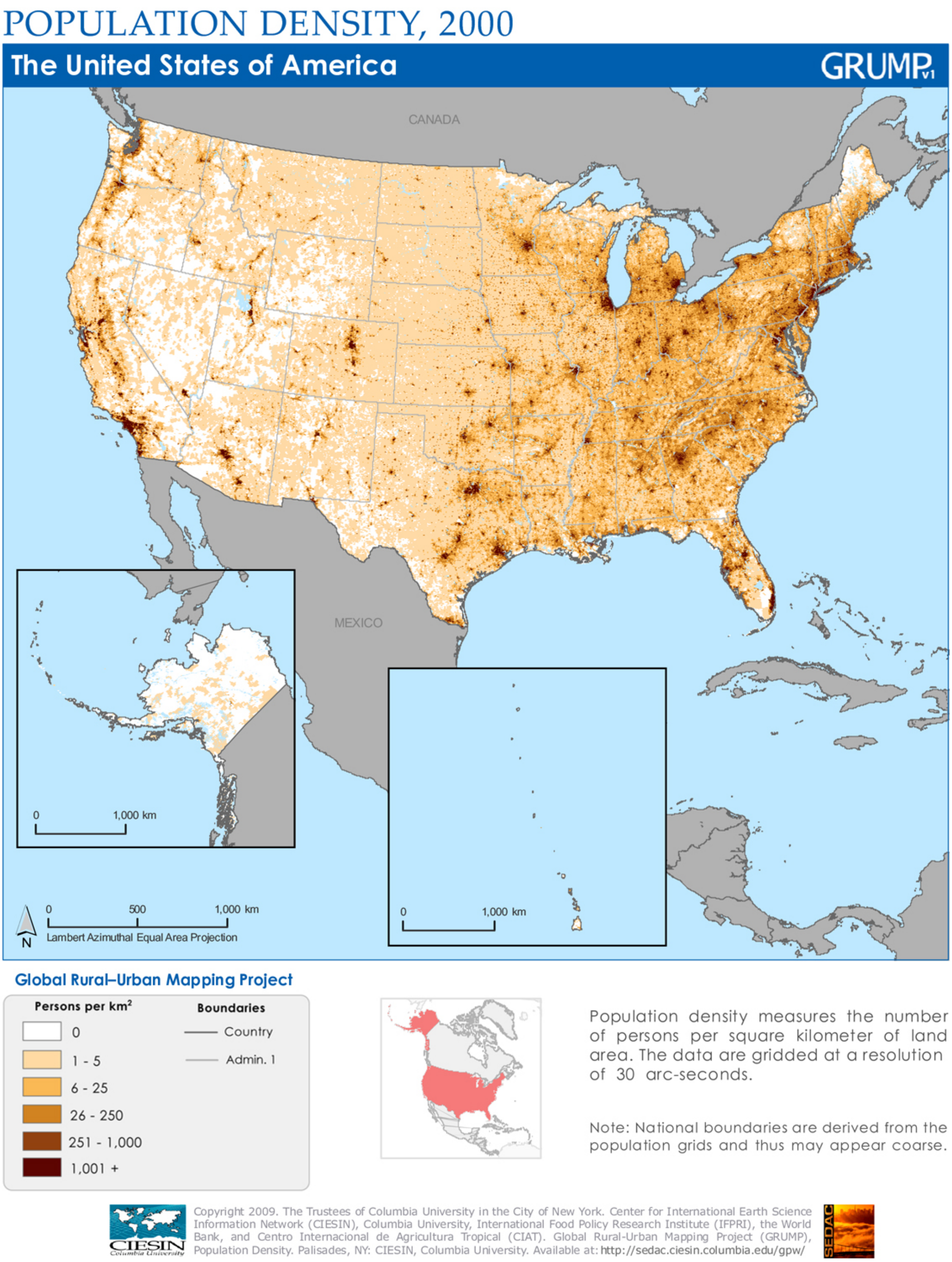
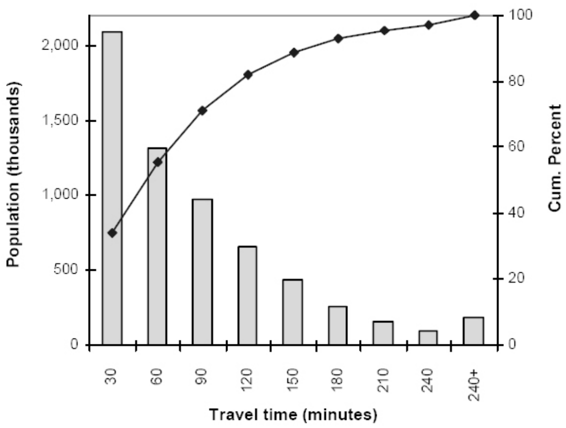


Figure 20: GRUMPv1 population density for the United States (SEDAC-CIESIN, 2013). Particularly evident is the accurate representation of uninhabited areas (see white spots, e.g. in wide areas of the Midwest and Alaska).

Considering a set of additional assumptions about real-world population distribution, another group of modeled datasets is based on the *accessibility concept*. Basic motive for that kind of methodology is that people tend to live in or close to cities and tend to move towards areas that are well connected with urban centers (Balk et al., 2006). This premise basically holds true even for rural regions for which it is expected that areas of higher population density are located preferentially close to transport links and bigger cities.

The concept of accessibility and related indicators has been in use for a long time in particular in transportation research (Koenig, 1980; Halden, 2003; Gutiérrez et al., 2010). Applying accessibility indicators to population distribution and reallocation models has however not been that popular until first implementations for producing continental-scale databases for Africa, Asia, and Latin America in the mid-to-late 1990s (Deichmann, 1994, 1996b; Hyman et al., 2000). Deichmann (1997) provides a comprehensive overview on the use of various accessibility indicators in GIS. He emphasizes that there are several ways to define accessibility and presents different concepts. Accessibility can be defined as the ability for interaction or contact with sites of economic or social opportunity. This definition is supported by Goodall (1987) who states that "*[the] concept expresses the ease with which a location may be reached from other locations. [It] summarizes relative opportunities for contact and interaction.*" Fig. 21 underlines the relation of population distribution and accessibility, by means of illustrating population patterns in two provinces in Madagascar (Antananarivo, Fianarantsoa) (Deichmann, 1997).



Travel time (minutes)	Pop ('000)	Cum. Percent	WRA* ('000)	Cum. Percent
30	2,086	33.9	537	36.8
60	1,314	55.3	297	57.2
90	970	71.1	217	72.1
120	656	81.7	148	82.2
150	438	88.9	101	89.1
180	258	93.1	59	93.2
210	153	95.5	35	95.6
240	93	97.1	22	97.1
> 240	181	100.0	42	100.0

*WRA... women in reproductive age (15-49)

Figure 21: Population by travel time from a service center location (from Deichmann, 1997).

Serving as example for broad-scale population data based on accessibility modeling the *African Population Database* is described in more detail. The currently available dataset is the fourth version of a database of administrative units with associated population figures for Africa (Nelson, 2004). The first version was initially compiled for UNEP's Global Desertification Atlas (Deichmann and Eklundh, 1991; Middleton and Thomas, 1992), with the second and third versions representing corresponding updates and expansions (Deichmann, 1994, 1998; WRI, 1995).

The method for the development of population raster grids consists of a set of processing steps. The most important input into the model is (1) information about the transportation network consisting of roads, railroads and navigable rivers. The second main component is (2) information on urban centers. Data on the location and size of as many towns and cities as could be identified were collected, and these settlements are linked to the transport network. Input variables are mapped in fig. 22.

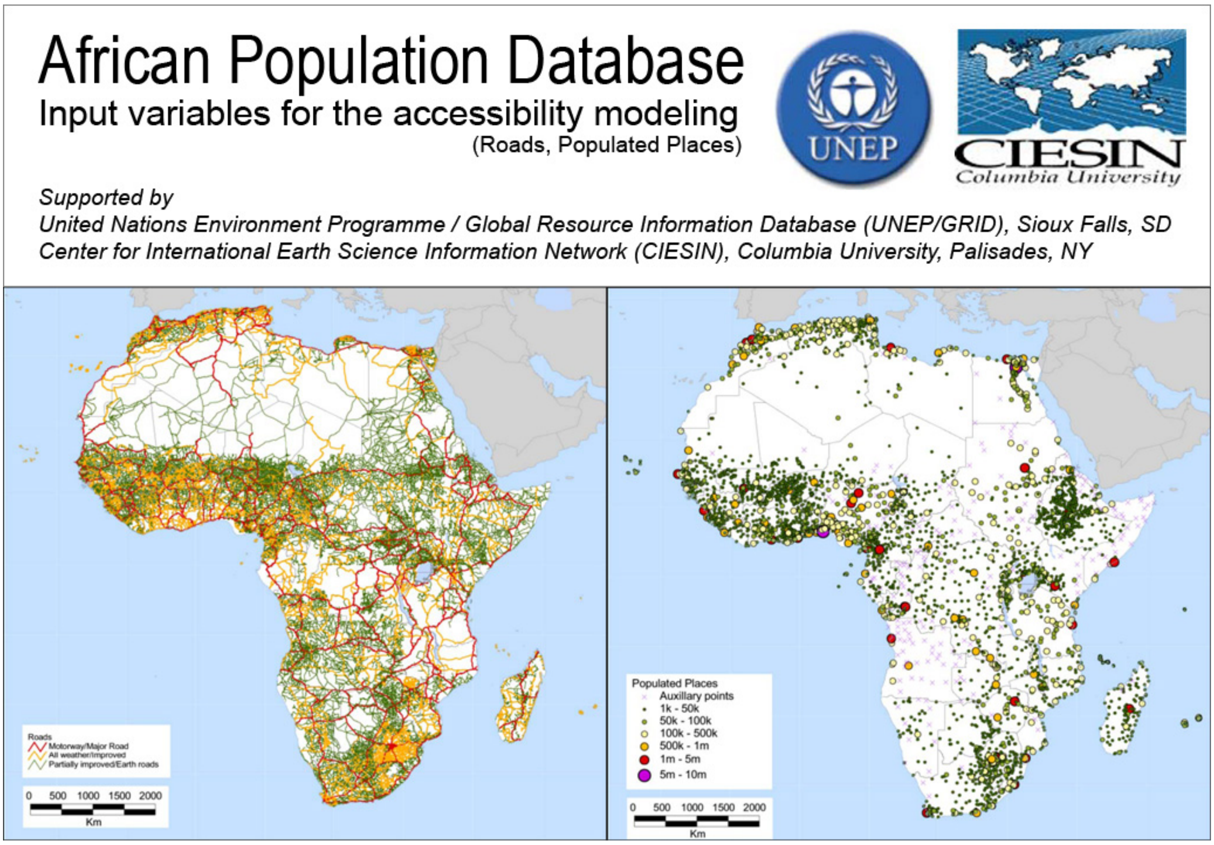


Figure 22: Road network and populated places as input variables for accessibility modeling.

That information was then used to compute a simple measure of accessibility for each node in the network. This measure, called population potential, is the sum of the population of towns in the vicinity of a specific node weighted by a distance function, where network distances are used rather than straight-line distances. The computed accessibility estimates for each node are subsequently interpolated onto a regular raster surface. Raster data on inland water bodies (lakes and glaciers), protected areas and altitude are then used to adjust the accessibility surface heuristically. Finally, the population totals estimated for each administrative unit are distributed in proportion to the accessibility index measures estimated for each grid cell. The resulting population counts in each pixel could then be converted to densities for further analysis and mapping.

The newest database release for Africa provides considerably more detail than its three precursors: more than 109,000 administrative units (83,000 of which are however in South Africa), compared to about 800 in the first, 2,200 in the second and 4,700 in the third version. In addition, for each of these units a population estimate was compiled for 1960, 70, 80, 90 and 2000 providing an indication of past population dynamics in Africa (fig. 23). The African administrative boundaries and population database was compiled from a large number of heterogeneous sources. The objective was to create a comprehensive database from existing sources and in a fairly short time period that is suitable for regional or continental-scale applications. The resources available did not allow for in-country data collection or collaboration with national census bureaus, as was done, for example, in the WALTPS study (Brunner et al., 1995). With few exceptions, the datasets thus do not originate from the countries themselves, and input boundary data have not been officially checked or endorsed by the national statistical or mapping agencies.

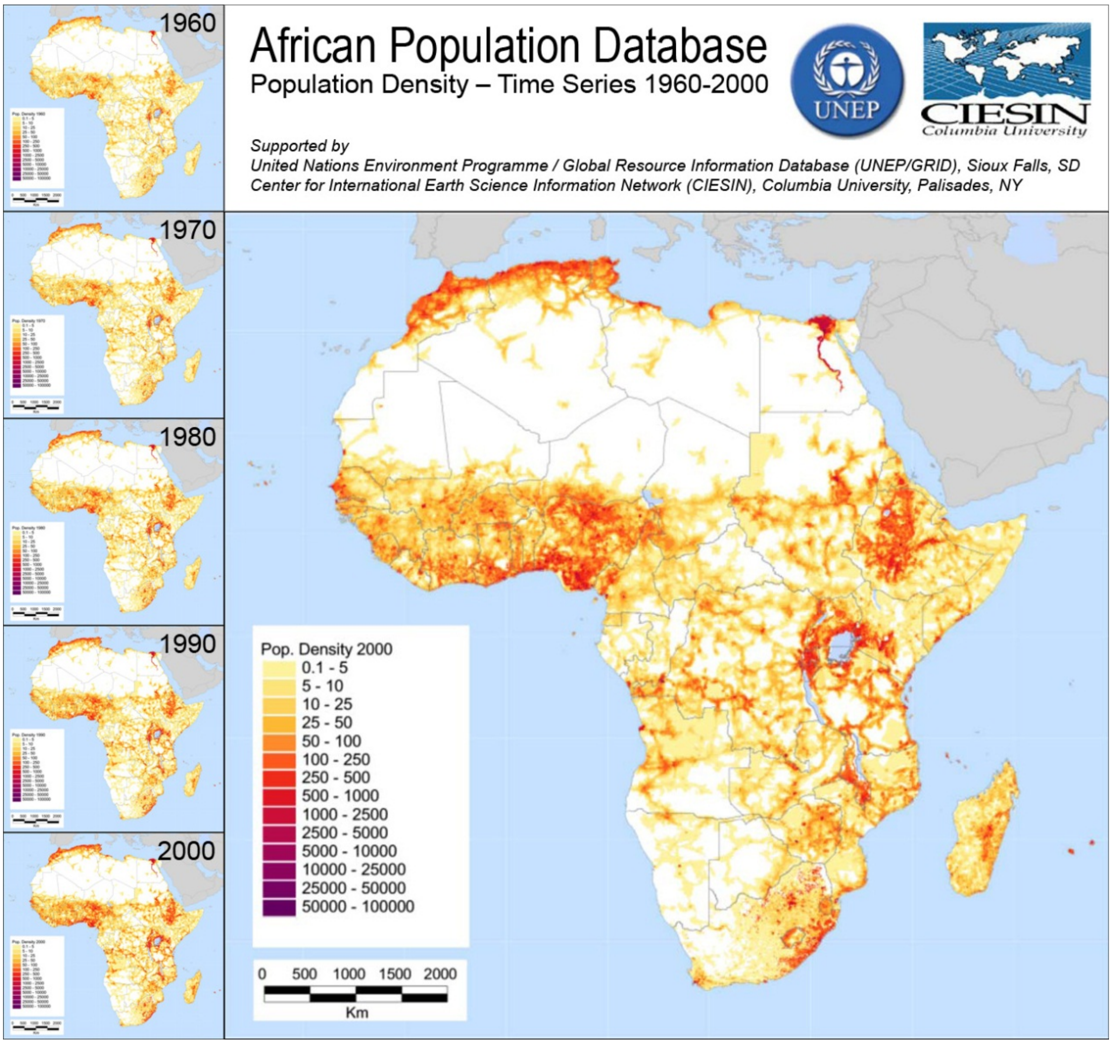


Figure 23: African Population Database - Time Series 1960-2000.

Besides the abovementioned global and continental-scale population databases that focus on representing and refining residential information, there is another widely used dataset available on that spatial level - *LandScan*^{TM} - comprising a worldwide population database compiled on a 30 arc-seconds latitude/longitude grid (approximately 1 km resolution). Exceeding the methodological complexity of the above-listed accessibility model approaches, in addition to transportation networks and populated places LandScan includes likelihood coefficients based on parameters such as land cover, roads, elevation, slope, and radiance-calibrated nighttime lights as well as high resolution imagery analysis for apportioning census counts and UN estimates to each grid cell while originally less effort was spent on using the highest-possible resolution population input information.

A multi-variable dasymetric spatial modeling approach (referred to as 'smart interpolation') is applied to disaggregate census counts within administrative boundaries, tailored to match data conditions and geographical nature of individual counties and regions. LandScan has been developed as part of the Oak Ridge National Laboratory (ORNL) Global Population Project for estimating ambient populations at risk. This dataset has a categorically different focus compared to the previously described population distribution models as it aims at measuring ambient population (average over 24 hours) instead of attempting to represent nighttime census resident population (Dobson et al., 2000; Bhaduri et al., 2002a). The objective of this averaging process to represent ambient population is to integrate diurnal movements and collective travel habits into one single measure. The initial motive in setting it up that way was to account for short-term population fluctuation patterns, bearing in mind that a disastrous event may occur at any time of the day. The database is updated annually (latest version: LS2011; Bright et al., 2012) by incorporating new spatial data and imagery analysis into the distribution algorithms. In contrast to above-described fully-automated models, the LandScan methodology includes manual verification and modification process steps (identification of population likelihood coefficients to correct or mitigate input data anomalies) in order to improve the spatial precision and relative magnitude of the population distribution (ORNL, 2013). That of course will improve overall data quality but at the same time (and in addition to limited algorithm documentation) substantially impedes methodological traceability. Also, LandScan is copyrighted (U.S. government), which means that a license fee is due for use of the data.

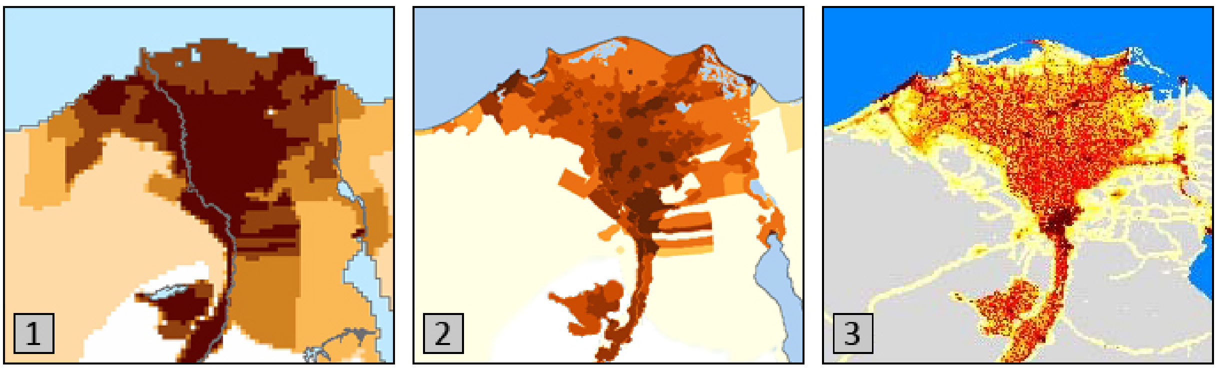


Figure 24: Comparison of GPWv3 (1), GRUMPv1 (2) and LandScan Global (3); illustrated for the Nile Delta, Egypt. In particular the accounting for roads in the LandScan reallocation process is evident.

Potere et al. (2009) provide a comprehensive overview and quantitative comparison of available datasets used for mapping global urban extent and modeling population distribution patterns on global scale. Fig. 25 illustrates those varying datasets by means of five cities from different regions on the globe. *DMSP-OLS nighttime lights*, for example, that are also applied both in the LandScan processing chain and the GRUMP urban extent identification method as described above are commonly used for demographic and socioeconomic studies (Elvidge et al., 2009, 2012; Levin and Duke, 2012), in particular for estimating settlement areas (Elvidge et al., 1997, 2001; Henderson et al., 2003; Small et al., 2005) and impervious surfaces (Elvidge et al., 2004, 2007; Sutton et al., 2009). There have been attempts to estimate population from nighttime lights only (Lo, 2001; Sutton et al., 2001; Zhuo et al., 2009; Anderson et al., 2010; Doll, 2010), even though it is acknowledged that in particular in less developed countries this approach comprises considerable problems and shortcomings. Nighttime lights can in that context then in fact be considered as main input factor for modeling poverty patterns, referring to missing or limited access to electricity (Elvidge et al., 2011).

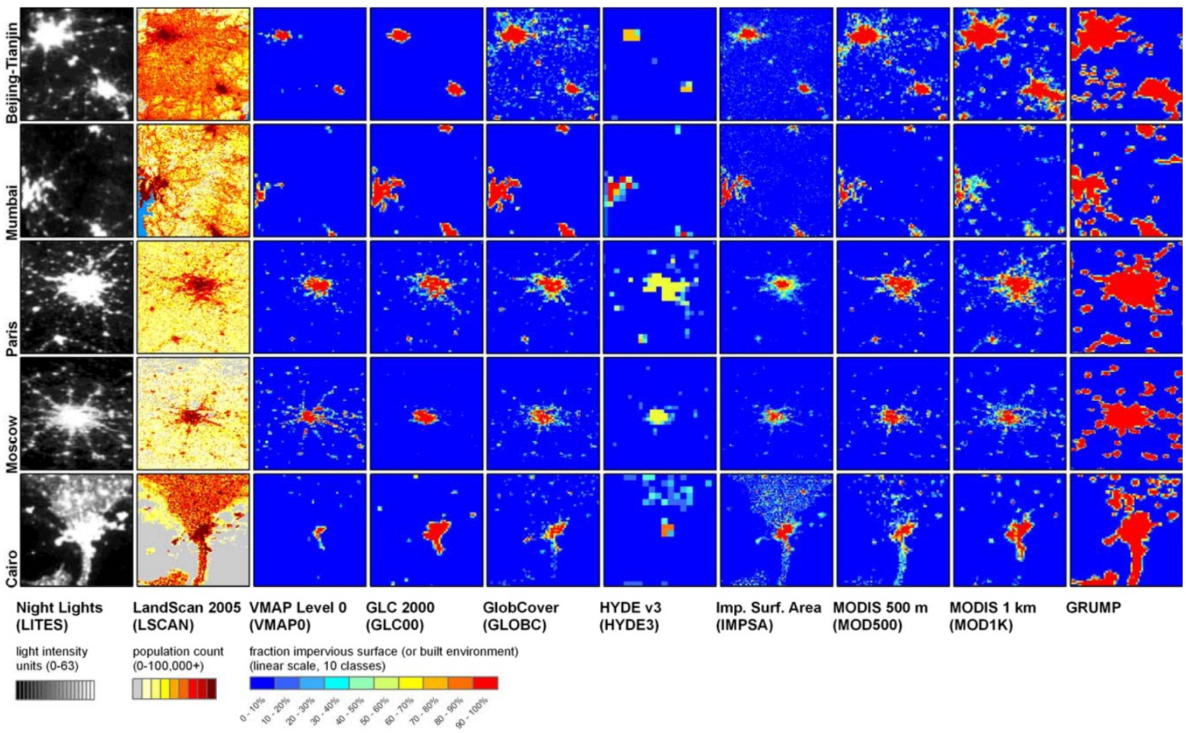


Figure 25: Comparison of datasets used for mapping global urban extent (from Potere et al., 2009).

All the described datasets have different objectives, make different assumptions, use different methodologies, and are designed to measure different indicators. As stated on the iSciences "Global Data Hound" blog in April 2009 (http://www.terraviva.net/data/blogs.htm) – in particular referring to the debate on LandScan vs. GPW/GRUMP preferences – "*it would not be fair to say that one or the other is 'better', it is more a question of what tool(s) are best for the job at hand*".

3.1.2 Illustrating and clarifying accuracy expectations on coarse-scale population models[6]

In the following, a case study is presented where an *accessibility surface* is produced *for the territory of Austria* and subsequently used for population disaggregation, following the UNEP/GRID approach applied for continental-scale databases such as the African Population Database (as outlined above). Referring to available high-resolution raster census data this study illustrates *first validation results* providing an idea of what can be expected from supra-regionally modeled population datasets in terms of accuracy and deviations.

High resolution population information (250 m grid cell size) available from the Austrian census 2001 is used as validation reference to identify deviation sources. Together with colleagues at CIESIN/NASA-SEDAC the algorithm that had been used for generation of the African Population Database (stand-alone program written in the C programming language) was adopted for the Austrian territory. An accessibility surface is produced (see figure 26) using populated places (GRUMP), water network, road and rail network (GISCO dataset based on EuroGlobalMap EGM 2.0 and EuroRegionalMap ERM 4.0), elevation information (SRTM) and protected areas (World Database on Protected Areas WDPA) as input variables. Population numbers on an aggregated district level – in that regard comparable to the level of availability of official population counts in African countries – are spatially disaggregated based on the calculated accessibility surface resulting in a refined population distribution dataset featuring a calculated 250 m resolution.

[6] Parts of this section refer to Aubrecht et al. (2010b)

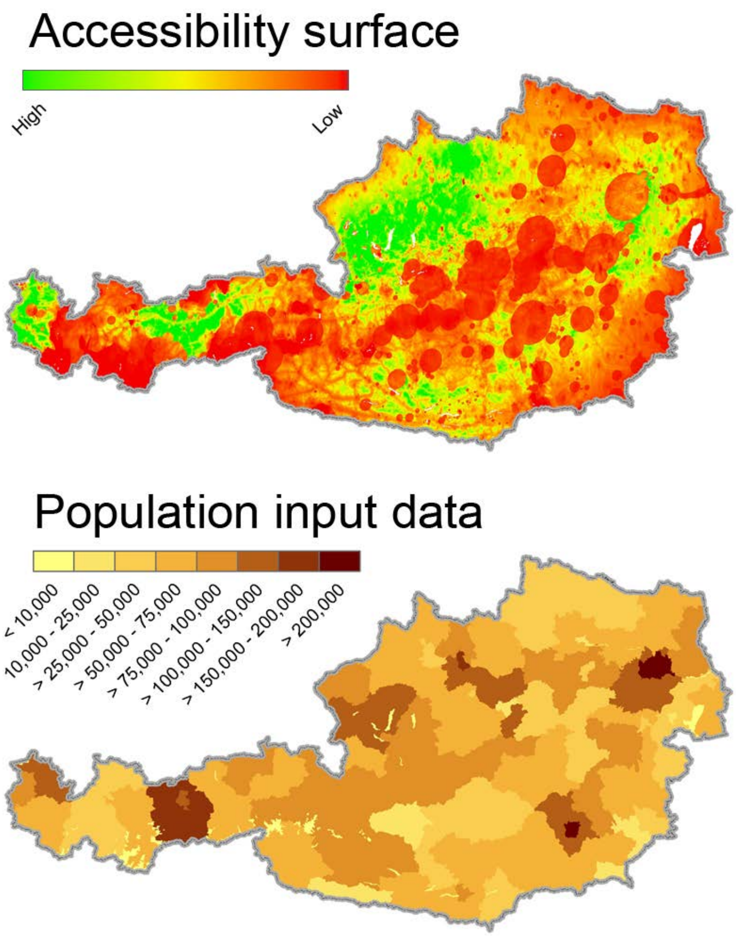


Figure 26: Input for population distribution - (1) accessibility surface, (2) district level census data.

First inter-comparison results of modeled population distribution and reference data from the census (figure 27, top left and top right respectively) show regional patterns of the degree of deviation (overall statistics of the study area: standard deviation 40.5, mean error 3.3). As expected, population numbers for suburban regions are overestimated while for the actual urban centers and areas in the broad vicinity of larger cities underestimations are reported (see Vienna, Linz, and Innsbruck in figure 27). The latter is mostly due to missing fine-scale information on the spatial distribution of small settlement regions which results in a 'shifting' of population towards the nearby suburban regions. The urban center underestimations can be explained by favoring factors not being weighted high enough in the accessibility model, thus not adequately accounting for the highest centrality characteristics. One idea in this context is to include satellite observed nighttime lighting (Elvidge et al., 1997, 2001, 2009) as centrality indicator in the accessibility model.

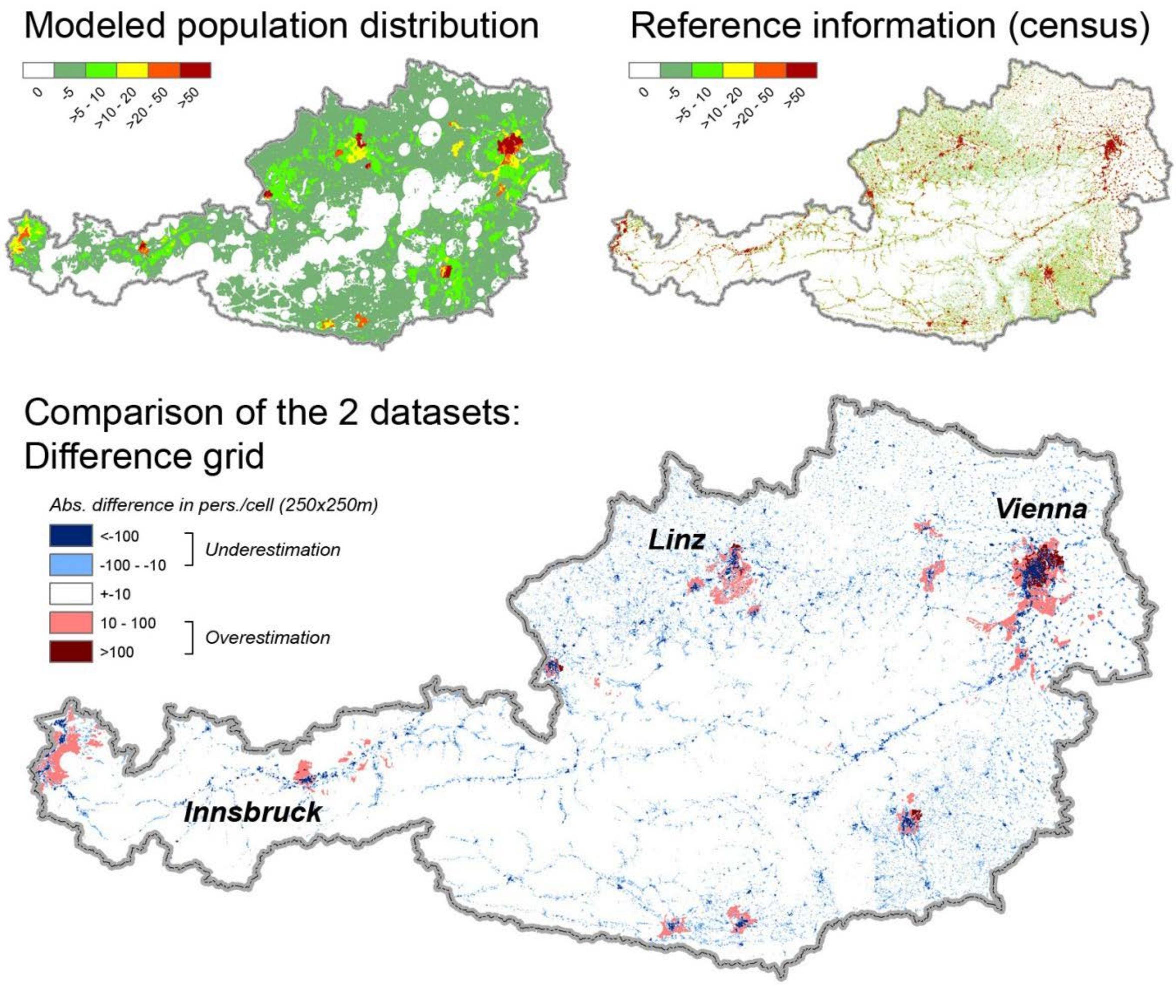


Figure 27: Comparison of modeled population distribution and reference data from the census.

At local scales the population surface has a mottled appearance due to the various different input factors. This and the underestimation of population in urban centers may be aided by applying pycnophylactic interpolation (see fig. 28), a mass-conserving algorithm for smoothing data (Tobler, 1979). A problem which becomes evident in visualizing the data is the inconsistent quality of the WDPA dataset. For Austria no exact protected area delineations are available, just center-points and corresponding total area information. As protected areas are introduced as limiting factor for population reallocation in the accessibility model, no population is assigned to these areas (see the white circular 'holes' in the modeled population data as shown in fig. 27). In Austria, just very few people actually live in formal protected areas, hence no big errors are introduced in the model that way. However, for other countries (e.g. in Africa) that issue is a problematic factor.

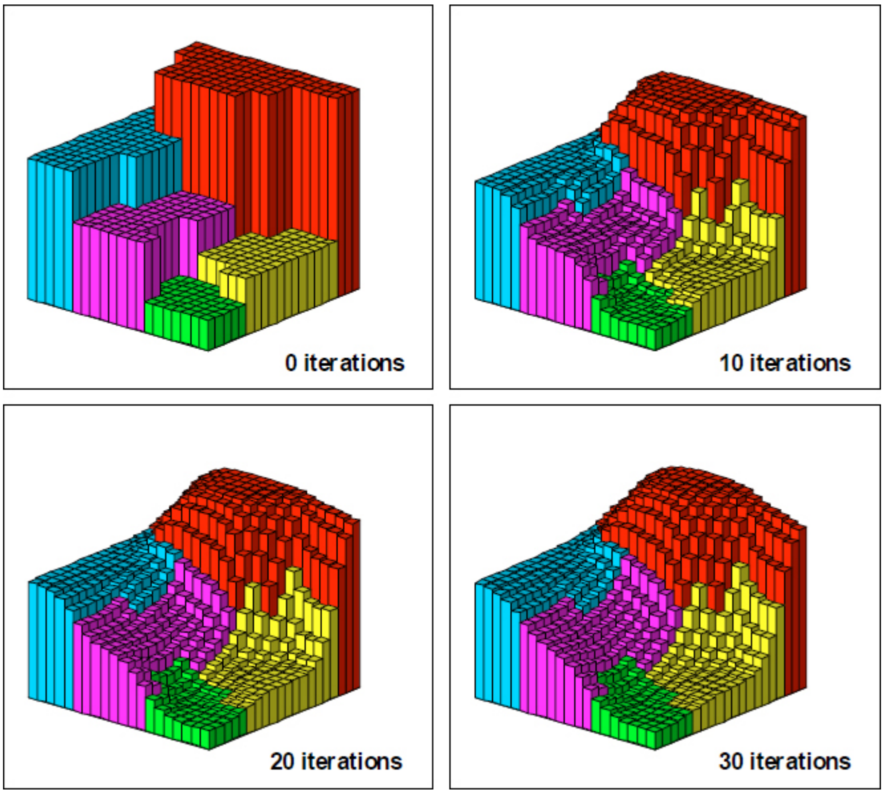


Figure 28: Pycnophylactic interpolation on a raster grid (from Deichmann, 1996a).

3.1.3 Refinement of coarse-scale population data aiming at more accurate exposure assessment in coastal areas[7]

Following the general description of data sets and modeling approaches and highlighting related accuracy issues, in the following paragraphs one *refinement option for coarse-scale population data* is presented. It aims at one of the main application areas of such data sets, i.e. coastal zone analysis in the context of global issues such as climate change induced effects including sea level rise and increasing coastal hazards (e.g., tsunamis). The ongoing discussion on climate change and its impacts necessarily leads to population related research including assessment of distribution and development patterns. Vulnerability and risk reduction of urban settlements in potentially affected areas is of utmost interest in particular in the context of DRM (including policy and decision making).

[7] Parts of this section refer to Aubrecht et al. (2010c)

Low-elevation coastal land areas and associated populations are particularly exposed globally to rising sea level and extreme events such as tsunamis and hurricanes. Those regions are nonetheless often densely settled and experience rapid urban growth. Based on population data for the year 2000 McGranahan et al. (2006, 2007) estimated that around 10 per cent of the world's population (more than 600 million people) lived in a low elevation coastal zone (LECZ) of less than 10 m above sea level at that time. Small island states have the greatest percentage of their populations in the LECZ (Pelling and Uitto, 2001), and in some cases entire nations (100% of the population) fall in that zone (e.g., Tuvalu, Maldives). However, the countries with the largest population figures in the 10 m LECZ are countries with heavily populated delta regions, such as the large Asian countries China and India, as well as Bangladesh and Vietnam. Globally, the population density in the coastal zone (175 persons per km²) is much higher than for any other ecosystem (Levy, 2009). Urban settlements in these zones generally have population densities of greater than 1,100 persons per km², compared to less than 800 for urban areas in cultivated inland regions.

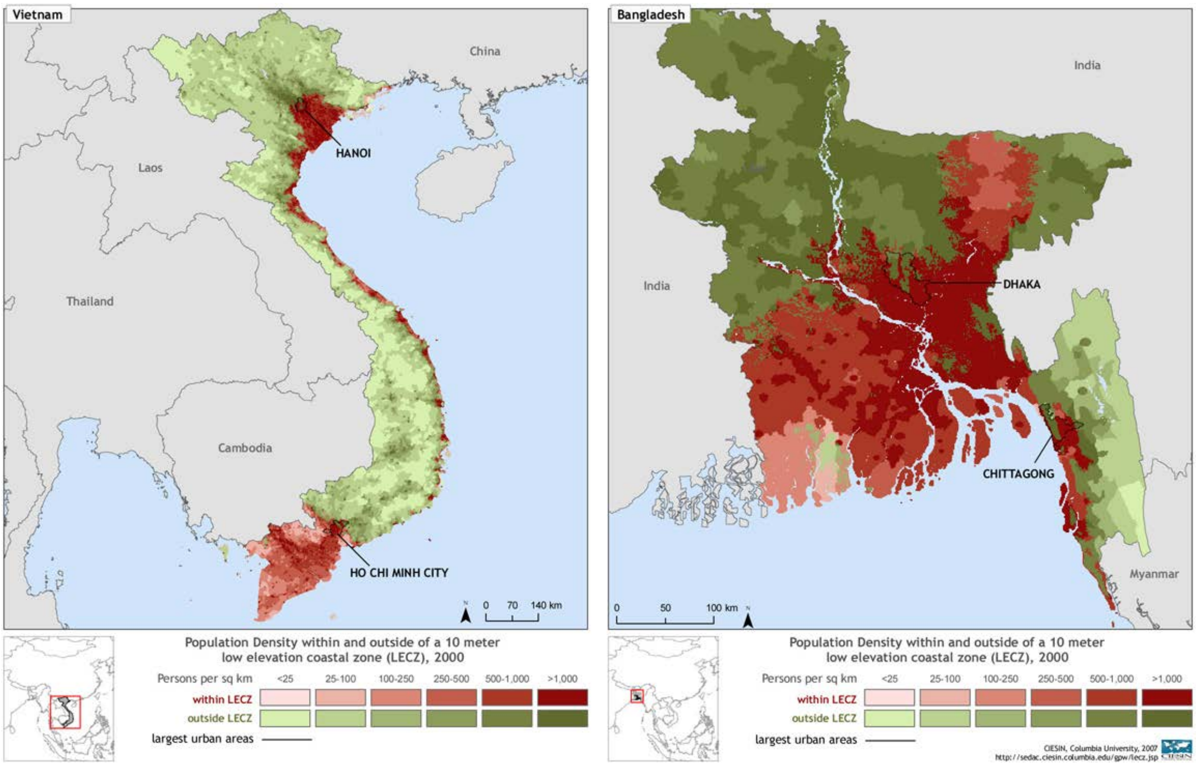


Figure 29: Population density of Vietnam and Bangladesh, within and outside of a 10 m low elevation coastal zone (LECZ) (from Levy, 2009).

Figure 29 shows Vietnam and Bangladesh as examples where several mega cities (more than 5 million inhabitants) are at least partially located in the predefined 10 m LECZ (Hanoi, Ho Chi Minh City, Dhaka). Coastal population estimates are based on integrated analysis of elevation data (SRTM, 90 m resolution) and gridded population data as introduced above (GRUMP, 1 km resolution). Prior studies confirm the trend of people tending to live near the water, i.e. within 100 km of coasts and near major rivers (Small and Nicholls, 2003; Small and Cohen, 2004). Focusing on the link from climate change science to the resulting impacts and their policy implications, Nicholls (2002) explored the impacts of sea level rise, in particular increased coastal flooding, on coastal populations. He came to the conclusion that despite several uncertainties this topic could be a significant problem if it is ignored, and hence needs to be considered within policy processes related to climate change mitigation and adaptation. Research on population-related coastal vulnerabilities has been carried out very intensively in recent years (Dasgupta et al., 2007; Levy et al., 2008; Hinkel and Klein, 2009; Sales, 2009). All these analyses rely on some sort of broad-scale spatial population distribution information when estimating numbers of exposed people. When using these data sets it is very important to know their structures and to be aware of potential uncertainties and error sources that might be introduced. Taking absolute numbers and spatial delineations for granted can result in wrong estimates and misleading conclusions.

Due to the varying resolutions of administrative input data and additional generalization effects, accurate identification of coastal zone boundaries is particularly problematic in the context of global and supra-regionally modeled population data sets. With regard to exposure analysis in the context of risk assessment two major problems appear. Imprecise coastal zone delineation can result in (1) population being distributed to areas which are in fact located below sea level or on the other hand in (2) populations being shifted up slope when they are in fact just above sea level. At the above mentioned spatial resolution commonly used for global spatial data sets (1-5 km) a 1-pixel shift can make a large difference with regard to potential exposure assessments. Considering a potential population density of more than 1,000 persons per km² in the immediate coastal zone such delineation problems can lead to crucial misinterpretation in terms of assessing the number of exposed people referring to potentially affected areas.

Existing global coastline data sets tend to be either too coarse in scale, have serious registration differences when used with high resolution raster datasets such as SRTM or Landsat data, or are incomplete. The *newly developed Global Coastline v1 data set* (ISciences, 2008; Metzler, 2009) features a 1 arc-second resolution (approximately 30 m at the equator) enabling a more accurate and consistent coastal delineation (fig. 30). The data set is based on USGS Shuttle Radar Topography Mission (SRTM) Water Body Data and refined using NOAA World Vector Shoreline as well as National Geospatial Agency (NGA) Global Shoreline data (to eliminate data voids and enhance co-registration). Geo-referencing is based on Landsat imagery and positional horizontal accuracy lies at 20 m.

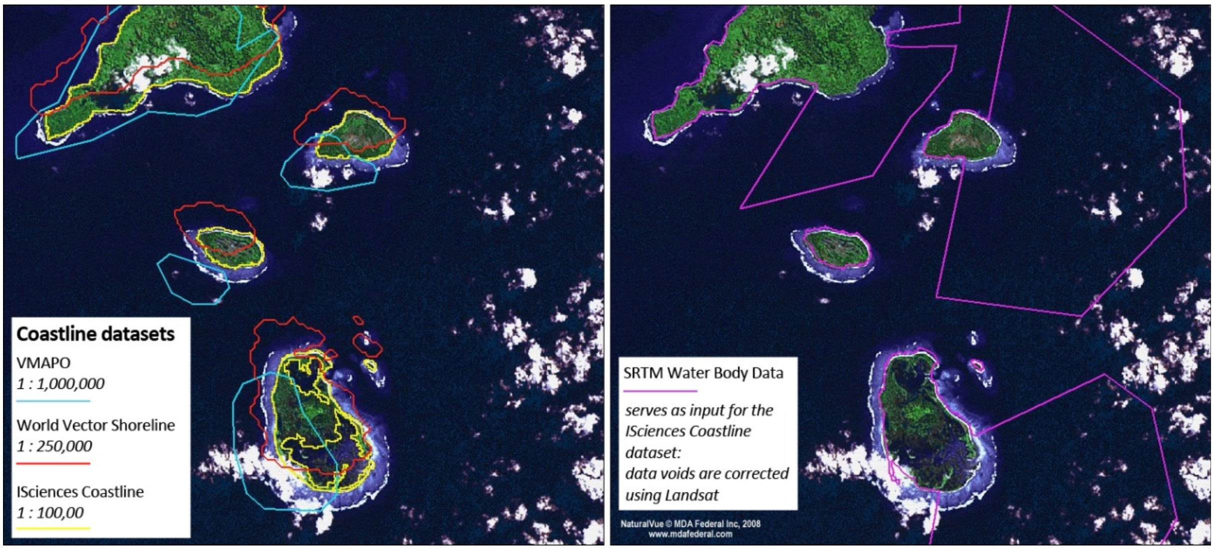


Figure 30: Comparison of the ISciences Global Coastline v1 to other available coastline datasets, illustrating positional inaccuracies as well as varying levels of detail (modified from ISciences, 2008).

Figure 31 shows the region of Western Indonesia, with the Western part of Java including the capital Jakarta highlighted. On the left, population density within and outside of a 10 m LECZ is illustrated in red and green color tones respectively. The North coast of Java is characterized by a very large number of persons living in the immediate low level coastal zone. On the right, the land-sea mask currently used in the GRUMP data set (grey color) is compared to the ISciences Global Coastline v1 (black line) for western Java. Red arrows highlight examples for the two above mentioned problems of imprecise coastal zone delineation. In the North a large land area is missing in the GRUMP data. Having approximately 40 km² (40 pixels) around 50,000 persons could potentially live in that area, but would be shifted upcountry in the course of population distribution modeling. Along the West coast the contrary happened, i.e. land and associated population is extended to areas which are in fact located below sea level.

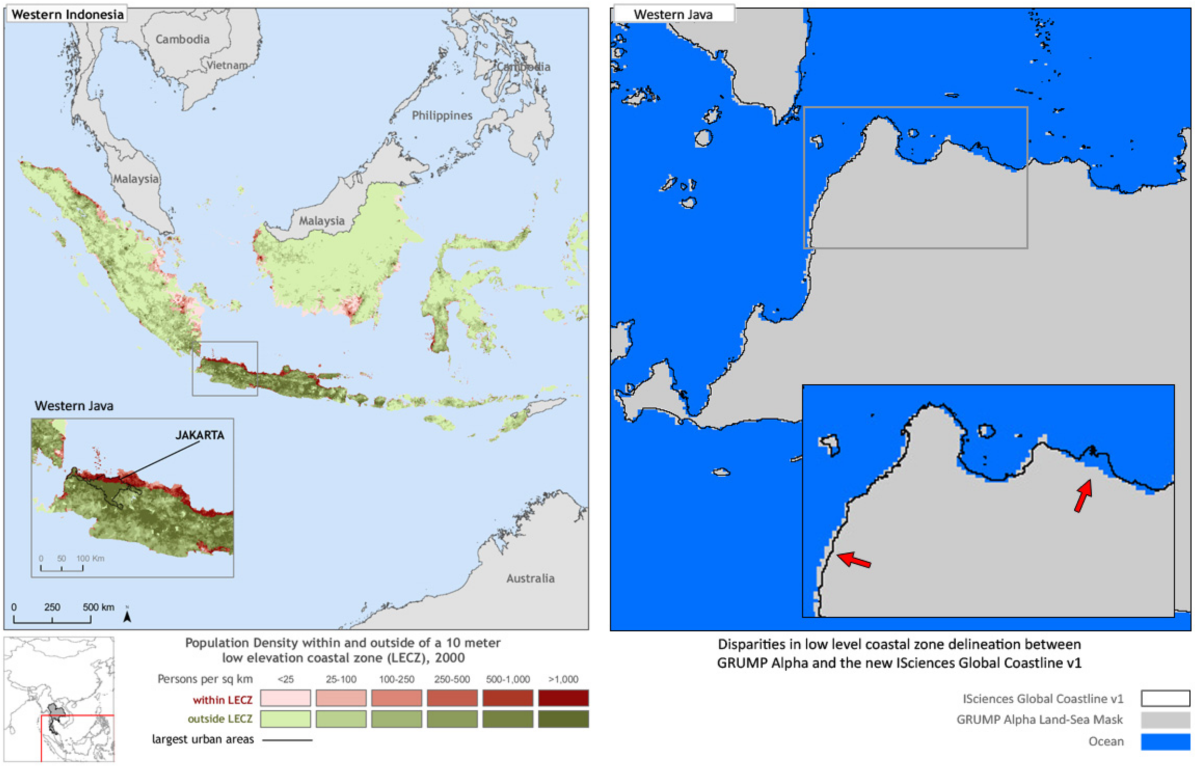


Figure 31: Population density of Western Indonesia (Java), within and outside of a 10 m low elevation coastal zone (LECZ). Disparities in low level coastal zone delineation between GRUMP alpha and ISciences Global Coastline v1 data sets.

Recommendations for next steps in GRUMP model setup therefore include (1) the integration of the current GRUMP land-sea mask with the new ISciences Coastline data and (2) spatial reallocation of population to the resulting newly derived spatial reference units (see also Levy, 2009). This will eventually allow for more accurate assessment of affected population on a global scale in the context of elevation related risk assessments (e.g. sea level rise, tsunami).

3.1.4 Shaping the European situation: Development of a population grid model picturing current and future conditions[8]

For the last couple of years the development of high resolution population grids has been a priority topic of the national statistical offices and Eurostat, the statistical office of the European Commission. A number of European countries have recently changed their population census to register-based statistics, with population numbers linked to address points (Aubrecht et al., 2009b). Based on these point data sets, population grids of any size can easily be generated, in due consideration of data privacy (Kaminger and Wonka, 2004). These activities led to a European initiative called Geostat[9] coordinated by Eurostat with the objective to establish a *1 km population grid for the member states of the European Union* (Holst Bloch, 2012). Those countries that already have a register-based census would deliver aggregated grid data in consistent format. For the remaining countries a disaggregation method should provide the required information.

As stated earlier already, disaggregation methods such as dasymetric mapping rely on ancillary data for spatially disaggregating and reallocating available coarse-scale population data to effective populated areas at a finer resolution. Mostly Land Use/Land Cover (LULC) maps are used in that regard, on a European scale for example CORINE land cover data (CLC) were applied as basis for spatial disaggregation of residential population data, by either (1) estimating population density weights for the CLC classes (Gallego, 2010) or (2) strictly considering mere residential CLC classes (Steinnocher et al., 2006). The drawback of these approaches is the limited spatial resolution of the CLC data set that leads to over- or underestimation of sparsely populated areas respectively.

With the recently published *EEA Fast Track Service Precursor on Land Monitoring* (EEA, 2008) a new data set is now available that provides the degree of soil sealing for the EU27+ countries. This dataset is a raster layer for built-up areas including the continuous degree of imperviousness ranging from 0-100% at a spatial resolution of 100 m.

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[8] Parts of this section refer to Aubrecht et al. (2013bf)

[9] Available at http://www.efgs.info/geostat/1A (accessed 30 September 2013)

An intermediate non-validated layer featuring a 20 m resolution exists as a core product for national and local-scale analyses (figure 32). The data set is based on ortho-rectified high resolution satellite imagery (Image2006 European Coverages; Müller et al., 2009), acquired primarily in the reference year 2006 (+/- 1 year). Supervised classification techniques were used to automatically map built-up areas, followed by visual improvement of the classification results. The degree of soil sealing for the classified built-up zones was derived from calibrated NDVI (normalized difference vegetation index). The data set covers EU27 and neighboring countries, 38 countries in total, and has just recently been updated for the reference year 2009 (EEA, 2008). This will allow extrapolations to the short to medium time scale in the near future. In the following this data set will be referred to as HR (High Resolution) soil sealing layer.

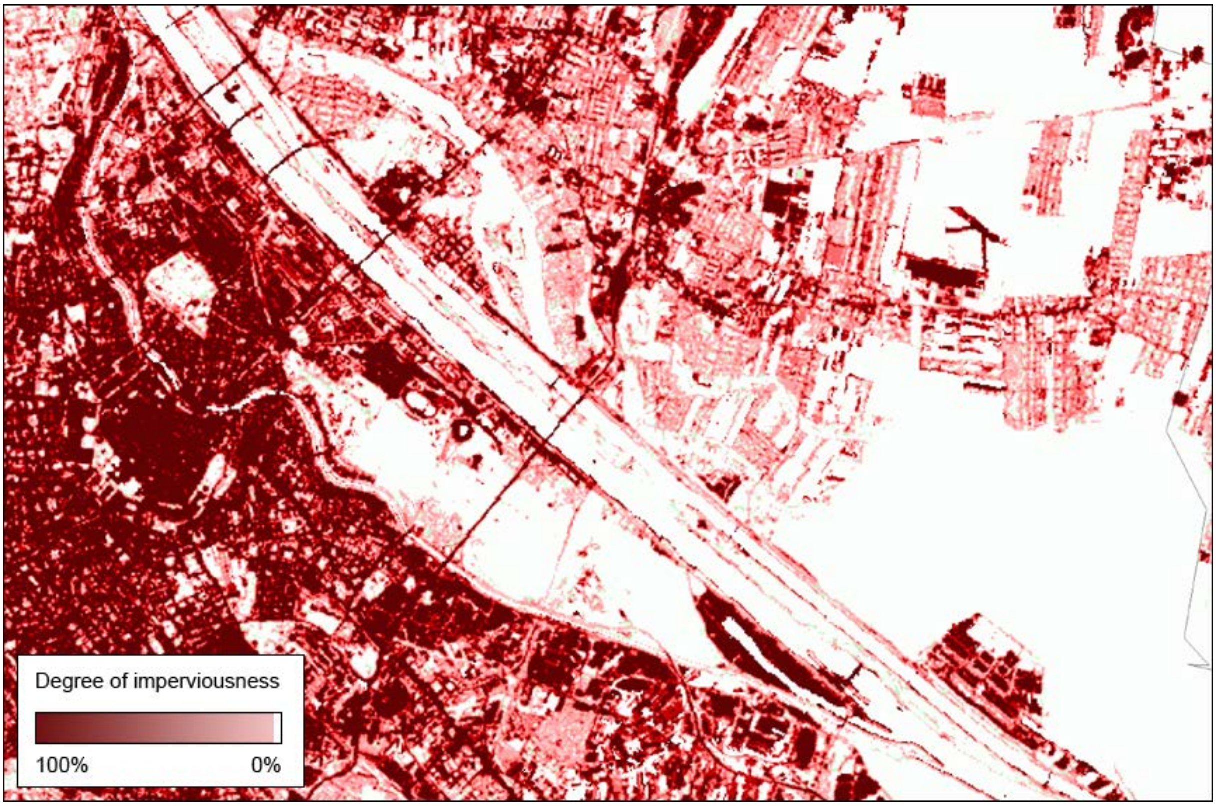

Figure 32: Sample of the EEA Fast Track Service Precursor on Land Monitoring core product (20 m resolution) which forms the basis for the aggregated 100 m layer used in this study showing the degree of soil sealing (imperviousness) for the city of Vienna, Austria.

Applying that HR soil sealing layer as a proxy for population (or rather housing) density, the accuracy of disaggregation results can be improved significantly. The method is based on the assumption that the population density is proportional to housing density, no population resides outside housing areas, and the ratio between population and housing density is constant within a region. The housing density is derived from the HR soil sealing layer, assuming that the degree of soil sealing is proportional to housing density. Since this assumption does not hold for all cases, the soil sealing layer requires further processing. In order to get a representation of housing densities it is necessary to mask out all sealed surface areas with non-residential function. These include road and rail networks, as well as industrial and commercial areas. Masking the transport network is based on linear road and rail data derived from Open Street Map, which are rasterized and expanded up to 50 m depending on the road type in order to cover associated areas as well. Non-residential built-up areas, such as industrial and commercial land use, are derived from respective CLC classes. Due to the large minimum mapping unit of CLC, masking is limited to areas larger than 25 ha. The remaining areas covered by the adapted HR soil sealing layer are assumed to represent residential building densities and are used as input to the population disaggregation approach (Steinnocher et al., 2011).

The methodology is applied to a European-wide data set, covering EU27 and EFTA (European Free Trade Association) countries. Population input data dated 2006 are provided by Eurostat on municipality level, thus temporally corresponding with the HR soil sealing layer. Disaggregation of the population counts is performed for each input region (basic reference unit: LAU 2; 'local administrative unit' referring to municipalities or equivalent units in the 27 EU Member States), with an output grid featuring a defined spatial resolution of 1 km^2 (fig. 33).

The *new European population grid* (labeled 'AIT Austrian Institute of Technology population grid dataset') was then validated against aggregated census grids from Austria, Denmark and the Netherlands following the Geostat initiative. All tested sites show an overall high correlation between the disaggregated grids and the respective reference layers (R^2 of 0.90, 0.86 and 0.92 respectively).

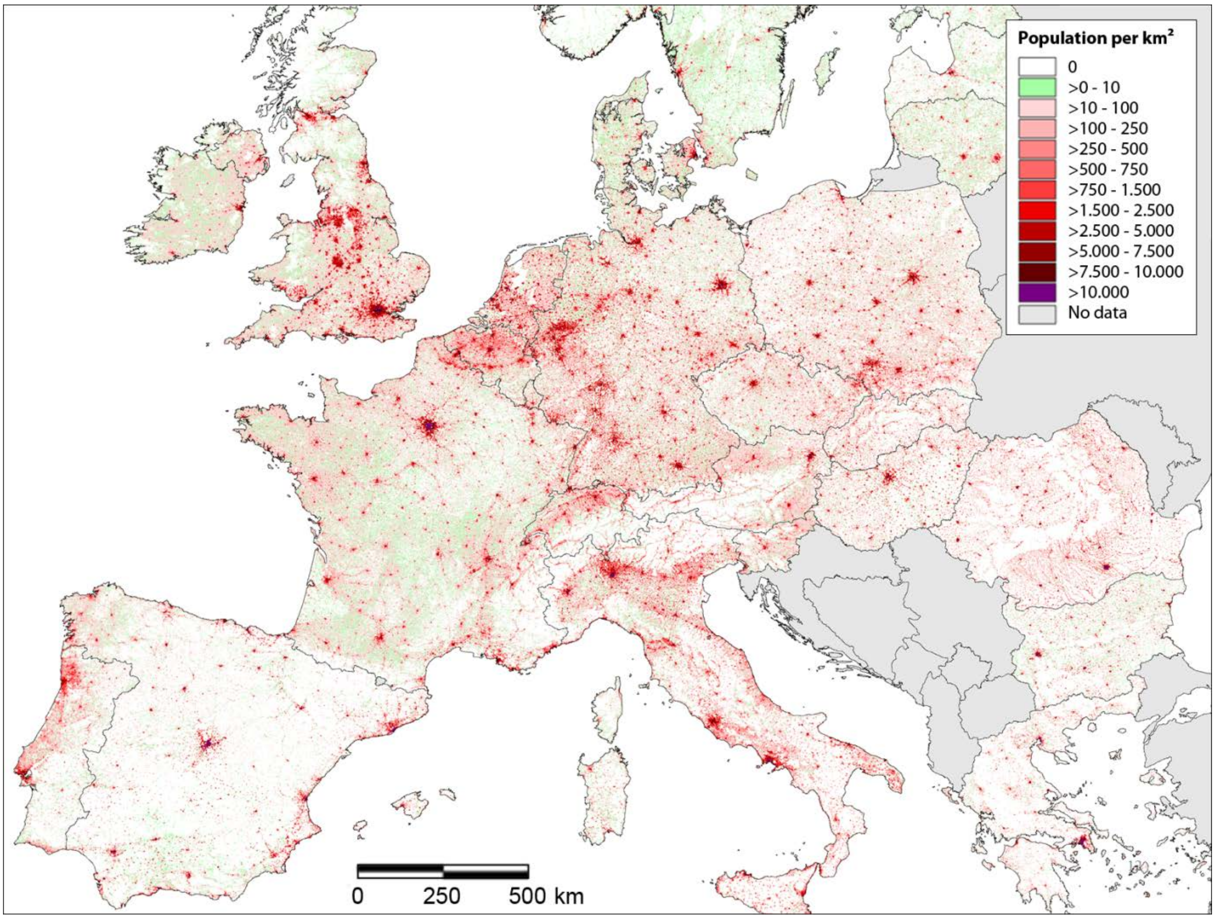

Figure 33: New population grid of EU27/EFTA countries based on disaggregation of LAU 2 population.

With regard to the Austrian validation (reference grid provided by Statistics Austria), the new disaggregation method shows significant improvement compared to the previous CLC based approaches mentioned above (Steinnocher et al., 2011). Figure 34 illustrates results of those two CLC based population grids for the central and eastern part of Austria and puts them in comparison to the new HR soil sealing layer based grid as well as the reference grid showing local-level census information. While the first approach (limited to residential CLC classes) clearly underestimates the sparsely populated areas (1), the second one (using population density weights for all potentially inhabited CLC classes) populates almost all areas except for high alpine regions and water bodies (2).In that regard the patterns of that second grid in fact resemble disaggregation results of the accessibility based model illustrated in chapter 3.1.2 (see fig. 27). In terms of the (visual) spatial distribution patterns the new population grid is by far closest to the reference census grid. Steinnocher et al.

(2011) also performed a numeric validation, analyzing single grid cell deviations. A general systematic tendency of overestimating less populated grid cells and underestimating highly populated ones is reported. While in the accessibility model discussed earlier limited accounting for increasing centrality of highly urbanized areas was identified as causing factor for that trend, now a more structural aspect could be the reason. With increasing building densities also the occurrence of higher buildings increases which leads to a non-linear relation between housing and population density that is not considered in the disaggregation model. Also, masking of industrial and commercial areas is limited to large complexes whereas smaller areas with industrial or commercial function cannot be identified (due to the minimum mapping unit of CLC). As such areas usually feature a high degree of imperviousness they are then assigned a far too large population number.

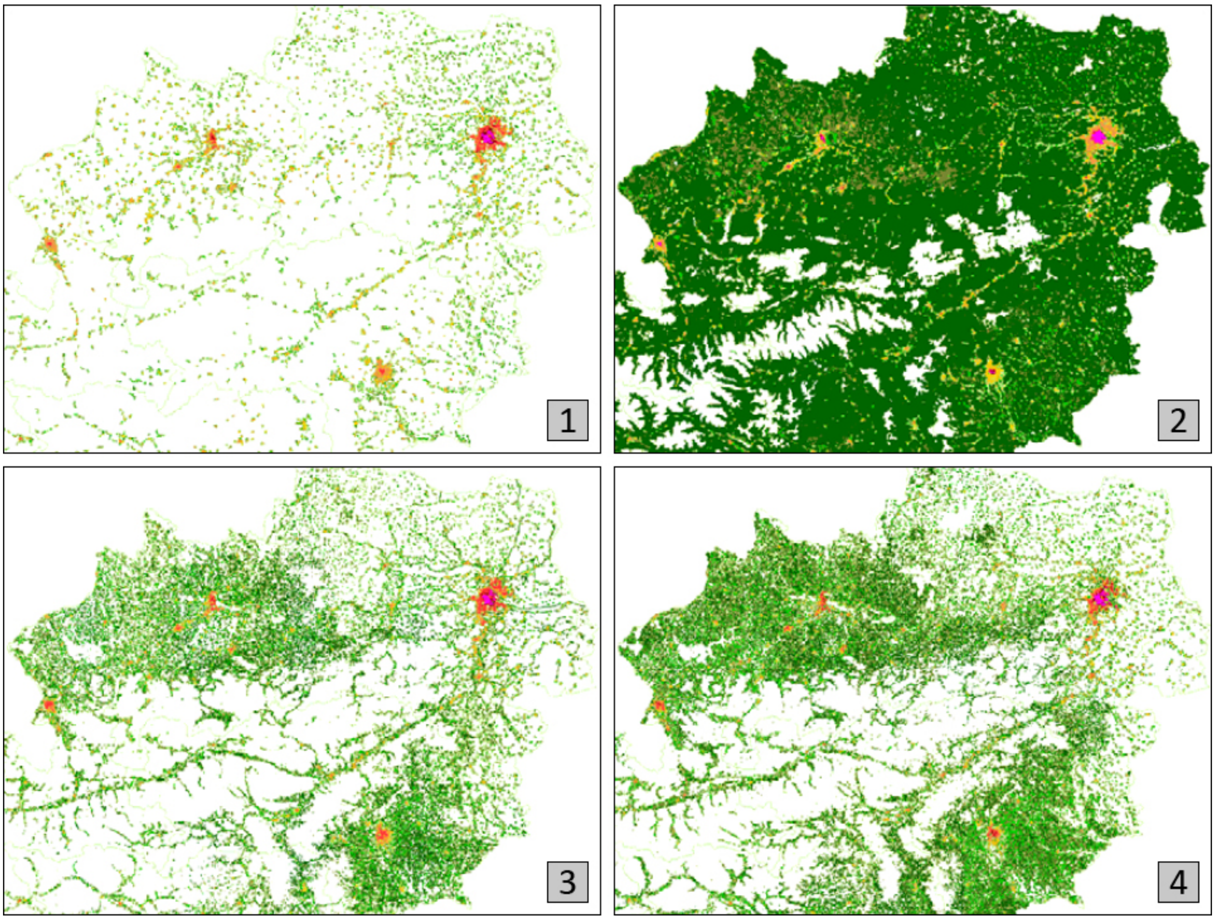

Figure 34: Comparison of population grids for an Austrian test case: Disaggregation based on (1) CLC residential classes, (2) population density weights for all CLC classes, (3) HR soil sealing layer; (4) Census reference grid (modified from Steinnocher et al., 2011).

In a final processing step the available bottom-up grids have been integrated by Eurostat in order to obtain the best available information on population in Europe. The resulting population grid is therefore a hybrid information layer, providing aggregated population grids from register based census for those countries where that source is available, and disaggregated population grids ('AIT Austrian Institute of Technology dataset') for the other countries. That *hybrid population grid* is available online, provided by the European Forum for Geostatistics[10]. Following the success and evident quality improvement of the above described methodology in applying high resolution soil sealing information to the disaggregation process, by now also the research group at the European Commission's Joint Research Center which previously promoted the CLC based population density weighting approach is working on similar implementations (Batista e Silva et al., 2013).

In addition to assessing the current status of a society in terms of its distribution patterns, it might also be essential to identify *future developments*, in particular when it comes to setting the social framework for analysis of long-term trends in hazard patterns and associated vulnerabilities and risks. Building on the population disaggregation methodology applied above, a study has been carried out for a test area covering a North-South transect of Europe ranging from Southern Scandinavia to Central Europe (covering Sweden, Denmark, Germany, Poland, the Czech and the Slovak Republic, Austria, Hungary, and Italy) (Aubrecht et al., 2013f). *Population prospects* for 2030 including relevant structural information (age structure) in addition to the basic distribution patterns on NUTS 2 level[11] were obtained from the 'EUROPOP2008 - Convergence scenario, regional level' provided by Eurostat (Eurostat, 2010). A related report on 'Populations and social conditions' describes what-if scenarios about the likely future demographic structure pointing out that this population projections convergence scenario is only "*one of several possible population change scenarios based on assumptions for fertility, mortality and migration*" (Giannakouris, 2008).

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[10] Available at http://www.efgs.info/data/GEOSTAT_Grid_POP_2006_1K (accessed 30 September 2013).
[11] NUTS 'Nomenclature of Units for Territorial Statistics', a geocode standard of the European Union for referencing the subdivisions of countries for statistical purposes; a hierarchy of three NUTS levels is established for all EU member countries by Eurostat. NUTS 2 corresponds to state or province level and in that regard is set on a coarser scale than the LAU 2 used for modeling current distribution patterns.

Predicted changes in population counts are disaggregated based on the assumption that the relative distribution patterns remain constant, i.e. reallocating population to those grid cells already populated in the 2006 reference year. Without doubt the characteristics of the population distribution itself will change over the more than 2 decades timescale being considered. Nonetheless, population densities for 2030 are again modeled based on the 2006 high resolution soil sealing layer for current lack of available future prospects in that regard. As briefly mentioned above, the EEA Fast Track Service Precursor on Land Monitoring has just recently been updated in the frame of the geoland2 project (geoland project consortium, 2012) for the reference year 2009. This will allow extrapolations to the short to medium time scale in the near future. Alternatively, urban growth - or in general land use change - simulations based on cellular automata or agent-based models could be applied for assessing future patterns of population distribution (Batty, 2005b). Accounting for extended needs of vulnerability assessments besides the identification of basic population exposure patterns, structural population information inherent in the Eurostat population convergence scenario is used for additionally calculating the change of the proportion of elderly people. These changes are again proportionally applied to the populated grid cells. In chapter 4.2 an application referring to these long-term development trends in terms of using it for climate change associated vulnerability assessment will be presented.

Figure 35 shows the modeled future population distribution for the European transect. On the left the absolute density numbers for the year 2030 are illustrated. The right-hand part of the figure highlights the absolute population change over the period under investigation (2006-2030). It is clearly visible that large parts of Germany are likely to experience massive population decrease. The region of Bavaria is an exception from that rule, being more in line with the Southern European regions such as the Po-Region and generally large parts of Italy that feature strong increases. Another characteristic that is illustrated well is the obvious trend towards further urbanization, in particular in terms of strong expected population increases in the main urban centers, sometimes showing that pattern for the entire surrounding region as well (e.g., Munich, Milan), and in other cases at the expense of the immediate suburban area (e.g., Berlin).

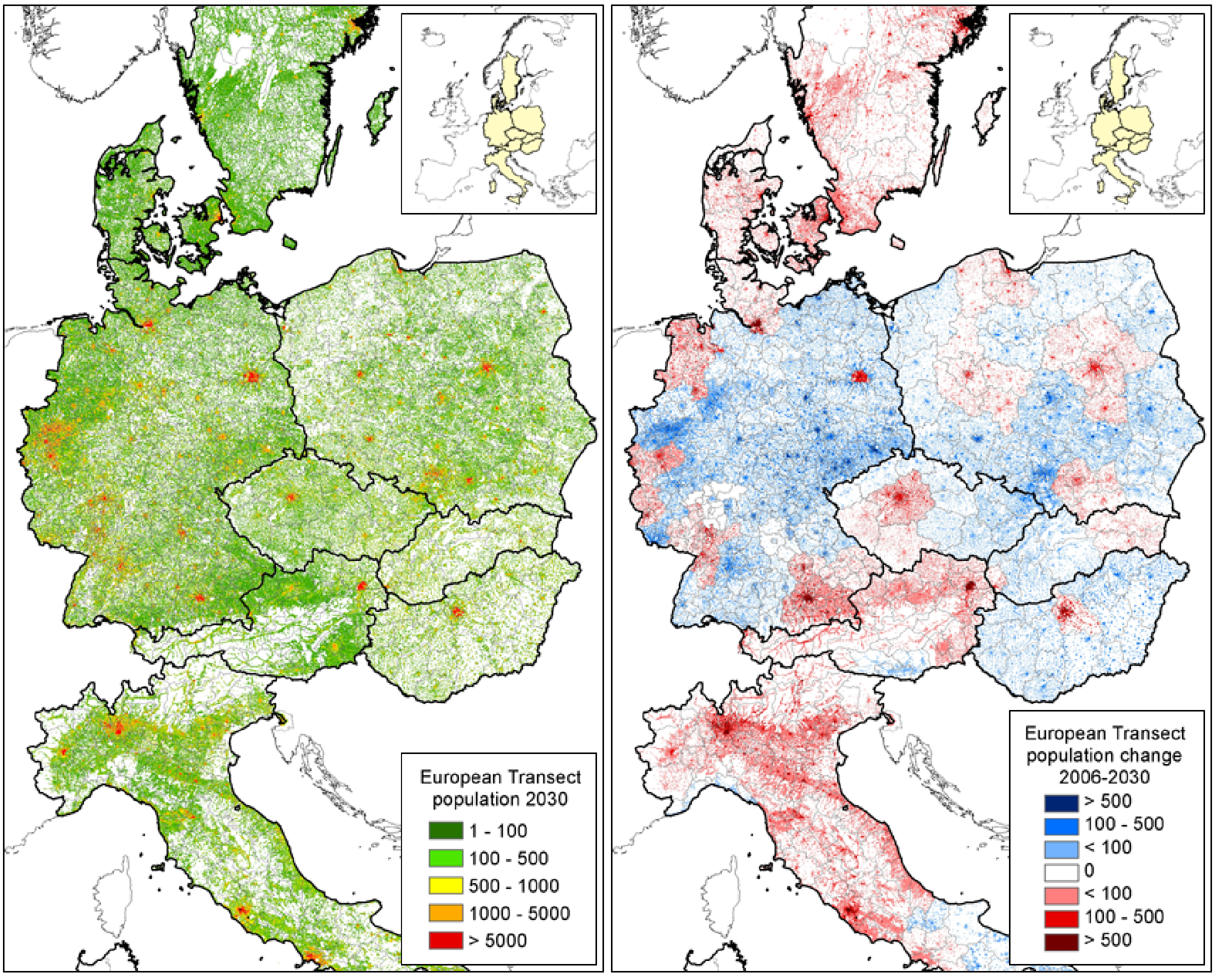


Figure 35: North-South European transect showing 1) the predicted population distribution for 2030 (left) and 2) the absolute population change from 2006-2030 (right), both on a 1 km resolution population grid.

3.2 Local-scale approaches

The level of aggregation of all the above described databases (30 arc-seconds/1 km resolution at best) is still too coarse to adequately support exposure assessment and risk analysis at a detailed local level. However, other information sources (e.g., remote sensing imagery) may allow disaggregation at a finer resolution. Furthermore, the development of the LandScan Global Population Database represented a (methodological) improvement over pure residence-based population data sets. However, its representation of 'ambient population' and the corresponding temporal averaging is not ideal for use in applications on time-specific hazards such as an earthquake or tsunami event. At a regional level, it has been attempted to overcome these limitations by developing population distribution databases featuring higher temporal and spatial detail (McPherson et al., 2006; Bhaduri et al., 2007; Freire and Aubrecht, 2010, 2012), including variation in the daily cycle but such efforts are still to be applied on global scale datasets.

Information on functional patterns in urban environments as well as high-level population distribution information is often not quickly available in case of emergency which is why rapid mapping concepts often rely on various Earth Observation data sources. For building comprehensive urban data management systems and mapping the complex urban environment at a high level of detail diverse input data is required, with functional information such as socio-economic and explicit demographic data on the one hand and 'real world' physical properties as derived from remote sensing on the other hand (Steinnocher and Köstl, 2007). Earth Observation data classification is limited to physical characteristics of the analyzed objects but does not include process-related functional information. With respect to manmade features this means that buildings can be detected as such, while building use and related socio-economic activities usually cannot be derived that way.

Urban system modeling based on remote sensing and geoinformation technology often does not go beyond a certain spatial and thematic level regarding the corresponding reference objects. Only the integration of population and socio-economic features and thus moving from land cover detection to land use assessment enables modeling of societal vulnerability as well as damage potential and impact patterns. Integrative approaches considering remote sensing and ancillary information are therefore expected to further increase in importance in the future (Aubrecht et al. 2009b).

3.2.1 Population and 'socio-economic' exposure assessment for complex urban environments on high level of detail [12]

In the following an integrative model approach is presented with the objective of identifying locational patterns of human activity and related functional and socio-economic characteristics in urban/suburban environments on a very high level of both spatial and thematic detail. Using very high resolution remote sensing data to define structural characteristics and jointly analyzing with ancillary information on address basis a *population distribution model on building level* is developed (Aubrecht et al., 2009b).

Results are eventually consulted for *multi-level exposure assessments* regarding two different case scenarios (Aubrecht et al., 2011a), implemented for a selected study area in Austria (covering parts of the Upper Austrian provincial capital Linz; fig. 36). Featuring mixed land use with urban and rural elements this region can be characterized as a heterogeneous suburban transition zone, thus serving as a perfect starting point for building a comprehensive knowledge base on human distribution patterns and further functional analyses. In addition to assessment of population exposure the classification of functional urban land use types also enables a new kind of 'socio-economic exposure' analysis.

Figure 36: Study area location in Upper Austria.

[12] Parts of this section refer to Aubrecht et al. (2009b, 2011a)

To analyze *land cover patterns* and derive a geometric framework for further functional and population related analyses two very high resolution (VHR) remote sensing data sets are used. Optical satellite imagery (IKONOS-2) forms the basis for standard high resolution land cover classification. The available IKONOS scene subset (recorded on 15 June 2002) is in pan-sharpened mode derived through image fusion of the four multispectral bands (4 m spatial resolution) and the panchromatic band (1 m spatial resolution). Pan-sharpening results in four multispectral bands with a calculated spatial resolution of 1 m covering blue (0.45-0.52µm), green (0.52-0.60µm), red (0.63-0.69µm) and part of the near-infrared (0.76-0.90µm) of the electromagnetic spectrum. Furthermore, Airborne Laserscanning (ALS) data provide essential information about structural patterns enabling a more detailed and also more accurate land cover classification on a potentially higher degree of automation (Rottensteiner et al., 2005). The ALS data set was acquired in the framework of a commercial terrain mapping project employing a first/last pulse ALS system (average flying height above ground: 1,000 m; average point density: 1 point/m^2). In early spring (acquisition date: 24 March 2003) favorable leaf-off conditions without snow cover could be guaranteed. Processing of the initial 3D point cloud results in various surface models at a 1 m spatial resolution, including a normalized Digital Surface Model (nDSM) containing height information above ground. Buildings and trees can be clearly identified in that product while flat areas such as water bodies, roads and meadows cannot be separated (Haala and Brenner, 1999; Pfeifer, 2003).

The availability of both VHR optical satellite imagery and ALS data offers great potential for identifying urban land cover patterns. Due to the complexity of the analyzed heterogeneous urban transition zone feature classification is a challenging task. VHR optical satellite imagery allows immediate visual discrimination of diverse spatial structures characterizing different urban and suburban zones. The integration of ALS data significantly improves the land cover classification both in terms of accuracy and automation. Object based image analysis (OBIA) is considered to be the most promising technique (compared to standard pixel based classification algorithms) for handling the high spatial resolution and complexity (Burnett and Blaschke, 2003; Blaschke, 2010) as well as differing properties of the two available data sets (Benz et al., 2004; Kressler and Steinnocher, 2008). Just considering single pixels without accounting for the spatial context often leads to an unwanted 'salt-and-pepper effect' (Willhauck, 2000) which would not be suitable for the desired object identification (creation of a building layer) that is needed for follow-on population pattern modeling. The analysis as implemented in the software package Definiens Professional can be divided into two processing steps: 1) segmentation of the data into homogeneous objects and 2) assignment of the segments to discrete classes (more detailed information is provided by Aubrecht et al., 2007, 2009b). These steps can also be applied alternately, i.e. classification results of one processing step can serve as input for subsequent segmentation. Basic land cover classes such as vegetation, water and sealed surface can be distinguished just using the multispectral IKONOS image. Based on the additional height information provided by the ALS data, both sealed areas and vegetated areas can be further differentiated. That, for example, enables the exact separation of buildings and streets, which would not be possible by merely considering optical parameters (Kressler and Steinnocher, 2008). Six land cover types are finally classified (buildings, streets, flat sealed area, trees, shrubs, water), in addition to separate classes for shadow and undefined areas. With regard to the further modeling steps special attention is turned to the delineation of building objects that then serve as the geometric basis for socioeconomic data integration. The information contained in the ALS data enables the calculation of mean height and volume for each image object (fig. 37).

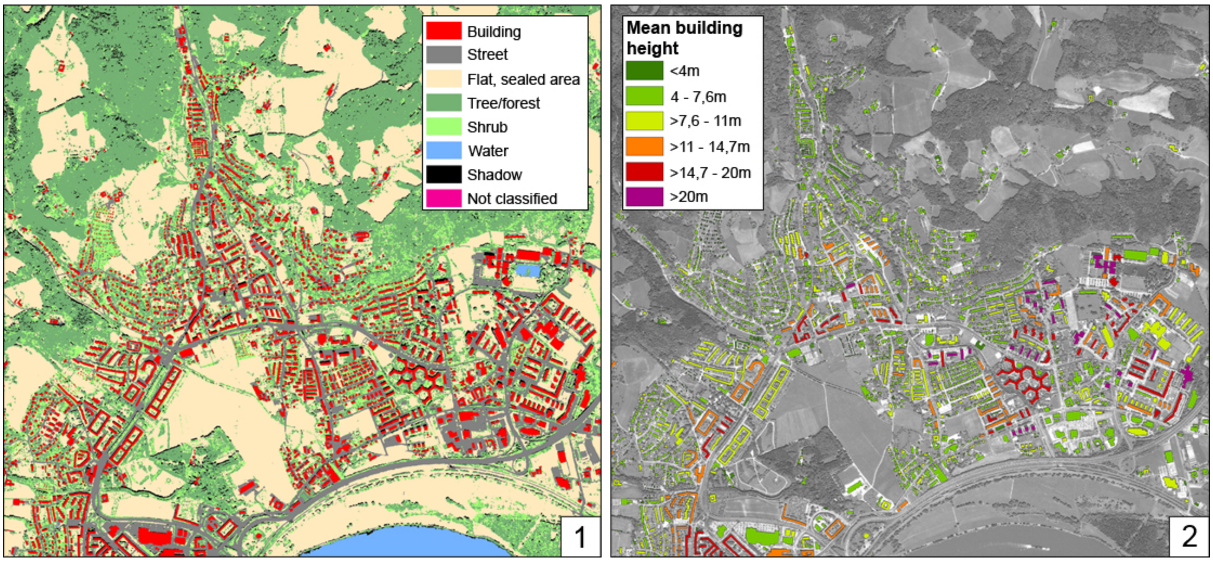


Figure 37: Land cover classification (1) and derived building block layer (2) for the Linz test site.

The increasing availability of spatial and space-related data enables *integrative urban system modeling* based on joint analysis of remote sensing data and ancillary information (Mesev, 2005). Remote sensing approaches produce good results on physical properties of urban structures, while functional information can hardly be identified that way. With demographic data mostly being available on the level of pre-defined geographic units (e.g., census tracts), remote sensing offers the chance to overcome this '*modifiable areal unit problem (MAUP)*' by deriving new reference units (Weeks, 2001; Chen, 2002). In addition to the EO data ancillary information featuring diverse spatial and thematic characteristics are used in order to progress from land cover to land use classification and specifically functional urban system analysis focusing on population related aspects (Aubrecht and Steinnocher, 2007; 2008). The main data set includes address point features, i.e. postal delivery addresses linked with precise geo-coordinates (collected by the Austrian mail service). Distributed under the name Data.Geo that database is updated twice a year and comprises more than 2 million addresses using a standardized naming convention. About 3,700 discrete points are used in the presented study. Address data acts as the essential link between geometric framework and thematic information, enabling the integration of all kinds of address-related information such as business and census data. Detailed suitability-oriented analysis of address point data was conducted by Aubrecht et al. (2009c) and Steinnocher et al. (2010).

Spatially linking the available georeferenced address data to the previously derived building layer relates each address point clearly to one building object. One building might however contain more than one postal address (e.g., apartment buildings and town houses), thus more than one point might be related to single building objects. A continuously unambiguous one-to-one relationship between address point features and building polygon objects is achieved through generation of Thiessen polygons based on the address points and subsequent intersection with the building layer. Attaching company information (derived from yellow pages database) to the resulting sub-building model via their joint address attribute allows precisely locating those building parts in which economic activities take place and identifying those parts being in residential use only. The integration of company data serves not only for the detection of buildings hosting economic activities but also provides information about the type of activity. Based on the yellow pages data coding which groups branches of business to more general types functional object grouping can be carried out (Aubrecht et al., 2008). This results in a building model providing feature information such as ‘residential use’, ‘public use’, ‘commercial’, or ‘agriculture’. Being able to delineate functional patterns in an urban system and to identify actual building use can be of utmost interest on various occasions. In case of emergency, it is essential to quickly locate critical infrastructures as well as being able to perform first-pass damage assessments. Information on functional characteristics rather than mere physical information and consequently in particular information on population distribution patterns is indispensable in that context in order to effectively implement disaster risk management concepts.

The final modeling step to enable high-level population exposure and eventually social vulnerability assessment is therefore the *integration of population data into the functional building model*. Backward projection of spatially aggregated census data is conducted by implementing spatial disaggregation methods (Eicher and Brewer, 2001; Chen, 2002; Mennis and Hultgren, 2006) based on the previously derived actual building use and associated corresponding potential residential capacities. Spatial disaggregation is based on the assumption that data provided ‘globally’ for an entire region can be distributed within that region by means of local parameters. The spatial reallocation is usually performed referring to weighted sums. A clear dependency between the regional and the local parameter is a prerequisite for this approach. Census population data can thus be refined from administrative units or grids based on underlying spatial information on building patterns (as derived from remote sensing). The global parameter in that regard would be the total population of the region or unit while the local parameter is the housing density or in refined version individual building characteristics. Applying housing density as a proxy for population density allows estimating the local population distribution (Steinnocher et al., 2006). For the Austrian territory census population data is available in raster format (for urban areas at a 125x125 m cell size). In order to disaggregate population from the raster to building objects, the latter have to be reduced to single points to establish a clear link to distinct census grid cells. Availability of the specific address point data set that served as basis for the census raster creation enables the attempt to inversely re-trace the aggregation process. As in previous steps buildings were split into buildings parts based on georeferenced postal address information those objects can now easily be linked to the census address points. Aubrecht and Steinnocher (2007) and Aubrecht et al. (2009b) provide more detailed information on this procedure. The availability of height information (from ALS) and hence the possible use of building volume instead of area for the assessment of residential capacities significantly enhance the accuracy of the population distribution model. As just those buildings in residential use should be included in the disaggregation process empirical weighting factors are introduced for different building types in order to calculate the potential residential ratio of each building part. Fully residential buildings are thus assigned a weighting factor of 1 (100 % of the building volume is considered for the calculation), while non-residential buildings get a factor of 0. Calculating the mean volume density of each grid cell (population of one grid cell referred to the summed-up relevant residential volume of all buildings in the same cell) results in sort of a '3D population density' (inhabitants/m³). That value is then multiplied with the object's relevant volume finally resulting in an assessment of the number of inhabitants per building part (fig. 38).

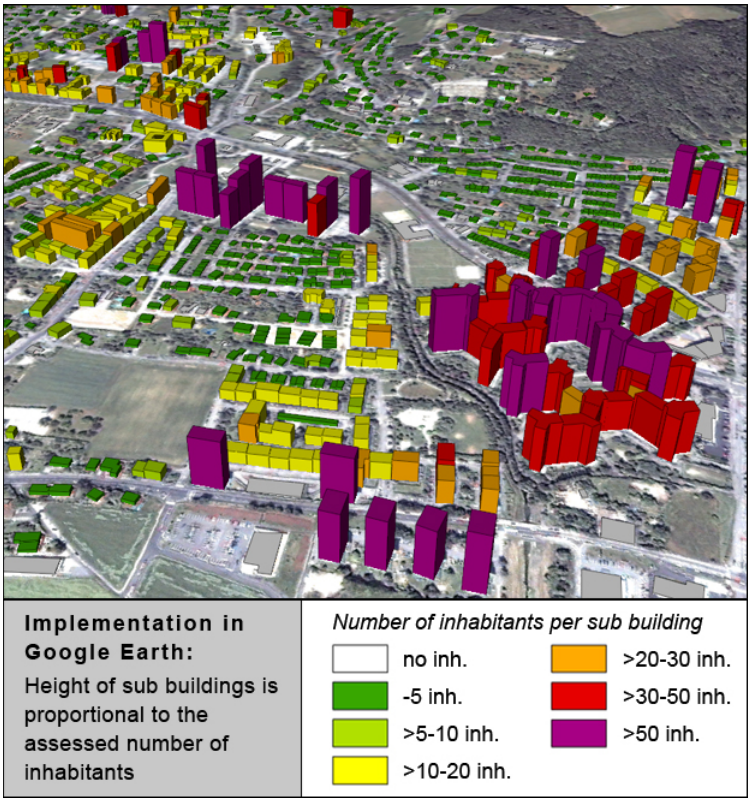


Figure 38: Population distribution information for Linz, disaggregated to sub-building level.

The above-described methodology to identify population distribution and functional patterns on previously unavailable level of detail proofs essential to provide input for comprehensive exposure assessments in complex urban environments. In addition to *residential population exposure* the classification of functional urban land use types also enables a new kind of '*social or socio-economic exposure*' analysis, i.e. locational identification of critical 'assets' where, for example, service interruption could have serious consequences with regard to potential social implications (e.g., hospitals or other buildings of public use) or economic impacts (e.g., industrial buildings or commercial centers) of a hazardous event.

In order to illustrate the significant improvement of estimation accuracy in population exposure assessment that results from implementing highly detailed population distribution models as described above, the available census population grids are compared to the new building-level dataset in the context of *exposure to street noise* originating from a highway. Traffic noise emissions or 'noise pollution' in general is considered to cause significant impact on public health and is therefore identified as a major environmental hazard at present (Arora and Mosahari, 2012). A simple linear street noise propagation model is considered and integrated with the population distribution datasets in order to assess the number of potentially affected persons. The applied model features two distance buffers to both sides of the expressway A7 which crosses the study area (fig. 39). According to the Austrian Traffic Association that part of the A7 in the urban area of Linz is amongst the most frequented street sections in Austria featuring more than 100,000 cars per day on working days (2008 traffic counts). Two potential noise propagation zones (illustrating noise pollution intensity levels) are simulated based on available Tele Atlas street network data considering 1) a 200 m and 2) a 500 m neighborhood. Assessment of potentially affected population is indispensable for sustainable planning of noise control and protection measures. While modeling of real-world noise propagation involves more sophisticated parameters such as atmospheric and topographic characteristics (Hritonenko and Yatsenko, 2003), acoustic parameters (Steele, 2001) as well as varying road surface types (Cho and Mun, 2008), the presented showcase study illustrates how the integrated use of functional information can significantly increase assessment accuracy of population exposure analyses.

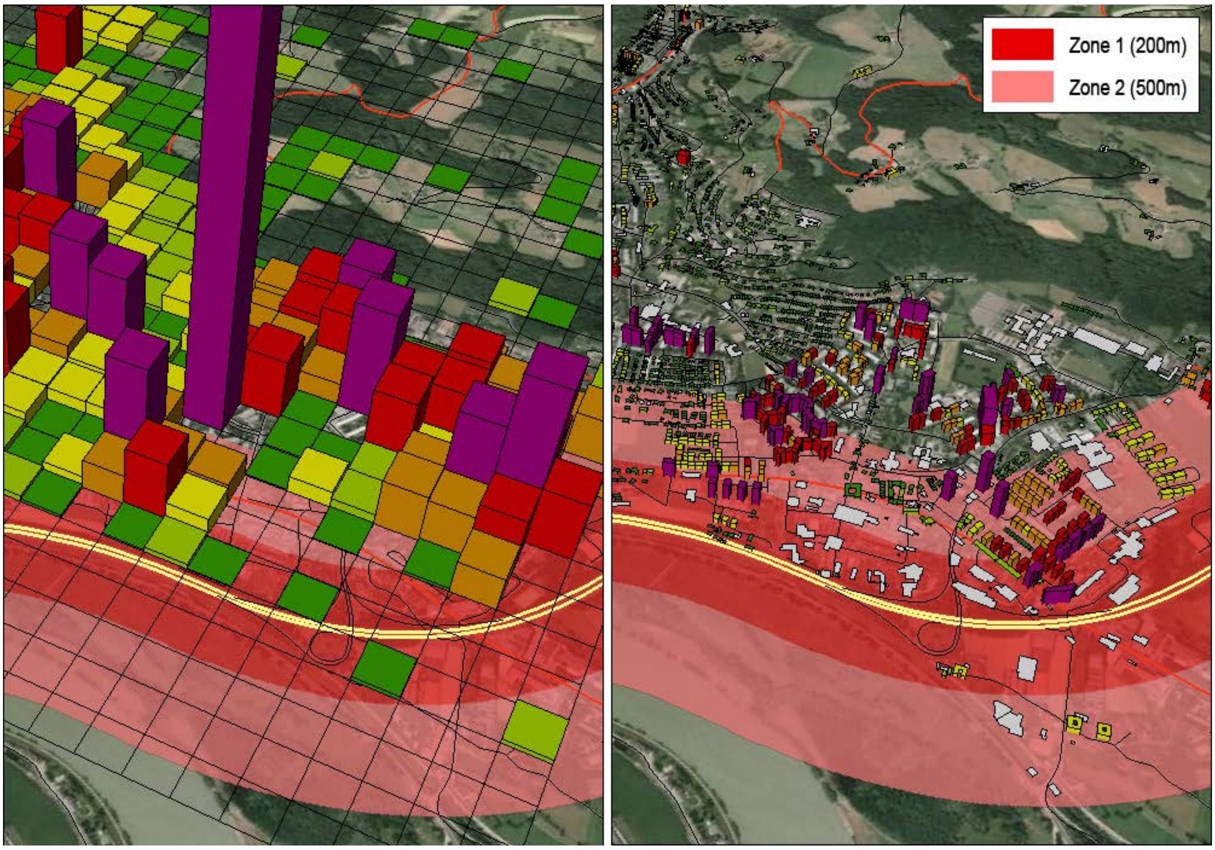


Figure 39: Highway noise propagation and exposed population for Linz according to census grid (left) and modeled building-level data (right).

Noise propagation zone*	Population exposure estimates				
	250 m raster		125 m raster		Building-part model**
Zone 1 (200 m buffer)	3,522 inh.	*+120 %*	1,894 inh.	*+19 %*	1,598 inhabitants
Zone 2 (500 m buffer)	8,489 inh.	*+37 %*	7,414 inh.	*+20 %*	6,199 inhabitants

* according to simplified assumption of linear noise propagation

** considered as reference value

Table 2: Population exposure estimates considering different population distribution datasets (two census grids of varying level of detail and the building-part model).

Comparison of estimated population exposure numbers considering the modeled population distribution patterns on sub-building level and the original census grids shows considerable differences. Table 2 illustrates the results taking a 250 m census raster (available for the entire Austrian territory), a 125 m raster (available for urban areas), and finally the newly generated sub-building population model as input for the exposure assessment. It is evident that for such local-level analyses 250 m raster are far too coarse and lead to massive overestimations. In the inner zone the 250 m raster shows more than 3,500 people being affected. With the sub-building model being quality-confirmed by Statistics Austria in terms of its minimal absolute population number deviations from the original census counts (Aubrecht et al., 2009b), its results serve as reference values. Considering the 250 m grid would therefore result in an overestimation of 120 % for the inner zone of high noise pollution level. Taking the 125 m raster as input already yields much better results in that regard with a calculated overestimation of approximately 19 %. Zone 2 shows a similar picture for the 125 m raster (+20 %), whereas a big improvement is observed with regard to the 250 m raster (+37 %). Of course such estimates depend to a large extent on real-world land use characteristics and associated population distribution patterns, i.e. location of building objects within single grid cells. Anyhow, the proposed results show the important role functional building models can play in case local-scale population data is needed as input or reference for high-level exposure analyses.

Further exploring the benefits of the highly granular functional urban land use model for exposure analyses, a *fictitious earthquake (EQ) scenario* is implemented for the study area (fig. 40). Varying levels of intensity are simulated originating from a theoretical epicenter close to the center of the study area (red and orange: high, yellow: medium, light and dark green: low). In real event EQ studies intensity zones are often delineated using the Modified Mercalli Intensity (MMI) Scale, a subjective measure describing how strong a shock is felt at a particular location reported on a scale of I to XII (USGS, 2013). Other standard EQ indices such as peak ground velocity (PGV; highest ground shaking velocity reached during an EQ) and peak ground acceleration (PGA; largest recorded acceleration) can give an indication to potential building damage. PGA is measured in units of %g where g is the gravity-enforced acceleration. A PGA of 10 (0.1g) may be enough to damage older buildings, while buildings constructed in line with EQ standards can even resist severe shaking up to 0.6g without significant structural damage. For advanced risk assessment some information on the structural quality of buildings would therefore be favorable. Relationships between quantitative measures (e.g., PGV and PGA) with qualitative measures (e.g., MMI) have been explored in various application studies (Wald et al., 1999; Wu et al., 2003).

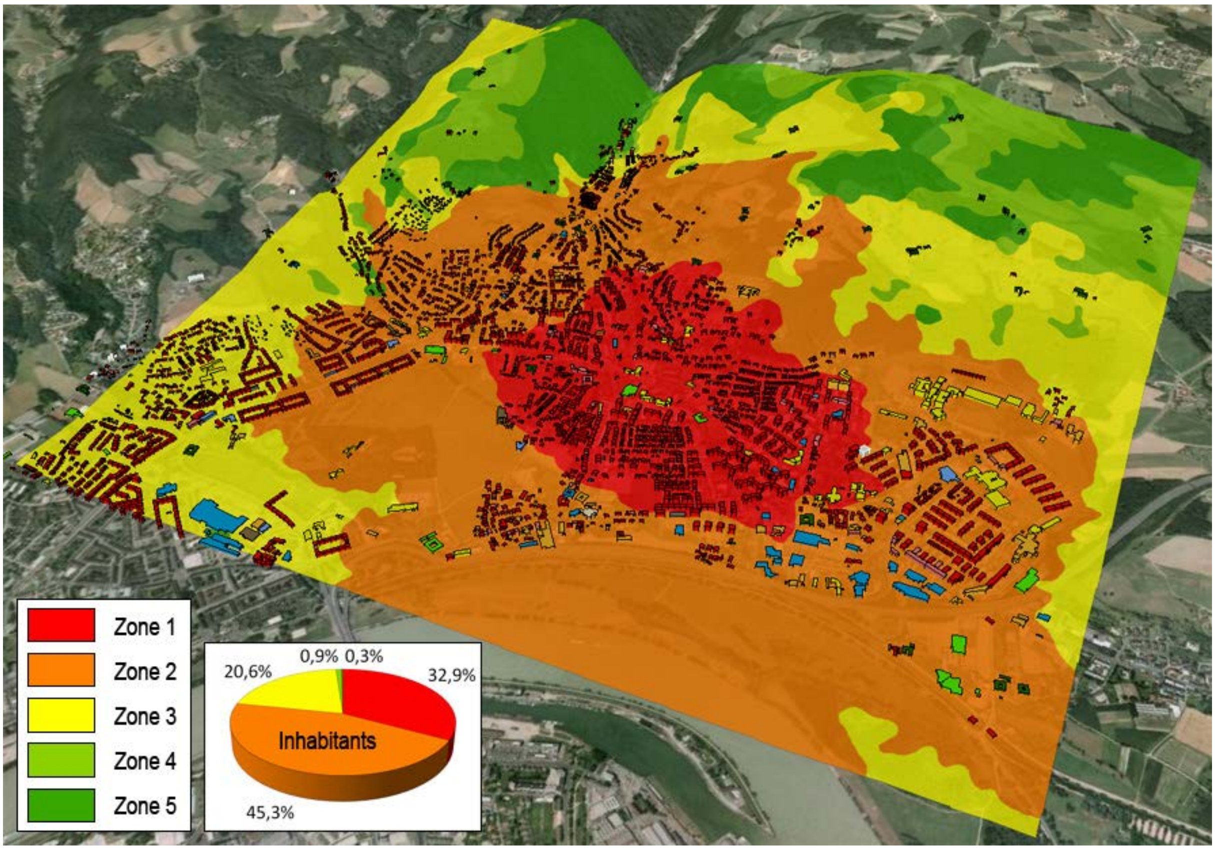


Figure 40: Simulated EQ hazard intensity zones and spatially overlaid functional building model.

Fig. 40 shows buildings visualized according to their previously derived functional land use category, i.e. on a generalized level, red indicating residential buildings, blue standing for commercial use, and yellow for public use. Large parts of the residential area are located in the inner zone of highest simulated intensity, and only few built-up areas are featuring medium to low intensities. Analyzing residential *population exposure* numbers, nearly half of the people living in the area are related to buildings in Zone 2 (45.3 %, see chart in fig. 40). In total, more than three quarters of the population (78.2 %) live in one of the two zones of highest intensity. The relative building/inhabitant ratio (referring to the total area) shows a positive value in Zone 2 (45 % of the total population are assigned to 47 % of all buildings) while in Zone 1 the contrary is observed (33 % of the population associated with 29 % of the buildings). With Zone 1 being located in the urban center of the area these numbers confirm that this part is also characterized by a higher specific population density (on average more inhabitants per building: 8.4) than the surrounding Zone 2 (inhabitants/building: 6.9).

Moving on from analysis of mere residential population exposure, the functional characteristics of the address-level building use model enables additional assessment of a kind of '*socio-economic exposure*', going beyond the concept of '*asset exposure*' as outlined in the introductory sections. With the latter primarily identifying financial values located in hazard zones that eventually account for overall damage cost potential, the socio-economic component also points to other important societal values such as public service facilities. Identification of exposure aspects in that context is crucial in several ways. On the one hand exposed infrastructure objects are detected where service continuance is critical for societal function in general and in particular also in the emergency response phase of a disaster event, including for example hospitals and firefighting service centers. On the other hand schools and other sites of public gathering are top priority in terms of potential early warning and hazard notifications and therefore need to be specifically considered in pre-event exposure assessment.

Regarding asset exposure and in that regard high financial damage potentials in the showcase study area, the functional urban land use model enables to identify car dealing companies as well as construction machinery industry facilities and furniture stores that are clustered in Zone 2 (selected blue buildings in the lower right of fig. 40). In terms of the social component, also the biggest nursing home of the area as well as the university and school complex fall into the orange zone while two major student homes are a bit farther away from the theoretical epicenter, thus being assigned to the yellow zone of medium intensity. Concerning potential critical service interruption, the main fire station is in fact located almost at the simulated epicenter position, so in the area where main shocks and structural impacts are expected.

With regard to possible *validation of the above presented exposure models* it is clear that this is usually only feasible to a very limited level. In terms of the identification of population numbers (then serving as *population exposure* proxies), the reason is that already the most detailed publicly available input data has been used as basis for the disaggregation process and the resulting spatially refined representation of population patterns. The provision of locational information of individuals is obviously constraint due to privacy concerns which leads to the preparation of aggregated representations on the basis of administrative units or regular grids. That information on single-person registrations is, however, of course processed and stored by the population statistics office in the course of census collection (i.e., address-based population register). The only way of validating is therefore in cooperation with this population office (in Austria that is Statistics Austria) that has access to the raw collected census data.

For the Linz case study disaggregated population counts (on address level) were provided to Statistics Austria who then compared those numbers to the raw census counts. Validation results can obviously not be illustrated in terms of absolute deviations, as this would enable derivation of the actual population figures which in turn implies privacy breach. Statistics Austria, for that reason, came up with a kind of anonymous representation of deviations and thus accuracy measure. Two different modes are provided in that regard: (1) absolute deviations per register record without georeference and (2) generalized deviation classes per register record with georeference. For mode (1) validation results show that the number of inhabitants of more than 80 % of the registered distinct addresses has been assessed correctly within a range of ±5 persons. In the spatially explicit mode (2) it is possible to identify specific sources of error such as misclassification of student homes and nursery homes in the course of the functional land use modeling process which then implies a mix-up of target zones for the spatial disaggregation. Detailed explanations on this validation process which was carried out on several levels of detail are provided by Aubrecht (2007) and Aubrecht et al. (2009b). By individually adapting the use of single building objects the overall model quality can be further improved and it is expected that the accuracy level of ±5 persons can be reached for 95 % of the register records.

With regard to potential validation of the modeled '*socio-economic exposure*' results actual disaster damage data can be included in an attempt to verify certain patterns such as overall higher damage levels for affected buildings in industrial and commercial areas compared to damage costs for residential buildings. Aubrecht et al. (2008, 2009d) show that by combining functional building modeling with information on pre-defined hazard zones as well as real-event damage records referring to the severe floods in the Western part of Austria in 2005.

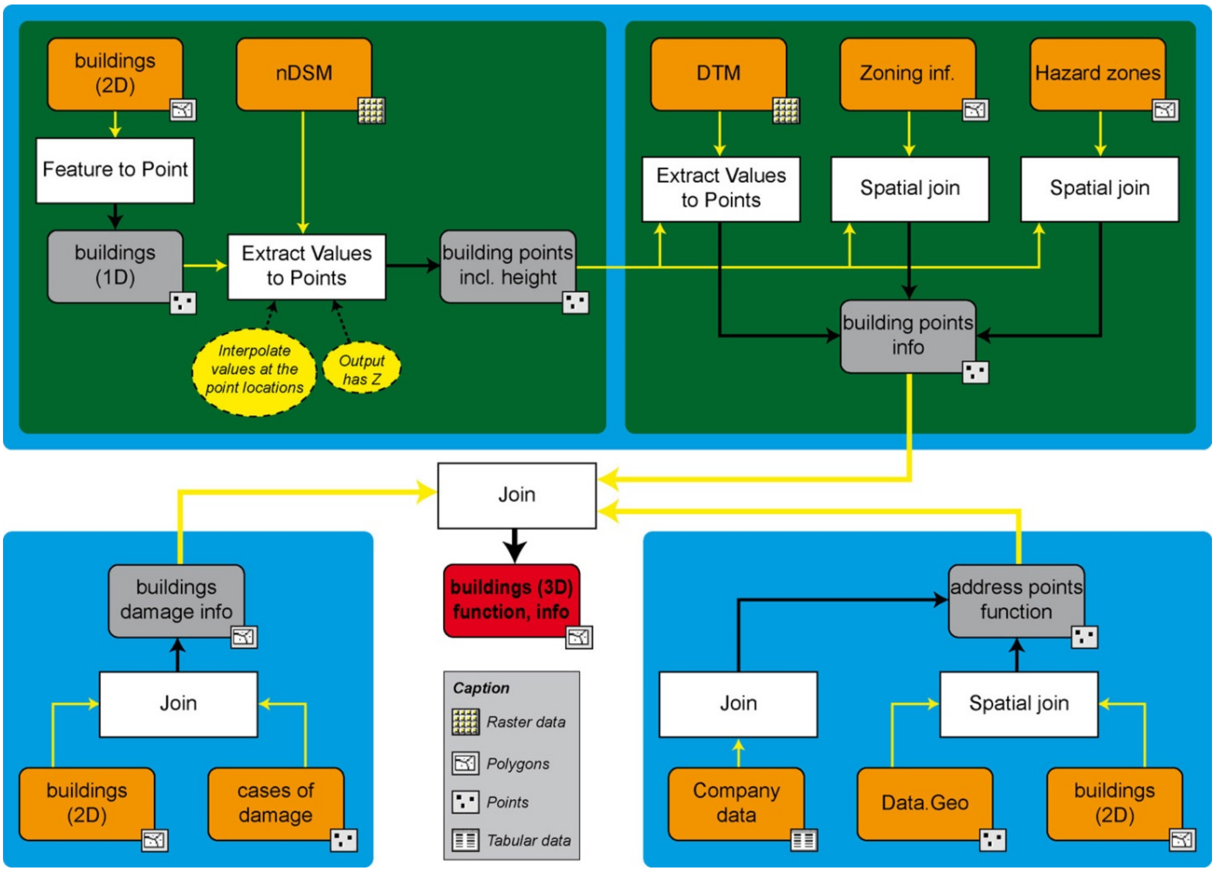


Figure 41: Integrating pre-event hazard and post-event damage data in functional building modeling.

Figure 41 shows the concept of this combination of pre-event exposure to flood hazard and post-event damage information. In addition to the identification of building function, damage cases are mapped to individual buildings and can thus be compared to relevant pre-event conditions such as official hazard zones and relative location of buildings to the later flood zone. For *actual exposure validation*, however, damage data can only provide one part of the picture and *in-situ verification is indispensable* for comprehensive accuracy analysis.

The focus of the presented study is on highlighting the benefits functional urban land use models can offer in terms of population related geospatial modeling and associated identification of social and socio-economic exposure characteristics. The fictitious EQ scenario illustrates how available functional information including building use and associated population distribution can help in getting an impression of multi-faceted exposure patterns and damage potentials. It is also possible to identify certain hot spots (e.g.

very high population density, or specific critical building use) for evacuation as well as search and rescue measures in case of emergency. Regarding real-time disaster management operations, however, dynamic information on human mobility (at least accounting for basic differences between nighttime residential and daytime working population) should be integrated (Freire and Aubrecht, 2010, 2012), which will be referred to in the following sub-chapter. Such efforts also correlate with recent recommendations for improving subsequent vulnerability analyses (Cutter, 2003; Balk et al., 2006; Birkmann, 2007; NRC, 2007).

Furthermore, in comprehensive risk and impact analysis applications it is not sufficient to just consider these social aspects of the model in high detail but also physical factors need to be accounted for. In terms of determining exposure to natural disasters this means that hazard zones need to be constantly improved and updated referring to the best available information (e.g. fault zones and general geological conditions for EQ hazard modeling; slope stability and surface roughness for landslides and avalanches etc.). When dealing with distribution models such as noise propagation or pollutant dispersal a lot of diverse input factors need to be considered to model the environmental hazard component, such as atmospheric conditions, wind fields and topographic features as well as shadowing effects.

3.2.2 Population exposure assessment considering basic spatio-temporal variation patterns[13]

The spatial distribution of population in general, and hence its exposure to hazards, is *time-dependent*, especially in metropolitan areas (Schmitt, 1956). Due to human activities and mobility, the distribution and density of population varies greatly in the daily cycle (Freire, 2010). The most important determinant factor in the context of these temporal population dynamics is whether an incident occurs at night or during the day (Dobson, 2007). Therefore a more accurate assessment of population exposure and risk analysis requires going beyond residence-based census maps and figures (representing a nighttime situation) in order to be prepared for events that can occur any time and day (e.g., 1755 Lisbon tsunami around

[13] Parts of this section refer to Aubrecht et al. (2012a), Freire and Aubrecht (2010, 2011, 2012)

10 a.m., 2010 Haiti earthquake at 4:53 p.m., 2011 Japan tsunami at 2:46 p.m.). In state-of-the-art applied research, however, temporal variations of risk induced by social dynamics are still rarely included in pre-event assessments (Kakhandiki and Shah, 1998). Reasons for that may include lack of appropriate data as well as distorted perception of risk dynamics. In any case, those standard static approaches fail to account for decision makers' shifting focus on temporal detail once a disaster strikes (Zerger and Smith, 2003; Goodchild, 2006).

In an attempt to address those issues of *population dynamics*, motivated by concerns related to homeland security and emergency management, the recently developed LandScan USA (Bhaduri et al., 2002b, 2007) is an expansion to the basic LandScan Global product (described in 3.1.1) that features ambient population distribution on a 1 km raster. A multi-dimensional dasymetric modeling approach allowed the creation of a high-resolution spatio-temporal population distribution dataset. At a 90 m resolution (3 arc-seconds) LandScan USA contains both nighttime residential and daytime population distribution information incorporating movement of workers and students (fig. 42). The development of LandScan USA as a U.S. nation-wide dataset represents a major improvement over previous static modeling methods. However, it is not openly accessible to the public or the scientific community having been formally initiated for the U.S. Department of Homeland Security.

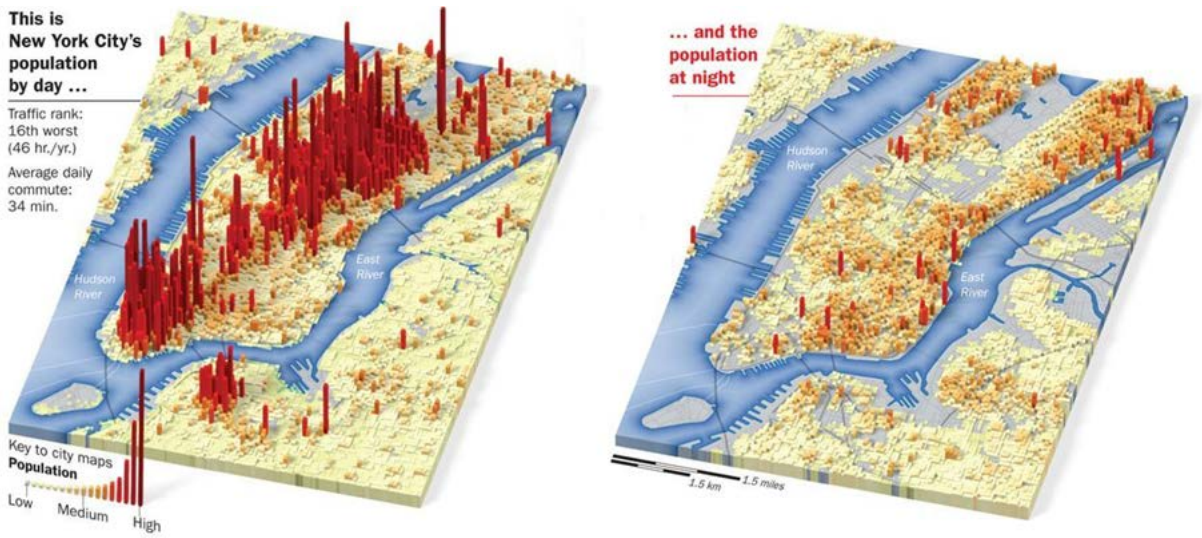
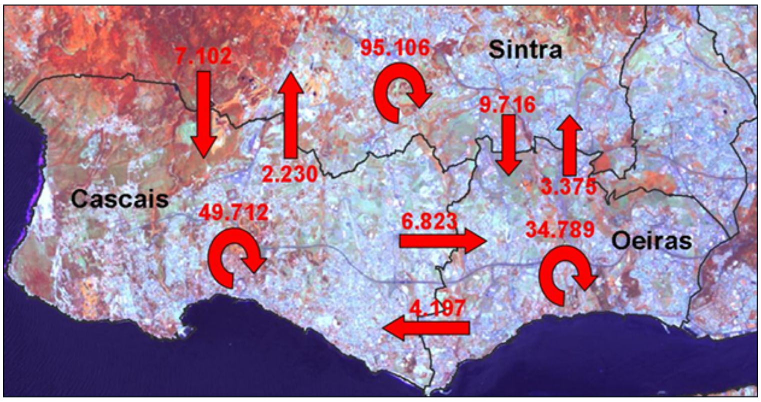


Figure 42: Daytime vs. nighttime population distribution information for Lower Manhattan in New York City, disaggregated to a 90 m grid (LandScan USA dataset).

Following along these lines, the modeling and analysis of *spatio-temporal population distribution in the daily cycle* is illustrated for the Lisbon Metropolitan Area (LMA) based on a dasymetric mapping approach developed by Freire (2010). In the context of the presented study the aim is to re-assess potential human exposure to natural hazards at a much improved level compared to the standard census based approaches (Aubrecht et al., 2012a; Freire and Aubrecht, 2010; 2011; 2012). The LMA – Portugal's main metropolitan area – accounts for 36% of the country's GDP. Its 18 municipalities occupy a total land area of 2,963 km² and are home to 2,661,850 residents (INE, 2001). Although the average population density is recorded at 898 inhabitants per km², these densities vary significantly in space and time. Beyond the more urbanized core the region includes numerous rural areas with scattered settlements whose uneven population density is not adequately captured and represented by heterogeneous census polygons, which can be quite large even at the block level. Also, due to concentration of activities and daily commuting, the daytime population distribution is significantly different from the nighttime period and their totals can vary by more than 50% compared to the residential figures from the census (fig. 43).



Municipality	Nighttime Pop. (Residential)	Daytime Pop.	Difference (%)
CASCAIS	170,683	151,115	-11.5
OEIRAS	162,128	148,937	- 8.1
AMADORA	175,872	141,253	-19.7
ODIVELAS	133,847	96,653	-27.8
SINTRA	363,749	291,421	-19.9
LISBOA	564,657	898,840	59.2

Figure 43: Nighttime and daytime population in selected municipalities of the Lisbon Metropolitan Area, in 2001 (derived from INE, 2001, 2003).

The modeling of population distribution for the LMA is based on raster dasymetric mapping using street centerlines as spatial reference units to re-allocate population counts. A top-down approach is employed to spatially disaggregate and refine population from official census and statistics for nighttime and daytime periods. The (at the time of the study) most recent available statistical and census data (2001) provide the population counts for each daily period, while physiographic data sets including CORINE Land Cover data (CLC2000) define the spatial units (i.e., grid cells) used to disaggregate those counts.

In order to approximate the pattern *variation between daytime and nighttime*, data on workforce and commuting statistics as well as land use and infrastructure information were integrated with the basic census counts in the spatial population disaggregation and reallocation process. Final population distribution grids are provided at a 50 m spatial resolution for analysis and visualization purposes (figure 44), aggregated from a 25 m grid calculation basis. The model combines the spatio-temporal approach proposed by McPherson and Brown (2004) with the innovative use of 'intelligent' dasymetric mapping (Mennis and Hultgren, 2006) to disaggregate official population counts to dedicated target zones. More detailed information on the modeling process is given by Freire and Aubrecht (2012) and initial pre-modeling steps to define density weights for daytime target zones are provided by Freire (2010).

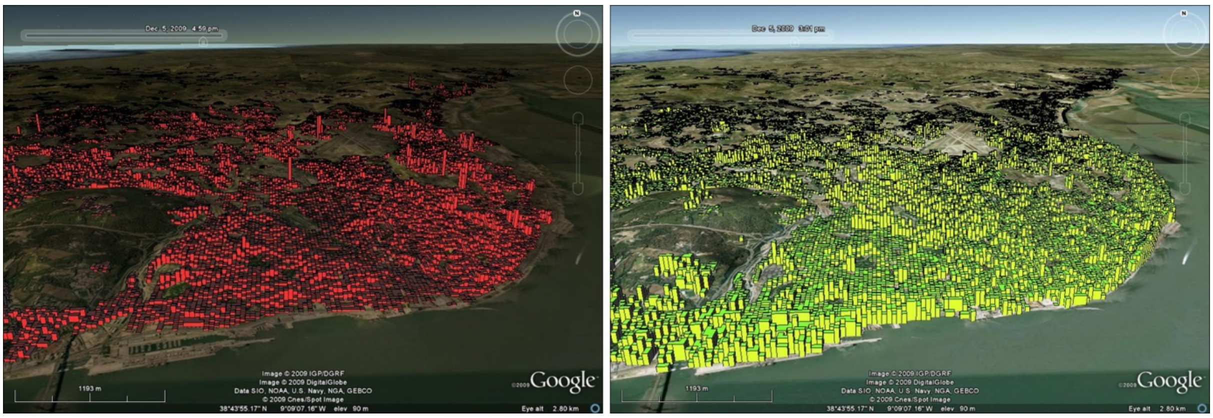


Figure 44: Nighttime (left) and daytime (right) population distribution in the central region of the Lisbon Metropolitan Area.

The LMA is characterized by a moderate seismicity with a diffuse pattern and has been affected by numerous earthquakes in the past causing many victims, severe damages and economic losses (Carvalho et al., 2006). Earthquakes are rapid-onset, short-duration, time-specific and potentially high-consequence events, having long been the prototype for a major disaster. In an assessment of human health impacts of past earthquakes, Alexander (1996) noted that the risk of injury varies significantly between night and day, leading to the recommendation that this temporal scale level should be considered for population exposure and vulnerability assessment.

The well-described 1755 event which struck the Lisbon area (M8.5-9.0) – regarded as one of the greatest seismic disasters to have affected Western Europe – occurred around 9:40 a.m. when many people were not at home and caused between 60,000 and 100,000 casualties (Chester, 2001). A 1755-type event, seen as worst-case scenario for the LMA region, is estimated to have a return period of between 3,000 and 4,000 years. In the Lower Tagus Valley, earthquake return periods vary between less than 100 years for M5 to about 1,000 years for M7. A 'Special Emergency and Civil Protection Plan for Seismic Risk' (PEERS-AML-CL), approved in 2009, was produced for the LMA and adjacent municipalities (ANPC, 2007). The Plan, based on a seismic intensity map, was devised as an operational instrument for organizing response to an event and is automatically activated for an earthquake having a magnitude equal or greater than 6.1 (Richter) or intensity level VIII (Modified Mercalli). However, the Plan only considers census resident population in vector format for the assessment of human exposure, therefore merely approximating affected population for a nighttime event. Estimation of vulnerabilities and adequate exposure assessment are still the main uncertainties in *earthquake scenarios in Lisbon* as it is the case for most other cities in the world that are potentially at risk. Improved inventory of population spanning the daily cycle is urgently required in that context (Oliveira, 2008).

Applying the newly developed spatio-temporal population distribution model, the number of people potentially exposed to various seismic intensity levels is assessed using zonal analysis to summarize nighttime and daytime population surfaces by seismic zone of the earthquake intensity map. In a next step major categories for seismic intensity and population density are defined in order to *derive, map, and quantify human exposure levels*. Using just a few categories for ranking purposes facilitates getting a clear perspective of the spatial distribution patterns. Avoiding cognitive overload is considered highly beneficial in visual risk communication (Lundgren and McMakin, 2009) and can assist in prioritizing areas for mitigation and response actions. Therefore, in order to reclassify the two variables (population density, seismic intensity) into a common and easily understandable ordinal scale, four main categories are defined: (1) Very High, (2) High, (3) Moderate, and (4) Low. The class breaks for population density (in persons/ha) are derived based on histogram analysis (adjusted by rounding). For the seismic hazard, the whole Modified Mercalli scale varying from I to XII is reclassified based on intensity levels and definitions (see USGS, 2013), using a cautious approach (i.e., including level IX in the highest category). Referring to the manner in which an earthquake is felt by people, the lower six levels are grouped in the Low and Moderate categories. The higher six levels, referring to observed structural damage, are classified as High and Very High. In the study area, the seismic intensity levels vary from VI to IX (marked with black box in fig. 45). Figure 45 shows the classification matrix including original levels and classes, corresponding categories, and combined human exposure classes.

			Population Density [Persons/ha]			
			401-	201-400	101-200	0-100
		Exposure Level	**VH**	**H**	**M**	**L**
EQ Intensity [M. Mercalli Scale]	XII	VH	VH	VH	H	M
	XI	VH	VH	VH	H	M
	X	VH	VH	VH	H	M
	IX	VH	VH	VH	H	M
	VIII	H	VH	H	H	M
	VII	H	VH	H	H	M
	VI	M	H	H	M	M
	V	M	H	H	M	M
	IV	M	H	H	M	M
	III	L	M	M	M	L
	II	L	M	M	M	L
	I	L	M	M	M	L

VH (very high), H (high), M (moderate), L (low)
Framed in black: Earthquake intensity classes in the study area

Figure 45: Classification approach to categorize human exposure levels (Freire and Aubrecht, 2012).

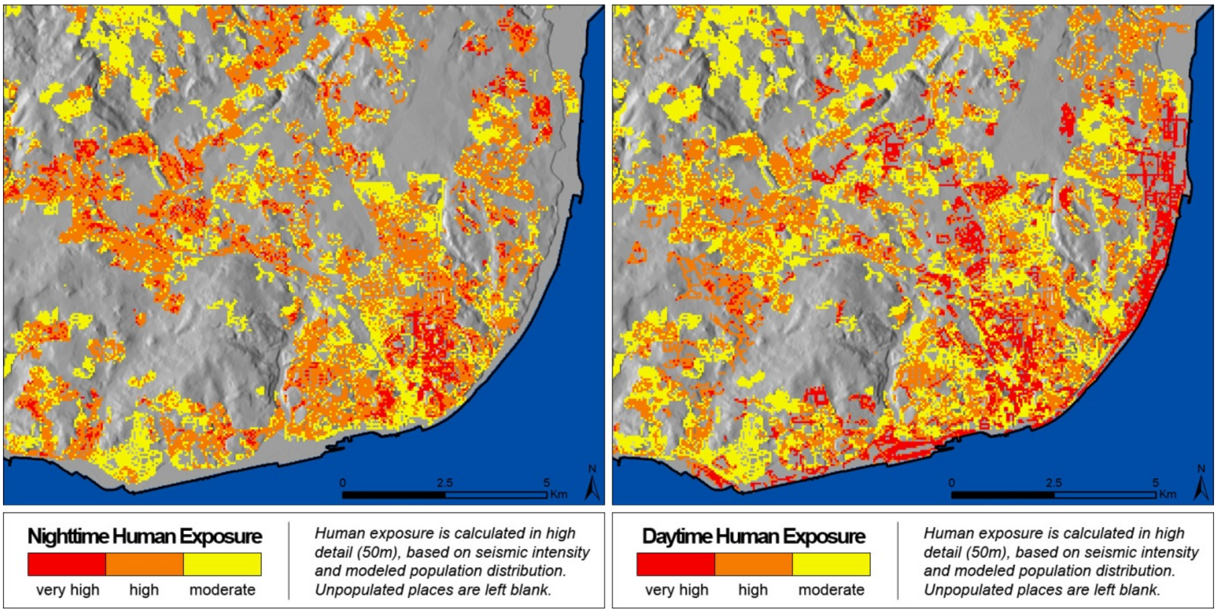


Figure 46: Map of human exposure to seismic hazard for the nighttime and daytime periods, centered on the city of Lisbon (Freire and Aubrecht, 2012).

The seismic intensity map (rasterized at 50 m resolution) is combined with the nighttime and daytime population density maps applying the illustrated classification approach, which results in maps of human exposure to seismic hazard picturing different time stamps (night vs. day). Two-color grading is used for symbolization, as recommended by Gaspar-Escribano and Iturrioz (2011) for this type of risk communication (figure 46). Total population and area are then summarized for the resulting human exposure categories in the LMA.

With the LMA also being subject to significant risk of tsunami, as confirmed by the occurrence of numerous events in the past (Baptista and Miranda, 2009), the exposure assessment approach was adapted from the earthquake test case to account for tsunami hazard. Although the probability of occurrence is lower than for other main natural hazards impacts can be devastating and tsunamis are considered a major risk for Lisbon coastal areas (Baptista et al., 2006). Tsunami hazard is usually represented by inundation maps that identify areas and depths of potential tsunami flooding or run-up. The Regional Plan for Territorial Management for the LMA (PROTAML) includes a Tsunami Inundation Susceptibility map for the area, showing that significant urban areas may be at risk (CCDR-LVT, 2010). However, no assessment of vulnerability or human exposure to that hazard was conducted in the framework setup of the plan. Results from integrating the above-described nighttime-daytime population distribution model with the PROTAML tsunami inundation map show an increase in potential *population exposure to tsunami inundation* by 100% during the day, with mostly the high hazard zone accounting for that increase (table 3).

Tsunami hazard level	**Population density**					
	Nighttime		**Daytime**		**Difference**	
	Absolute	*Relative*	*Absolute*	*Relative*	*Absolute*	*Relative*
High	125,730 pers.	59 %	334,000 pers.	78 %	208,270 pers.	166 %
Moderate	86,929 pers.	41 %	93,444 pers.	22 %	6,515 pers.	7 %
Total	212,659 pers.	100 %	427,444 pers.	100 %	214,785 pers.	101 %

Table 3: Variation in population exposure to tsunami inundation during nighttime and daytime.

In ongoing research the described spatio-temporal approach has been further extended to include evacuation modeling considering tsunami hazard for part of the same study area whereby the initial 50 m grid output was advanced to a high-level 3D building model (Freire et al., 2011, 2012, 2013). Figure 47 shows the evacuation model (illustrating evacuation travel time in minutes) for population in buildings potentially exposed to tsunami flood waters. The model considers both horizontal exits and vertical shelters for evacuation, whereby specific flood depth and building height are identified in 3D pre-processing.

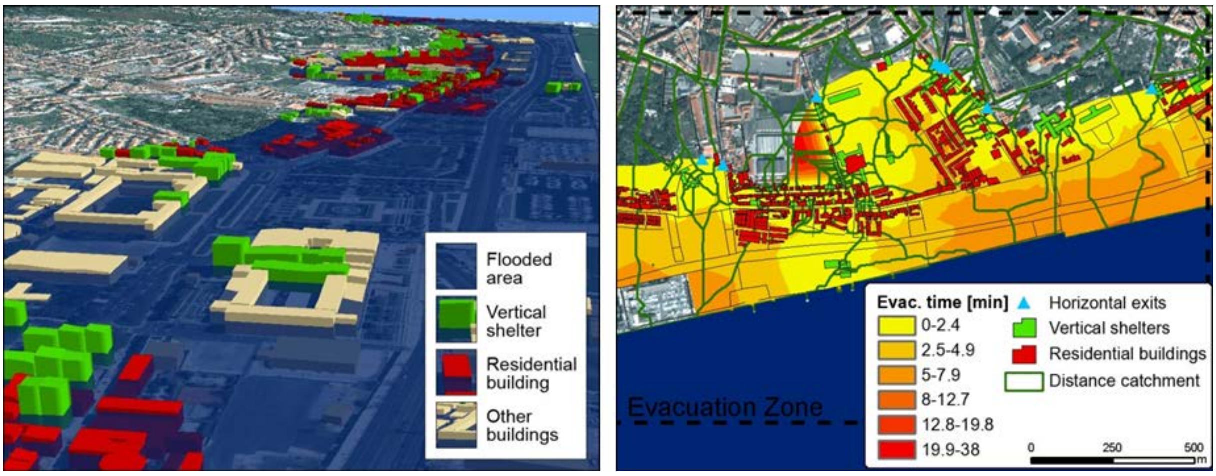


Figure 47: Evacuation time model (right) for population in buildings potentially exposed to tsunami flood waters (left) in the Lisbon test site (Freire et al., 2012).

3.2.3 Inclusion of time use statistics for assessing seamless spatio-temporal distribution dynamics

As shown above, the integration of commuting information and locations of work and study enables modeling basic population distribution pattern variations between the residential nighttime situation and the 'working' situation during daytime. Furthermore, being disaggregated to uniform grid cells this constitutes a huge advancement compared to the use of standard census information (i.e., mere residential) based on heterogeneous administrative units. Reality, however, shows a still much more diverse picture, particularly considering the daytime. Human activities naturally go far beyond mere commuting from home to work and back. Leisure activities and especially lunch and dinner habits add another important dimension to a usual working day, while weekends and seasonal holidays need to be regarded separately anyway. Individual and community *time usage statistics data* – by providing information on the activities of a population and placing the performance of a specific activity within the context of other activities – proof valuable for application areas from many different domains (Fleming and Spellerberg, 1999). Methods and approaches to collect this kind of data have their origins in studies of family budgets at the end of the 19th century with the longest traditions of *time use survey studies* being recorded in the former Soviet Union, the UK and the USA (Niemi, 1995). Until the late 1960s related surveys were only sporadically performed and did not feature any parameter standardization. A European project involving 12 countries – the 'Multinational Comparative Time-Budget Research Project' (Szalai, 1972) – then established a number of methodological conventions as well as international cooperation that resulted in the setup of the International Association of Time Use Research. Currently these initiatives are continued and progressed both in the USA and Europe with the main purpose set at harmonizing time use data collection across nations that allow the development of more detailed and homogenized social indicators e.g. in the context of women and family policy considerations (Sturgis and Lynn, 1998). Eurostat runs the HETUS (Harmonized European Time Use Survey) initiative in that regard (Eurostat, 2009) with similar activities going on in the U.S. having the ATUS (American Time Use Survey) installed by the Department of Labor (U.S. Census Bureau, 2013).

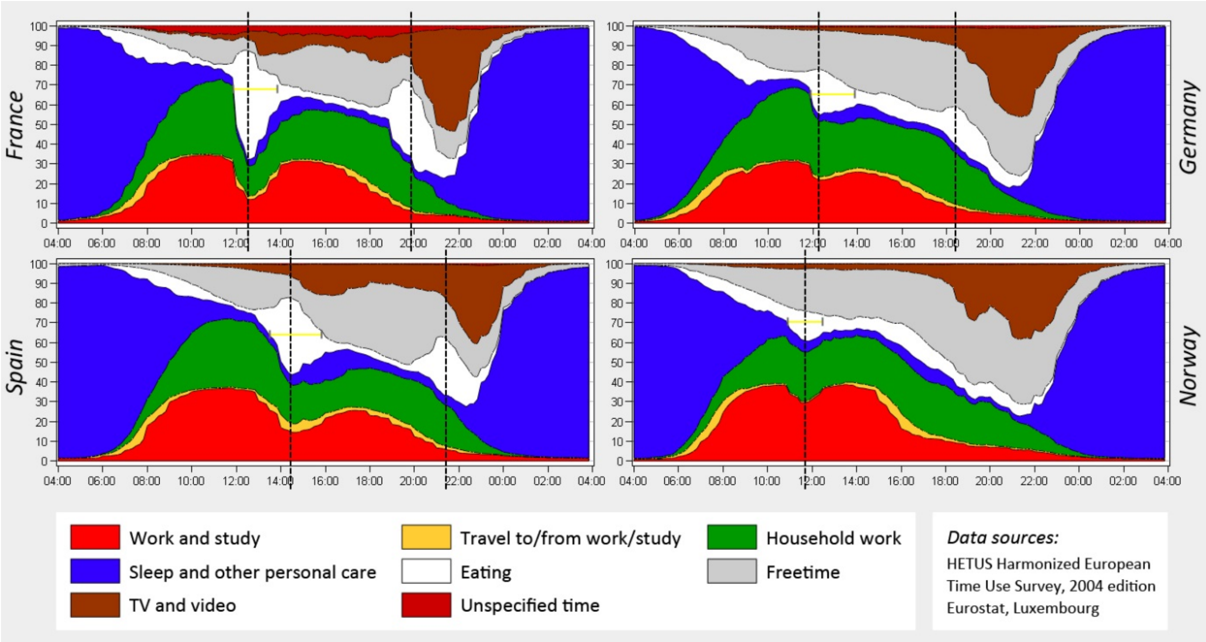


Figure 48: Average time use during a usual weekday according to HETUS data for 4 selected European countries (Statistics Sweden, 2013).

Figure 48 illustrates the *average time use during a usual weekday* for a sample set of European countries based on HETUS survey data. Clear differences between regions and cultures become evident, in particular with regard to strongly differing habits in terms of lunch and dinner time or *eating activities* in general. While in Mediterranean countries like France and Spain lunch and dinner form an essential part of their identity and therefore also claim a significant amount of time for a large part of the population, the Northern European and especially Scandinavian countries such as Norway do not show such a clear pattern at all. While lunch still seems to be a kind of integral point during the day for many people, there is even no 'clustered' dinner time apparent in the survey data with eating activities stretched throughout the afternoon and evening. Another important feature affecting location-specific population patterns is the *temporal backward-shifting* of such activities in Southern countries, e.g. Spain shows its peaks for lunch and dinner almost 2 hours later than France (14:00 and 22:00 compared to 12:00 and 20:00 respectively). Other interesting characteristics include the varying ratio of 'external' work to (mostly unpaid) household work which is significantly higher in Northern European countries (i.e., lower percentage of household work).

With people's time use being the main determinant for their respective time-specific location it serves as a major indicator for the detection of seamless spatio-temporal distribution dynamics. The UK research project '*Population 24/7*' therefore developed an approach to incorporate time usage information in the production of time-specific gridded population models (Cockings et al., 2010). Population grid modeling as previously developed for static residential population distribution assessment is employed in that context, operating on a database of activity locations at which the presence of population is described in both time and space (Martin et al., 2009, 2010). All locations are treated as centroids in a GIS environment with an associated time profile for population presence (figure 49). The conceptual model follows an earlier proposed *Finnish case study* on spatio-temporal population modeling which identifies relationships between geographical objects and their occupation at different times by different population sub-groups and specifically applies this for decision support in a risk assessment and damage analysis framework (Ahola et al., 2007). Furthermore, in an *Italian case study* time use statistics were applied to determine when population is mainly at home or in other indoor places in order to build an exposure information basis for earthquake casualty assessment (Zuccaro & Cacace 2011). Also weekend variations and seasonal tourist influence were considered in that study.

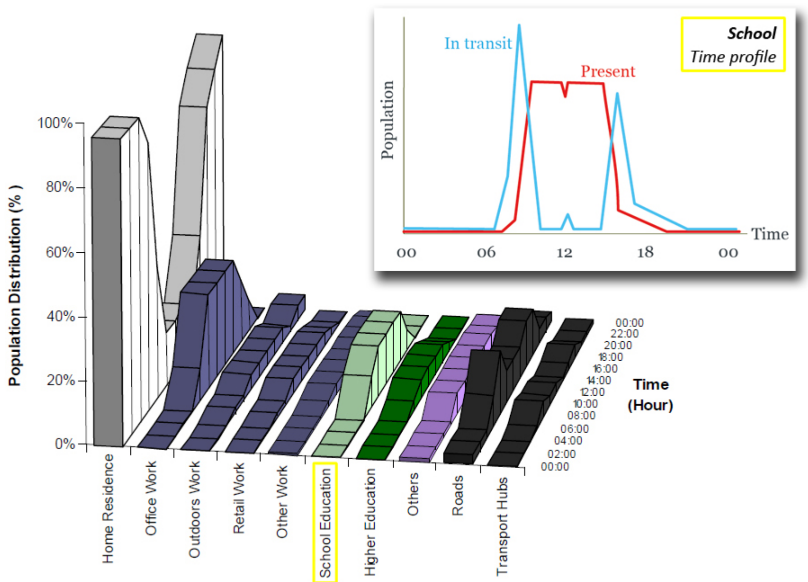


Figure 49: Human location-specific activities and respective associated survey-based time profiles as used for Population 24/7 (adapted from Cockings et al., 2010; Martin et al., 2010).

The latter applications highlight the widespread demand for more temporally specific population maps that realistically represent distribution patterns at certain timestamps, a requirement particularly pertinent to population exposure analysis. In the framework of the EU FP-7 Integrated Project CRISMA (see also 2.1) the above described approaches (1) using mobility and workforce data for daytime population distribution identification and (2) employing time use statistics for further discriminating population dynamics in seamless manner during the day are combined and integrated in adapted form. Applying spatial disaggregation and interpolation techniques the objective is to come up with an *advanced dynamic population model* for *time-specific exposure assessments* (Polese et al., 2013). Various land cover data sources as well as infrastructure and building locations are used to identify time-specific target zones (or cells in the gridding approach). Region-specific time usage survey data and mobility data are integrated to reallocate the population fluctuations for certain timestamps (fig. 50). With one pilot study on assessing impacts of a cascading disaster event carried out in the L'Aquila area in Italy, e.g. recent Italian time use and labor force statistics (Romano, 2008) are consulted.

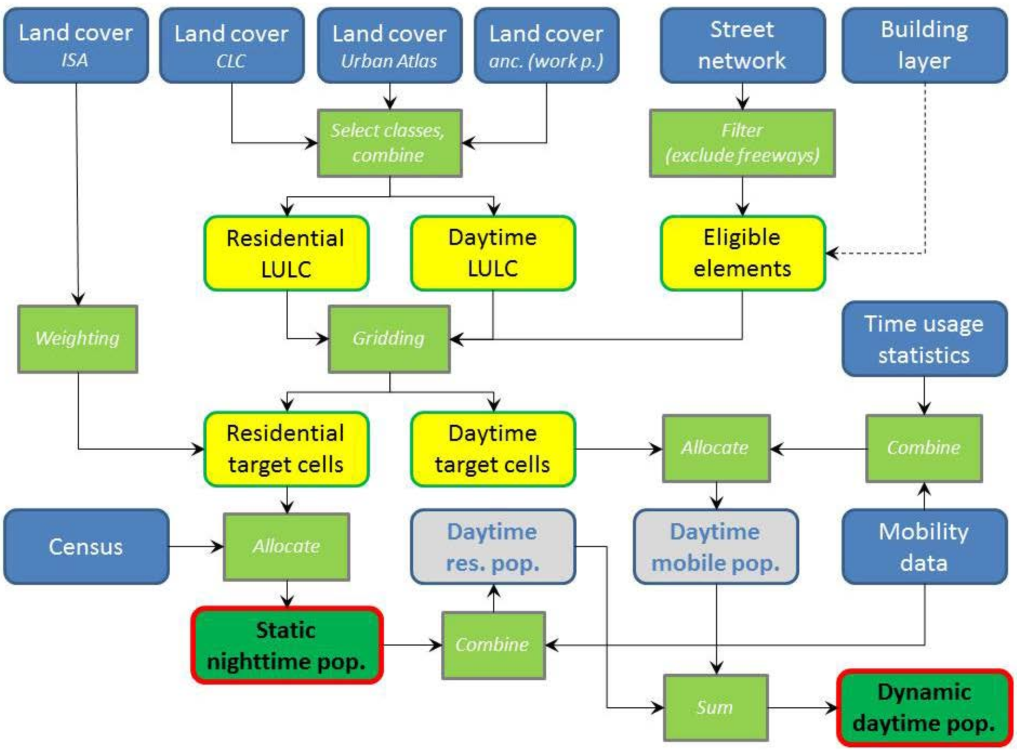


Figure 50: Conceptual framework for dynamic population modeling employed in the CRISMA project.

3.2.4 Dynamic population exposure assessment considering real-time human activity and mobility[14]

Extending distinct daytime population distribution characteristics by location-type specific time profiles and therefore moving towards a sort of seamless mapping of population dynamics and potentially exposure in a pre-event stage is a major improvement compared to standard census based models, but does however still only display part of reality. The above-described approaches have one thing in common, i.e. they do not model individuals or their actual movements. What is done in those models is in fact 'just' redistributing available aggregate population counts onto the most realistic locations for specific timestamps (Cockings et al., 2010). New technology driven advancements including improved data storage and processing capabilities now allow moving into the field of *real-time representation of human movement* (Aubrecht et al., 2012c). Two main categories in that context are (1) the mapping of *cell phone user activity*, and (2) the use of *volunteered geographic information (VGI)*.

One way to record time-specific population distribution information in case of emergency situations (e.g., dynamic population exposure information providing decision support for impact assessment and rescue services) is *mapping cell phone subscriber locations and motion patterns*. With advanced mobile communication technology and particularly increased wide-scale market penetration during the last decade huge volumes of spatially explicit data are being collected by provider companies. The exploration of such data is a novel field of research and only few in-depth analyses have been documented so far (e.g., Hu et al., 2009). In a disaster context, one of the first extensive applications was recorded in the course of the 2010 Haiti earthquake where cell phone data was used to illustrate population movement out of affected regions in the event's aftermath (Bengtsson et al., 2011). General disaster relief assistance in terms of population exposure information provision as well as detailed monitoring of the associated large-scale cholera outbreak was the main objective of that study (fig. 51).

[14] Parts of this section refer to Aubrecht et al. (2011d, 2012cd, 2013b)

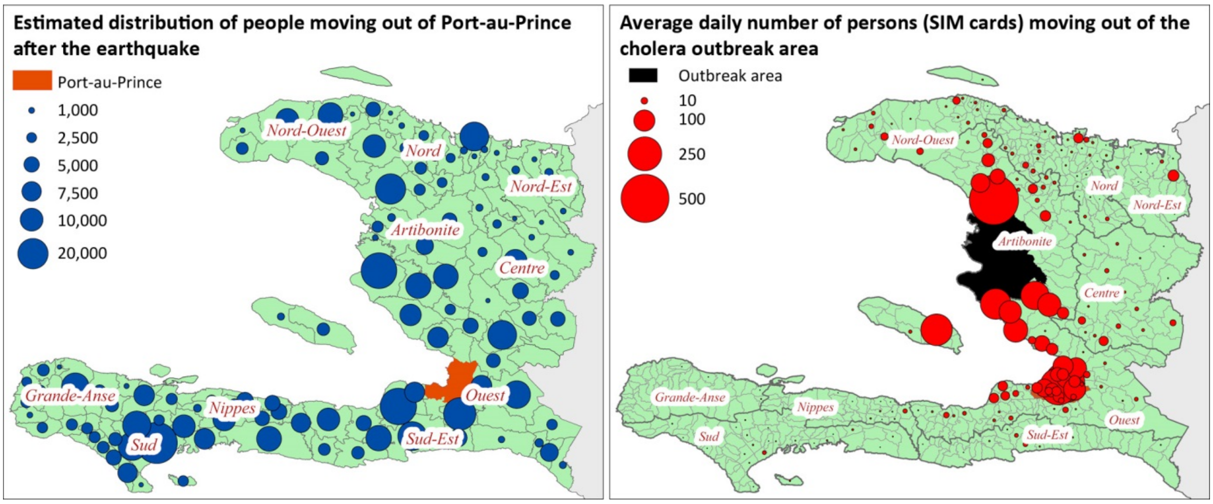


Figure 51: Results from population movement analysis using cell phone data following the 2010 Haiti earthquake and associated cholera outbreak (adapted from Bengtsson et al., 2011).

Privacy concerns, data access constraints due to conflicting commercial interests, lacking of data management rules, as well as exhaustive raw data pre-processing needs hamper more comprehensive scientific studies and applications. Loibl and Peters-Anders (2012) provide a detailed listing of features and characteristics of mobile device data for clarification, both in terms of content (also regarding the locational information accuracy and reliability) and processing requirements.

Cell phone subscribers are always linked to the nearest cell phone antenna station. User actions like phoning, texting, and internet access as well as user motion (provoking handovers between cell-phone antennas) trigger so called 'events' that are recognized by the mobile communication system (Ratti et al., 2005). Distinct time and location information of these events allow mapping the spatio-temporal distribution of the cell phone subscribers and applying that as proxy for time-specific population distribution. To map the cell phone subscriber distribution a set of requirements must be fulfilled:

(1) Availability of mobile communication network infrastructure location information
(2) Dense cell phone antenna coverage for sufficient location accuracy
(3) Mobile device users featuring a representative sample of the total population
(4) User actions triggering a log file entry with time and location information of each event

A study aiming at explicit dynamic population density mapping is currently conducted in the course of the EU FP7 project *urbanAPI*[15] using data from Austria's largest cell phone provider 'A1' (featuring 5 million subscribers of in total 13 million national cell phone contracts, held by 8 million inhabitants). These 5 million A1-subscribers create more than one billion mobile device events per day. Monitoring subscriber distribution patterns is carried out by counting the users connected to each of the cell phone network antennas during certain time steps (e.g., every 15 minutes). The numbers of cell phone users by antenna allow monitoring changes in cell phone user activity and location. Aggregating the user numbers, connected to all antennas within a certain area (e.g., within 500x500 m grid cells), serves to map subscriber distribution variation as effect of the collective population motion within a city during the day (fig. 52). Mapping time-specific cell phone user distribution therefore potentially allows extrapolating the urban *population distribution and its temporal variation* in short time slices (Loibl and Peters-Anders, 2012). Thus, the population number at a certain time in a certain area can be examined and in a further step the *potential exposure* to a dangerous situation or hazard evaluated (Aubrecht et al., 2012cd). The wealth of parameters attached to cell phone log data also allows identification of origin-destination matrices and target areas, eventually enabling the quantification of interaction patterns.

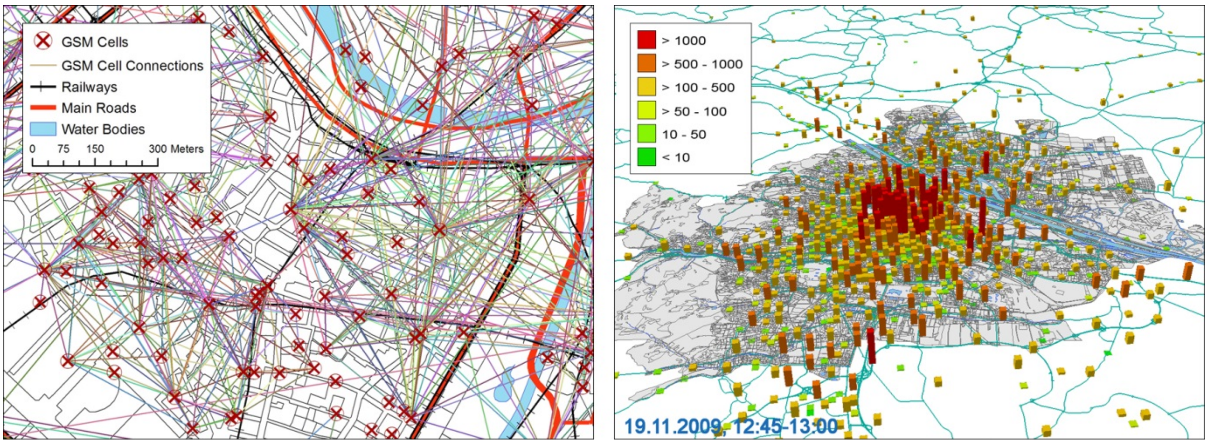


Figure 52: Cell phone subscriber distribution and movement patterns (left) used as proxy for mapping population presence in 15 min time slices (right) in Vienna, Austria.

[15] More information available at http://www.urbanapi.eu/ (accessed 30 September 2013)

Moving on from referring to the 'mere' locational cell phone signal data for dynamic population distribution identification, there is another emerging trend with regard to real-time information on human activity which even includes additional parameters such as the actual type of activity. In recent years an incredible increase in location-specific information has been observed provided voluntarily by individuals and disseminated via the web. The emergence of this *Volunteered Geographic Information (VGI)* as Goodchild first described in 2007 has attracted considerable interest within the GIScience community. As a special type of user-generated content, it offers great potential to produce up-to-date and near real-time information related to any place on Earth, even though overall accuracy remains an issue of debate. Location sharing services (LSS) such as 'foursquare', 'Gowalla', and 'Facebook Places' collect hundreds of millions of user-driven footprints or 'check-ins'. Those footprints provide a unique opportunity to (1) study social and temporal characteristics of how people use these services and (2) model *patterns of human mobility*. However, the amount and frequency of VGI is not evenly distributed and recent research (Cheng et al., 2011; Li and Goodchild, 2011) considers it directly related to socioeconomic characteristics of its contributors (i.e., geographic and economic constraints, individual social status).

Particularly in the context of population dynamics studies, VGI may provide a data source that is more accessible and current as well as less expensive and time-consuming than traditional activity survey data as described previously (in 3.2.3). VGI generated on micro-blogging services and location-based social networks (LBSN) bear the greatest resemblance to the activity diary that time geographers are familiar with (Rush and Kwan, 2011). Noulas et al. (2011) present a large-scale study of user behavior on the LBSN platform 'foursquare', analyzing user check-in dynamics and demonstrating how that reveals spatio-temporal patterns as well as information on user mobility and characteristics of urban spaces. Particularly in urban areas an increasing number of persons are equipped with 'location sensors' in the form of GPS-enabled mobile devices. The willingness to share situational experiences with others is generally increasing rapidly and is boosted by rising new technologies supporting the spatial component of social networks. These new developments result in collection of a vast amount of data about people's locations and enable analyses of spatio-temporal movements.

Taking the recently developed census and spatial statistics based daytime ‘working’ population surface for the Lisbon Metropolitan Area (compare 3.2.2) as basis for comparison, we examine functionally categorized location-specific check-in information from the LBSN platform ‘foursquare’ picturing one working week in the Lisbon Metro Area (Aubrecht et al., 2011d). The objective of that particular study was to analyze potential correlation patterns and explore options for modeling *fine-scale spatio-temporal population dynamics* and characteristics of urban land use *based on VGI*.

‘Foursquare’ is a location-based social network (LBSN) relying on the growing usage of GPS-enabled mobile devices. Sharing their location with friends, users ‘check in’ at given venues to collect user points and virtual ‘badges’. Earning badges stands for increasing the user’s social status in the network. Users are also able to add new venues and thus extend the database, which in a further step can be verified by the respective venue owner to assure data quality. Foursquare counts over 30 million users worldwide (as of January 2013), checking in around 6 million times per day (Foursquare, 2013; Frier, 2013). Due to privacy policies it is not possible to access the raw data individually. However, there is an application programming interface (API) provided for companies and mobile application developers enabling retrieval of certain restricted data views. For the Lisbon study the ‘foursquare venues project (beta)’ API endpoint was used to (1) extract the locations and types of venues and (2) get the number of users currently checked in at these locations. With venues also containing functional information (e.g., office, restaurant, gym) it is possible to categorize the types of user activities. This can support in-depth analysis of *time-dependent user behavior* which would not be possible referring to the above-described locational cell phone signal data, but neither with other popular social network data like Twitter. From 8-15 May 2011 (Sunday till Sunday) the entire area covered by approx. 1,400 request points (i.e., each identifying the respective 30 nearest venues) was observed on an hourly basis. In total, more than 250,000 requests were made eventually resulting in a PostGIS database containing 10,185 venues and 22,664 check-ins. Figure 53 illustrates the human activity patterns in selected aggregated classes for the urban center of Lisbon Metro. Certain activity location types such as restaurants and work places as well as travel and leisure hotspots are very well captured and offer the chance to analyze *real-time context-specific population movements*.

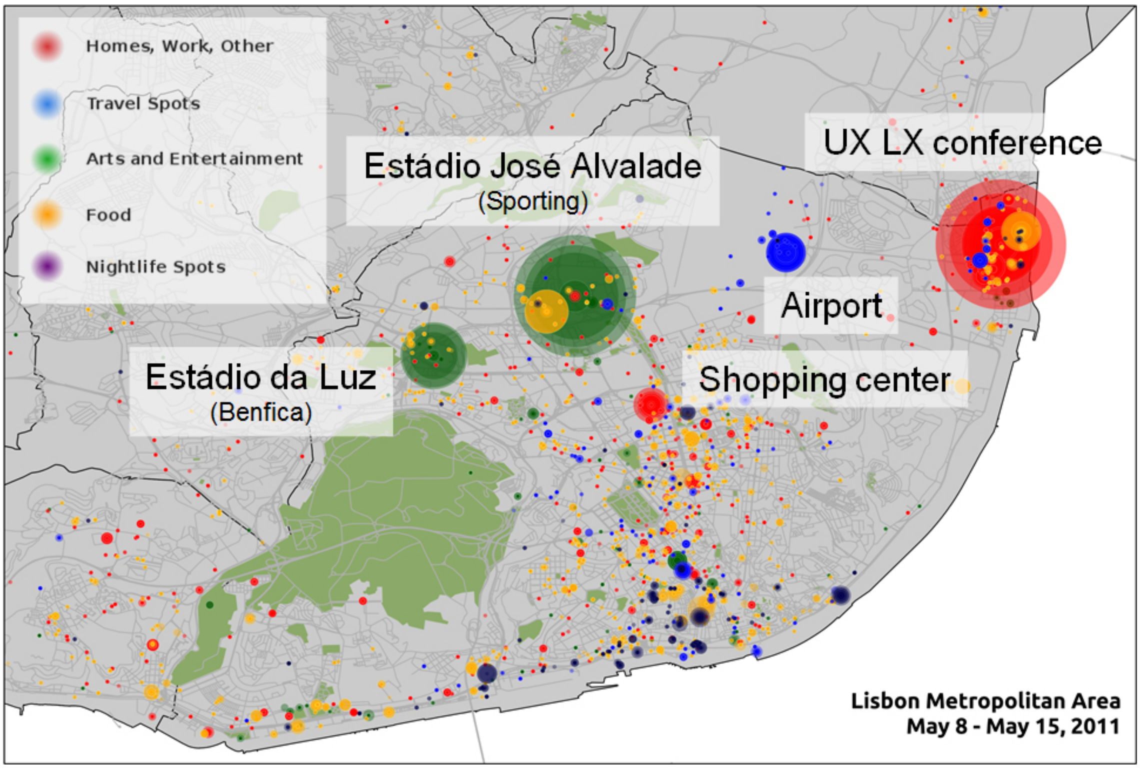


Figure 53: Foursquare venue types and location as well as respectively recorded user check-in numbers for the urban center of Lisbon Metro during the week of 8-15 May 2011.

Attempting to make the recorded foursquare data sort of comparable to the disaggregated daytime 'working' population raster some requirements had to be defined:

(1) Covering a typical workday, only user activity between 9:00 and 17:00 is considered.
(2) Only user activity between Monday and Friday is taken into account (working week).
(3) Only those foursquare venue categories relevant for daytime working population are used for the analysis (e.g., office, education).

Rasterizing the foursquare data to a 50 m cell size (i.e., resolution of the reference dataset) showed little useful spatial patterns and a rather small area covered. In order to cope with this issue the spatial resolution was decreased and two raster surfaces of 100 m and 200 m respectively were produced. In an additional step the previously modeled daytime working population grid is aggregated accordingly and overlaid with the foursquare grids in order to apply some spatial correlation measures. Due to de-facto incomparability in absolute terms, relative density patterns are checked in that context rather than absolute numbers (fig. 54).

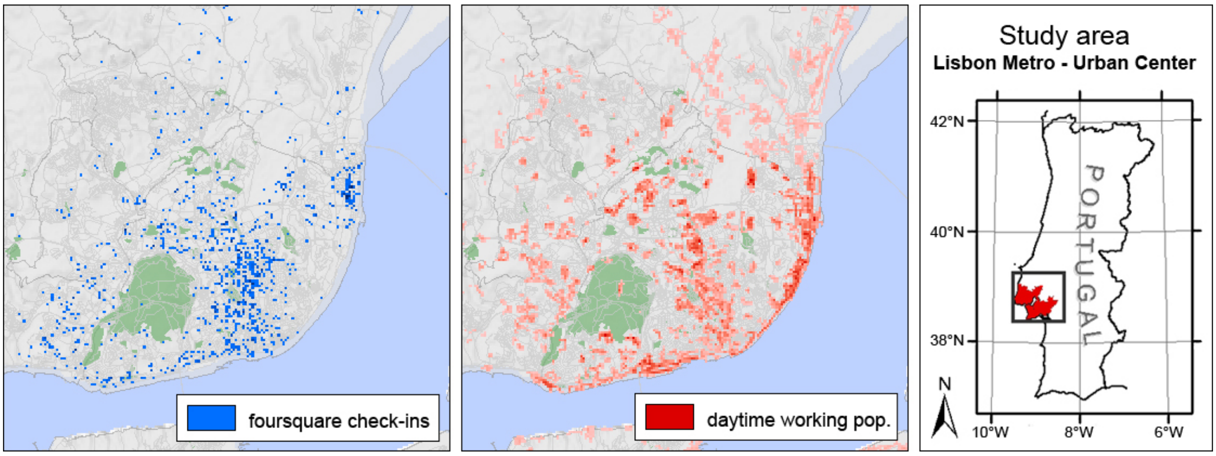


Figure 54: Comparison of 100 m foursquare check-in density raster (working week) and 100 m modeled daytime working population grid for the urban center of Lisbon Metro.

Bearing in mind that the two data sets do not refer to the same point in time (2001 and 2011 respectively), checking spatially explicit but nonetheless relative patterns is assumed a worthwhile approach. In fact, the subjects of comparison in that context are not two population distribution models per se, but rather illustrations of daily averaged location-specific 'online' activity vs. work- and study-related human mobility patterns. With further research certainly needed, this kind of data has a high potential to be very useful in the future for urban planning purposes, disaster and crisis management and for other fields requiring population data on high spatio-temporal resolution. Undoubtedly the data in its current form still show gaps and are biased to some extent by various factors:

(1) Up to date there has not been any quantitative information available on the socio-economic structure of LBSN users. This is most welcome for privacy reasons but complicates the assessment of how representative the data is with respect to the total population.
(2) LBSN users usually use the services on a regular basis which leads to redundant records when aggregating data from multiple days or weeks.
(3) The motivation of users to check in varies depending on a multitude of factors including their general social behavior, activities (e.g., special events), and rewards like badges or free items (e.g., coffee, ice cream) they receive from the individual LBSN application or the venue owners.

Therefore, the captured information is considered to just cover a sample of the total user mobility in real life. Nonetheless, the data provided some very interesting patterns and characteristics of *real-time dynamic population distribution* and exposure in a next step that could not be derived in a different way. For example, context-specific activities can be aggregated and analyzed individually in order to produce *real-time time use statistics* that can then be compared with results of traditional survey methods or even taken to update and calibrate those. Figure 55 shows an averaged time profile for a weekday based on the foursquare check-in records of the Lisbon study as well as the entire weekly time profile where the significantly differing weekend patterns are identified. Basic characteristics like commuting, work and eating habits are clearly depicted whereby particularly for the latter an interesting trend becomes evident. Compared to time use survey information the peaks of lunch and dinner activities seem to be shifted backwards by about 2 hours. One reason for this might be the aggregative nature of check-ins, i.e. people staying checked-in at one location until they check in at a different location and venues thus sort of pile up 'occupants' over time even though some might have left already.

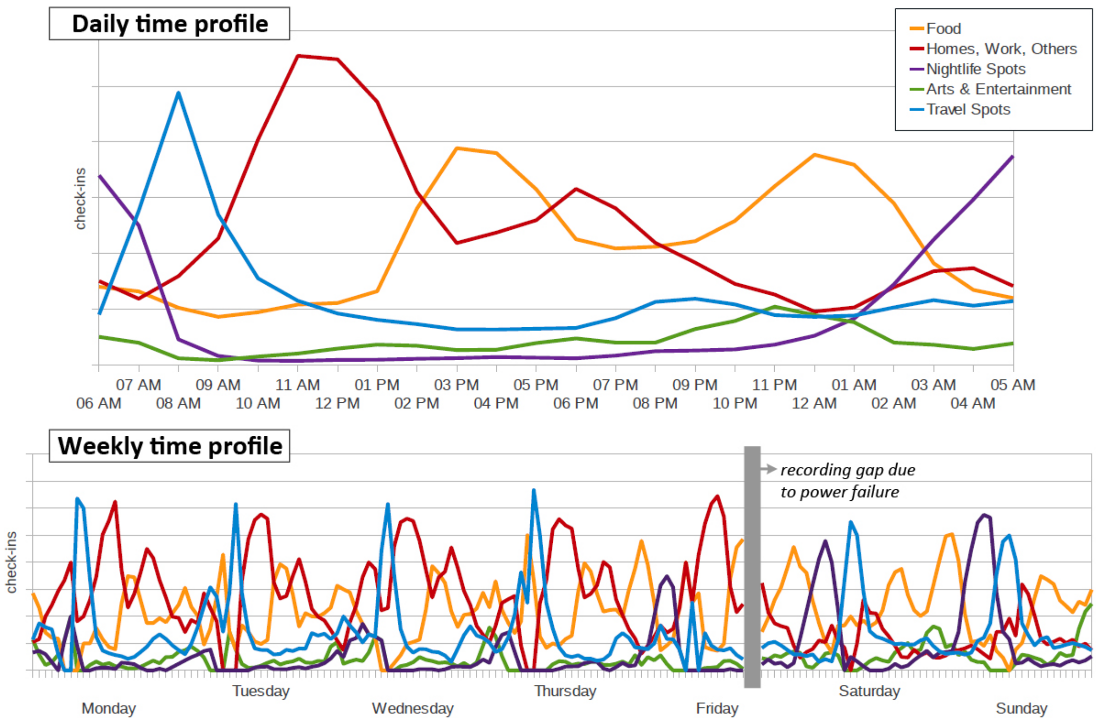


Figure 55: Daily and weekly time use profiles derived from foursquare user check-in records in the Lisbon test site.

Data quality and availability as well as privacy concerns have been highlighted and considered as important issues in the past few sub-chapters. Furthermore, objectiveness and lack of conceptual consensus for model development have to be discussed. With the recent focus on data sharing and integration initiatives such as INSPIRE, GEOSS, GMES, and others (Havlik et al., 2011), particularly *in emergency situations* reliable and consistent input *data for local scale analysis will likely become available for authorized users* as it is already the case for certain purposes on higher level with regard to satellite imagery (e.g., Disaster Charter, SAFER). In line with near real-time coverage of spatial and temporal characteristics of human activities including population movements and functional socio-economic aspects this would enable activity parameter downscaling and thus allow *exposure mapping at high spatio-temporal resolution or even near real-time*.

When *issues and challenges of model validation* were described earlier on for the local-level census-based static population disaggregation it was highlighted that in fact there is no suitable reference data available (in the public domain) to assess the reallocation accuracy when already the highest level of detail (again, publicly available) is used as input source. To carry on along these lines possible *validation becomes even more of a challenge the more dynamic the representations aim to be*. Commuting surveys and work place statistics can itself become more reliable when the sample size is increased, but in terms of assessing the accuracy of derived gridded products only actual field data collection at the respective location can deliver reasonable reference data. Freire (2010) performed such an in-situ model validation approach for the Lisbon Metro Area. When it comes to time use statistics it has been outlined that time use graphs as derived from actual VGI-based mobility patterns have the potential to serve as validation source or even refinement option for classical survey based statistics. However, representativeness will remain the major challenge in that regard for literally all kinds of VGI due to its biased user profiles. Referring to population motion patterns as derived from cell phone activity those spatially and temporally explicit locational depictions might indeed serve as validation source for other reallocation models in the future – in case those data become more widely available (at least in anonymous form). For measuring their accuracy there is no reference information available.

4 Vulnerability and risk implementation: Spatial and temporal aspects[16]

In the context of the introductory elaborations on disaster risk research and integrated disaster risk management (chapter 2) Crichton's risk triangle (1999) combining the parameters of *hazard*, *exposure*, and *vulnerability* was highlighted to set the basis for a comprehensive *risk* assessment framework. With the exposure of elements at risk to a certain hazardous phenomenon being identified as the main defining starting point – i.e. without exposure further analyses are pointless – context specific vulnerability characteristics indicate the next level of complexity in terms of detecting variations in the risk profiles of the study elements or system. Mapping and analysis of human exposure therefore forms an essential preceding step for the assessment of the social dimension of vulnerability. Measures of exposure can thereby include a quantitative assessment of types of assets or the number of people in a certain area at a certain point in time. As UNISDR (2009) illustrates, these can then be combined "*with the specific vulnerability of the exposed elements to any particular hazard, [in order] to estimate the quantitative risks associated with that hazard in the area of interest.*" Integration of social structure and varying aspects of both hazard susceptibility and resilience enables development of social vulnerability indicators and eventually differentiation of situation-specific risk patterns on various scales (Aubrecht et al., 2011b). As research conducted for this thesis mainly considers population as the study element, this chapter follows or rather advances along the lines of the previous one and focuses on population-related aspects of vulnerability, i.e. *human and social*

[16] Parts of this section refer to Aubrecht et al. (2011e, 2013bf), Aubrecht and Özceylan (2013) as well as Özceylan and Aubrecht (2013)

vulnerability, and associated risk patterns resulting from final integration with hazard parameters. From an engineering perspective most attention is put on the vulnerability of infrastructure and building objects in particular. Nonetheless human society is generally seen as the main focus of concepts of vulnerability (Birkmann, 2006a). The question came up in that context if "*human vulnerability [can actually] be adequately characterized without considering simultaneously the vulnerability of the 'surrounding' ecosphere*" (Turner et al., 2003). As outlined earlier on social or in a broader sense societal vulnerability describes the status of a society with respect to imposed hazards and potential impacts or further emerging internal and external changes, including its ability to cope with and adapt to these new circumstances. Undoubtedly the environmental setting that a social system is placed in has significant influence on the system's structure and thus on its potential capacities to cope with or adapt to adverse conditions. For example in the context of wildfire hazard, potential ignition spots are usually detected in environment-specific vulnerable areas, i.e. in terms of excessive dryness and favorable fire fuel conditions, which in turn has direct implications on the overall vulnerability of a potentially exposed social system in that region. Identification of hazard specific environmental vulnerability – such as illustrated by Aubrecht et al. (2011f) for wildfires in Africa – can therefore serve as massive decision support for efficiently targeting mitigation and early warning measures for social systems.

Similar to the previous chapter different scale levels both in spatial and temporal terms are highlighted in the following. However, with increasing thematic complexity, i.e. integration of structural parameters in addition to the 'mere' locational aspects of elements at risk, the explicit *context of a study* becomes more and more essential. While basic exposure patterns are to some extent considered 'universally' applicable in different hazard settings, vulnerability is very much context and situation specific. In the analysis of exposure spatio-temporal dynamics can be understood as a main context-defining factor, i.e. mobile population may not directly be affected by some slow-onset hazard event. In the assessment of vulnerability the *thematic characteristics* are the major determinant as for example an entirely different set of social indicators needs to be considered in a heat stress context compared to a winter storm or flooding scenario.

4.1 The specific context of heat stress as hazard factor affecting humans

There are growing concerns about the impact of weather extremes on society, particularly in the context of climate change and global warming (Diffenbaugh and Ashfaq, 2010; Birkmann, 2011). Climate change and associated consequences are very likely to have substantial implications for human health in particular. Climate change does not turn out as a single variable, but is rather characterized by a multitude of influencing parameters that are relevant for human well-being (McMichael et al., 2006). Long-term changes of human-natural coupled systems are associated with both *direct and indirect impacts on society*. Climate induced changes in biological processes can eventually indirectly increase human health related vulnerability, e.g. one of the most serious and far-reaching health impacts of climate change being increased frequency and geographical spreading of vector-borne contagious diseases (Githeko et al., 2000; Sutherst, 2001). With regard to direct impacts a set of known health effects of weather and climate variability have been described based on evidence from epidemiological studies (Kovats and Akthar, 2008). *Heat stress*, for example, includes heat-related illness and death due to heat waves as well as associated deaths from cardio-respiratory disease as was experienced during the 2003 European summer heat waves that caused more than 70,000 deaths (Robine et al., 2008).

Higher mean summer temperatures are expected in many regions of the world and fluctuations will likely result in more frequent and intense extreme events such as heat waves and their associated risks (Patz et al., 2005). An increase in heat stress is considered one of the most certain impacts of climate change. There is therefore a need for a better understanding of the spatial and temporal patterns of heat-related risk. Mortality figures, e.g., reportedly increase more from sustained periods of high temperatures (heat waves), rather than from individual days (Hajat et al., 2006). Heat related risk and vulnerability studies have received considerable attention in that regard in recent years, many of them investigating the important causal relations between *hazard-specific vulnerability* and societal impacts.

'Heat' is a subjective term that varies according to context and location. A definition of a 'heat wave' would therefore imply that it is an *extended period of some kind of elevated-temperature stress*. In general, heat waves are considered continuous periods of temperatures exceeding some threshold for several days (Costello et al., 2009). An absolute definition of a heat wave would thus require a certain number of days that exceed some pre-determined fixed temperature value (Robinson, 2001) or heat stress index level (Smoyer-Tomic et al., 2003). The definition of a heat wave often varies by study design in terms of the number of consecutive days that exceed a threshold temperature, the threshold temperature used, and whether heat waves are distinguished according to severity (Kinney et al., 2008). The relationship between heat and health is even more complex as the absence of nighttime relief from heat for urban inhabitants, i.e. high minimum temperatures (T_{min}), is also considered a factor in excessive heat-related deaths. Dankers and Hiederer (2008) include the assessment of the number of such 'tropical nights', defined as a day with T_{min} exceeding 20°C, in their description of extreme temperature indicators. Gershunov et al. (2009) used T_{max} and T_{min} to study daytime and nighttime heat wave events in the US. Heat index (a combined measure of temperature and relative humidity, as defined by NOAA's National Weather Service) is also listed as one way of measuring heat-mortality relations, in addition to using basic maximum or minimum temperature thresholds (Rey et al., 2009), or more complex air-mass condition monitoring (Patz et al., 2000). However, temperature is still the most frequently used variable in analyses of heat-related vulnerability and risks, mainly because of its simplicity and because it illustrates health impacts of heat similarly to the more complex methods (Kyselý and Huth, 2004). Smoyer-Tomic et al. (2003) refer to that as univariate heat stress measures, which typically designate subjective cut-off points above which health effects are expected to occur. They list exemplary T_{max} levels (30/35/40°C, etc.) and the number of consecutive hours/days above a specified T_{max} threshold in that context.

This sub-chapter illustrates the case of *heat stress as hazard factor* in order to set the basis for subsequent appropriately designed context-specific vulnerability and risk analysis. In terms of scale levels both the broad scale and the local level will be covered as well as rather short-term fluctuations in frequency and duration and climate change induced longer-term variability of heat stress.

4.1.1 Broad-scale assessment of climate change induced heat stress variability[17]

In the present study heat stress and climate change induced variability is analyzed on European level, i.e. specifically for the North-South transect ranging from Southern Scandinavia to Central Europe introduced earlier on (chapter 3.1.4), where also disaggregated population prospects are available for subsequent long-term vulnerability considerations. In a Central European context the heat wave definition after Kyselý (Kyselý et al., 2000; Kyselý, 2004) proved to be most adequate, consisting of three requirements imposed on the period under consideration: 'Heat waves' are thus defined as

1) consecutive periods of at least 3 days during which the daily maximum temperature (T_{max}) is higher than or equal to 30°C,
2) the mean T_{max} over the whole period is at least 30°C, and
3) the T_{max} must not drop below 25°C.

In the Eastern Alps such heat waves do not occur every year, but nonetheless have been observed several times in recent decades. Also in historical data series an increase in frequency and duration is noticed. Referring to episodes rather than single (hot) days allows for more robust statements regarding meteorological characteristics in future decades.

Critical future environmental conditions intensified through climate change are modeled based on the consortial-simulations (Keuler et al., 2009; Lautenschlager et al., 2009) of the *regional climate model* COSMO-CLM performed by the Model and Data group (M&D) of the Max-Planck-Institute for Meteorology which operates as the data management division of the German Climate Computing Center (DKRZ). The CLM (Climate Local Model) evolved in the early 2000s as a climate-application of a high resolution non-hydrostatic local weather forecast model (less than 10 km). Local-scale weather and climate models were eventually integrated into the unified limited area model for operational weather forecast and regional climate modeling COSMO4. COSMO-CLM is the special setup of this model for climate

[17] Parts of this section refer to Aubrecht et al. (2011e, 2013f)

simulations with the Consortium for Small-scale Modeling (consisting of two large groups of several European National Weather Services and the CLM-Community) currently working on further developments (Rockel et al., 2008). The applied CLM consortial-simulations are driven by the global climate model ECHAM5/MPI-OM1 (being a coupled atmosphere-ocean model; Roeckner et al., 2006) that considers two climate scenarios assuming different greenhouse gas concentration increase trends due to certain economic, technological and demographic developments (A1B and B1, as defined by the Intergovernmental Panel on Climate Change, IPCC; Nakicenovic and Swart, 2000) with two realizations each for the time period 1960-2100 (Schubert, 2007). The spatial resolution of the output geographical raster representations is approximately 18 km in mid-European latitudes.

In order to assess future patterns of climate change related heat stress, results of the European regional climate model COSMO-CLM are consulted for projecting the situation in the 2030s. For the present study the IPCC scenario A1B is considered, projecting a rather moderate increase in CO_2 concentrations for the time period 1960-2100. Various critical climatic variables are calculated annually averaged over a 10-year reference period (2030-2040), such as 'hot night' and 'heat wave' counts.

The left part of figure 56 illustrates the future patterns of heat wave frequency in populated areas, averaged for a 10-year reference period spanning 2030-2040 to come up with a mean annual heat wave count number. As expected, the Southern and Eastern parts of the North-South European transect including Italy, Hungary, the Slovak Republic, and Austria are likely to be most affected with more than three heat waves per year predicted for large parts of the populated regions. However, looking at the relative change in heat wave frequency (right part of figure 56), comparing the 2030-2040 prospect period to the 'present' state of origin (2000-2010), a rather strong increase is detected particularly in the more Northern countries along the transect such as Denmark, Germany, and furthermore the Czech Republic, while for example Italy is likely to feature stable conditions or even a slight relative decrease in heat wave frequency in the future. The stronger relative increase in the Northern parts is easily explained through their current low base level. That way, even small absolute increases can result in rather high relative values.

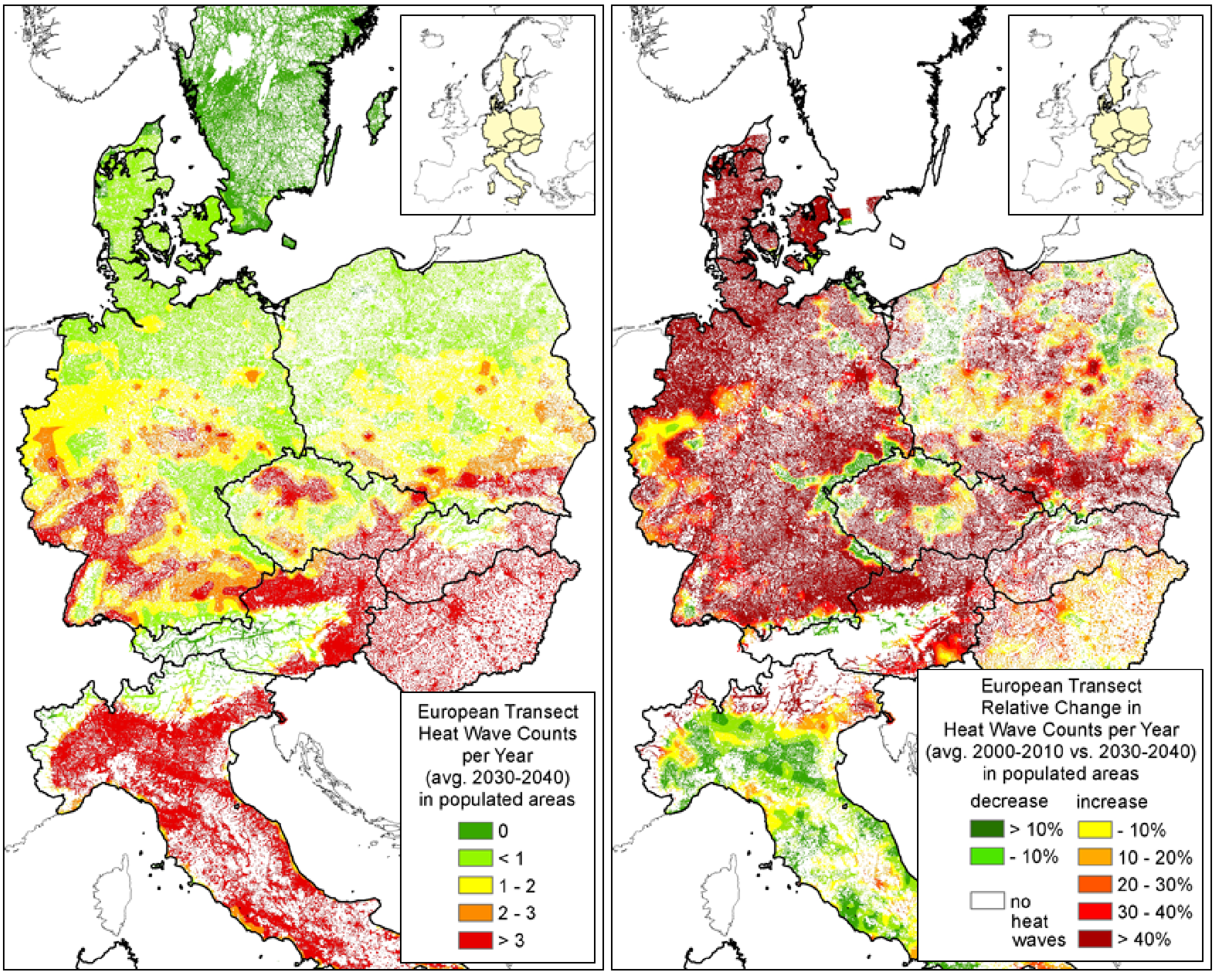


Figure 56: North-South European transect showing 1) the predicted average annual number of heat waves for the period 2030-2040 (left) and 2) the relative change in heat wave frequency comparing 2030-2040 to 2000-2010 (right), both calculated only for populated 1 km grid cells (to decrease computation time).

4.1.2 Local-scale heat stress assessment integrating frequency and duration in an annual index[18]

During July 2010 the eastern parts of the United States were affected by a sustained heat wave. The event set many new high temperature records from New England to North Carolina exceeding 100°F (37.8°C) for large sections of the region (Grumm and Lipton, 2011). The heat that the Mid-Atlantic experienced was the result of a 'Bermuda high', a high

[18] Parts of this section refer to Aubrecht and Özceylan (2013) and Özceylan and Aubrecht (2013)

pressure zone between Bermuda and North Carolina, pushing hot and humid air into the region. With the extreme heat and humidity combining for a possible heat index of over 110 degrees, the National Weather Service and various other authorities issued excessive heat alerts for the metropolitan areas of Washington and Baltimore (Shipkowsky, 2010).

Taking this as the main motivation for a local-level analysis, the study area encompasses Washington D.C. and the surrounding metropolitan area consisting of parts of the U.S. states of Maryland, Virginia, and West Virginia. That area is commonly named the Washington Metropolitan Area, sometimes also referred to as the National Capital Region (NCR). According to the 2010 census, its 22 counties have a total population of about 5.5 million, which ranks it among the 10 largest metropolitan areas of the USA. Of these top 10 the NCR is the third-fastest growing area at an estimated annual population growth rate of 2.2% while also containing considerable heterogeneity in terms of its population composition which makes it particularly interesting for vulnerability considerations. Being a typical metropolitan area with a densely developed core and some satellite cities in the vicinity (see development patterns in figure 57), it is ranked as the highest-educated metropolitan area in the USA and recently also topped the list as the highest-average-income metropolitan area.

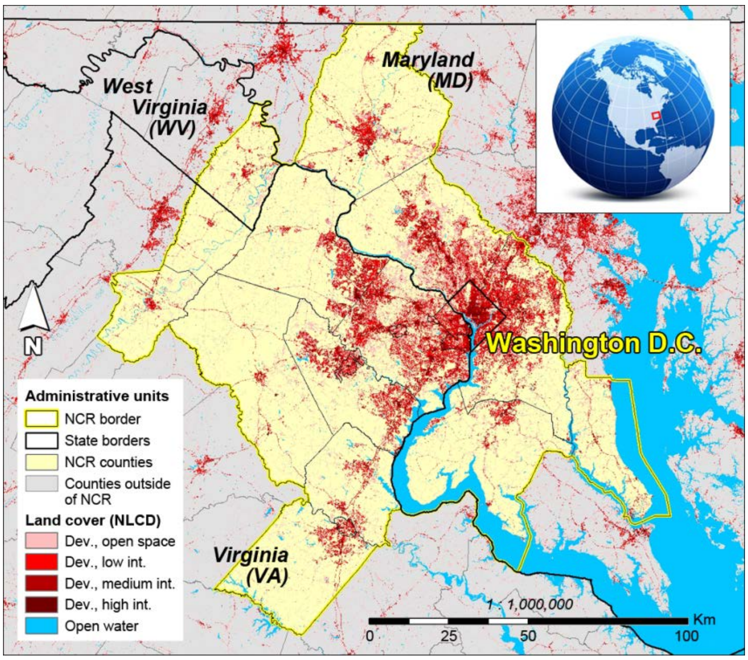


Figure 57: Study area Washington Metropolitan Area – U.S. National Capital Region (NCR).

The specific heat wave definition applied for this particular study is chosen because of the study's fine analysis scale and corresponding data availability. GHCN (Global Historical Climatology Network)-Daily climate station observational data are provided and hosted by the National Atmospheric and Oceanic Administration's (NOAA) National Climatic Data Center (NCDC) via their Climate Data Online Portal. GHCN-Daily is a composite of climate records from numerous sources that has been subjected to extensive quality assurance reviews. Observed meteorological parameters include but are not limited to daily minimum and maximum temperature, total daily precipitation, and wind speed. The dataset was developed for a wide variety of potential applications that require data at a daily time resolution, including climate analysis and monitoring studies. To this end assessment of changes in heat wave frequency and duration has been explicitly mentioned in that context (Della Marta et al., 2007; Menne et al., 2012).

A set of weather stations was downloaded and selected based on their location within a bounding box around the NCR to avoid interpolation errors at the study area boundaries. In order to achieve the high final spatial resolution and level of detail (census block level) for the study, the selected network of stations needs to be dense enough to allow reasonable interpolation and high grid size. Thus, not only the professionally maintained first-order synoptic weather stations (primarily through the National Weather Service (NWS) or Federal Aviation Administration) are included, but in addition also voluntarily manned cooperative weather stations that are part of the U.S. Cooperative Observing Network. This secondary network consists of several thousand temperature and/or precipitation stations, though unfortunately some first-order station parameters (such as humidity) are not recorded. First-order sites are primarily located at airports and use ASOS (Automated Surface Observing System) instrumentation, introduced by the NWS during the 1990s. The combination of first-order and cooperative observer weather stations for heat wave assessment has proved feasible in a recent study for California and Nevada (Gershunov et al., 2009).

Due to the limited parameters collected at some of the stations, for example at most locations no data records on humidity are available, it is chosen to follow a similar *univariate temperature-based heat wave definition* as illustrated before on European level and already applied in various previous studies (e.g., Kyselý et al., 2000; Huynen et al., 2001; Kyselý, 2004). A heat wave is thus again defined as a consecutive period of at least three days during which the daily T_{max} is higher than or equal to 30°C. Although it is acknowledged that such an absolute threshold might be considered rather low for the NCR study area, it is used bearing in mind that the final index particularly shows and considers the 'relative' heat distribution in the study area (i.e., in a 0-1 range). Adapting the definition of the absolute threshold (e.g. increasing) would obviously decrease the number of detected heat wave days throughout. The relative distribution, i.e. North-South spatial pattern, would however not change much. Considering the short one-year timespan of the analysis, using the lower 30°C threshold also guarantees that the data set is sufficiently large for proper analysis.

Based on the daily maximum temperature data available in the GHCN-Daily records *daily temperature distribution grids* are created using spatial interpolation techniques in a GIS environment. About 140 climate/weather station observations are integrated for each individual grid. Various methods and techniques exist for spatial interpolation of irregular point-based data and have been applied for creation of temperature grids, including inverse-distance weighting, 2-dimensional splines, trend-surface regression, kriging, and artificial neural networks (Myers, 1994; Sluiter, 2009). These methods all usually work well over relatively flat, homogeneous terrain. Using additional elevation information can help improve accuracy, especially considering the strong relationship between temperature and elevation in mountainous terrains (Dodson and Marks, 1997). In the summer, however, the direct spatial correlation between surface temperature and elevation decreases due to the additional heating caused by the increased positive radiation balance (Ishida and Kawashima, 1993).

Due to the characteristics of the study area which has limited elevation differences and the fact that heat waves mostly occur during the summer months, it was decided to use universal kriging as the spatial interpolation technique. This also significantly reduces computation time compared to techniques such as co-kriging that integrate additional parameters. Kriging is arguably the best method that does not use additional elevation information (Collins Jr., 1996) or other ancillary data (Yang et al., 2004). Considering the unknown calibration accuracy and measurement precision of the mostly voluntarily manned cooperative weather stations, minor improvements in the spatial interpolation model might not particularly improve interpolation output accuracy. In addition, daily T_{min} and T_{max} measurements tend to be far noisier than monthly or annually averaged temperature data, which further increases interpolation difficulties (Dodson and Marks, 1997). Universal kriging, a common method in meteorology (Haylock et al., 2008; Ishida and Kawashima, 1993), compared to ordinary and simple kriging, takes into account the effect of a trend/external drift (more details are provided by Tveito et al., 2007); in the presented study linear drift is applied. Eight of the nearest input sample points are used to perform the interpolation with the output resolution of the resulting temperature grids defined at 0.005 degrees (~0.5 km).

ESRI ArcGIS model builder is used to automate the process, starting with spatial interpolation based on the point-based daily temperature data, and also including heat wave parameter selection and final calculation of the annual summed number of heat wave days (see figure 58 for a conceptual illustration). With respect to the duration of single individual heat wave events Frich et al. (2002) introduced a "Heat Wave Duration Index" illustrating the maximum period of consecutive days (> 5) with a T_{max} exceeding the long-term daily T_{max} average by more than 5°C. Also "heat wave frequency (HWF)" has been used as a parameter in previous studies, i.e. the total number of continuous days during which the daily maximum temperature is higher than a certain threshold (Wu et al., 2012). Epidemiological studies reveal that increased intensity and duration of heat waves result in increased mortality risk (Anderson and Bell, 2009) and overall public health impacts (Bernard and McGeehin, 2004).

Following on these lines, the applied measure of an *annual heat wave days count* is a novel approach of *integrating heat stress duration and frequency over time* in the assessment, two factors considered essential when it comes to assessing heat stress impacts and severity affecting a region. This is opposed to the study of single extreme events (e.g., Stone et al., 2010; Conti et al., 2005) and the analysis of mere absolute numbers of heat waves that are independent of the length of the respective events as presented before for Europe.

For the final *heat stress index (HSI)* calculated at the census block level, the heat wave day count grid values are assigned to the centroid of each block polygon. This then guarantees consistent integration with the subsequent vulnerability index. The heat stress values are finally normalized by maximum and minimum records ([value] – [min] / [max] – [min]), in order to have an index domain ranging from 0 to 1 {HSI(x) : x ∈ (0-1)}. This way of normalization can be likened to the Human Development Index (HDI) and related indicators (Klugman, 2011). Figure 58 illustrates the model on conceptual basis, i.e. starting with the point based input data and eventually resulting in HSI values on census block level.

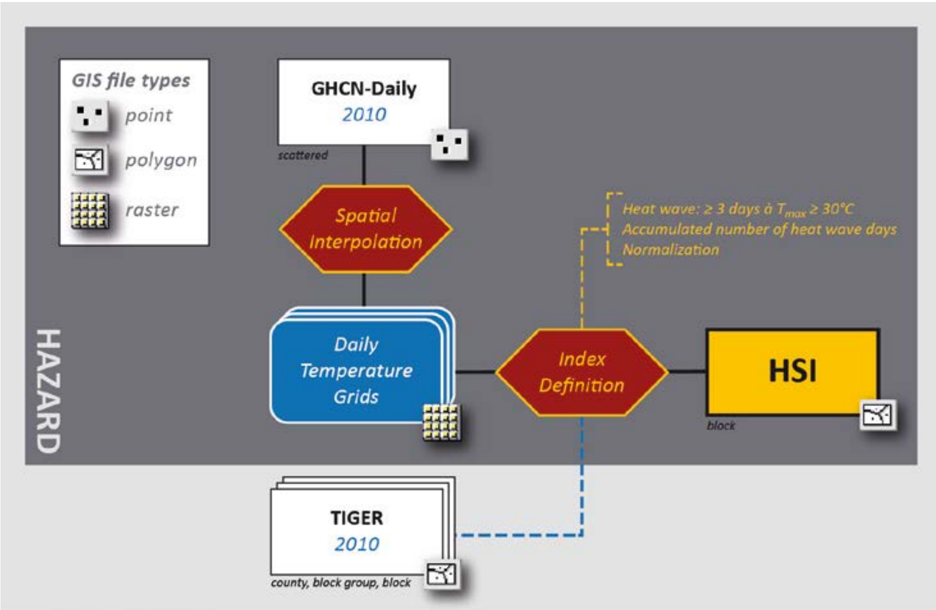


Figure 58: Conceptual illustration of the Heat Stress Index (HSI) development.

HSI values were calculated for all census blocks in the NCR. Before getting to that spatial level subsequently required for consistent integration with the results of the heat stress vulnerability index (HSVI) model, the annually aggregated number of heat wave days for 2010 is available as a 0.5 km resolution grid (see figure 59). A general distribution pattern is immediately evident; a basic north-south trend with considerably less accumulated heat wave days in the northern and north-western part of the study area and peak values in the southern most section. It is also worth noting that with regard to the analyzed extended periods of high daily T_{max} an expected heat island effect with anomalously elevated temperatures in dense urban areas as a result of increased thermal storage capacity (Oke, 1973) does not seem to be apparent in the most developed core urban area centered on Washington D.C. However, to assess that effect in more detail, also daily T_{min} would have to be included in the assessment, in order to analyze the impact of reduced nighttime cooling during 'tropical nights' (Dankers and Hiederer, 2008).

As there are no comparable results and metrics for other cities or metropolitan areas available, the magnitude of the aggregated number of heat wave days is analyzed in a relative rather than an absolute manner for the study area. Therefore green colors in figure 59 do not necessarily mean that these regions experience low heat stress. It merely illustrates relatively lower values compared to other parts of the NCR. In any case, it is interesting that 97% of the study area suffered at least 50 or more heat wave days accumulated over the year in 2010. The maximum length of individual heat wave events that any part of the NCR experienced in that period ranges from 11 to 28 days.

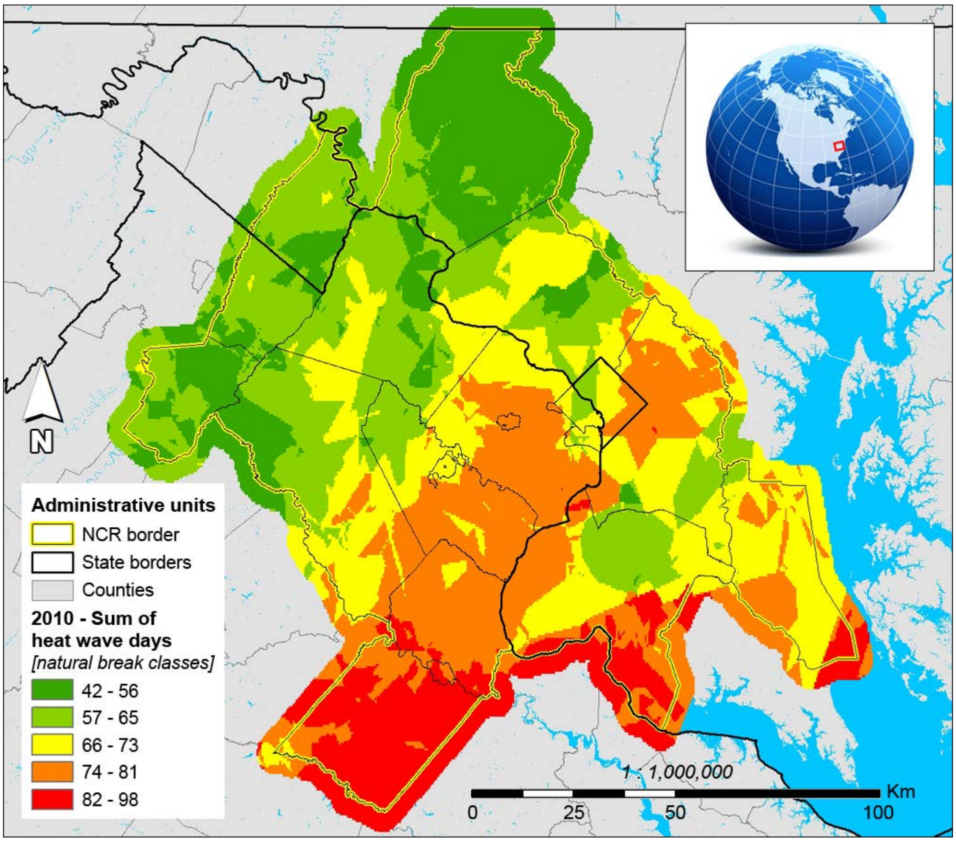


Figure 59: Aggregated number of heat wave days in the NCR during the year 2010.

For assessing heat stress, *alternative approaches* include using temperature information derived from satellite data or climate data assimilation models. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) onboard of NASA's Terra satellite currently provides the highest-available spatial resolution for satellite-based thermal data (90 m) and has been used successfully to measure heat exposure (Uejio et al., 2011). However, its revisit time of 16 days is a major limitation for studying rapidly changing surface conditions including heat waves and related daily temperature distribution patterns. NASA provides parameters such as daily and hourly air temperatures and heat index derived in the framework of the North America Land Data Assimilation System (NLDAS). Due to the rather coarse spatial resolution (0.125 degree grid size) these data were considered insufficient for the current study. For studies operating on a less detailed spatial level, e.g. counties, it might however be an interesting alternative or even *calibration* source. The high temporal resolution also enables exact nighttime vs. daytime heat exposure time series analysis (Rui et al., 2012). In particular the first-mentioned source (ASTER) could also be applied for *validation* purposes, i.e. comparing the temporally sparse local level control sample patterns to the point based interpolation results. If high spatial resolution was not considered of such high importance, then the selection of the NOAA ground station network could be limited to the first-order sites, which would allow integration of additional recorded parameters in the assessment, such as humidity. This would subsequently offer the chance to apply '*apparent temperatures*' (Steadman, 1984) as a heat stress indicator instead of absolute temperature values, as has been demonstrated in previous studies at relatively coarse scales (e.g., Gaffen and Ross, 1998; Davis et al., 2003; Stone et al., 2010). Even with the same approach presented in this study, absolute temperature thresholds could be adjusted to be in line with other studies that suggest a common heat wave definition for the United States as "*three consecutive days with temperatures above 90°F (32.2°C)*" (e.g., Tamrazian et al., 2008).

In addition to alternative data sources and term definitions, other interpolation techniques could be applied to create the daily temperature grids. Co-kriging could be used to account for additional parameters relevant for temperature distribution patterns such as elevation differences. However, as outlined above, due to the study characteristics this basic methodological improvement might not necessarily result in improved results.

4.2 Heat stress vulnerability and subsequent risk evaluation

Screening global change literature overall associated vulnerability is described as "*the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt*" (Adger, 2006). In a climate change context it is therefore very important to recognize the *(spatio-temporal) variability in exposed vulnerable populations* and consider that in pro-active adaptation plans as particularly human health related impacts correlate strongly with population clusters in general and with the distribution characteristics of certain especially vulnerable groups specifically. *Disparities in the socio-economic structure of a society* shape social vulnerability and resilience of local communities and result in uneven impact of a potential catastrophic event or varying capacity to adapt to changing environmental conditions (Finch et al., 2010).

The adverse effects of hot weather on human beings are of increasing public health concern particularly for urban areas (Bassil and Cole, 2010). Extended periods of extreme conditions can have dramatic impacts on human health. Extreme or 'excessive' heat events are the leading cause of weather- related mortality in the United States (U.S. EPA, 2006; Grundstein and Dowd, 2011). In 2010, 138 people died as a result of extreme heat, a significant increase from 45 fatalities the year before. This number is well above the 10-year average of 115 annual heat related fatalities (NOAA National Weather Service, 2011). However, the precise distribution of mortality associated with heat stress remains unknown, and is likely to vary as a function of severity and duration of elevated temperature as well as other factors (Kinney et al., 2008) whereby *context-specific vulnerability* plays a key role. Temperature extremes do generally affect all classes of population, but studies show that heat mortality risk varies with several social factors including age and others (Kovats and Hajat, 2008). However, if heat exposure is severe enough, even healthy people are seriously susceptible to heat stroke. Ancillary factors such as access to warning information and cooling are considered of utmost importance then in a vulnerability context. The assessment of vulnerability hot spots is essential for preparation and eventual best-possible impact mitigation.

Referring to the above-described climate- and weather-related extreme events or conditions – in particular in terms of excessive heat – it is necessary to once again highlight the *varying conceptual understandings between the climate change (CC) and natural hazards (NH) research communities*. The gap between CC and NH communities prevails in many aspects and when specifically referring to the rather vague concept of vulnerability some researchers even proclaim its running the "*danger of losing its analytical value*" (Cannon, 2008) due to conflicting interests and interpretations. As elaborated in detail earlier on in the IDRiM terminology section (chapter 2) there is still no universally accepted definition of vulnerability despite extensive research efforts in recent years (Birkmann et al., 2013).

While basically this thesis follows the (inherently consistent) conceptual perceptions of the natural hazards and disaster risk research community (in this regard being largely in line with UNISDR) in particular when referring to exposure in its analytical sense (chapter 3), the implementation of population related vulnerability in a heat stress context and especially on different temporal scales (long-term variability vs. short-term effects) requires understanding and consideration of both approaches.

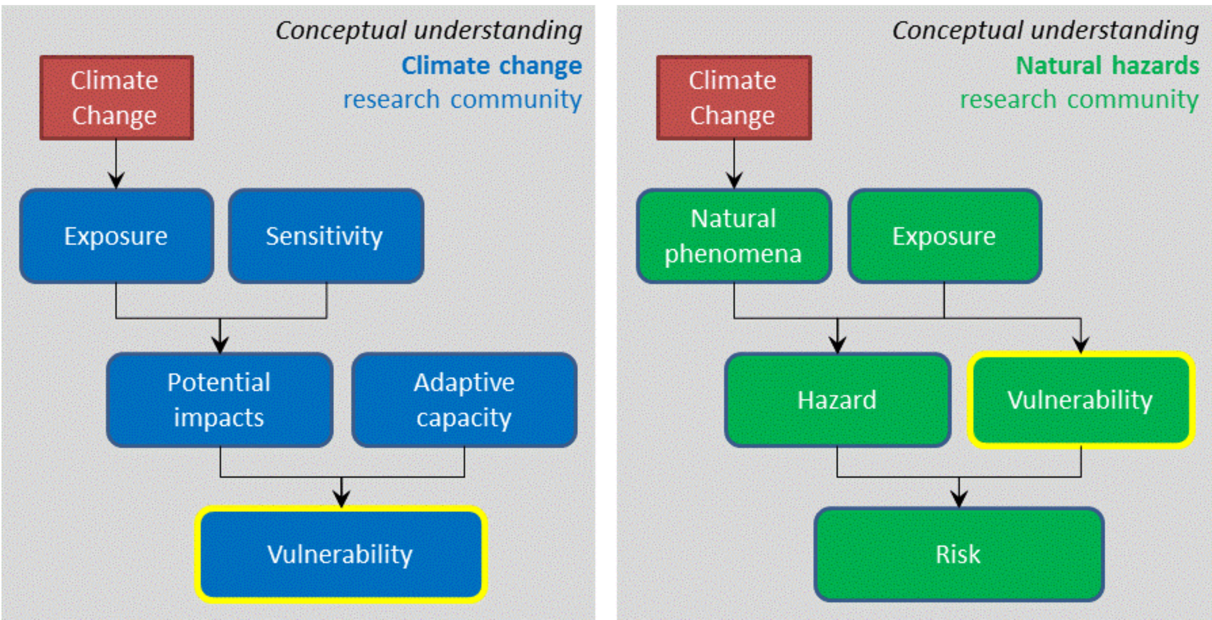


Figure 60: Varying perception of vulnerability in the conceptual understandings of the climate change and natural hazards research communities.

As illustrated in figure 60, the CC community (following IPCC) commonly sees vulnerability as "*a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity*" (IPCC, 2001). Sensitivity, in this framework, is the degree to which a system is affected in either direction, i.e. either adversely or beneficially, by climate variability or change. This inclusion of actual positive potential of change is a distinct difference to the concepts used in the NH literature. Anyway, Brooks (2003) in that regard in fact highlights that even within the CC research community strong conceptual inconsistencies exist which he tries to 'solve' by distinguishing *externally shaped vulnerability* (biophysical) and *inherent vulnerability* (social). He also acknowledges that this biophysical vulnerability (as shown in fig. 60 on the left) has actually much in common with the concept of risk as elaborated on in the NH research literature (as shown in fig. 60 on the right). In the following two sub-chapters both approaches are covered – in the longer-term climate change driven perspective vulnerability is dealt with in its externally shaped perspective, while in the immediate rather short-term heat stress hazard perspective inherent vulnerability characteristics are analyzed that eventually lead to risk identification.

4.2.1 Coarse-scale approach to model long-term variation in heat stress implications[19]

In this first study on coarse-scale European-level population distribution models for both current conditions and future prospects (compare chapter 3.1.4) are integrated with regional climate simulation results (chapter 4.1.1) to *assess future patterns of vulnerability* associated with or rather driven by climate change. Vulnerability is hereby understood as an externally shaped concept, i.e. strongly depending on the actual development of the natural environment and its potential implications on an exposed social system. Integrated analysis of the population information that includes relevant structural characteristics in addition to mere distribution patterns and the climate prospects data enables *identification of vulnerability hot spots*, thus highlighting regions of high general and specific (age) population densities spatially correlating with particularly demanding projected climatic patterns.

[19] Parts of this section refer to Aubrecht et al. (2011e, 2013f)

Exposure to extreme weather (both hot and cold) has been associated with increased morbidity and mortality. Extreme meteorological conditions like heat waves and associated effects such as increased air pollution (in particular elevated concentrations of ozone and PM10) are regarded as especially strenuous for *elderly and physically weak persons* while additional gender-stratified analysis showed insignificant results overall (Kyselý and Huth, 2004; Gosling et al., 2008; Vaneckova et al., 2008; Sheridan and Kalkstein, 2010), i.e. some study cases showing women to be more vulnerable while others reporting elevated male mortality.

For the presented study, results of the calculated climate variables (heat stress) are spatially overlaid on modeled future population distribution patterns and jointly analyzed considering relevant structural population characteristics (i.e., parameter age). In order to come up with a specific measure of vulnerability patterns, a *vulnerability index* is created and applied to the spatial domain. Figure 61 shows the vulnerability classification approach using a correlation matrix of two selected variables, 1) the average annual number of heat waves, and 2) the density of elderly people (60+ years of age). Both input parameters are re-sampled to 5 categories which are then integrated to 4 distinct classes of vulnerability: low (LV), medium (MV), high (HV), and very high (VHV). In case an area does not feature any (predicted) heat waves the vulnerability index is set to zero (-). The classification scheme is applied to both the present state and future conditions, thus enabling an illustration of vulnerability trends on European scale driven by changing climatic characteristics.

Vulnerability Index		*Average annual number of heat waves*				
		0	< 1	1 - < 2	2 - 3	> 3
Elderly pop. (60+ y.)	1 - < 100	-	LV	LV	MV	HV
	100 - < 500	-	LV	MV	MV	HV
	500 - < 1000	-	LV	MV	HV	VHV
	1000 - 2000	-	MV	MV	HV	VHV
	> 2000	-	MV	MV	VHV	VHV

Figure 61: Heat-related vulnerability classification matrix featuring 5 classes of vulnerability.

Regarding the future *distribution of elderly people*, which are considered one group of the total population particularly vulnerable to extreme climatic conditions, predicted structural population developments from the earlier-described 'EUROPOP2008 - Convergence scenario, regional level' (Eurostat, 2010) were applied in the disaggregation process. Those population prospects model the most likely future demographic structure based on statistical trends and economic developments. Figure 62 illustrates the distribution patterns of an increasing number of aged people (60+ years of age) in the future. The left part shows the current (2006) situation for a sample region in Austria, compared to the predicted future (2030) patterns on the right. The clustered spreading of population older than 60 years is particularly manifest in the highlighted three largest cities of Austria (Vienna, Graz, and Linz). According to the Eurostat scenario of 2030 the relative share of elderly people in the total population will be increasing in all EU member states, Norway and Switzerland (Giannakouris, 2008), but most vigorously in countries like the Slovak Republic and Poland, as well as in some parts of Germany. In the North-South European transect analyzed, only one small region located in the Northern part of Germany (around the city of Hamburg) is likely to experience a relative decrease in the proportion of aged people. In terms of validation Eurostat and UN apply adaptations to the prospects on a rather sporadic basis but only time will really show after all how accurate those current prospects match with reality.

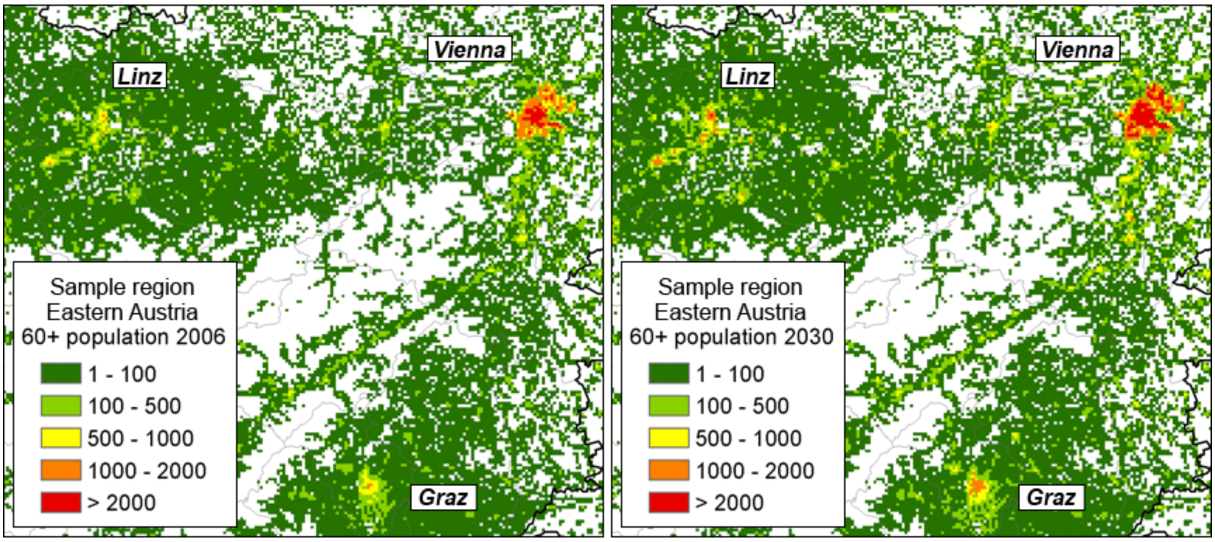


Figure 62: Sample region in Eastern Austria showing 1) the distribution of 60+ population for 2006 (left) and 2) the distribution of 60+ population for 2030 (right), both on a 1 km population grid.

Applying the newly developed vulnerability index classification scheme using the modeled results of population distribution and heat stress related climate conditions enables a first consistent spatial assessment of future vulnerability patterns on European scale. Figure 63 shows the climate change induced changing patterns of (heat stress related) vulnerability considering elderly people the main focus due to their specifically high sensitivity to extreme meteorological conditions and associated effects. The left part of the figure illustrates the present state (2006) which is compared to the modeled future prospects (2030) on the right. It is evident that the areas of medium to high vulnerability are spreading towards the North (e.g., North-Austria, South-Germany). Regions of very high vulnerability are primarily found in major metropolitan areas, mostly driven by the increasing density of elderly population.

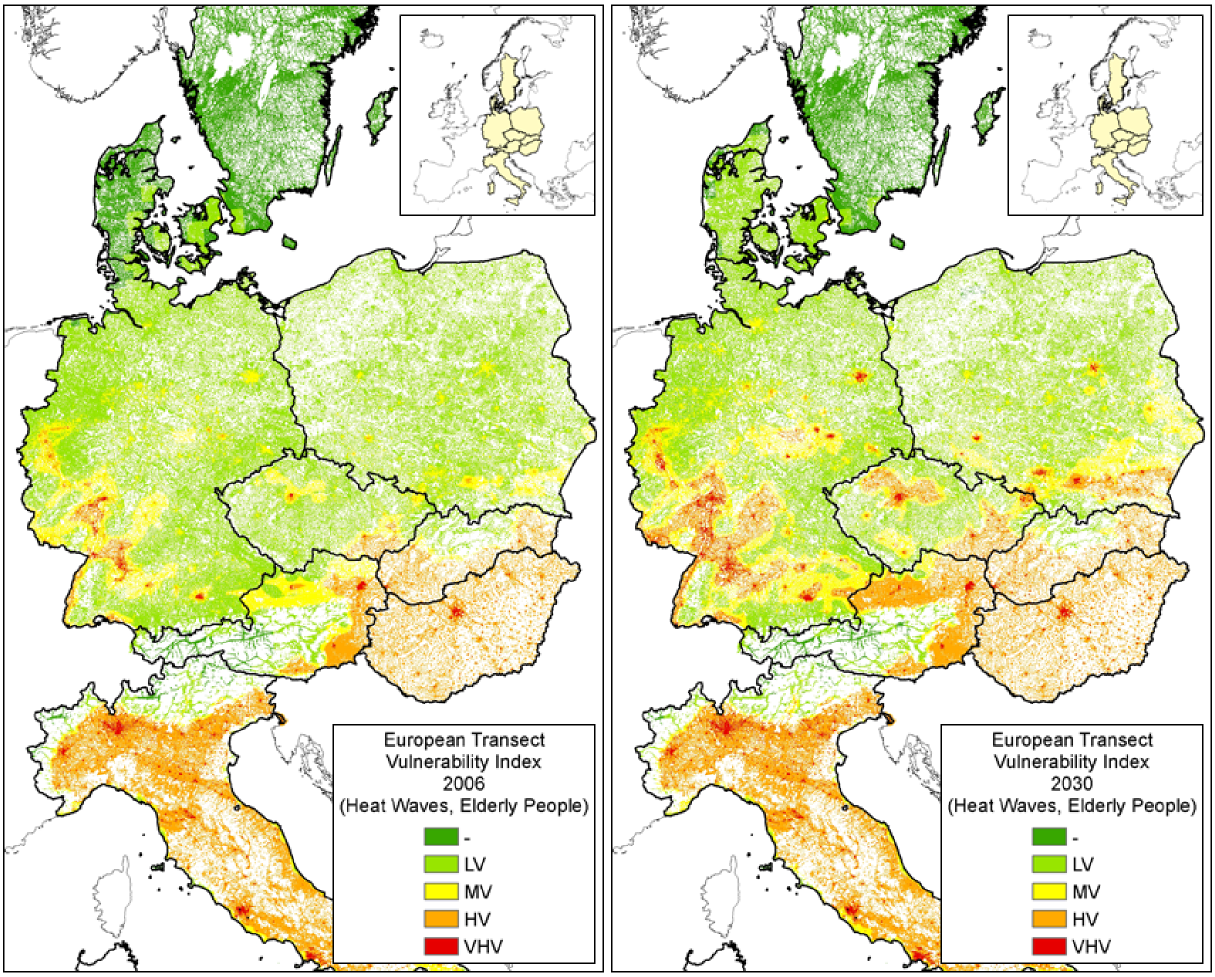


Figure 63: North-South European transect showing vulnerability index results for 1) the present state in 2006 (left) and 2) the predicted future state in 2030 (right), both on a 1 km population grid.

Climate change entails an increase in problematic conditions for human health. It is thus considered a potential threat for all population classes with elderly people highlighted as being particularly susceptible to extreme climatic conditions. Kovats and Lloyd (2010) explain that in the near term, many of the mechanisms affecting human health are known, although the magnitude of impacts and effectiveness of prevention are highly uncertain. Involving ecological shifts or emerging infections many changes are likely to occur that are not anticipated at present. Consideration of higher emission scenarios further increases *uncertainty* which involves unknown implications to social systems.

A recent editorial of the journal Global Environmental Change (Kovats, 2012) discusses the wide ranging and potentially serious implications of global environmental changes for human population health and in that context highlights "*the need for a new generation of impact models that take into account feedbacks and the dynamic nature of interactions between environmental factors and human populations*". It is pointed out that "*evidence for current or future impacts on population health need to address policy relevant objectives, such as the magnitude and distribution of future impacts*". Following that path in assessing potential climate change induced future impacts on population can therefore only be successful by integrating both physical and social parameters into impact scenario analyses which shows exactly the focus of the presented study.

In the context of climate impact mitigation as well as for the assessment and management of future risks and emergency situations, consistent spatial analyses (on a continental scale) are of utmost importance for decision making processes as well as for risk communication and future safety and security considerations (Aubrecht et al., 2009a). The combination of changing demographic and climatic patterns introduces increased stress on local social networks that have long been critical to climate adaptation (McLeman, 2010). Several studies have also linked increased temperatures to increases in the rates of violent crimes and other aggressive behavior (Anderson, 1989; Anderson and Anderson, 1998; Rotton and Cohn, 2000). Climate change vulnerability hot spots can thus undoubtedly be considered potential conflict areas. Community preparedness and strengthening coping capacity is essential for mitigating risks in that regard.

The concept of vulnerability has various dimensions applicable in the context of climate change research (Füssel, 2007) as illustrated in detail earlier on. The presented approach of assessing and classifying vulnerability makes no claim to be complete. Certain selected parameters have been modeled and integrated in order to come up with prospects of future patterns. With 'increased heat stress' a parameter was applied for the analysis that is considered among the most certain impacts of climate change induced future environmental conditions and is associated with severe implications on human beings such as excess human mortality and illness (Smoyer-Tomic et al., 2003). The model presented pictures *one possible scenario of the future*. Some of the used input data sets such as the Eurostat population prospects imply a range of *uncertainty* that has not specifically been accounted for in this study. Especially migration scenarios are strongly policy-dependent and might for example as well have an important impact on the future of Europe's overall age structure. Estimations of ageing trends in general involve several varying approaches with some kind of acceleration considered highly likely, but particularly the exact timing being uncertain. Further uncertainties are introduced by assumptions made in the regional climate modeling process. As stated above, the consideration of higher emission scenarios would for example involve further unknown implications to social systems.

In the following subchapter a much more sophisticated parameter and indicator set will be included in terms of heat stress vulnerability, applied to the local level. That would obviously also be very interesting on broad-scale spatial level as just presented. However, spatial disaggregation of socio-structural parameters is a challenging or mostly in fact unfeasible task, with the definition of target zones and therefore identification of weighting factors being highly uncertain. Under these given circumstances, the study presented in the following 'operates' on the highest resolution available in terms of spatial base data for population statistics (census block), illustrated by means of a large metropolitan area (U.S. National Capital Region). Spatially homogeneous depictions (gridded approach) are therefore not considered and heterogeneity in terms of the administrative polygons is accepted, but in turn the highest possible set of relevant thematic information can be integrated. Eventually that refers back to the need for *context-dependent analysis* when it comes to vulnerability identification.

4.2.2 Local-scale approach to assess societal root causes of heat stress risk in a temporally integrative way[20]

Establishing *who is most at risk* for heat-related mortality or morbidity and how to reduce heat stress exposure in general is a complex issue involving a combination of location-dependent physiological variables as well as other social and environmental factors (Harlan et al., 2006; Kovats and Hajat, 2008). Statistics for 2010 (NOAA-NWS, 2011) indicate that elderly adults and seniors aged above 60 are most strongly affected by extreme heat, a situation of concern given society's aging trend (Luber and McGeehin, 2008). According to the U.S. Census Bureau's Population Projections (U.S. Census Bureau, 2012a) the U.S. population aged 65 or older is expected to double in size (from currently around 40 million to more than 80 million) within the next 30 years. Much of the elderly cohort's excess mortality from heat waves is related to cardiovascular, cerebrovascular, and respiratory causes (Haines et al., 2006). The elderly are not the only ones at risk though as people suffering from diabetes, neurological disorders, and psychiatric illnesses are also vulnerable (Schwartz, 2005) as are the environmentally disadvantaged and the economically and socially marginalized.

In this study it is aimed to explore the interaction between heat stress hazard and heat related vulnerability and how risk patterns are distributed within communities on a local level. As already becomes clear in the terminology used, this study applies the risk-driven conceptual understanding of the NH research community where *vulnerability is treated as inherent characteristics of a social system*, as opposed to the CC community driven perspective of externally shaped vulnerability that was followed in the previous subchapter. Reason for that is not only the overall focus of this thesis on the disaster risk focused view, but most of all the varying set up of the two presented heat stress related studies. While the former one focused in particular on future prospects in many aspects (therefore being associated with the climate change domain), the current study deals with *heat stress as an immediate hazardous factor* that can lead to impacts in the short-term time scale.

[20] Parts of this section refer to Aubrecht and Özceylan (2013) and Özceylan and Aubrecht (2013)

Heat stress and related impacts vary across time periods, regions, and populations. The underlying reasons for these differences remain only partially understood, which introduces uncertainty regarding how to extrapolate from one location or time to another, especially given different population demographics and health status, climate conditions, etc. (Kinney et al., 2008). Few studies have examined *heat vulnerability on a sub-metropolitan area level* (Sheridan and Dolney, 2003) with the scale of analysis generally remaining at rather coarse level and much less attention being given to differential vulnerabilities and coping capacities at the fine scale (Obrist, 2003). Because not all populations are at equal risk from heat stress, knowing in more detail where vulnerable populations are located can help in targeting resources more effectively (Reid et al., 2009). This study offers a *framework for local-level heat stress risk assessment* and highlights the individual risk components as an attempt to be able to provide input and decision support for successful implementation of preventive measures as well as response action plans as outlined by the U.S. EPA (2006).

With the study area being the above-described U.S. National Capital region (motivated by the sustained heat waves in the Eastern USA during summer 2010) census block level GIS data is used as basic spatial reference units for the analysis. The U.S. Census Bureau offers extensive geospatial data sets in that context, i.e. the TIGER (Topologically Integrated Geographic Encoding and Referencing) Line Shapefiles including administrative boundaries. The 22 counties of the NCR comprise approximately 3,500 census block groups and at the highest level of detail about 92,000 census blocks of which around 53,500 (58 %) are populated according to the 2010 census. Input in terms of data on population patterns and characteristics come from both the *U.S. Census* 2010 and the *American Community Survey* (ACS). The decennial census was most recently conducted in 2010 and resulting data illustrate residential counts on block level for all of the United States. Collected parameters include e.g. sex, age, race, and household type (U.S. Census Bureau, 2012b). Certain relevant parameters (e.g., language usage, poverty, educational attainment) were previously recorded in the 'long-form' census files until Census 2000. These variables are now integrated in the annual American Community Survey. Launched in 2005, ACS data are collected continuously throughout the year and throughout the decade from a relatively small sample of the population (an annual average of slightly in excess of 1% of the housing units). Since the ACS is conducted every year, it provides more current data throughout the decade. ACS data are provided in three different forms: (1) 1-year estimates, (2) 3-year estimates, and (3) 5-year estimates. The more years that are included in the statistical averaging, the larger the sample size becomes, which improves reliability at the expense of currency (U.S. Census Bureau, 2008). Due to the high level of spatial detail of the presented study, i.e. analysis of very small populations, the 2006-10 '5-year estimates' is used (having an accumulated sample size of close to 7% for the study area), as these are the only data sets released at the census block group level. Information on land cover patterns is derived from the U.S. Geological Survey (USGS) National Land Cover Database 2006 (NLCD2006), which results from a 16-class classification scheme that has been applied consistently across the conterminous United States at a spatial resolution of 30 meters. NLCD2006 is primarily based on unsupervised classification of Landsat ETM+ (Enhanced Thematic Mapper) circa 2006 satellite data (Fry et al., 2011).

Vulnerability is mainly a characteristic of the exposed element or society and its ability to cope with and respond to a hazard or stressor (Birkmann, 2006a). To classify a population in order to understand not only who may be more or less vulnerable, but also in what ways they are vulnerable (Eakin and Bojórquez-Tapia, 2008) it is helpful to use a set of *indicators* for the assessment. Indicators are a means of encapsulating a complex reality in a single measurable construct (Vincent, 2004) and can offer a systematic approach to discuss and quantitatively *evaluate different root causes of risk* and to provide recommendations how to strengthen capacities for disaster risk and vulnerability reduction before an event occurs (Birkmann, 2007). In recent years, an increasing number of researchers have been working on aggregating multiple indicators to create composite indices for vulnerability and risk assessments (Cutter et al., 2003; Vincent, 2004; Peduzzi, 2006; Özceylan and Coşkun, 2012). In order to determine heat related vulnerability, various population and land cover characteristics are selected for the study area and a *composite vulnerability index* is defined based on aggregation of the following groups of indicators: demographic status (indicator 1: ages 65 and older), socio-economic status (indicator 2: living alone; indicator 3: population below poverty level; indicator 4: poor English skills; indicator 5: educational attainment), and land cover influence on human well-being (indicator 6).

The census block is defined as the basic *spatial reference unit* for the index, being the highest level of detail for which data are provided through the most recent U.S. Census 2010. American Community Survey data in its 5-year-estimates form is only available at the census block group level. In order to consistently incorporate all the data for the indicators and index development, therefore an even parameter distribution within block groups is assumed for ACS-derived information, even though some error will result in terms of the actual spatial pattern within each enumeration unit. Other data sources for potential indicators (e.g., health-related) were not available for analysis at a fine enough scale for this study and so are not included in the high-level index. For future studies it might be interesting to step down on the spatial detail and in return rather aim at an even more comprehensive level of thematic detail.

Indicator 1 (I1): Age is an important factor for vulnerability as the elderly tend to be inherently more susceptible to heat exposure (McGeehin and Mirabelli, 2001; Harlan et al., 2006) and have higher mortality and hospital admission rates than the general population (Semenza et al., 1999). About 80% of older adults have at least one chronic condition that makes them more vulnerable than healthy people (Aldrich and Benson, 2008) during a heat wave. In addition to chronic health conditions, older adults may have impaired physical mobility or cognitive ability, diminished sensory awareness, and social and economic limitations and need extra assistance to evacuate, survive, and recover (Fernandez et al., 2002). For this study the *ratio of elderly people* (65 years of age and older) is derived from Census 2010 data. The higher the ratio, the greater the area vulnerability.

Indicator 2 (I2): Social isolation, particularly of elderly people (Tomassini et al., 2004), has been identified as another key factor during heat waves and excessive heat events in general (Naughton et al., 2002; U.S. EPA, 2006). Living alone possibly resulting in fewer contacts with family and friends is a significant indicator pointing to increased vulnerability and eventually mortality as was found during the 1995 Chicago heat wave (Semenza et al., 1996; Klinenberg, 2002). For this study household information from Census 2010 is used to identify *elderly householders that live alone*. Increasing numbers again stand for an increase in vulnerability.

Indicator 3 (I3): Economic factors inevitably play a key role in affecting an individual's vulnerability to heat stress (McGeehin and Mirabelli, 2001; Harlan et al., 2006). The poor are likely to be at the greatest risk (Poumadere et al., 2005), because of their lack of access to material and information resources (McMichael, 2003). Poor people often suffer from inadequate housing conditions and are less likely to be able to afford air-conditioning (Patz et al., 2000). Their livelihoods are therefore more vulnerable to heat stress and so are they. Poverty information is available in the ACS 5-year estimates data. The variable 'poverty status of individuals in the past 12 months' is used to calculate the *ratio of those living below the poverty level*. Within order to achieve a 0-1 indicator value range again, the poverty ratio values are normalized, where high values depict high vulnerability.

Indicator 4 (I4): Inadequate English language skills or *linguistic isolation* may hinder protective behaviors during extreme heat events by impeding the understanding of heat warnings (Uejio et al., 2011) and reduce awareness both of the potential dangers from heat exposure and of the ways to reduce related risk (McGeehin and Mirabelli, 2001). For this study, 'language spoken at home by the ability to speak English' is used as collected by the ACS. Records of speaking English 'not well' and 'not well at all' are aggregated for this indicator and the ratios are eventually normalized again. A high ratio of low English speaking skills means a high vulnerability.

Indicator 5 (I5): Low-educated members of a society are likely to be the most vulnerable to heat stress (Harlan et al., 2006) in terms of understanding the relationship between changes in their physical environment and heat exposure, as well as receiving and understanding warning information. Individuals whose education level did not exceed high school had higher heat-related death rates in recent studies of U.S. cities (O'Neill et al., 2003; Medina-Ramon et al., 2006). *Education* is also strongly related to other factors of socio-economic status. For the presented study the variable 'educational attainment for the population 25 years and over' is derived from the ACS and 'less than high school' is selected as the relevant threshold for the indicator. Values are normalized again with high indicator values illustrating a high level of vulnerability.

Indicator 6 (I6): Land cover characteristics are also important determinants of heat-related vulnerability, due to their contribution and general influence on human well-being. People living in cities are more vulnerable than those living in rural areas (Hajat et al., 2007), partly because of the urban heat island effect (Kinney et al., 2008). This special characteristic of urban areas is defined as the difference between temperatures in a city and the surrounding sub-urban and rural area (Kovats and Menne, 2003). It is created primarily by dense concentrations of heat-absorbing, impervious building materials that conserve more heat during the day and release it more slowly at night than natural ground cover, such as soil and vegetation (Voogt, 2002). On the other hand, *green areas* may reduce this effect and eventually contribute to a decrease of vulnerability. Such areas of positive influence are derived from the NLCD2006 data by aggregating all green area classes to calculate the green area ratio for each of our basic reference units. With this variable having a different direction (influence) on vulnerability, the inverse is used accordingly.

Once the set of indicators have been defined and selected and the data has been processed, their actual values are normalized to relative positions between 0 and 1. Furthermore, it is assumed that all the indicators are of equal importance and they are thus weighted equally. Values of all indicators are aggregated and again normalized to form a *composite heat stress vulnerability index (HSVI)* with a range between 0 and 1, with 1 representing the highest level of vulnerability to heat stress.

$$HSVI = \Sigma_{norm} (I1, I2, I3, I4, I5, I6); \{HSVI(x) : x \in (0\text{-}1)\}$$

This approach helps avoid additional subjectivity in the index development. Un-weighted quantitative aggregation (additive approach) and indicator standardization (to a 0-1 range) is a common approach (UNEP, 2002) and promoted in indicator composition (e.g., Briguglio, 1995; Crowards, 1999; Esty, 2001; Tapsell et al., 2002; Wu et al., 2002; Turvey, 2007). Alternative strategies include expert judgment (e.g., Özceylan and Coşkun, 2012) or multivariate statistical techniques such as principal component and factor or cluster analysis (e.g., Clark et al., 1998; Cutter et al., 2003). These approaches introduce subjectivity in addition to that of the selection of indicators.

Index development, indicator weighting and composition subjectivity has been discussed in detail in the literature (e.g., Vincent, 2004). In particular for heat-related vulnerability and risk involving many social aspects there is no clear or commonly accepted indicator set. For the presented study no emphasis is placed on any individual component in the calculation of the composite because the literature does not support any single variable's higher impact in a heat-context. In order to reduce the over-interpretation of single values and further account for uncertainties, resulting index values are presented in five classes (very low, low, medium, high, very high) based on the Jenks optimization method (statistical natural breaks analysis).

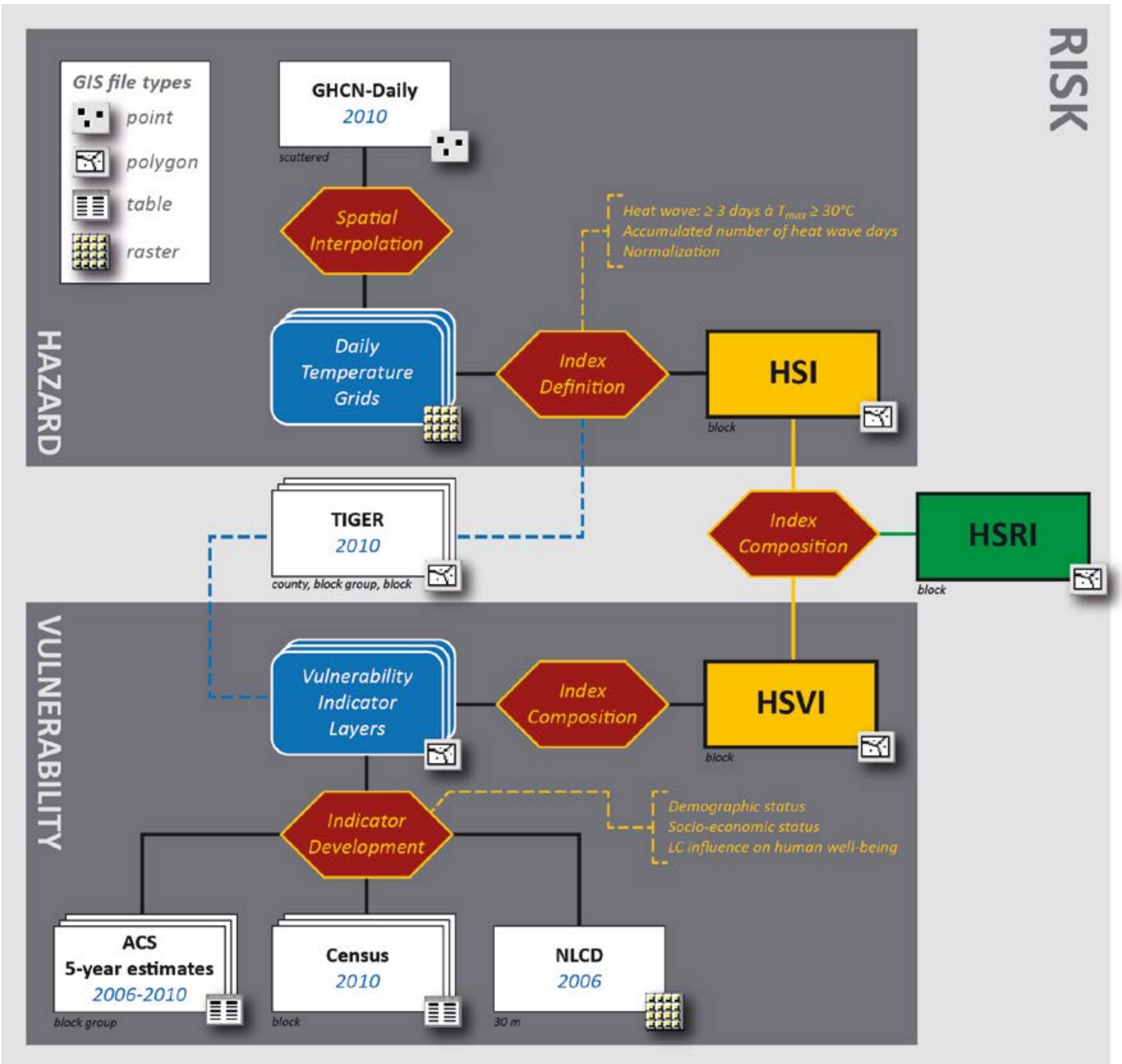


Figure 64: Conceptual illustration of the Heat Stress Risk Index (HSRI) development consisting of the phases of hazard (HSI) and vulnerability identification (HSVI).

Since risk is considered an aggregate measure of hazard and vulnerability, heat stress risk for this study is set as a function of the modeled heat stress and heat related vulnerability described above. Impacts of extreme heat events must be attributed to changes in these aspects. The multiplication of these two equally weighted risk components defines the score of the *heat stress risk index (HSRI)*. Modeling current patterns of heat related risk can improve our understanding of underlying causes of heat stress and inherent vulnerability interaction in creating adverse effects for human beings. Figure 64 illustrates the conceptual modeling framework as outlined above. It also again includes the phase of hazard identification that was described in detail earlier on (chapter 4.1.2) in order to clarify the relationship between heat stress hazard and heat stress vulnerability and how risk is eventually mapped by integrating these two aspects. Input data sources and their specific data types are shown (in white) and the processes are highlighted (red boxes) that lead to intermediate modeling results (in blue) and eventual risk index values (HSRI) integrated from pre-identified hazard (HSI) and vulnerability (HSVI) patterns. The *temporal basis* is specifically indicated with 2010 being the reference year for the analysis (i.e., both climate/weather data and census data were collected for that year as well as the associated administrative reference units). Worth noticing in that regard is the applied 5-year aggregated estimate of the ACS data which exclusively allows local-scale analysis.

Following the data preparation and processing for the six individual vulnerability indicators, the composite heat stress vulnerability index (HSVI) is derived by equally-weighted aggregation and subsequent normalization as outlined above. Results show the population's vulnerability to heat stress in the NCR. Only populated census blocks are considered for the 5 classification categories ranging from 'very low' to 'very high' (see figure 65). In general, large sections of the study region are assigned low and very low vulnerability index values, with 87% of the NCR's land area only accounting for 44% of the populated census blocks. The smaller-sized blocks in urbanized areas more likely tend to be characterized by high vulnerabilities. Figure 66 shows the District of Columbia as an example illustrating this issue. While only 4% of the NCR area is considered highly or very highly vulnerable, 64% of Washington D.C. is classified as such.

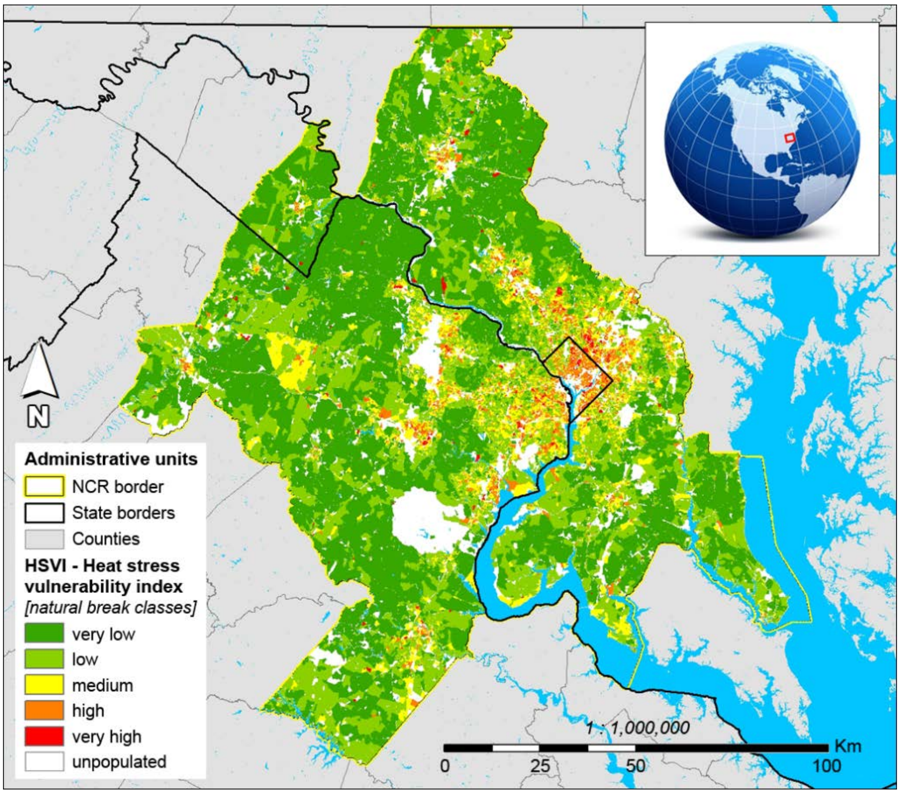


Figure 65: Heat stress vulnerability index (HSVI) for the NCR on census block level.

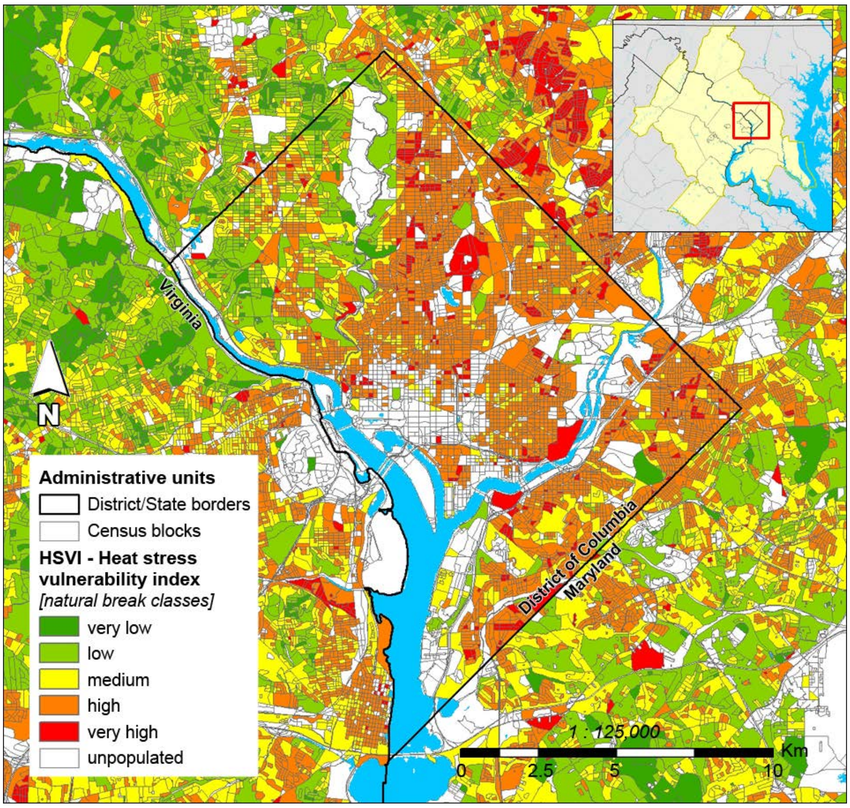


Figure 66: Heat stress vulnerability index (HSVI) for the District of Columbia on census block level.

populated area	Heat stress (HSI)				Vulnerability (HSVI)				Risk (HSRI)			
	NCR		DC		NCR		DC		NCR		DC	
	[km²]	*[%]*	*[km²]*	*[%]*	*[km²]*	*[%]*	*[km²]*	*[%]*	*[km²]*	*[%]*	*[km²]*	*[%]*
very low	2,335	18	0	0	6,943	54	2	2	6,138	48	2	2
low	3,761	29	29	25	4,292	33	17	14	4,127	32	17	15
medium	2,379	18	31	27	1,108	9	23	20	1,759	14	22	19
high	2,594	20	41	36	463	4	64	56	780	6	57	50
very high	1,822	14	13	11	85	1	9	8	88	1	16	14
total [a]	12,892	100	114	100	12,892	100	114	100	12,892	100	114	100

[a] Sum of individual values might slightly differ from total due to rounding

Table 4: Index class ratios for populated area – Comparison of NCR and DC.

Risk is calculated as an aggregate interacting measure of hazard and vulnerability as described earlier on. Looking at the HSRI index values and their spatial distribution in the study area (see figure 67), patterns seem to be *driven by the vulnerability distribution*. Similar to the vulnerability patterns outlined above, almost half of the NCR region features very low risk index values and only 7% falls into the high risk categories. Table 4 illustrates that, while still having the bigger part in the two low classes, the initial heat stress (hazard) assessment does not provide such clear patterns.

Washington D.C. shows again a very different picture (see figure 68), being largely characterized by high risk index values (64% of the District's populated areas). It is evident for this region that there is a clear east-west divide, with census blocks east of the Rock Creek almost entirely classified as being at high or very high risk. This does not only include the very high risk areas southeast of the Anacostia River such as Historic Anacostia, Lincoln Heights, Deanwood, and Hillbrook, but also the central areas of Downtown, Chinatown, and Capitol Hill, as well as Columbia Heights and Brightwood in the North, that are all predominantly categorized as high risk areas. On the other hand, almost the entire less than 20% of lower risk regions are located in the Northwest of DC, including parts of Georgetown, Foxhall Crescent, and Palisades, as well as Chevy Chase.

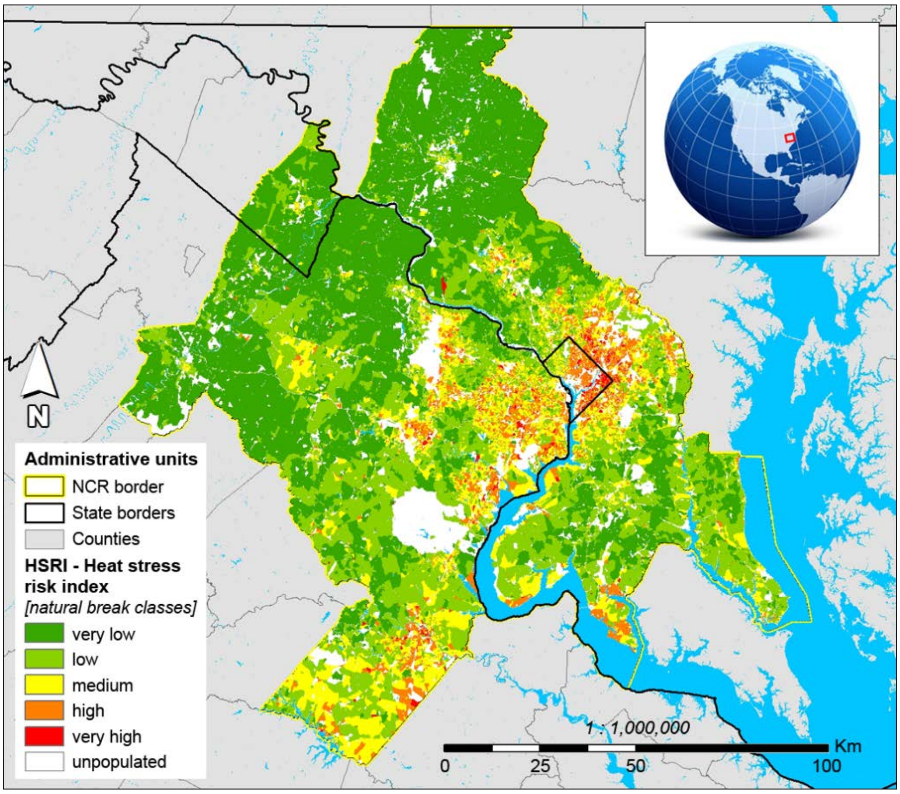


Figure 67: Heat stress risk index (HSRI) for the NCR on census block level.

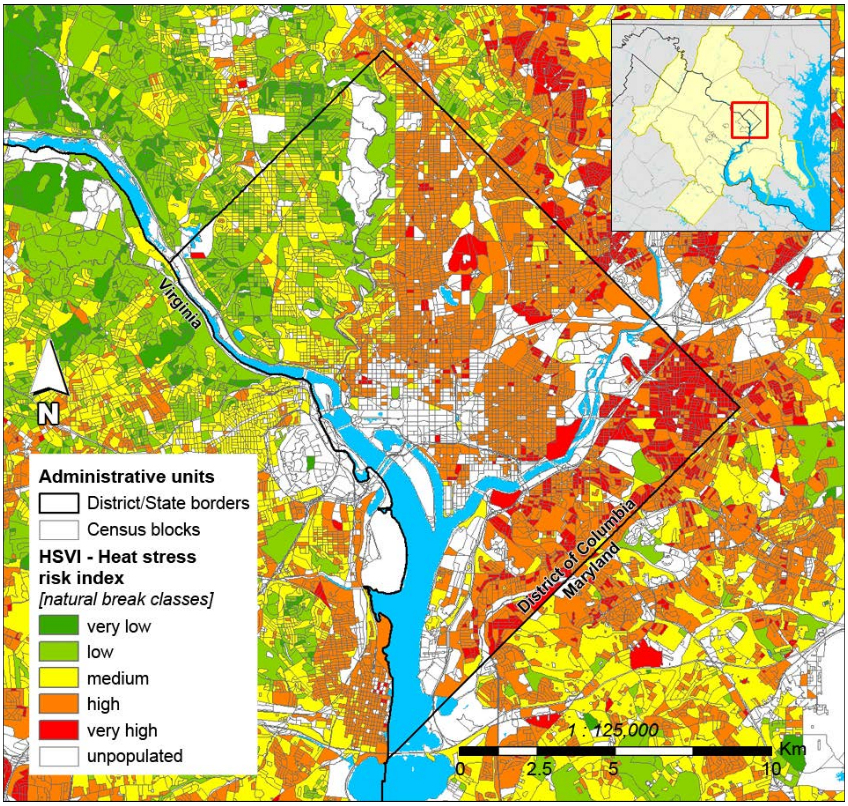


Figure 68: Heat stress risk index (HSRI) for the District of Columbia on census block level.

There are a couple of *uncertainties* associated with the various assessments and inherent assumptions that should be highlighted. Alternative data sources could be integrated as well as additional indicators for both the heat stress (hazard) and the vulnerability analyses. However, the spatial scale of the study results in limited data availability that eventually led to the current setup.

In terms of the development of the vulnerability and risk indices, the choice of the census block as the basic spatial reference unit requires having to integrate lower-level indicators in a 'spatially-generalized' way. Assuming an even parameter distribution within higher aggregation units is problematic as the underlying spatial-social pattern is ignored. Improvements can be attempted, for example, spatial interpolation and disaggregation methods have been used to refine distribution patterns of general residential population (Eicher and Brewer, 2001; Mennis and Hultgren, 2006) and workforce population (Bhaduri et al., 2007; Freire and Aubrecht, 2010), primarily based on ancillary land cover and functional land use information (Aubrecht et al., 2009b, 2013b). Statistical inference models have been tested to estimate small-area populations by age and sex (Cai et al., 2006), but solid disaggregation of socio-economic characteristics such as poverty and educational attainment proves more challenging due to the lack of adequate high-level data that could be applied for weighting purposes (as already mentioned briefly in the previous section). An alternative option would be to perform the analysis at the block group level though the purpose of this study was to concentrate on the finest possible aggregations.

ACS data also introduces a degree of uncertainty even on its dedicated spatial level of block groups, as a result of the rather small sample size (around 7% aggregated over a 5-year period) and related statistical weighting for the extrapolation (Starsinic, 2005). ACS characteristic 'total' estimates for a given tabulation area must therefore not be mistaken to be census count totals. Even so, sophisticated weighting is used in ACS ratio estimation procedures to bring the characteristics of the sample more into agreement with those of the full population (Alexander et al., 1997).

Developing an index is generally a quite complex process involving various uncertainties. Composite indices are multidimensional and uncertain with different determinant scenarios based on indicator selection and composition. Coupling effects might even amplify the results and impacts of individual components. However, indices do play an important role in encapsulating a complex reality in a single construct (Vincent, 2004), thus providing a summarized reality that otherwise could not be seen and analyzed easily. In the presented HSVI, alternative indicators could be integrated, such as the degree of imperviousness to capture the urban heat island effect. Also building structure and living arrangements have an impact in a heat stress context.

In the following section an important thematic factor is highlighted that is 'missing' in the developed index due to limited high resolution data availability, i.e. *heat stress-related human health issues* such as pre-existing health problems (general health status, heart-related conditions, cardiovascular diseases, diabetes, etc.), access to public health infrastructure, as well as heat-related morbidity and mortality that could serve for *validation purposes* in similar fashion as illustrated for local-level population exposure (chapter 3.2.1) – i.e. in terms of checking if damage patterns indeed overlap with pre-identified high risk areas (risk 'materialization'). These types of data are mostly collected and provided for the United States by the Centers for Disease Control and Prevention (CDC). Information on health insurance coverage, which is generally considered as a factor of access to health service is documented by the U.S. Census Bureau. All these above-listed data are generally not available on levels more detailed than county-level, which makes it impossible to include them in the presented index. However, for studies dealing with human impacts of heat stress at least at the city-level they have previously been successfully applied (e.g., Curriero et al., 2002; Anderson and Bell, 2009; Sheridan and Kalkstein, 2010).

Table 5 shows data for all the NCR counties for three selected heat-related parameters: (1) *mortality* (CDC, 2012), (2) diabetes as example for *pre-existing health problems* (CDC, 2013), and (3) health insurance coverage standing for *access to public health infrastructure* (U.S. Census Bureau, 2012c). To enable comparability with the indices presented in this study, the values are again categorized into 5 classes. The color coding ranges from red for the most 'negative' class, orange ('negative'), yellow ('medium'), and light green ('positive'), to the most 'positive' category colored in dark green.

States/ district	**Counties/ independent cities**	**Heat-related mortality** [a] *[deaths/100k]*	**Diabetes** [b] *[%]*	**Health insurance** [c] *[% uninsured]*
DC	Washington D.C.	263	8.5	9.0
MD	Calvert C.	226	8.8	8.7
	Charles C.	204	10.0	9.8
	Frederick C.	208	8.2	9.5
	Montgomery C.	175	6.5	13.2
	Prince George's C.	214	11.0	17.0
VA	Arlington C.	138	7.5	12.0
	Clarke C.	288	8.8	13.8
	Fairfax C.	127	8.1	12.9
	Fauquier C.	175	8.7	13.4
	Loudon C.	83	7.9	8.7
	Prince William C.	96	9.4	15.5
	Spotsylvania C.	160	9.5	13.5
	Stafford C.	118	8.4	10.7
	Warren C.	305	9.7	16.7
	C. of Alexandria	153	7.8	15.0
	C. of Fairfax	276	9.0	13.7
	C. of Falls Church	217	8.9	8.2
	C. of Fredericksburg	233	9.7	18.1
	C. of Manassas	121	9.9	21.1
	C. of Manassas Park	108	9.5	23.6
WV	Jefferson C.	245	10.6	14.6

[a] Death related to 'major cardiovascular diseases' (data are based on death certificates for U.S. residents; each certificate identifies a single underlying cause of death and demographic data) derived from CDC's Underlying Cause of Death database (1999-2009); (CDC, 2012)
[b] derived from 2009 database of CDC's Division of Diabetes; (CDC, 2013)
[c] derived from U.S. Census Bureau's Small Area Health Insurance Estimates (SAHIE) program, 2010 release; (U.S. Census Bureau, 2012c)

Table 5: NCR county-level listing of health-related parameters (mortality, morbidity, insurance coverage) relevant in the context of heat stress assessment.

Warren County, VA, is selected as an example where high risk is expected based on or rather in explanation of the county-level data presented in table 5, to have a more detailed look and analyze the patterns apparent in the HSVI and HSRI assessment. Warren County tops the list in terms of heat-related deaths for the NCR when compared to the total population (deaths per 100,000 persons) and also falls into the 'orange' categories for both the diabetes and health insurance coverage parameters. Figure 69 shows the final HSRI results for Warren County mapped at the census block level. While the overall pattern, being characterized almost entirely by very low risk values, seems to contradict the expectations of high risk, a closer look reveals the *significant value of sub-county assessments*.

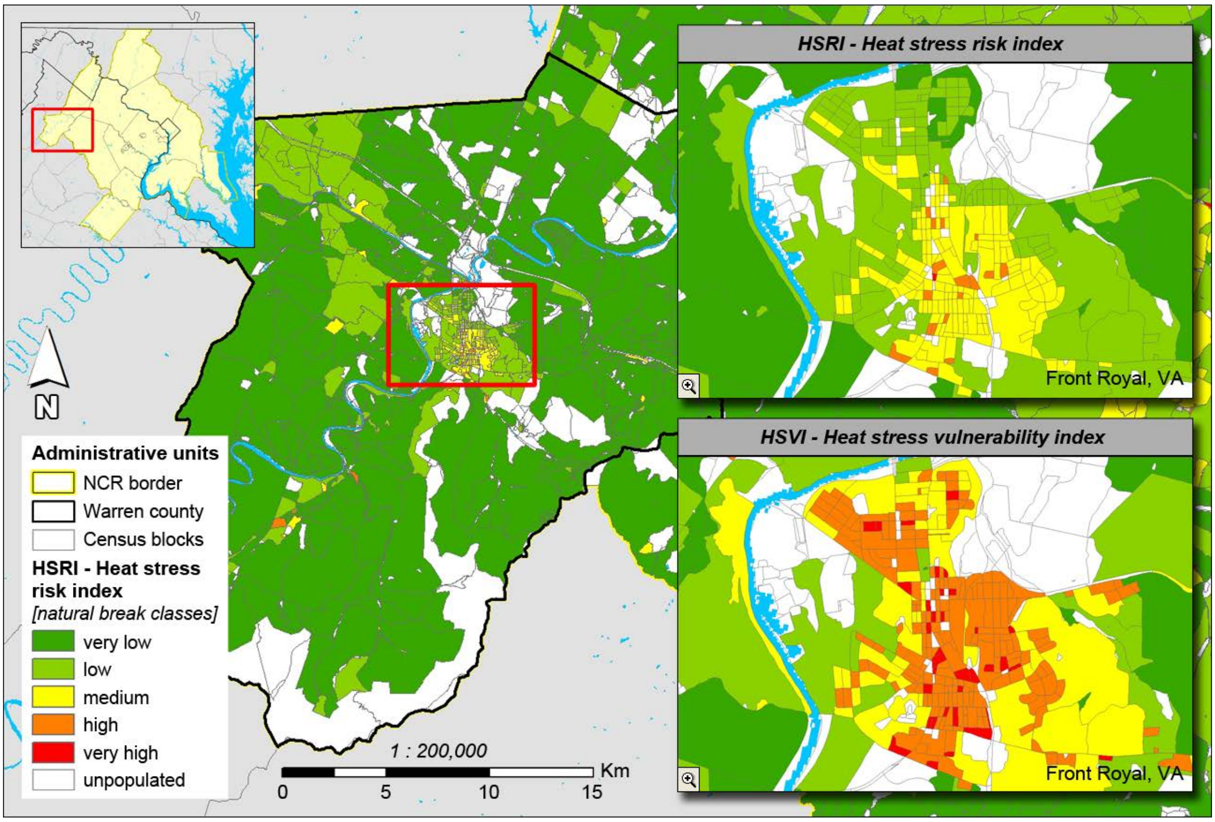


Figure 69: Heat stress risk index (HSRI) for Warren County, VA, on census block level – Details focused on Front Royal, the central town in the county.

The two detail boxes show a zoom-in of the central town of Warren County, Front Royal. In particular the largely high and *very high vulnerability index values* can serve as sort of explanation or validation for the county-level picture in table 5 (and vice versa). Risk index values are lower for that region, due to the relatively low heat stress it experienced in the year 2010. In order to determine a comprehensive risk analysis, therefore time series analysis would be necessary, comparing heat stress distributions over several years.

In this study an approach has been presented to assess heat risk at a local level by integrating heat stress (hazard) and related vulnerability patterns and developing an aggregate composite heat stress risk index. This approach can provide valuable input and decision support for people concerned with climate adaptation planning in the rather long-term as well as emergency managers aiming at risk reduction and optimization of resource distribution on the short-term time scale.

Applying the developed risk index to the U.S. National Capital Region, which suffered sustained heat waves during the summer of 2010, the additional value gained by sub-county-level analysis was illustrated and limitations were discussed e.g. in terms of health-specific data availability. HSRI index values and their spatial distribution seem to be strongly driven by the vulnerability distribution, showing a clear divide between high-risk urban areas and wide areas of low risk in the sub-urban and rural environments. This is particularly obvious for the core center of the study area around the District of Columbia, which is largely characterized by high index values despite not having experienced the peak of the heat stress as compared to the more southern regions of the metropolitan area.

Applying a very *granular approach at a high level of spatial detail* enables the detection of hotspot areas within cities. It can therefore provide valuable decision support in directing risk mitigation measures which in a heat stress context particularly implies increasing the local communities' adaptive capacity. Thinking about *risk reduction* in that regard, it is illustrated that *in particular the vulnerability factors should be addressed and minimized* by disaster and emergency management, considering variations on community level and below. On a community level, municipal heat response plans can be very effective, and vulnerability mapping can target efforts even more effectively (Bernard and McGeehin, 2004).

In terms of addressing social vulnerability characteristics, this might include raising awareness particularly among highly vulnerable groups, e.g. creating additional community and multi-language information centers. Promoting public health heat-relief shelters (that provide cool-down facilities and supplementary drinking water supply) in high-risk areas is considered a main factor in extreme heat impact prevention (CDC, 2009). In times of extreme heat stress emergency service personnel and neighborhood volunteer organizations should become proactive in potential high risk areas and put an increased focus on monitoring people pre-identified as highly vulnerable. Also a sustainable distribution of green areas would be favorable as these help reduce heat build-up in buildings and decreases the urban heat island effect which is considered an effective strategy in city planning.

For *follow-up research*, it is planned to analyze heat stress in different years and assess trend effects, which can also provide more reliable longer-term heat stress validation. Furthermore, it is also aimed to investigate nighttime temperature distribution patterns, in order to capture the missing cooling effect during 'tropical nights', which is considered as to strongly intensify impacts on human health (Meehl and Tebaldi, 2004). Performing county-level analysis and therefore being able to integrate available heat-related morbidity and mortality data could again help with validation and also serve as an interesting comparative study in terms of analyzing differences to local-level results and even better identify and quantify the benefits of spatial detail vs. thematic comprehensiveness. Last but not least, the developed risk identification and mapping approach has already been and will continue to be promoted in the relevant public health communities, aiming at providing decision support for municipal and local heat response planning.

5 Conclusions and outlook

This thesis provides a comprehensive overview on *multi-level geospatial information and modeling approaches* with the focus set on laying a foundation for implementing population exposure and vulnerability applications. Conceptually the presented study is well-grounded in an *integrated disaster risk management framework* where risk in its multi-faceted nature and various components (e.g., 'risk triangle') and associated aspects are outlined in the context of past scientific developments as well as current state-of-the art in the field. Varying dimensions and related implications are illustrated following the proclaimed need for assessing spatial and temporal as well as contextual aspects and scale domains in disaster risk research as identified in the benchmark literature. This includes e.g. the promotion of the *spatio-temporal footprint* as being one of the most important characteristics of an emergency situation (i.e., timing of event and area impacted) as well as the importance of placing great emphasis on *context* in the course of related "*spatial thinking*" (Goodchild, 2008a). The latter in fact highlights the necessity of focusing on the essence of a complex problem – especially when studying it in both spatial and temporal domains – and leaving out excessive details and variables (Goodchild, 2010). In the geospatial perspective that particularly refers to the long-promoted "*fundamental concern about the 'proper' scale of analysis*" (Anselin, 1999) whose pre-identification is considered the core element in designing any scientific inquiry associated with geospatial assessments. Most recently, the scale debate has also been introduced specifically into vulnerability studies, by e.g. comparing macro-level dynamics and micro-level components. In that regard it was also highlighted that "*apart from the spatial-scale implications, the temporal scale effects remain a challenge*" (Fekete et al., 2010). Following along those lines, this thesis has its emphasis put on the *integration of space-time variation and contextual aspects*, both for the primary elaborations on methods applied to assess *population exposure* as well as for the subsequent integration of social structure and the development of aggregative *vulnerability* indicators which eventually enable the differentiation of situation-specific *risk* patterns.

In terms of the *spatial domain* the entire range from the global scale to the local level is addressed in a top-down structure for both the initial analysis of population exposure and the following step of integrating social structure for vulnerability assessment implying increased thematic complexity. *Temporal aspects* are continuously highlighted and accounted for on various scale levels with the probably most striking implications apparent in the domain of local spatial scale and lower level of thematic detail (i.e., basic exposure). While at the global scale temporal aspects are mostly evident in a *longer-term* timeframe and thus become relevant for example in the study of climate change induced vulnerability variation (such as presented for the heat stress context), the local scale is particularly characterized by its high spatio-temporal dynamics and (social) motion patterns which can be assessed in increasingly sophisticated manner in the context of *short-term* imminent risk evaluations. Novel geospatial modeling concepts and approaches are presented to integrate commuting and time use statistics for analysis of basic population dynamics. Furthermore it is illustrated how newly available geodata such as cell phone logs and VGI are applied for assessing seamless and near-real time population distribution and human activity patterns.

The above-mentioned higher thematic complexity for characterizing vulnerability as compared to assessing exposure patterns, i.e. integration of structural parameters in addition to the 'mere' locational aspects of elements at risk, makes the explicit *context of a study* increasingly important. While basic exposure patterns are considered to be 'universally' applicable in different hazard settings, vulnerability is strongly context-dependent and situation-specific. In the analysis of exposure spatio-temporal dynamics as outlined above are therefore understood as a main context-defining factor, i.e. mobile population may not directly be affected by some slow-onset hazard event (referring to potential imminent threat to an individual, not accounting for associated assets). In turn, for the assessment of vulnerability the thematic characteristics of the identified elements at risk are the major determinant factor (as the presented specific example of heat stress as hazard factor illustrated). While this thesis mainly refers to population for vulnerability considerations, the basic concept is similar for assessing asset vulnerability (e.g., infrastructure, buildings). For asset exposure, however, the situation is different, with most assets not being mobile and therefore the locational aspect serving as core study element.

5.1 Main novel scientific ideas and innovative modeling approaches

There are several *novel issues* addressed in this thesis that progress the state-of-the-art in the field or rather in several fields of research. In particular the integrated consideration of spatial and temporal aspects has not yet been elaborated on in this detail and the conceptual introduction of context further accounts for long-identified needs. With disaster management being referred to as an "*inherently spatial problem*" (Goodchild, 2005), novel geospatial modeling concepts are put in context with regard to setting a consistent framework for exposure, vulnerability, and subsequent risk analyses on multiple levels.

On the *global scale* available modeling concepts for population distribution modeling and related exposure assessments are outlined comprehensively, with elements highlighted that have been specifically framed in the course of this PhD study. These include the clarification of accuracy expectations for coarse-scale population data sets by sort of retracing model processes applied to prominent data sets (accessibility concept as applied e.g. for the African Population Database) and subsequently comparing it to publicly available and reliable reference data (Austrian local level census grids). Recommendations are provided to refine global scale population distribution models such as GPW/GRUMP specifically addressing coastal areas, thus those regions commonly considered at highest risk to natural hazards both due to their general physical situational characteristics (susceptibility to imminent coastal hazards as well as climate change related variability) and their significant clustering of high-density population areas. Moreover, a novel spatial disaggregation approach relying on satellite derived depiction of imperviousness has been developed and is presented here that has shaped the European situation in terms of homogeneous gridded population information on regional scale. That new data set which also includes basic structural social characteristics and temporally extends to future prospects is then applied for vulnerability analysis in a heat stress context which enables for the first time to point out climate change induced variability and associated future patterns in a spatially consistent manner.

On the *local scale level* models have been developed and are presented in this thesis covering the full range of highest possible spatial detail and temporal dynamics. Advanced functional urban system modeling is outlined in a disaster risk context where population disaggregation is performed down to the highest possible resolution other than (privacy-constricted) representation of individual persons, i.e. on address level. Despite still being static in terms of time display this local level spatial depiction is unique in its application for population exposure analysis and thus creates an entirely new standard in terms of potential estimation accuracy. Derivation of high-level asset or 'socio-economic' exposure is another benefit that comes along with the address-level functional land use modeling (e.g., identification of potentially exposed business types). Integration of basic mobility and work statistics in a next step enables increasing the temporal resolution in terms of illustrating basic variation patterns between daytime and nighttime. That is even further extended by referring to individual survey-based time use profiles for different types of 'disaggregation target venues' such as schools and restaurants. The sort of 'binary' daytime-nighttime mapping approach (developed initially for a distinct case study area covering parts of the Lisbon Metropolitan Area by Freire, 2010) has been evaluated and put in a disaster risk and specifically exposure perspective in the course of studies in the context of this thesis. While that model relies on previously identified area-specific weighting factors for determining daytime target zones the subsequently outlined approach that is now also applied in the CRISMA project is more area-independent as well as more dynamic. The corresponding model developed in this thesis also accounts for individual time use statistics in addition to mobility figures in order to illustrate population distribution patterns for short-term time stamps. It has also been elaborated and specified here how location-based VGI can be consulted to derive time use profiles in near-real time which can in turn serve as calibration and validation source for the above-described survey-based statistics. In addition to VGI that provides highly detailed spatio-temporal information on human activity patterns an outlook is also given on the analysis of spatially-explicit cell phone user logs. Compared to VGI data these are less biased in terms of user profiles and thus much more representative and reliable for comprehensive population distribution and associated dynamic exposure measures. However, privacy constraints prohibit in-depth and large-scale data mining which leaves this kind of analysis still in its early stages. Eventually, putting the thematic context forward again, a novel framework for local-level analysis of social vulnerability is presented considering a broad wealth of indicators in setting up a final composite index. Cross-validating with superior-level impact data the significance of local-scale analysis is shown.

The following scheme (figure 70) shows the *most important novel aspects* outlined above in compact form, so that the key innovative approaches (advancing the state-of-the-art) developed in the context of this PhD study are made clear. The graphic once again highlights the interdependencies between the different scale domains including space and time as well as the underlying context domain referring to DRM as a basic backbone. Specific (spatio-temporal) modeling approaches are associated with all the points listed which are considered novel either already in the initial setup or in the model integration and context-specific implementation.

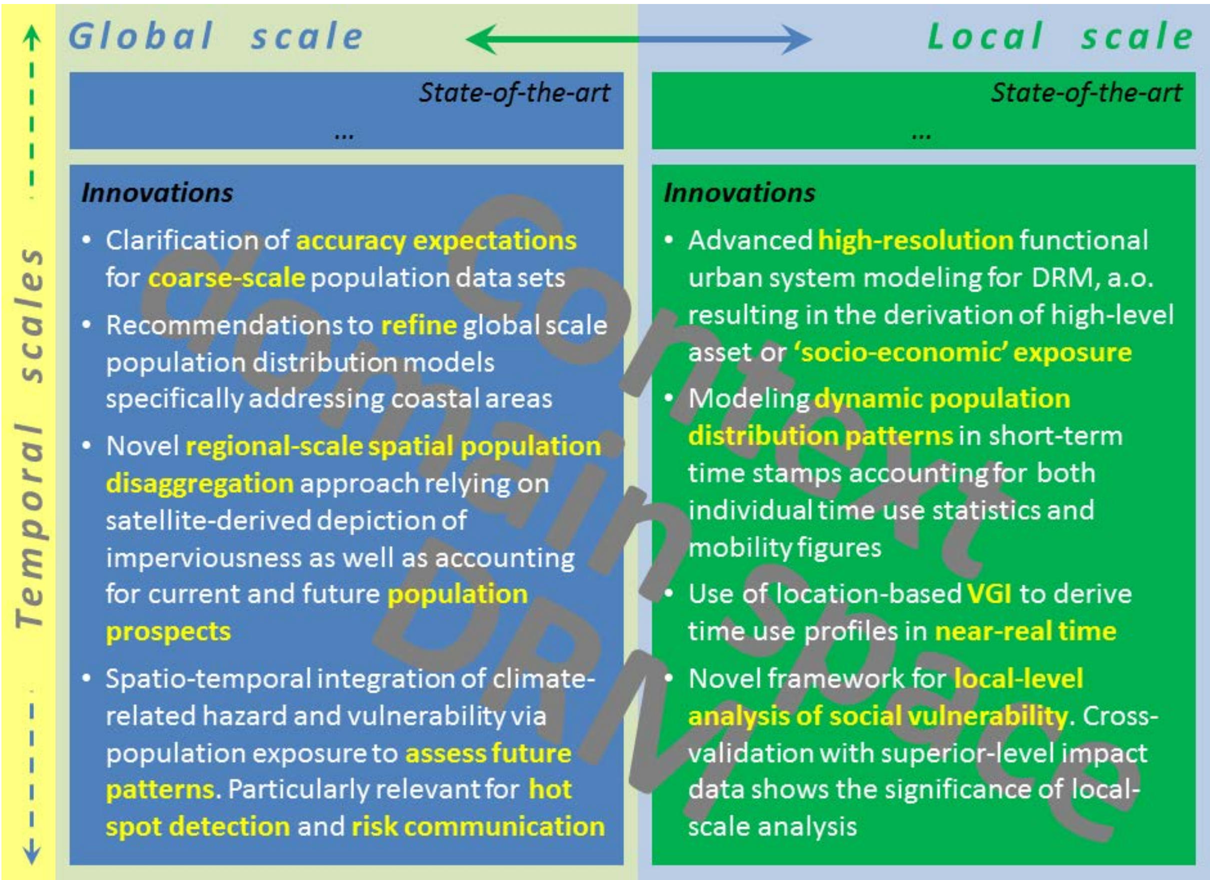


Figure 70: Scheme illustrating the main innovative scientific aspects and approaches of this PhD study.

5.2 Application-oriented outreach

The models and approaches developed and elaborated in the course of the presented study imply significant *value in an application-oriented perspective* as in fact highlighted throughout this thesis. On the *local level* population exposure in high detail and in particular in a highly dynamic spatio-temporal representation as well as and social vulnerability considerations are of utmost importance for emergency management and related decision support. Contacts with local authorities have been initiated already on various levels related to models and approaches presented in this thesis in order to raise awareness on the value of high-detailed comprehensive geospatial modeling and to promote the integration of respective consistent concepts in real-world considerations such as emergency mitigation and response plans.

These efforts include the Lisbon Metro Area for which it has been continuously highlighted also in regional media that the current way of considering static resident census population as exposure input information for the recently approved 'Special Emergency Plan for Seismic Risk' is highly insufficient (referring to the significant population differences in the core central area of up to 60 % between nighttime and daytime). Also in Upper Austria the developed high resolution modeling concepts have been presented on various occasions to local authorities such as the governmental spatial planning department in order to point out potential application fields and enhanced value for planning activities. In the course of the comprehensive heat stress related vulnerability and risk assessment for the U.S. National Capital Region, there has in fact been continuous communication and exchange of needs and requirements with related relevant authorities including the U.S. Census Bureau's Population Division[21] and the National Center for Environmental Health's Division of Environmental Hazards and Health Effects[22] associated with the Centers for Disease Control & Prevention. Considerable interest has been shown throughout and ongoing efforts intend to eventually

[21] More information available at http://www.census.gov/people/ (accessed 30 September 2013)
[22] More information available at http://www.cdc.gov/nceh/ehhe/ (accessed 30 September 2013)

stimulate or initiate implementation of similar modeling concepts in official authority's disaster risk management.

This approach of involving decision makers is followed intensively in the framework of the ongoing CRISMA project where an expert end user advisory board (including e.g. civil protection, NGOs and first responders) is constantly kept updated and even involved in actual guiding project decisions.

5.3 Looking forward

In terms of looking forward and giving an outlook to new and *future developments on the high level of spatial detail*, the highlighted CRISMA project is considered to generally set new standards in terms of integrated disaster risk modeling and management. Concepts developed in the course of the presented PhD study are applied and further advanced there in a multi-hazard context including integration of population and asset exposure and vulnerability measures as well as mitigation, impact, and dynamic resource management planning for all stages prior, during, and following a crisis event. Temporally complex cascading event scenarios add another dimension to this scene that has not yet been covered by state-of-the-art disaster models (Aubrecht et al., 2013c). Eventually the project aims at providing an integrated tool enabling accurate decision support to responsible crisis and emergency management as well as civil protection agencies both during real-world events and for training scenario purposes.

In terms of publicly available and easily accessible high resolution data there is in any case the constant debate on privacy concerns that hinders some methodological advancements. This has in fact become particularly evident in the course of the setup of the CRISMA project which is funded within the European Commission's FP7 security research program scheme being rather tightly constricted in that regard. However, particularly in emergency situations privacy constraints can be overcome at least for authorized users which is already the case for certain purposes on higher level with regard to satellite imagery (e.g., Disaster Charter, SAFER). With recent technological developments and advanced capabilities as well as an increased focus in the geospatial community being put on data sharing and integration initiatives (such as INSPIRE, GEOSS, GMES) it seems likely or at least probable that also local-level highly detailed input data – e.g. on human movement patterns – could become available in similar fashion (i.e., for authorized users). In line with increased near real-time coverage of spatial and temporal characteristics of human activities including population movements (such as derived from cell phone data logs) and functional socio-economic aspects as outlined in this thesis that would enable activity parameter downscaling and thus allow exposure mapping at high spatio-temporal resolution or even near real-time to support disaster response and overall management more effectively.

On *global scale* applications go into a slightly different direction than at the local level. Homogeneous gridded population representations are increasingly requested by regional authorities in order to consistently check cross-national clusters and exposure patterns or on an even more aggregated level to compare 'risk profiles' of individual countries. With the European population grid presented in this thesis being incorporated into the official Eurostat population dataset ('GEOSTAT 2006 population grid dataset') that particular spatial modeling approach has received increased attention and is likely to be regularly referred to for regional-level analyses and projects in Europe. GPW/GRUMP that were also extensively described in an exposure context have been applied for global analyses for many years and the presented refinement options improve accuracy particularly for extreme events exposure assessments as well as climate change considerations such as sea level rise. As outlined earlier on, coarse-level mapping techniques are particularly relevant for identification of certain hot spots in every sense ranging from exposure and vulnerability to risk and damage potentials. Especially climate change related analyses estimating conditions in the somewhat medium- to long-term future commonly operate on rather coarse spatial levels which is obviously due to increasing uncertainties in regional climate models the more parameters have to be accounted for. Studies like the long-term heat stress vulnerability dynamics assessment presented in this thesis that incorporate spatial and temporal aspects consistently for both physical and social developments therefore set the ground for 'scale-aware' spatial modeling approaches, referring to the much-cited "*proper scale of analysis*" in that context.

With regard to *future developments on the global scale* the most significant progress in terms of consistent population distribution representation is reported in current efforts by the U.S. Oak Ridge National Laboratory (ORNL) to develop a high resolution update of the LandScan Global product mainly based on WorldView satellite imagery, thus scaling down to LandScan USA resolution at a 90 m grid cell size. A feasibility study for that new 'LandScan HD' data product has been successfully demonstrated using ORNL's supercomputing resources and full-scale production is supposed to be initiated in fiscal year 2013. Keeping in mind the specific LandScan characteristics (ambient representation) for analysis design, that dataset will introduce a totally new scale dimension to global-level assessments. On the currently commonly implemented scale dimension for global approaches (i.e., km grids), there is a variety of ongoing initiatives dealing with global scale exposure determination. These include the setup of a Global Exposure Database in the framework of the Global Earthquake Model (GED4GEM[23] – Huyck et al., 2011) as well as exposure and advanced subsequent vulnerability and risk assessments associated with the UN's series of Global Assessment Reports (GAR[24] – UNISDR, 2013b). Also the World Bank's CAPRA[25] initiative (Disaster Risk Information Platform for Probabilistic Risk Assessment – Linares-Rivas, 2012) follows a similar top-down approach that might eventually be conceptually cross-coordinated with GAR efforts. All these mentioned initiatives basically aim at setting up a consistent database on relevant exposure parameters including population distribution, building stock and preferably some kind of economic capital stock (Aubrecht, 2012). Acknowledging that "*sub-national data on the exposure of economic assets and vulnerability factors are scarce or non-existent*", it is concluded that "*proxies have to be used*" (UNISDR, 2009), thus spatial disaggregation models as developed and presented in this thesis have to be implemented. In particular with regard to the infrastructure features one of the main objectives is to collect and model the spatial, structural, and occupancy-related information necessary for damage, loss and human casualty assessments (e.g. for earthquake scenarios such as employed in GEM). In terms of the economic features, the estimation of global scale

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[23] More information available at http://www.nexus.globalquakemodel.org/ged4gem (accessed 30 September 2013)
[24] More information available at http://www.preventionweb.net/gar (accessed 30 September 2013)
[25] More information available at http://www.ecapra.org/ (accessed 30 September 2013)

damage potentials is particularly relevant for the reinsurance industry. In any case demographic data and specifically information on population distribution patterns is among the core parameters modeled and compiled in all those efforts serving as starting point for regional exposure analyses.

Summing it up, models and approaches presented in this thesis are considered to be at the forefront of current scientific developments which basically applies to all covered levels of detail. With ongoing progress in leading roles in the CRISMA project as well as through consulting contribution to the CAPRA initiative further advancements are envisaged on a continuous basis.

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Department of Geodesy and Geoinformation, Research Group (former Inst.) Photogrammetry & Remote Sensing (Vienna, Austria)
Contact persons: W. Wagner, M. Hollaus

Since 2007 (Nov)	Cooperative doctoral researcher (Scientific collaboration, AIT) - *'Assessment of natural hazards risk in complex human-natural coupled systems using Earth Observation and GeoInformation'*
2007 (Jan)	Visiting scientist (within the scope of the Master's thesis) - *'Semi-automatic building generalization'*

University of Vienna, IfGR/CG
Institute of Geography and Regional Research, Cartography and Geoinformation (Vienna, Austria)
Contact person: W. Kainz

Since 2008 (Mar)	Associate lecturer *Image Processing and Remote Sensing, Introduction to GIS, Methods of GIS-based data acquisition, GIS-based spatial analysis and modeling*
2004 (Feb - Mar)	Research assistant *'ISOHIS (Isotope Hydrology Information System): GIS-based coastline generalization'*
2003 (Oct) - 2007 (Jul)	Teaching assistant *Remote Sensing, Fuzzy Logic & GIS, Geodatabases, Cartography & Geocommunication*

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Employment record and research experience (National & International) 1/2

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Global Facility for Disaster Reduction and Recovery / GFDRR Labs (Washington, DC, USA) Contact persons: U. Deichmann, K. Saito	
2012 (Jun - Sep)	GeoInformation Technology Specialist (short term consultant) - *'Strategic development for improving and analyzing spatially detailed social and economic exposure/vulnerability indicators on global scale'*
University of Southern California / Spatial Sciences Institute / GIS Research Laboratory (Los Angeles, California, USA - USC University Park Campus) Contact persons: T. Longcore, A. Curtis	
2010 (Aug)	Guest researcher - *'Ecological consequences of artificial night lighting'* - *'Multi-dimensional social vulnerability in a disaster management context'*
Columbia University / The Earth Institute / CIESIN - NASA / SEDAC Center for International Earth Science Information Network - National Aeronautics and Space Administration / Socioeconomic Data and Applications Center (Palisades, New York, USA - Lamont Doherty Campus) Contact persons: A.M. de Sherbinin, R.S. Chen	
2009 (Jul - Sep)	Visiting scientist - *'Refinement of global population data for human exposure mapping related to coastal hazards'* - *'Using regional accessibility indicators for population distribution modeling - Local scale accuracy assessment'* - *'Global assessment of light pollution impact on protected areas'*
NOAA / NESDIS / NGDC / EOG National Oceanic & Atmospheric Administration / National Environmental Satellite, Data and Information Service / National Geophysical Data Center / Earth Observation Group (Boulder, Colorado, USA – David Skaggs Research Center) Contact person: C.D. Elvidge	
2009 (Sep - Oct)	Visiting researcher - DMSP - *'Remote sensing of coral reef bleaching'* - *'Spatio-temporal analysis of coral reef stress'*
2008 (Jul)	Visiting researcher - DMSP - *'Detection of coral bleaching in multi-temporal satellite imagery'* - *'Temporal trends in human activity in proximity to coral reefs'*
2007 (Jul - Sep)	Visiting scientist (Foreign national research affiliate) - DMSP - *'Monitoring the temporal trends in anthropogenic stress to coral reefs'* - *'Satellite detection of power outages following natural disasters'* - *'Coral bleaching observation through change detection in VHR satellite imagery'*
2006 (Aug - Sep)	Internship - Defense Meteorological Satellite Program (DMSP) - *'A global inventory of coral reef stressors based on satellite observed nighttime lights'*
ASFINAG Austrian Freeway Company (Vienna, Austria) Contact person: P. Aubrecht	
2008 (Mar - Jun)	Project associate (contractor) *'Tunnel map 2008: second edition'* (Holding, Service East - coop. with the Fed. Min. of Transport, Innovation & Technology)
2007 (Oct - Nov)	Project associate (contractor) *'Tunnel map 2007: updated version including new features'* (Holding - cooperation with the Federal Ministry of Transport, Innovation & Technology)
2007 (Jan - Jun)	Project associate (part-time) *'GISNET: junctions, positioning points, routes, ramps; Tunnel map 2007'* (Holding, Vehicle Telematics, Service East)
2005 (Mar - Jul)	Project associate (part-time) *'Base map 2005; Motorway stations; Linear referencing'* (Holding, Toll Service)

Teaching experience

University of Vienna, IfGR/CG Institute of Geography and Regional Research, Cartography and Geoinformation (Vienna, Austria)	
Since 2008 (Mar) SS 13 WS 09/10/11/12/13 SS 09 SS 08/10/11	Associate lecturer *- 'EGI (Introduction to GIS)'* *- 'IPRS (Image Processing and Remote Sensing)'* *- 'SAM (GIS-based spatial analysis and modeling)'* *- 'MEGIDA (Methods of GIS-based data acquisition)'*
2003 (Oct) - 2007 (Jul) SS 07 WS 06/07 SS 06, SS 07 WS 03/04, SS 04, WS 04/05, SS 05	Teaching assistant - *'Remote Sensing II: Practical applications'* (course leader: K. Steinnocher) - *'Fuzzy Logic and Geographic Information Systems (GIS)'* (course leader: W. Kainz) - *'Geodatabases'* (course leader: W. Kainz) - *'Cartography and Geocommunication I & II'* (course leader: K. Kriz)
University of Education (PH), Upper Austria Working Group Geography	
2006 - 2010 02/02/2010 10/30/2007 03/22/2006	Lecturer (continuing education for teachers) *- 'Nature at risk / Risk of nature - Applications of satellite based research at the U.S. agency NOAA'* *- 'Coral reefs at risk - Applications of satellite based research at the U.S. agency NOAA'* *- 'The Southwest of the USA - Geoinformation technologies in practice'*

Scientific record 3/3

Editorial activities	
Since 2013	CMES: Computer Modeling in Engineering & Sciences (Tech Science Press) - Special Issue Guest Editor 'Modeling of dangerous phenomena for risk mitigation'
Since 2011	ISPRS International Journal of Geo-Information (MDPI) - Editorial Board Member
	Georisk (Taylor & Francis) - Editorial Board Member (Managing Editor) (since 2012) - Special Issue Guest Editor 'Innovative risk modeling techniques' (2011-2013)
Since 2008	Earthzine (IEEE Committee on Earth Observation) - Board of Directors, Senior Advisor (since 2012) - Deputy Editor-in-Chief (2009-2012) - Associate Editor for 'Disasters' (2008-2009) - Special Issue Guest Editor 'Wildfires' (2013) - Special Issue Guest Editor 'Disaster Management' (2010-2011) - Special Issue Guest Editor 'Disaster Mitigation and Response' (2008-2009)
	Disaster Advances (Govt. of India) - Editorial Board Member
	Journal of Geography & Regional Planning (Academic Journals) - Editorial Board Member for 'GIS, EO/RS, Hazards/Disasters'
2011 - 2013	Natural Hazards (Springer) - Special Issue Guest Editor 'Spatio-temporal aspects in IDRiM'
2010 - 2012	Physics and Chemistry of the Earth (Elsevier) - Special Issue Guest Editor 'Disaster Risk Reduction'
	Land Use: Planning, Regulations, & Environment (Nova Pub.) - Book Volume Development Editor
Organizations	
2007 - 2008	ISPRS Technical Commission II - Scientific Secretary (International Society for Photogrammetry & Remote Sensing)
Conferences	
2014	IAEG XII Congress, Intl. Association for Engineering Geology and the environment (Torino, Italy) - Session Co-Convener 'Approaches to landslide risk modelling and mitigation'
	ISCRAM 2014, 11th Intl. Conf. on Information Systems for Crisis Response and Management (University Park, PA, USA) - Track Chair 'Geographic Information Science for Disaster Risk and Crisis Management'
	IDRC Davos 2014, 5th Intl. Disaster and Risk Conf. (Davos, Switzerland) - International Scientific and Technical Committee Member

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Scientific record	**2/3**
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2013	19th IMACS World Congress, Intl. Association for Mathematics and Computers in Simulation (Madrid, Spain) - Session Co-Convener 'Modeling of dangerous phenomena for risk mitigation'
	GEOG-AN-MOD 13, 8th Intl. Workshop on "Geographical Analysis, Urban Modeling, Spatial Statistics" (Ho Chi Minh City, Vietnam) - Program Committee Member
	EGU 2013, European Geosciences Union GA (Vienna, Austria) - Session Convener 'Incorporating spatio-temporal variability into risk management' - Session Co-Convener 'Modelling of dangerous phenomena, and innovative techniques for hazard evaluation and risk mitigation'
2012	CompIMAGE 2012, Computational Modeling of Objects Presented in Images, 3rd Edition (Rome, Italy) - Scientific Committee Member
	IDRC Davos 2012, 4th Intl. Disaster and Risk Conf. (Davos, Switzerland) - International Scientific and Technical Committee Member
	GEOG-AN-MOD 12, 7th Intl. Workshop on "Geographical Analysis, Urban Modeling, Spatial Statistics" (Salvador/Bahia, Brazil) - Program Committee Member
	EGU 2012, European Geosciences Union GA (Vienna, Austria) - Session Co-Convener 'Incorporating spatio-temporal variability into risk management' - Session Co-Convener 'Modelling of dangerous phenomena, and innovative techniques for hazard evaluation and risk mitigation'
	CUEE 2012, 9th Intl. Conf. on Urban EQ Eng. (Tokyo, Japan) - Session Chairperson 'Human Behavior' - Evaluation Panel Member 'Young Researchers Session'
2011	7VCT, 7th Virtual Cities and Territories (Lisbon, Portugal) - Session Chairperson 'Modeling for urban and spatial analysis'
	IDRiM 2011, Second Conf. of the International Society for Integrated Disaster Risk Management (Los Angeles, CA, USA) - Session Organizer, Chairperson 'Social vulnerability: A multifaceted and interdisciplinary concept – Definitions, needs and recent examples of geospatial applications'
	GEOG-AN-MOD 11, 6th Intl. Workshop on “Geographical Analysis, Urban Modeling, Spatial Statistics” (Santander, Spain) - Program Committee Member
	EGU 2011, European Geosciences Union GA (Vienna, Austria) - Session Convener, Chairperson 'Risk management in a changing world considering spatio-temporal variability' - Session Co-Convener, Chairperson 'Modelling of dangerous phenomena, and innovative techniques for hazard evaluation and risk mitigation'
2010 - 2011	ISG, Intl. Symp. & Exhibition on GI (Kuala Lumpur, Malaysia) - International Advisory Board Member
2010	GiT4NDM, 3rd Intl. Conf. on Geoinformation Techn. for Natural Disaster Management & Rehabilitation (Chiang Mai, Thailand) - International Advisory Committee Member
	IDRiM 2010, First Annual Conf. of the International Society for Integrated Disaster Risk Management (Vienna, Austria) - Session Co-Chair 'Integrating society in risk management'
	ISDA ‘10, Intelligent Spatial Decision Analysis (Baltimore, USA) - Program Committee Member
	ISPRS Technical Commission VII Symp. (Vienna, Austra) - Session Co-Chair 'Remote Sensing Applications'
	IDRC Davos 2010, 3rd Intl. Disaster and Risk Conf. (Davos, Switzerland) - International Scientific and Technical Committee Member - Session Chairperson 'Climate Change Adaptation'
	EGU 2010, European Geosciences Union GA (Vienna, Austria) - Session Co-Convener, Chairperson ‘Innovative techniques for evaluating, mapping, and decreasing the risk posed by dangerous phenomena'
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Scientific record	1/3
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2010	GEOG-AN-MOD 10, 5th Intl. Workshop on "Geographical Analysis, Urban Modeling, Spatial Statistics" (Fukuoka, Japan) - Program Committee Member
2009	VipIMAGE 2009, II. Eccomas Thematic Conf. on Computational Vision and Medical Image Processing (Porto, Portugal) - Session Chairperson 'Segmentation of Objects in Images'
2008	IGARSS'08, IEEE Intl. Geoscience & Remote Sensing Symp. (Boston, MA, USA) - Session Co-Chair 'Optical Sensing in the Coastal Ocean'
2006, 2007	Annual 'GIS in the Rockies' Conf. (Denver, CO, USA) - Volunteer (Assistance with the conference organization)

Reviewer (Journals and scientific magazines)
Advances in Space Research (Elsevier)
Computers, Environment and Urban Systems (Elsevier)
Disaster Advances (Govt. of India)
Earthzine (IEEE Committee on Earth Observation - ICEO)
Ecological Modelling (Elsevier)
GIScience and Remote Sensing (Bellwether Publishing)
International Journal of Health Geographics (BioMed Central/Springer)
Journal of Environmental Planning and Management (Taylor & Francis)
Journal of Geography and Regional Planning (Academic Journals)
Natural Hazards (Springer)
Physics and Chemistry of the Earth (Elsevier)
PLoS ONE (Public Library of Science)
Population, Space and Place (Wiley)
Population and Environment (Springer)
Remote Sensing (MDPI Publishing)
Remote Sensing of Environment (Elsevier)
Transactions on Geoscience and Remote Sensing - TGARS (IEEE-GRSS)
Reviewer (Conference proceedings)
VipIMAGE 2011 - Satellite Image Analysis for Env. Risk Assessment (Olhão, Algarve, Portugal)
Asia-Pacific Advanced Network APAN - 30th Meeting (Hanoi, Vietnam)
Third Intl. Disaster and Risk Conf. - IDRC 2010 (Davos, Switzerland)
Fifth Intl. Workshop on "Geographical Analysis, Urban Modeling, Spatial Statistics" & 2010 Intl. Conf. on Computational Science and its Applications (Fukuoka, Japan)
ISCRAM Intl. Conf. on Information Systems for Crisis Response and Management 2011 (Lisbon, Portugal), 2012 (Vancouver, Canada)
EGU European Geosciences Union, General Assembly 2010-2013 (Vienna, Austria)
IEEE Institute of Electrical and Electronics Engineers - Intl. Geoscience & Remote Sensing Symp. - IGARSS 2008 (Boston, USA), 2009 (Cape Town, South Africa), 2010 (Honolulu, Hawaii, USA), 2011 (Vancouver, Canada)
ISPRS International Society for Photogrammetry and Remote Sensing - ISPRS Technical Commission VII Symp. 2010 (Vienna, Austria) - XXI. ISPRS Congress 2008 (Beijing, China)
Reviewer (International project proposals)
◦ Strategic Research Programme "Healthy and Sustainable Living Environments" RIVM, National Institute for Public Health and the Environment (The Netherlands) - 2010

Scholarships and awards	
Research awards, fellowships	
2009 (Nov)	Talentförderungsprämie des Landes OÖ - Wissenschaft [Engl.: Talents Sponsorship Award 2009 - Science] - Federal State of Upper Austria
2009 (Sep - Oct)	UCAR Scholarship for carrying out research at NOAA-NGDC UCAR JOSS (U. Corporation for Atmosph. Research, Joint Office for Science Support)
2008 (Dec)	ÖGG Förderpreis 2007 for Best Diploma Thesis [Engl.: ÖGG Sponsorship Award 2007] - ÖGG Austrian Geographical Society
2008 (Aug)	Young Scientist Travel Award for an outstanding poster at the IV. ESA Earth Observation Summer School on Earth System Monitoring and Modelling Awarded by the European Meteorological Society
2008 (Jul)	3rd place in the 'GI_Forum'08 & AGIT 2008 Poster Competition'
2007 (Summer)	NOAA (National Oceanic & Atmospheric Administration) Research Fellowship ICSU (International Council for Science), Panel on World Data Centers
Travel and membership grants, miscellaneous	
2013 (May)	Invitation to present as keynote speaker at the PSCE-2013 conference in Brussels, Belgium Forum for Public Safety Communication Europe
2012 (Mar)	Invitation to present as keynote speaker at the CUEE-2012 conference in Tokyo, Japan Tokyo Institute of Technology
2011 (Apr)	Recipient of the Albert Einstein Award of Excellence for 2011 ABI (American Biographical Institute, Inc.), Raleigh, NC, USA
2011 (Mar)	Inclusion in the Top 100 Scientists 2011 IBC (International Biographical Centre), Cambridge, England
2010 (Oct)	Invitation to present as plenary keynote speaker at the DPTM-2010 conference in Chongqing, China Chongqing University & Disaster Advances Journal
2010 (Sep)	Conference support sponsorship 'IDRiM 2010' (Vienna, Austria) Japan Foundation
2010 (Jul)	Inclusion in the 28th (2011) and 29th (2012) Edition of Marquis Who's Who in the World
2010 (May)	Website of the Month declared by EIS News Recipient: Earthzine www.earthzine.org
2010 (May)	ESRI grant 'AGILE 2010' (Guimarães, Portugal) ESRI Europe
2009 (Jun)	Comenius EduMedia Medaille for 'Interaktives Medienpaket OÖ' (Recipient: BildungsMedienZentrum des Landes Oberösterreich, Linz) IB&M (Institut f. Bildung u. Medien d. GPI Gesellschaft f. Pädagogik u. Information e.V.)
2009 (May)	ESA Sponsorship 'Intl. Symp. on Remote Sensing of Env.' ESA Education Office (European Space Agency)
2008 (Jun)	Research grant for attending 'Mountain Risks Intensive Course' Marie Curie Research Training Network (Dortmund U. of Technology & U. of Vienna)
2007 (Summer)	Special grant for temporary employment abroad (Nat. sciences) State government of Upper Austria
2006 (Sep)	GSIS Award: 'Sponsored Student Membership 2006' Geoscience Information Society
University, Pre-University	
2006/07, 2005/06, 2004/05, 2002/03 (Academic years)	Excellence grants (§§ 57-61, 64 StudFG) - University of Vienna; Federal Ministry of Education, Science and Culture (bm:bwk)
2006 (Calendar year)	Excellence grant (out of the foundation funds and separate assets / 'Points scholarship') - University of Vienna
2001 (May)	4th Prize at 'Känguru der Mathematik' (Kangaroo of Mathematics), Upper Austrian competition Schools council of Upper Austria, Linz

For a list of memberships in scientific societies (national/international) and for a list of research projects (related tasks/leading roles) and partners please refer to my personal web page.

Additional qualification

NASA 2012 Summer Short Course on Earth System Modeling and Supercomputing Organized through the NASA Earth Exchange (NEX) program - focus on training researchers in the use of NASA High Performance Computing resources for running and analyzing Earth system models applied to extremely large datasets.	
2012 (Jul)	'Global land cover research' Venue/Scientific Organization: NASA Ames Research Center, Mountain View, CA, USA Online attendance of selected theme 'Terrestrial Ecosystem Modeling' Live online webcast (Speaker: John Townshend)
ESA Earth Observation Summer School 2008 Organized by the European Space Agency (ESA) to promote the exploitation of Earth Observation (EO) data across disciplines, with a specific focus on their assimilation into Earth System models. Topics: Global Observing Systems, Earth System Modelling, Data Assimilation, Global Change.	
2008 (Aug)	'Earth System Monitoring and Modelling' Venue: ESRIN (the ESA Center for Earth Observation), Rome (Frascati), Italy Scientific Organization: European Space Agency (European Space Research Institute)
MOUNTAIN RISKS Intensive Course 2008 Organized within the framework of the project 'Mountain Risks' - from prediction to management and governance - a Marie Curie Research Training Network in the 6th Framework Program of the European Commission.	
2008 (Jun)	'Mountain risks and risk governance' Venue: Kempten University of Applied Sciences, Germany Scientific Organization: Dortmund University of Technology (Faculty of Spatial Planning), University of Vienna (Dept. of Geography and Regional Sciences)
NPOESS Education & Training Series – UCAR / COMET / MetEd National Polar-orbiting Operational Environmental Satellite System – University Corporation for Atmospheric Research / Cooperative Program for Operational Meteorology, Education and Training / Meteorology Education & Training	
2007 (Aug) (Date of completion: 08/02/2007)	'Microwave Remote Sensing: Resources' Web-based Training Course (T. Lee)
2007 (Mar) (Date of completion: 03/05/2007)	'Feature Identification Using Environmental Satellites' Web-based Training Course (T. Lee)
2006 (Sep) (Date of completion: 09/11/2006)	'Microwave Remote Sensing: Overview' Web-based Training Course (T. Lee)
ESRI Virtual Campus Environmental Systems Research Institute (Redlands, California, USA)	
2006 (Aug) (Date of completion: 08/17/2006)	'Spatial Analysis of Geohazards (Using ArcGIS 9)' Web Course (18h, Dr. W. Harbert)

Skills

Languages		*Spoken*	*Written*	*Reading*
	German	native speaker		
	English US research stays, High school: 8 years, graduation	very good	excellent	excellent
	French High school: 6 years, graduation	fair	fair	good
	Spanish High school: 4 years	fair	fair	good

For a description of technical skills please refer to my personal web page.

Publications and presentations

Publications currently include several editorial contributions (7 special issues, 1 edited book), one book and several book chapters (5), articles in scientific journals and magazines (23), fully-reviewed conference papers (23), abstract-reviewed conference papers (11), conference abstracts and posters (26), miscellaneous reports (29).

In addition to around 50 presentations of above-listed conference contributions, there is an extensive list of keynotes and solicited talks at conferences (15) as well as invited talks and research seminars (15) and more than 20 further presentations in other contexts.

For an updated list of publications and presentations please refer to my personal web page.