

# Ecosystems, Communities, and Resilience: Nature-Based Solutions for Climate Change Adaptation and Disaster Risk Reduction in Brazil



Doctoral thesis

for

the award of the doctoral degree

of the Faculty of Mathematics and Natural Sciences

of the University of Cologne

submitted by

Wolfram Johannes Lange, Dipl.-Geogr.

accepted in the year 2025

# Table of contents

Table of contents .....	2
List of Figures.....	5
List of Tables .....	6
List of Acronyms.....	7
Abstract .....	9
1. Introduction .....	12
2. Nature-Based Solutions for Disaster Risk Reduction and Climate Change Adaptation.....	16
3. Research Design and Analytical Framework.....	23
3.1. Analytical framework: Integrating Vulnerability, Risk Perception, and Ecosystem Services .....	25
3.2. Overview of methodological approaches .....	27
4. Ecosystem-Based Approaches for Disaster Risk Reduction and Climate Change Adaptation in Rio de Janeiro State .....	30
4.1. Introduction .....	32
4.2. Ecosystem-Based Approaches for Reducing Risks and Adapting to Climate Change .....	33
4.3. CCA and DRR Policies at National and State Level.....	35
4.4. Linkages Between CCA/DRR, Land And Ecosystem Management In Rio De Janeiro State .....	37
4.5. Status of EbA and Eco-DRR Measures in Rio de Janeiro State .....	40
4.6. The Potential and Limitations of Eba and Eco-DRR in Rio de Janeiro State	44
4.7. References.....	45

5. Risk Perception for Participatory Ecosystem-Based Adaptation to Climate Change.....	49
5.1. Introduction .....	50
5.1.1. Objectives .....	50
5.1.2. Disaster Risks and Climate Change in Rio de Janeiro State .....	50
5.1.3. DRR and CCA in Rio de Janeiro State .....	52
5.1.4. Effective DRR and CCA Based on Ecosystem Services.....	53
5.1.5. Importance of Perception for Participation .....	55
5.1.6. Four Key Factors for Active Participation .....	55
5.1.7. Methodology .....	57
5.2. Results.....	62
5.2.1. Perception of Risks and Adaptation Measures in Teresópolis.....	62
5.2.2. Perception of Vulnerability with Respect to Disaster Risks .....	62
5.2.3. Perception of Ecosystem Services and Their Functions to Reduce Disaster Risks .....	65
5.2.4. Perception of Responsibility to Protect and Restore Ecosystems.....	67
5.2.5. Perception of Possibilities to Conserve and Restore Ecosystems .....	70
5.3. Conclusion .....	72
5.4. References.....	73
6. Nature-Based Solutions for landslide risk reduction in informal settlements of Salvador da Bahia, Brazil .....	78
6.1. Introduction .....	78
6.2. Background.....	81
6.2.1. Ecosystem-based Adaptation and Disaster Risk Reduction .....	81
6.2.2. Risk and climate change profile of Salvador .....	84
6.2.3. Materials and methods.....	88
6.3. Results.....	91
6.4. Discussion.....	100

6.5. Conclusions .....	103
6.6. References.....	103
7. Synthesis .....	112
7.1. Summary of Key Findings .....	112
7.2. Discussion.....	115
7.3. Conclusions .....	121
8. References for chapters 1, 2, 3 and 7 .....	124

## List of Figures

Figure 1: Map A showing the city of Salvador da Bahia and the State of Rio de Janeiro and map B the municipality of Teresópolis within the State of Rio de Janeiro .....	23
Figure 2: EbA and Eco-DRR starting points, focal areas and common measures ...	34
Figure 3: Deforestation for housing in Teresópolis .....	38
Figure 4: Protective structures with shotcrete, drainage pipes and drain ditch in an informal settlement in Rio de Janeiro .....	40
Figure 5: Geotextiles for initial slope stabilization on a roadside in Teresópolis .....	41
Figure 6: During the extreme rainfall event in the Serrana Region in 2011, many slopes collapsed. Shortly after the event, Pesagro-Rio implemented slope stabilization and restoration measures, such as the one shown in the figure above in the municipality of Nova Friburgo. The slope was stabilized using palisades (a); later vetiver ( <i>Chrysopogon zizanioides</i> ) and other grasses and single trees were planted (b) ....	42
Figure 7: After a landslide, this slope bordering an informal settlement in Rio de Janeiro is being terraced and reforested. The measure is part of the program Mutirão Reflorestamento in 2015 .....	42
Figure 8: Area in Teresópolis affected by the disaster in 2011, 2 years later: flooded area with abandoned houses in the foreground and still visible landslides in the background .....	51
Figure 9: Four dimensions as basis for better participation .....	57
Figure 10: Research areas within the municipality of Teresópolis .....	58
Figure 11: Perception of vulnerability and its constituent dimensions.....	64
Figure 12: Perception of responsibility of the population and of the government .....	68
Figure 13: Perception of responsibility of the population .....	69
Figure 14: Perception of obstacles to contribute to conservation and restoration of ecosystems .....	71
Figure 15: Density of landslides occurrences based on data provided by REINDESC (Cemaden), referring to the period 2016–2024. ....	87
Figure 16: Relation of specific objectives and methods and data sources for operationalization .....	89
Figure 17: Photos of different solutions for landslide risk reduction.....	92

## List of Tables

Table 1: Overview of study's methodological approach.....	29
Table 2: Key sectors related to the environment: Overall goals and ecosystem-based approaches in rural Rio de Janeiro.....	39
Table 3: Summary of the landslide risk reduction measures in relation to function, co-benefits, costs, and challenges. ....	96

## List of Acronyms

APP	Área de Preservação Permanente [Permanent Preservation Area]
CCA	Climate Change Adaptation
DRR	Disaster Risk Reduction
CEMADEM	Centro Nacional de Monitoramento e Alertas de Desastres Naturais [National Center for Monitoring and Alerts of Natural Desasters]
CBD	Convention on Biological Diversity
CAR	Cadastro Ambiental Rural [Rural Environmental Register]
CODESAL	Defesa Civil de Salvador [Civil Defense of Salvador]
DRR	Disaster Risk Reduction
EbA	Ecosystem-based Adaptation
Eco-DRR	Ecosystem-based Disaster Risk Reduction
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit mbH
GI	Green Infrastructure
IBGE	Instituto Brasileiro de Geografia e Estatística [Brazilian Institute of Geography and Statistics]
IKI	Internationale Klimaschutzinitiative [International Climate Protection Initiative]
INPE	Instituto Nacional de Pesquisas Espaciais [National Institute of Space Research]
IPBES	Intergovernmental Science-Policy Platform on Biodiversity
IPCC	Intergovernmental Panel on Climate Change
MMA	Ministério do Meio Ambiente [Ministry of Environment]
NBS	Nature-Based Solutions
NGO	Non-Governmental Organization

NUPEDEC	Núcleo de Proteção e Defesa Civil [Center for Civil Protection and Defense]
PNMC	Política Nacional de Mudança do Clima [National Policy on Climate Change]
PNPDEC	Política Nacional de Proteção e Defesa Civil [National Policy of Civil Protection and Defense]
PNA	Plano Nacional de Adaptação [National Adaptation Plan]
REINDESC	Registros de Eventos de Inundação e Deslizamentos do Cemaden [Flood and Landslide Event Records of CEMADEN]
RL	Reservas Legais [Legal Reserves]
SDG	Sustainable Development Goals
SuDS	Sustainable Urban Drainage Systems
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Org.
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations Office for Disaster Risk Reduction
UNU-EHS	United Nations University Institute for Environment/Human Security

## Abstract

In recent decades, Brazil's relationship with hazards and disasters has become increasingly fraught. For instance, the devastating 2011 Rio de Janeiro floods and mudslides, which killed over 900 people, changed how researchers and policy makers considered disaster risk. Consequently, this thesis analyzes environmental issues not through the traditional more engineering lens but by investigating whether nature itself might offer better solutions.

Therefore, this research analyzes Nature-Based Solutions (NBS), which are actions to protect, restore, and sustainably manage ecosystems to address societal challenges such as climate change and disaster risk while providing certain co-benefits. This thesis examines this idea through three interconnected studies across different Brazilian contexts, from Rio de Janeiro's mountainous regions to Salvador da Bahia's informal settlements.

Brazil's vulnerability to disasters extends beyond the impacts of extreme weather events, although the exacerbating role of climate change cannot be overlooked. A significant contributing factor to this problem is the longstanding deforestation and environmental degradation, particularly within the Atlantic Forest (*Mata Atlântica*), coupled with less controlled urban development. These combined factors have undermined the natural systems that once provided protection to the region. The loss of forest cover, for example on steep slopes, and its replacement with informal settlements, significantly increases the likelihood of disasters.

The first major component of this thesis explores policy analysis in Rio de Janeiro State. Generally, Brazil has passed progressive environmental legislation, including the National Forest Code, which mandates Permanent Preservation Areas (APPs) along waterways and on steep slopes, among other landscape features. On paper, these laws should significantly protect against landslides and floods. In practice, however, enforcement has been uneven, particularly in areas where vulnerable populations have few housing alternatives.

This policy analysis reveals that the country is not lacking less in intentions or laws to protect the environment and adapt to climate change. For instance, the country has established the National Climate Change Policy, various disaster risk reduction

frameworks, and support ecosystem-based approaches. However, such guidelines are not always implemented, displaying what researchers call the “policy practice gap.” Frequently, local authorities favor more technical or engineering solutions, such as concrete barriers and drainage systems over, e.g., forest restoration that might be less effective in the long run.

The second study involves community perceptions, specifically in Teresópolis in Rio de Janeiro’s mountainous region. This research reveals a complex dynamic: while it may be assumed that populations residing in disaster-prone regions would readily adopt NBS to mitigate the risks of landslides and floods, the reality is more nuanced. Although local residents are aware of their vulnerability to such hazards, there appears to be a limited understanding of the relationship between ecosystem health and personal or community safety.

This finding suggests that measures to reduce disaster risk with NBS can succeed only if communities understand and support these measures revealing an “ecological literacy gap”. For instance, people might see forests as potential fire hazards or sources of pests rather than protective barriers. This perception highlights the need for more sophisticated public education about ecosystem services.

The third study examines the technical effectiveness of NBS in Salvador da Bahia’s informal settlements, comparing them directly with conventional engineering approaches. Through interviews and participatory workshops the authors found that experts frequently viewed NBS to be as effective as and more cost efficient than traditional technical or engineering measures for landslide prevention.

The potential cost-effectiveness of NBS warrants careful consideration. While engineered solutions such as retaining walls typically require substantial upfront investment and ongoing maintenance, research suggests that vegetation-based slope stabilization may provide comparable protection at potentially lower cost while delivering additional co-benefits including improved air quality, carbon sequestration, and enhanced biodiversity. However, the economic assessment of NBS remains complex, as comprehensive cost-benefit analyses must account for temporal variations in ecosystem performance, uncertainty in long-term effectiveness, and the challenge of monetizing multifunctional benefits that accrue to different stakeholder groups over varying time horizons.

Additionally, this thesis investigates broader questions about governance and financing. Implementing Nature-Based Solutions at scale requires coordination across multiple agencies and sectors—environmental, urban planning, disaster management, and social services. Brazil’s institutional landscape appears fragmented, with different agencies operating in silos.

Financing presents another challenge for increased implementation of NBS. Although NBS might be cost effective in the long run, they require different funding models than traditional infrastructure. The benefits of such solutions are diffuse and long term, making them difficult to quantify for budget-conscious officials seeking immediate results.

Overall, this research reveals a situation with significant potential constrained by institutional, social, and technical barriers. NBS are not panaceas, but they appear to offer genuine advantages over purely engineered approaches, particularly when implemented thoughtfully with community input. Ultimately, successful disaster risk reduction requires frequently hybrid approaches combining natural and engineered systems while addressing the social and governance factors that determine whether an intervention succeeds.

# 1. Introduction

In Brazil, the escalating frequency and severity of landslides and floods—rooted in complex interactions between geophysical vulnerabilities, anthropogenic landscape degradation, and climate change—underscores the urgent need for transformative approaches to disaster risk reduction (DRR) and climate change adaptation (CCA). Much of Brazil's population resides in densely populated urban centers along its extensive, and in large parts mountainous coastal zone; these regions are particularly susceptible to the impacts of extreme weather events and associated hydro-meteorological hazards. For instance, the January 2011 Rio de Janeiro floods and mudslides, which claimed over 900 lives and displaced 35,000 people, displayed the devastating consequences of these hazards (Marengo et al., 2021). Similarly, the 2022 Petrópolis floods, with 258 mm of precipitation in three hours, caused 231 fatalities, highlighting recurrent systemic failures in risk governance and land-use planning (Alcántara et al., 2023). An earlier disaster, the 1988 landslide in Petrópolis, claimed 171 lives and left 4,000 people homeless (Coelho-Netto et al., 2009), while the 1996 landslides in Rio de Janeiro destroyed 222 homes and killed 44 people (Fernandes et al., 2004). Furthermore, Salvador da Bahia experienced devastating landslide events in 2015 and 2022, and a notable disaster in 2015 claimed 14 lives and destroyed numerous hillside homes (Barretto & Silva, 2023). Climate change projections have indicated an increase in the intensity and frequency of extreme rainfall events in Brazil's coastal regions, which will likely exacerbate landslide and flood risk (Marengo et al., 2021).

Research demonstrates that historical deforestation of the Atlantic Forest (*Mata Atlântica*), unplanned urbanization on vulnerable slopes, and unsustainable land use practices have severely impaired important ecosystem services such as soil stabilization and water regulation (Nehren et al., 2013). For instance, a post-2011 study revealed that 92% of landslides occurred in areas where anthropogenic alterations had destabilized slopes, highlighting the interplay between ecosystem degradation and disaster vulnerability (MMA, 2011). In Brazilian cities, the rapid and unplanned urbanization processes have produced the occupation of exposed areas by socially vulnerable populations, significantly increasing disaster risk (Lange et al., 2018b). These informal settlements, known locally as *favelas*, are characterized by

precarious infrastructure, inadequate drainage systems, and the removal of natural vegetation, increasing susceptibility to landslides during extreme rainfall events (Coelho-Netto et al., 2009; Machado et al., 2019).

Despite Brazil's progressive policies, such as the National Climate Change Policy (PNMC) and the Forest Code implementation gaps persist. In this vein, DRR strategies remain overly reliant on engineered solutions (e.g., concrete barriers, drainage systems), which address symptoms rather than underlying risk drivers (Lange et al., 2018a; Renaud et al., 2016).

Ecosystem-based Adaptation (EbA) and ecosystem-based disaster risk reduction (Eco-DRR) are approaches under the Nature-Based Solutions (NBS) umbrella concept that integrate conservation, restoration and sustainable land management offer shared benefits for resilience, biodiversity and livelihoods (CBD – Secretariat of the Convention of Biological Diversity, 2009; Renaud et al., 2016; Doswald et al., 2021). However, their potential has remained underutilized due to fragmented governance, limited community awareness, and a lack of cost–benefit evidence (Doswald & Estrella, 2015).

Consequently, this thesis employs a tripartite structure to advance understanding of NBS for climate change adaptation and disaster risk reduction in Brazil, applying policy analysis, community engagement frameworks, and technical-evaluative approaches. The three publications included in this work address distinct yet complementary dimensions of NBS implementation, united by their focus on bridging the gap between ecological potential and operational realities in high-risk landscapes.

The publication “Ecosystem-Based Approaches for Disaster Risk Reduction and Climate Change Adaptation in Rio de Janeiro State” (Chapter 4; Lange et al., 2018a) establishes the macro-level context of this study, analyzing policy arrangements and institutional barriers to mainstreaming NBS in Brazil and especially in the State of Rio de Janeiro. Drawing from Rio de Janeiro's post-2011 disaster reforms, this work evaluates the interplay between national legislation (e.g., Forest Code, National Policy of the Civil Protection and Defense, abbreviated as PNPDEC in Portuguese) and local implementation challenges. The study reveals how Permanent Preservation Areas (Áreas de Preservação Permanente - APPs), while legally mandated, often fail to reduce risks due to enforcement gaps and competing land-use priorities. This analysis

highlights practical EbA/Eco-DRR initiatives, distinguishing between those already implemented and those currently proposed in the region. The discussion evaluates the viability of scaling these NBS while addressing logistical, ecological, and socio-political constraints specific to Rio de Janeiro's geographic and institutional landscape. The chapter concludes with a critique of Brazil's "siloed" risk management, proposing integrated planning frameworks aligning NBS with the Sustainable Development Goals (SDG) and climate resilience agendas.

Focusing on the municipality of Teresópolis in the *Serrana* Region of the state of Rio de Janeiro, the second publication (Chapter 5; Lange et al., 2016) investigates the human behavioral underpinnings of NBS adoption, analyzing community perceptions. Assessing these perceptions is critical in designing effective awareness initiatives and fostering local engagement in Eco-DRR and EbA. To identify barriers to engagement, the researchers conduct a mixed-methods perception analysis. The findings reveal a complex set of perceptions among residents, who recognize their vulnerability to disasters but lack a clear understanding of how ecosystem health influences risk. Furthermore, the study identifies a limited sense of personal responsibility for mitigation efforts and a perception of few opportunities for meaningful involvement in Eco-DRR and EbA initiatives. The study concludes that addressing gaps in ecological literacy, fostering ownership, and creating participatory opportunities should form the foundations of awareness programs to advance Eco-DRR and EbA adoption in the region. Thus, NBS success hinges not only on biophysical efficacy but also on culturally resonant education campaigns and trust-building between communities and institutions. These findings challenge top-down DRR models, advocating for co-designed interventions that leverage local knowledge and address socio-economic inequities.

The third publication, "Nature-Based Solutions for Landslide Risk Reduction in Informal Settlements of Salvador da Bahia, Brazil" (Chapter 6; Lange et al., submitted, after review currently under revision) examines NBS as a strategy for landslide risk reduction in Salvador da Bahia. This study compares the efficacy and benefits of NBS to those of conventional engineering approaches. Using qualitative social research methods, including semi-structured interviews and participatory workshops within vulnerable communities, the research evaluates stakeholder perspectives and practical outcomes. The findings indicate that experts frequently perceive NBS to be

as effective as engineered structural measures, but NBS are frequently more cost efficient. Additionally, NBS offer co-benefits such as enhanced ecological resilience and support for sustainable urban development. The study highlights a critical gap in awareness, emphasizing the need for sensitization to improve acceptance and implementation of NBS.

Together, these three publications form a cohesive body of work that both addresses critical research gaps and provides a comprehensive, multi-faceted explanation of the complexities and opportunities for mainstreaming NBS for CCA and DRR in Brazil.

## 2. Nature-Based Solutions for Disaster Risk Reduction and Climate Change Adaptation

Nature-Based Solutions (NBS) have emerged as promising alternatives to conventional engineering approaches for DRR and CCA. Although this doctoral thesis focuses on these solutions' application in these two critical societal challenges, NBS represent a broader concept encompassing diverse environmental interventions contributing to food and water security, human health, biodiversity loss, and environmental degradation. The United Nations Environment Assembly (UNEA, 2022: page 2) defines NBS as “ ... actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits ,... ”. Overall, NBS encompass various approaches, including two complementary frameworks central to this thesis: Ecosystem-based Disaster Risk Reduction (Eco-DRR), which emphasizes on reducing disaster risks through sustainable ecosystem management, and Ecosystem-based Adaptation (EbA), which emphasizes to build climate resilience (Doswald et al, 2021; Nehren et al., 2023; Ruangpan et al., 2020; Walz et al. 2021). These frameworks align with global agreements such as the Sendai Framework for DRR and the Paris Agreement, underscoring NBS's role in achieving the SDGs (UNEP, 2021).

In Brazil, the application and recognition of NBS have been steadily growing, albeit with challenges and opportunities (Seleguim et al., 2024; Campello Torres et al., 2023). Historically, Brazil has had a rich tradition of conservation, particularly through its extensive protected areas system and the National Forest Code (Lange et al., 2018a; MMA, 2011). More recently, the concept of NBS has gained traction within national policy dialogues, driven mainly by increasing awareness of the potential of NBS for addressing societal challenges in Brazil (Seleguim et al., 2024; Campello Torres et al., 2023). Equally important, urban planning initiatives in cities like Rio de Janeiro and Salvador da Bahia have begun exploring NBS, often in response to severe climate-related disasters, highlighting a reactive rather than proactive integration of NBS (Lange et al., 2018a; Sandholz et al., 2018).

The evolution of NBS terminology has reflected its interdisciplinary roots. For instance, early concepts like green infrastructure (GI) and sustainable urban drainage systems (SuDS) laid the groundwork for modern NBS by emphasizing nature-mimicking techniques for stormwater management to reduce flood risk (Apostolaki, 2025; Fletcher et al., 2015). Over time, NBS expanded to include strategies such as wetland restoration, afforestation, and agroecological practices, which reduce risks like floods, droughts, and landslides while fostering biodiversity (Ruangpan et al., 2020).

Research has indicated that NBS reduce risks through biophysical processes that stabilize ecosystems and regulate hydrological cycles (Bowyer et al., 2024; Johnson et al., 2022; Keesstra et al., 2018; Ruangpan et al., 2020). For landslides, vegetation root systems enhance slope stability by increasing soil cohesion and reducing pore-water pressure (Arce-Mojica et al., 2019; Coelho-Netto et al. 2009; Lann et al., 2024). Studies have shown that forests and grasslands improve water infiltration, attenuating surface runoff and erosion (Lele, 2009). In flood-prone areas, riparian buffers and floodplain restoration dissipate flood energy (Serra-Llobet et al., 2021).

Ecosystem-based approaches have demonstrated strong empirical support for reducing climate-linked risks and disaster vulnerabilities, with studies confirming their efficacy across diverse contexts (Bowyer et al., 2024; Keesstra et al., 2018). Both, EbA and Eco-DRR, exhibit high reliability in hazard mitigation, particularly in urban settings, coastal settings and mountainous regions. Evidence has underscored the critical role of ecosystem functions in risk reduction, such as forest management for wildfire control; urban green spaces for flood regulation; and slope-stabilizing vegetation for landslide prevention (Johnson et al., 2022; Ruangpan et al., 2020; Sudmeier-Rieux et al. 2021).

Moreover, research has demonstrated that NBS often exhibit greater cost-efficiency compared to conventional grey infrastructure, particularly when accounting for the value of multiple ecosystem services and long-term sustainability (Chausson et al., 2020; Vicarelli et al., 2024). For instance, vegetated slopes reduce landslide susceptibility 20–40%, more than engineered retaining walls (Vicarelli et al., 2024). Similarly, urban green spaces can cut flood volumes by up to 30% through rainwater retention (Apostolaki, 2025). Cost–benefit analyses have further revealed that NBS

frequently have lower lifecycle costs than conventional measures due to reduced maintenance and co-benefits like carbon sequestration (Sudmeier-Rieux et al., 2021).

Beyond risk reduction, NBS deliver multifaceted co-benefits aligned with the sustainable development goals (SDGs). Diverse ecosystems support pollinators; improve soil health; and sequester carbon, which is critical for mitigating global warming (Eggermont et al., 2015; Seddon et al., 2020). Additionally, urban NBS, such as green roofs and permeable pavements for flood reduction, reduce heat island effects and improve air quality and public health (Kabisch & van den Bosch, 2017). Socially, NBS can empower marginalized communities by integrating traditional ecological knowledge into adaptation planning. For example, community-led reforestation in Nepal reduced landslide risks while restoring livelihoods through non-timber forest products (Sudmeier-Rieux et al., 2021). However, equitable outcomes depend on inclusive governance because marginalized groups often face exclusion from decision-making (Toxopeus et al., 2020; Tozer et al., 2020).

Applying NBS in informal urban contexts involves distinct challenges and opportunities that demand nuanced approaches (Ronchi & Arcidiacono, 2019). In Global South countries, where informal settlements are prevalent and highly vulnerable to climate impacts, NBS offer particularly relevant, equitable solutions for DRR and CCA (Kibii et al., 2025). Case studies from Rio de Janeiro highlight persistent obstacles, including precarious land tenure systems, high-density built environments, and inadequate drainage infrastructure, which hinder ecosystem-based interventions (Handzic, 2010; Lange et al. 2018a; Lourenço, 2020; Sandholz et al. 2018). Divergences between formal planning frameworks and on-the-ground realities in informal settlements require innovative governance frameworks to reconcile institutional and community priorities (Alfonsin & Mota Júnior, 2024; Balbim, 2023). Successful implementation requires proactive community engagement to address initial skepticism, particularly where natural vegetation is misperceived as a hazard source rather than a protective measure (Lange et al., 2016; Lesser & Brandes, 2023). Inclusive participatory mechanisms that integrate informal residents into consultation and decision-making, alongside cross-sectoral coordination among disaster management, urban planning, and environmental agencies, have emerged as important success factors (Fianoo et al., 2024; Lange et al., 2018a; Nalumu & Perrotti, 2024). Given urgent safety needs in high-risk zones—characterized by steep slopes and pre-existing structural

vulnerabilities, among other factors—hybrid strategies blending green and gray infrastructure often present the most viable solutions (Anderson et al., 2022; Depietri, & McPhearson, 2017; Lange et al., 2018a). In such circumstances, gray infrastructure comprises conventional, human-engineered structures designed to provide services such as water management, flood control, and coastal protection. Examples of these services include dams, levees, seawalls, pipes, tunnels, and treatment plants and green infrastructure utilizes natural or semi-natural systems to deliver similar services, often with added ecological and social benefits (Browder et al., 2019).

Implementing NBS involves multifaceted challenges, including governance fragmentation, financial constraints, and technical knowledge gaps. Frequently, governance barriers stem from siloed policies, inadequate stakeholder engagement, and path dependencies favoring traditional grey infrastructure over NBS, hindering integrated planning and long-term maintenance (Martin et al., 2023; Ruangpan et al., 2020). Financial limitations arise from high upfront costs, misaligned funding models prioritizing short-term returns, and difficulties in quantifying NBS co-benefits to justify investments (Vicarelli et al., 2024). Technically, the lack of standardized metrics for evaluating NBS performance, limited long-term monitoring data, and site-specific ecological requirements complicate scalability and replication (Gonzalez-Ollauri et al., 2021; Kumar et al., 2021).

Overall, NBS offer transformative potential for DRR and CCA by harmonizing ecological integrity with societal needs. Despite technical and governance challenges, the cost-effectiveness, multifunctionality, and alignment with global sustainability agendas position NBS as indispensable tools. Bridging science–policy divides and fostering community-led innovation will be pivotal to mainstreaming NBS. As the UNEA Resolution (2022) affirms, NBS are essential strategies for building a resilient future (Calliari et al., 2022; Nehren et al., 2023; Welden et al., 2021).

Despite the growing recognition of NBS as effective approaches for DRR and CCA, several significant research gaps remain, particularly in rapidly urbanizing areas and informal settlements of the Global South. These gaps are detailed below:

- Governance and Institutional Barriers

A critical gap exists in understanding the governance frameworks required to mainstream NBS. In this vein, Martin et al. (2023) highlighted institutional

fragmentation, path dependencies favoring gray infrastructure, and a lack of political commitment as major barriers. Multi-level governance—collaboration across sectors and scales—has been proposed as an enabler but remains under-researched in practice (Kabisch & van den Bosch, 2017). Frequently, legal and policy frameworks lack specificity for NBS, resulting in voluntary measures that cannot compete with traditional infrastructure projects (European Commission, 2020). Thus, further research is needed to design adaptive governance models that integrate NBS into urban planning, disaster risk reduction, and climate adaptation policies (Martin et al., 2023).

- Scaling from Local to Systemic Implementation

Most NBS research has examined small-scale, urban applications (e.g., green roofs and rain gardens), with limited attention to large-scale, systemic approaches (Ruangpan et al., 2020). Although small-scale NBS are effective for frequent, low-intensity events, their scalability for mitigating extreme hydro-meteorological risks (e.g., riverine floods, droughts) remains uncertain (Thorslund et al., 2017). Hybrid solutions—combining NBS with gray infrastructure, have been understudied despite their potential to enhance resilience (Alves et al., 2019). Consequently, research should address spatial mismatches, such as upstream-downstream dynamics in watershed management, and evaluate long-term performance across diverse biogeographical contexts (Seddon et al., 2020).

- Quantifying Co-Benefits and Cost-Effectiveness

Currently, there is not a robust evidence base on the multifunctionality of NBS. Many have praised NBS for their co-benefits (e.g., biodiversity, carbon sequestration), but there are no standardized metrics to quantify these outcomes (Arce-Mojica et al., 2019; Martin et al., 2023; Raymond et al., 2017). Cost–benefit analyses often overlook intangible benefits (e.g., health improvements, social cohesion), skewing comparisons toward gray infrastructure (Cohen-Shacham et al., 2016). Along these lines, Ruangpan et al. (2020) emphasize the need for lifecycle assessments and tools to evaluate trade-offs between ecological, economic, and social outcomes. Developing region-specific databases on NBS performance and costs is critical to justify investments (Faivre et al., 2017).

- Maladaptation and Ecosystem Disservices

Recent research highlights the importance of carefully considering potential ecosystem disservices and the risk of maladaptation when implementing nature-based solutions (NbS) in urban environments (Seddon et al. 2020). Ecosystem disservices—such as increased allergenic pollen production and the proliferation of pest populations—can arise if urban green spaces are not properly planned and managed (Pereira et al., 2023). For example, high vegetation density may boost biodiversity but can also elevate allergen exposure and pest issues, especially if excessive watering is used or if species with high allergenic potential are selected (Pearlmutter et al., 2019). Additionally, maladaptation may occur when tree or plant species are chosen without regard to their suitability for future urban climates, leading to high mortality rates and a subsequent loss of intended ecosystem benefits (Duffaut et al., 2022). To maximize the positive impacts of NbS and minimize negative outcomes, it is essential to integrate adaptive management, select appropriate species, and consider both ecosystem services and disservices during the planning and implementation phases

- Financing and Private Sector Engagement

Current financing models rely heavily on public funding, which is insufficient for large-scale NBS (Faivre et al., 2017; Martin et al., 2023). In this vein, Martin et al. (2023) identified a lack of private sector involvement due to perceived risks and the public-good nature of NBS. To date, innovative mechanisms, such as green bonds, payment for environmental services schemes, and blended finance, have been understudied (European Commission, 2020). Additionally, integrating NBS into corporate sustainability strategies requires clearer regulatory incentives and market-based valuation of ecosystem services (Seddon et al., 2020).

- Stakeholder Engagement and Equity

Frequently, equitable stakeholder participation in NBS design and implementation is neglected. For example, Martin et al. (2023) note that top-down approaches exacerbate conflicts, particularly when NBS displace vulnerable communities or prioritize elite interests. Conversely, inclusive co-design processes enhance legitimacy but require methodologies to reconcile divergent values and knowledge systems (Kabisch & van den Bosch, 2017). Implementing NBS requires both community participation and acceptance, yet there has been limited research on how residents

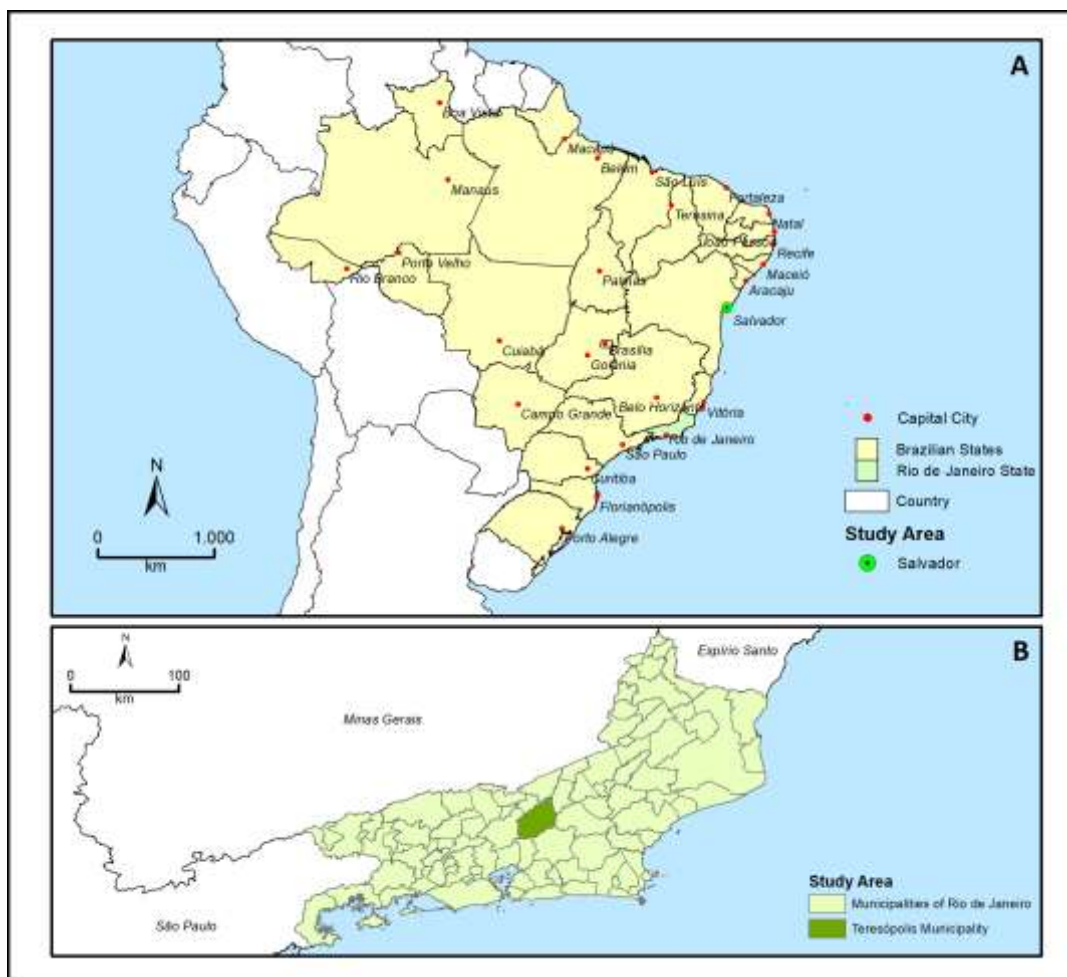
perceive and value ecosystem services for DRR and CCA (Anderson & Renaud, 2021; Ke et al., 2024; Quintas-Soriano et al., 2018). Therefore, research needs to explore participatory frameworks that empower marginalized groups and address distributive justice, particularly in contexts where land ownership and access complicate NBS deployment (Kibii et al., 2025).

The persistent gaps in governance frameworks, scalable implementation strategies, standardized co-benefit quantification, equitable stakeholder engagement, and sustainable financing mechanisms underscore the multifaceted challenges facing NBS for DRR and CCA adoption. As Martin et al. (2023) and Seddon et al. (2020) argue, overcoming these barriers would require not only interdisciplinary research but also a paradigm shift in how policymakers, scientists, and communities conceptualize infrastructure and risk management. For instance, integrating polycentric governance models (Kabisch & van den Bosch, 2017) with hybrid infrastructure designs (Alves et al., 2019) could bridge the spatial and institutional mismatches that currently limit NBS scalability. Simultaneously, advancing participatory frameworks that prioritize distributive justice (Raymond et al., 2017) and leveraging innovative financing instruments (Faivre et al., 2017) are critical to ensuring that NBS transcend pilot projects and become embedded in systemic climate resilience strategies. Without urgent progress in these areas, the transformative potential of NBS will remain constrained by fragmented implementation and undervalued co-benefits, perpetuating society's reliance on unsustainable gray infrastructure.

### 3. Research Design and Analytical Framework

Addressing some of the aforementioned research gaps, this dissertation addresses critical gaps in understanding the role, efficacy, and socio-institutional dynamics of NBS for DRR and CCA in Brazil.

Figure 1: Map A showing the city of Salvador da Bahia and the State of Rio de Janeiro and map B the municipality of Teresópolis within the State of Rio de Janeiro (Author: Adriano Vasconcellos, source data from IBGE, 2025)



Drawing on three interconnected studies presented in chapter 4, 5 and 6 (Lange et al. 2018a; Lange et al. 2016; Lange et al. submitted, after review currently under revision) conducted in the municipality of Teresópolis, the State of Rio de Janeiro and the City of Salvador da Bahia (Fig. 1), the research questions are meant to explore governance and socio-economic and technical dimensions of NBS implementation in high-risk urban and rural contexts in Brazil, as explored below.

## **1. How can ecosystem-based approaches (EbA and Eco-DRR) be effectively integrated into disaster risk reduction (DRR) and climate change adaptation (CCA) strategies in Rio de Janeiro State?**

This question unpacks into three interrelated sub-questions addressed by Lange et al. (2018a):

1. **Linkages:** How do deforestation, land-use changes, and ecosystem degradation amplify disaster risks in Rio de Janeiro, and what role can ecosystem restoration play in reducing these risks?
2. **Policies:** What are the existing CCA/DRR policies at the national and state levels, and how do they incorporate biodiversity and ecosystem management?
3. **Implementation Potential:** What is the status and future potential of EbA/Eco-DRR measures in reducing risks due to natural hazards like landslides and floods, and what barriers limit their broader adoption?

## **2. What factors influence community acceptance and participation in NBS implementation?**

This main research question raises three sub-questions to be addressed in Lange et al. 2016 and Lange et al. (submitted, after review currently under revision):

- **Risk perception:** How do risk perception, knowledge of ecosystem functions, and trust in institutions shape willingness to adopt NBS?
- **Participation:** What participatory approaches enhance long-term stewardship of NBS?
- **Customization:** How can NBS be tailored to provide immediate socio-economic co-benefits to incentivize participation?

## **3. How do NBS compare to conventional engineering measures in reducing landslide risks in informal settlements?**

The third study (Lange et al., submitted, after review currently under revision) examined NBS for landslide risk reduction, based on a case study in *favelas* of Salvador da Bahia, contrasting them with gray and hybrid infrastructure such as retaining walls and reforestation. Key sub-questions include the following:

- **Effectiveness of NBS implementation:** Under what social conditions are NBS equally or more effective than conventional measures?
- **Benefits of NBS:** What are the benefit trade-offs between NBS, hybrid and engineered solutions?

Together, these questions advance a holistic understanding of NBS as socio-ecological interventions. By bridging governance aspects (Question 1), social perception and participation (Question 2) and technical efficacy (Question 3), this thesis provides a framework for transforming DRR/CCA paradigms in Brazil.

### 3.1. Analytical framework: Integrating Vulnerability, Risk Perception, and Ecosystem Services

Integrating vulnerability, risk perception, and ecosystem services into a cohesive analytical framework is critical for addressing socio-ecological challenges exacerbated by climate change and anthropogenic pressures such as land use intensification and urbanization. This approach bridges disciplinary silos, offering actionable insights for building resilience in complex human-environment systems. By foregrounding the Intergovernmental Panel on Climate Change's (IPCC, 2023) definition of vulnerability, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) conceptualization of ecosystem services, and contemporary risk perception concepts, this framework transcends reactive disaster management, advocating for proactive, holistic stewardship.

The IPCC's Sixth Assessment Report (AR6) defines vulnerability as the predisposition or propensity to be adversely affected by climate-related hazards (IPCC, 2023). This work encompasses a system's sensitivity to harm and its capacity to cope and adapt. Sensitivity is the degree to which systems are adversely affected by climatic stressors, and adaptive capacity is the ability to adjust to impacts through institutional, technological, or behavioral changes. This concept emphasizes that vulnerability is not static but shaped by factors such as intersecting socio-economic inequalities, governance structures, and ecological degradation. For instance, marginalized communities in coastal regions frequently exhibit heightened sensitivity due to limited infrastructure and unequal access to resources,

perpetuating cycles of poverty and environmental risk (Calil et al., 2017; Phuong et al., 2023).

Risk perception involves the cognitive, emotional, and social processes through which individuals and communities interpret environmental hazards and is shaped by factors such as knowledge, experience, values, attitudes, and social context (Slovic & Weber, 2002). Risk perception influences community responses to environmental hazards and is as the linchpin between vulnerability and NBS when better participation of local population is needed (Wong-Parodi et al., 2024). Contemporary research has identified three key dimensions of risk perception, as described here:

1. **Cognitive distancing:** The tendencies to perceive climate risks as temporally or geographically remote, often observed in populations with low direct exposure to extreme events (Cipriani et al., 2024).
2. **Agency and trust:** The willingness to adopt adaptive measures correlates strongly with perceptions of governance credibility and transparency (Wong-Parodi et al., 2024).
3. **Socio-cultural filters:** The traditional knowledge systems mediate scientific risk assessments, creating synergies or conflicts in hazard interpretation (Cipriani et al., 2024).

Addressing cognitive distancing, agency-trust dynamics and socio-cultural filters enables the operationalization of risk perception as a bridge between vulnerability assessments and NBS, particularly in contexts requiring equitable local engagement (Aslam & Rana, 2022; Jang et al., 2020).

The IPBES 2019 Global Assessment defined ecosystem services as “...nature’s contributions to people,...” encompassing provisioning (e.g., food); regulating (e.g., flood mitigation); cultural (e.g., recreational value); and supporting (e.g., soil formation) services (IPBES, 2019: page 15). A critical advancement in this framework has been the emphasis on cascading benefits, where regulating services (e.g., flood control) directly reduce exposure to hazards while simultaneously enhancing adaptive capacity through co-benefits like livelihood diversification (Maund et al., 2020). For example, urban green infrastructure in temperate regions mitigates heat islands (regulating service) while fostering community cohesion (cultural service), addressing both

ecological and social vulnerabilities (Pan & Qu, 2024). Similarly, agroforestry systems in tropical zones improve soil stability (supporting service) and reduce crop sensitivity to droughts, illustrating the multifunctional role of ecosystems in risk reduction (Munns et al., 2017). The IPBES framework further introduced biocultural linkages, recognizing indigenous knowledge systems as vital to sustaining ecosystem services in contexts where formal governance structures are absent or ineffective (Maund et al., 2020). Ecosystem services provide the conceptual foundation for NBS such as EbA and Eco-DRR by contributing to multi-scale resilience. Additionally, the concept of ecosystem services within NBS prioritizes both ecological functionality and equitable socio-economic outcomes.

The integrative analytical framework synthesizes vulnerability, risk perception, and ecosystem services into a cohesive socio-ecological model that recognizes their bidirectional interdependencies, where vulnerability is both a driver and outcome of risk perception, mediated by the availability, accessibility, and cultural valuation of ecosystem services (Peter, 2020; Yang et al., 2024). This tripartite relationship operates through dynamic feedback loops, wherein adaptive actions alter ecosystem services, which subsequently reshape vulnerability thresholds and collective risk narratives (Caro et al., 2020; Peter, 2020). Contemporary scholars have emphasized the necessity of moving beyond siloed assessments to adopt a systems-based approach considering nonlinear interactions across spatial, temporal, and institutional scales (Thiault et al., 2021; Yang, 2024).

### 3.2. Overview of methodological approaches

The three studies examined in this work collectively employed interdisciplinary, mixed-methods frameworks to analyze NBS for DRR and CCA in Brazil, integrating social, ecological, and technical dimensions.

The Rio de Janeiro policy analysis (Chapter 4; Lange et al., 2018a) explored institutional and governance challenges through document reviews of national/state policies (e.g., PNPDEC, Forest Code) and case studies of programs like *Mutirão Reflorestamento*. Stakeholder consultations with policymakers and civil defense teams revealed fragmentation in DRR/CCA governance. Beyond this, field observations assessed slope stabilization interventions and highlighted the protective roles of APPs.

In Teresópolis (Chapter 5; Lange et al., 2016), mixed-methods participatory research explored risk perception and adaptive capacity. Household surveys with structured questionnaires quantified residents' awareness of landslide triggers and ecosystem services, whereas focus groups and participatory mapping identified spatial risk patterns and culturally valued ecological features. Key informant interviews with community leaders and NGOs highlighted behavioral barriers, such as skepticism toward NBS, which informed targeted sensitization campaigns linking ecosystem restoration to DRR.

In Salvador da Bahia (Chapter 6; Lange et al., submitted, after review currently under revision), the research combined qualitative and quantitative approaches to evaluate landslide risk reduction measures. Semi-structured interviews with municipal staff, engineers, and academics provided expert insights, while participatory workshops and focus groups in high-risk communities captured local perceptions. Quantitative analyses compared the cost effectiveness of NBS versus hybrid and gray infrastructure. Site selection was collaborative, involving Salvador's Civil Defense (CODESAL) to prioritize areas with high risk, institutional capacity, and community engagement.

Common methodological dimensions across the studies included interdisciplinary integration (e.g., blending geotechnical data with social surveys); stakeholder engagement (e.g., co-design workshops with communities, expert snowball sampling); and policy-informed fieldwork (e.g., aligning NBS with Brazil's Forest Code). Participatory techniques ensured context-specific methods, whereas mixed-methods frameworks balanced qualitative depth (e.g., narratives from focus groups) with quantitative approaches (e.g., cost–benefit estimates). Collectively, these approaches addressed the socio-ecological complexity of NBS implementation.

To provide a concise overview of the methodological approaches employed across the three publications, key aspects of each study are summarized (Tab. 1).

Table 1: Overview of study's methodological approach

<b>Paper (Chapter)</b>	<b>Research Design</b>	<b>Study Location(s)</b>	<b>Data Collection Methods</b>	<b>Key Data Sources / Participants</b>
Lange et al., 2018 (Chapter 4)	Policy analysis, case study	Rio de Janeiro State, Brazil	Document analysis	National and sub-national legislation, policy documents, academic literature
Lange et al., 2016 (Chapter 5)	Mixed-methods, perception Analysis	Teresópolis, Rio de Janeiro State, Brazil	Surveys, focus groups, stakeholder interviews	Community residents, local leaders, civil defense representatives
Lange et al., submitted, after review currently under revision (Chapter 6)	Qualitative social research, case study	Salvador da Bahia, Brazil (informal settlements)	Semi-structured interviews, focus groups	Local experts (e.g., urban planners, environmental specialists), community members

The diverse methodological approaches adopted in each paper are highlighted (Table 1), reflecting the multi-faceted nature of NBS research, from macro-level policy analysis to micro-level community perceptions and technical efficacy assessments in specific urban contexts.

## 4. Ecosystem-Based Approaches for Disaster Risk Reduction and Climate Change Adaptation in Rio de Janeiro State

Lange, W., Sandholz, S., Viezzer, J., Becher, M., & Nehren, U. (2018a). Ecosystem-Based Approaches for Disaster Risk Reduction and Climate Change Adaptation in Rio de Janeiro State. In Springer series on environmental management (pp. 345–359). [https://doi.org/10.1007/978-3-319-89644-1\\_22](https://doi.org/10.1007/978-3-319-89644-1_22)

This is the author's original manuscript of the submitted article.

**Abstract** In the mountain ranges of the Rio de Janeiro state (Região Serrana), natural hazards such as landslides, mudslides and flooding are recurrent, causing considerable human and economic losses. These events are of natural origin, but landscape degradation contributes significantly to increased disaster risk. Extreme climatic events that triggered past disasters are predicted to increase in frequency and intensity in the future. The approaches of Ecosystem-based Adaptation (EbA) and Ecosystem-based Disaster Risk Reduction (Eco-DRR) aim at the sustainable management, conservation and restoration of ecosystems to cope with the adverse effects of climate change and reduce the impacts of natural hazards. In this context, this chapter provides a comprehensive overview of climate change adaptation (CCA) and disaster risk reduction (DRR) policies at national and state level, before analyzing the linkages between CCA/DRR and biodiversity and ecosystem management. Finally, EbA/Eco-DRR measures that are currently planned or have already been implemented are presented, and the further potential and limitations of EbA/Eco-DRR in Rio de Janeiro state is discussed.

**Keywords** Natural hazards, Disaster risk reduction, Climate change adaptation, Ecosystem-based approaches, Rio de Janeiro state

## **Resumo (Português) Abordagens Ecosistêmicas para a Redução de Risco de Desastres e Adaptação às Mudanças Climáticas no Estado do Rio de Janeiro**

Na Região Serrana do estado do Rio de Janeiro, os riscos naturais, tais como deslizamentos de terra e inundações, são recorrentes, ocasionando consideráveis perdas humanas e econômicas. Esses eventos são de origem natural, mas a degradação da paisagem contribui significativamente para aumentar o risco de desastres. A previsão é que os eventos climáticos extremos que provocaram desastres passados aumentarão em número e intensidade no futuro. As abordagens da adaptação baseada nos ecossistemas (EbA na sigla inglesa) e a redução do risco de desastres baseada em ecossistemas (Eco-DRR na sigla inglesa) visam a gestão sustentável, conservação e restauração de ecossistemas para enfrentar os efeitos adversos das mudanças climáticas e reduzir os impactos dos riscos naturais. Neste contexto, este capítulo fornece uma visão abrangente das políticas de adaptação às mudanças climáticas (CCA na sigla inglesa) e redução de risco de desastres (DRR na sigla inglesa) a nível nacional e estadual, antes de analisar os vínculos entre CCA/DRR, biodiversidade e gestão de ecossistemas. Finalmente, algumas medidas exemplares de EbA/Eco-DRR que estão atualmente planejadas ou já foram implementadas são apresentadas antes de concluir sobre potenciais e limitações adicionais.

**Palavras-chave** Riscos naturais, Redução de risco de desastres, Adaptação às mudanças climáticas, Abordagens baseadas nos ecossistemas, Estado do Rio de Janeiro

## **Resumen (Español) Enfoques Ecosistémicos para la Reducción de Riesgo de Desastres y Adaptación al Cambio Climático en el Estado de Río de Janeiro**

En la región serrana del estado de Río de Janeiro, los riesgos naturales como deslizamientos de tierra, deslaves e inundaciones son recurrentes y ocasionan considerables pérdidas humanas y económicas. Si bien estos fenómenos son de origen natural, la degradación del paisaje contribuye significativamente a aumentar el riesgo de desastres. Se estima que los mismos eventos climáticos extremos que provocaron desastres en el pasado, aumentarán en número e intensidad en el futuro. Los enfoques de adaptación (EbA por sus siglas en inglés) y de reducción del riesgo

de desastres (Eco-DRR por sus siglas en inglés) basados en los ecosistemas, tienen como objeto el manejo sostenible, la conservación y la restauración de los ecosistemas para hacer frente a los efectos adversos del cambio climático y reducir los impactos de los riesgos naturales. En este contexto, el presente capítulo busca proporcionar una visión comprensiva e integral de las políticas de adaptación al cambio climático (CCA por sus siglas en inglés) y de reducción del riesgo de desastres (DRR por sus siglas en inglés) existentes a nivel nacional y estatal, como base para analizar los vínculos entre CCA/DRR, biodiversidad y el manejo de ecosistemas. Finalmente, se presentan algunas medidas de EbA/Eco-DRR implementadas o en fase de planeación, su potencial y las limitaciones adicionales que conllevan para el caso particular del estado de Río de Janeiro.

**Palabras clave** Riesgos naturales, Reducción de riesgo de desastres, Adaptación al cambio climático, Enfoques basados en ecosistemas, Estado de Rio de Janeiro

#### 4.1. Introduction

In the state of Rio de Janeiro (RJ), natural hazards such as landslides, mudslides and floods are recurrent, causing considerable human and economic losses. Natural and climatic factors, such as pronounced topography as well as rock formations and weathering mantels that are prone to slipping, promote the occurrence of such events. These natural risk factors are, however, considerably reinforced by human interventions. The Atlantic Forest (*Mata Atlântica*), which contributes to stabilize the slopes, has seen large scale deforestation since European colonization, and thus significantly increased the risk of flooding and landslides (Heinrich et al. 2010; Nehren et al. 2013). On top of this, extreme climatic events already known to trigger disasters are predicted to increase in number and intensity in the future (Marengo 2014).

To cope with such challenges, disaster risk reduction (DRR) in RJ state relies mainly on technical safeguarding and early warning systems, whereas the implementation of concrete measures for climate change adaptation (CCA) are still in an early stage. Ecosystem-based measures for DRR (Eco-DRR) or Adaptation (EbA) have only rarely been planned and implemented although they have a high potential for reducing underlying risk factors and contribute to more sustainable development in general due to their multiple co-benefits. Therefore, according to Emerton et al. (2017:38), “ecosystems should be treated, counted and invested in as an integral part of climate-

compatible development infrastructure — as a stock of facilities, services and equipment which are needed for the economy to function, grow, adapt and maintain its resilience in the face of climate change and other hazards”. The growing importance of EbA and Eco-DRR as well as the recognition of their benefits are proven by their acknowledgment in two major global initiatives, the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals (SDGs).

This chapter is a science-policy paper based on a review of the relevant scientific literature and policy documents as well as own observations. Section 2 describes the concepts of EbA and Eco-DRR as a basis for further understanding of the chapter. Section 3 provides an overview of general policies at national and RJ state level regarding CCA and DRR focusing on ecosystem-based policies. For a better understanding of the linkages between CCA/DRR, land and ecosystem management in RJ state, section 4 shows how deforestation and overexploitation contributes to increased disaster risk. Section 5 describes existing ecosystem-based approaches in RJ state and analyzes the potential of these measures before concluding the chapter with an overview of existing challenges on broader implementation of ecosystem-based policies and measures in Southeastern Brazil.

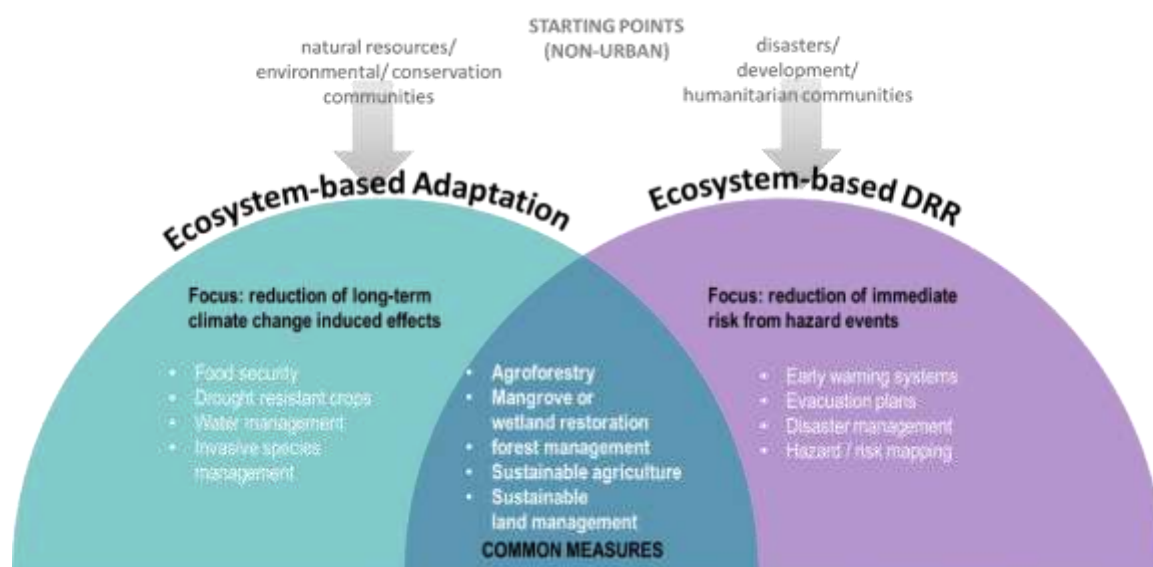
## 4.2. Ecosystem-Based Approaches for Reducing Risks and Adapting to Climate Change

EbA and Eco-DRR both aim at the sustainable management, conservation and restoration of ecosystems to cope with the adverse effects of climate change or to reduce the impacts of natural hazards (Munang et al. 2013; Renaud et al. 2013).

“Ecosystem-based adaptation is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change” (CBD 2009: 41). The goal of EbA is to reduce the vulnerability of people and ecosystems against climate change impacts to maintain and increase resilience (Lo 2016). For example, maintaining or restoring mangroves along coastlines could reduce the risk of coastal flooding, storms, coastal erosion and saline intrusion, and supports adaptation to sea level rise (Barbier 2016; Guannel et al. 2016).

Eco-DRR can be defined as “the sustainable management, conservation, and restoration of ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilient development” (Estrella and Salismaa 2013: 30). Eco-DRR approaches are often called no-regret strategies as they provide additional co-benefits that traditional, mostly engineering-based approaches, do not usually offer (Renaud et al. 2016; Daigneault et al. 2016). Common examples are the reforestation of slopes to reduce landslide risks or the use of wetlands as retention areas to reduce flood risks (Lange et al. 2014, 2016; Brink et al. 2016). Both EbA and eco-DRR overlap in making use of well-managed and functioning ecosystems, their goods and services, to help people and communities adapt to the adverse impacts of climate change and disasters, often with similar measures, despite the different focal areas (Fig. 2). Both allow for hybrid approaches that link natural with engineered approaches, e.g. by combining dykes with mangrove areas for coastal protection (van Bohemen 2012; UNEP et al. 2014). In addition, they also share a multi-sectoral and cross-scale nature, requiring cross-disciplinary approaches and thus a multi-actor approach.

Figure 2: EbA and Eco-DRR starting points, focal areas and common measures (Lange and Sandholz 2016 modified from Lange et al 2014)



A growing number of case studies prove the suitability and comparable advantages of Eco-DRR and EbA measures (Renaud et al. 2016, Doswald and Estrella 2015). Some of these studies point out that, in addition to their comparably lower costs and often longer durability, they can support local livelihoods and mitigate climate change

impacts if planned and maintained in a proper way (Renaud et al. 2013; Renaud et al. 2016; Daigneault et al. 2016), e.g. in the case of protected areas (Murti and Buyck 2014; Dudley et al. 2015).

Among the challenges that have to be considered is the duration until an ecosystem-based solution is fully effective. Furthermore, such approaches can also fail, e.g. if non-suitable species are used for reforestation. Furthermore, responsible authorities have to be aware of their potential as well as the necessary skills to apply such methods. In addition, the multi-disciplinary and multi-sectoral nature of Eco-DRR and EbA is challenging for planning which usually follows a sectoral approach (Renaud et al. 2013; Renaud et al. 2016). However, it may be possible to overcome such challenges by working through development planning and initiatives that serve as an 'umbrella' framework for multi-sectoral engagement (Estrella et al. 2016).

#### 4.3. CCA and DRR Policies at National and State Level

CCA and DRR, and more so EbA and Eco-DRR, are relatively new topics in Brazil. On the one hand, a major boost in the formulation of policies targeting the reduction of natural and environmental hazards has come from international discussions and frameworks. At the same time, new policies were also formed in response to disasters that happened in the country; especially the landslides in the Região Serrana of RJ state in 2011.

As a reaction to this latter event, in 2012 the National Congress legally approved implementation of the National Policy on Civil Protection and Defense (Política Nacional de Proteção e Defesa Civil – PNPDEC, Law n.12.608/2012), which establishes responsibilities at the national, state and municipal level. A milestone of this legislation was the paradigm shift from disaster response to incorporating disaster risk prevention and mitigation in disaster risk management. However, although risk professionals confirm that this was the right step, risk prevention and mitigation strategies still lack implementation. According to national authorities, this has mainly to do with a lack of knowledge, as state and municipal disaster specialists were until now mainly trained in disaster response and are not familiar with most risk prevention and mitigation approaches, with the exception of technical safeguarding and early warning systems.

The implementation of the PNPDEC itself strongly depends on political will and financial possibilities. While national and state authorities received a strong financial and staff boost in the years after the release of the PNPDEC, the current financial crisis has also left its mark on the disaster management sector, cutting financial and human capacities. On the municipal level, the assignment of human and financial resources depends even more on the current political agenda. In those cities that were most affected by the 2011 events and where disaster events occur repeatedly, the memory of destruction is still fresh. Therefore, DRR is still high on the agenda. In other municipalities, such as Duque de Caxias, the Municipal Department of Civil Defence was drastically reduced in budget and staff after the change of government in early 2017.

Beyond DRR policies, CCA has been on the national political agenda since 2009, when the National Climate Change Policy (*Política Nacional sobre Mudança do Clima* – PNMC, Law n.12.187/2009) was established. Among others, it defines the elaboration of the National Adaptation Plan (*Plano Nacional de Adaptação* – PNA), which was instituted in May 2016, after a substantial participatory process. The PNA defines adaptation guidelines for 11 different sectors, including biodiversity, disaster management and cities.

Most sectoral strategies in the PNA (10 out of 11) include EbA as a crosscutting approach. However, the document points out that the main bottleneck hindering EbA from becoming a mainstream topic in governmental and private sector plans is the lack of evidence of its efficiency. Therefore, many EbA-related activities of the PNA should first focus on generating cost-benefit information on EbA, identifying areas for its implementation to reduce climate risks, and on monitoring and evaluation.

The most common EbA measure cited in the PNA is conservation and restoration of riparian and other types of forests, which are closely linked with related national policies. An example is the implementation of the Forest Code (*Lei de proteção da vegetação ativa*, Law n.12.651/2012), which establishes permanent preservation areas (*Áreas de Preservação Permanente* – APP) and legal reserves (*Reservas Legais* – RL) in private areas, besides the public Protected Areas system. APPs aim to protect water bodies and deep slopes. In addition, landowners have to reserve a minimum percentage of their land, between 20 % and 80 % depending on the biome,

for native vegetation, constituting their RL. When this vegetation is not existent, landowners are required to restore it in the short to medium term. In addition, the National Policy for National Vegetation Recovery (*Política Nacional de Recuperação da Vegetação Nativa*, Decree n.8.972/2017) is fundamental. Another example are the Municipal Plans for the Conservation and Recuperation of the *Mata Atlântica* (Plano Municipal de Conservação e Recuperação da Mata Atlântica) for which the handbook for its elaboration recommends to research the vulnerability of the ecosystems and the services they offer for people for CCA and to propose measures for CCA (Dutra et al. 2013).

One of the most important instruments for implementing the Brazilian Forest Code is the Rural Environmental Register (Cadastro Ambiental Rural – CAR), which collects data, among others, of APPs and RLs of the whole country. Although these areas are not defined by a climate risk analysis and were not conceived with the intention to reduce climate vulnerability, they can show positive adaptation effects and could therefore be declared as EbA measures. Thus, the CAR is also an important tool for planning and implementing EbA in Brazil.

The same argument is also followed in the Guandu river basin, located in RJ state. In 2009, the river basin committee, together with the state government, civil society and research institutions started a large process to restore key areas with native vegetation. Big companies, such as Latin America's largest beverage producer Ambev, quickly joined the initiative. The goal is to guarantee adequate water quality and water supply of the river basin that is also key to ensuring water security in the metropolitan area of RJ. However, implementing organizations argue in this case as well that their measures are also reducing vulnerability to climate change and can therefore be labelled as EbA.

#### 4.4. Linkages Between CCA/DRR, Land And Ecosystem Management In Rio De Janeiro State

The World Risk Report (2012) pointed out that environmental degradation is an important factor that reduces the adaptive capacity of societies to deal with natural hazards. In the same year, the special report on “Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation” (IPCC 2012)

demonstrated the close linkages between natural hazards and extreme events in the context of CCA. On page 69 of the report it is explicitly mentioned that “the intensity or recurrence of hazard events can be partly determined by environmental degradation and human intervention in natural ecosystems.” This statement can certainly be transferred to the state of RJ.

*Figure 3: Deforestation for housing in Teresópolis (photo credit: Wolfram Lange)*



Several research studies have shown that deforestation and overexploitation, in particular due to historical exploitation cycles, modern land use intensification and urbanization processes (Fig. 3), have caused severe land degradation that in turn has increased vulnerability to natural hazards and climatic extreme events. Reforestation and rehabilitation are therefore key concepts in the context of EbA and Eco-DRR to maintain or restore protective ecosystem services and thereby enhance landscape resilience. However, so far most reforestation and land rehabilitation initiatives in RJ state either focus on biodiversity conservation, erosion prevention and soil restoration, or agricultural management, while specific Eco-DRR/EbA measures are underdeveloped. Table 2 shows goals and ecosystem-based approaches in the five key sectors (a) agricultural management, (b) water resources management, (c) ecosystem management and biodiversity, (d) climate change adaptation, and (e) disaster risk reduction. Forest ecosystems including agroforestry systems play a crucial role in each of these sectors. However, until now there has been little cross-

sectoral cooperation on both the state and municipal levels to achieve the specific sectoral goals with joined ecosystem-based strategies and measures. For the municipality of RJ (metropolitan region), Lange et al (2017) demonstrated that there is a particular gap between those authorities responsible for urban planning, conservation and disaster risk management. Moreover, there is a lack of inter-municipal exchange and coordination, so that there are disproportionately high administrative expenses in each of the 91 municipalities of the state.

*Table 2: Key sectors related to the environment: Overall goals and ecosystem-based approaches in rural Rio de Janeiro*

	<b>Agricultural Management</b>	<b>Ecosystem Management and Conservation</b>	<b>Water Resources Management</b>	<b>DRR</b>	<b>CCA</b>
Overall goals	Maintain soil fertility and ensure food security	Provide ecosystem goods and services and preserve biodiversity	Secure water supply and guarantee good water quality	Reduce disaster risk for people and their assets	Adapt to the medium and long term impacts of climate change
Ecosystem-based approaches used in Rio de Janeiro state (at least as pilot measures)	<ul style="list-style-type: none"> <li>▪ Introduce agroforestry systems</li> <li>▪ Implement reforestation and rehabilitation measures on degraded lands</li> <li>▪ Preserve key ecosystems and habitats that protect water resources and soils</li> </ul>	<ul style="list-style-type: none"> <li>▪ Establish nature protection zones, conservation corridors, and areas of permanent protection (APPs)</li> <li>▪ Foster the implementation of private natural heritage reserves (RPPNs)</li> </ul>	<ul style="list-style-type: none"> <li>▪ Protect rivers and streams by preserving or restoring riverine forests (APPs)</li> <li>▪ Protect headwater regions by preserving or restoring the natural vegetation (APPs)</li> </ul>	<ul style="list-style-type: none"> <li>▪ Stabilize landslide-prone slopes by terracing and reforestation</li> <li>▪ Protect flood-prone areas by maintaining or restoring riverine forests and creating retention room</li> </ul>	<ul style="list-style-type: none"> <li>▪ Reforest larger areas to improve the regional climate and mitigate climate extremes</li> </ul>

After the 2011 event, a study by the Brazilian Ministry of Environment (MMA 2011) demonstrated the relation between APPs and environmental conservation units versus risk areas. Based on aerial and satellite imagery, areas affected by the heavy rainfall clearly showed the unequivocal linkage between damages due to the force of the water, landslides and mudslides, and the APPs. A major finding of the study is that more than 92 % of the landslides within the researched area occurred where some

type of anthropic alteration had taken place and only 8 % in areas where natural vegetation predominated. However, as pointed out in chapter 24, natural vegetation does not provide complete protection from landslides.

#### 4.5. Status of EbA and Eco-DRR Measures in Rio de Janeiro State

So far, disaster risk management in RJ state relies mostly on technical measures, i.e. protection dams, dykes, water reservoirs, rainwater retention basins and river bank stabilization against flooding. The risk of landslides and sludge flows in settlements are mitigated with protective walls, the installation of drainage systems and the sealing of sloped areas with shot concrete (Fig. 4). Along main traffic routes, large-scale hanger rides and geotextiles are used (Fig. 5). In some particularly vulnerable areas, early warning systems and evacuation plans have also been implemented.

*Figure 4: Protective structures with shotcrete, drainage pipes and drain ditch in an informal settlement in Rio de Janeiro (photo credit: Udo Nehren)*

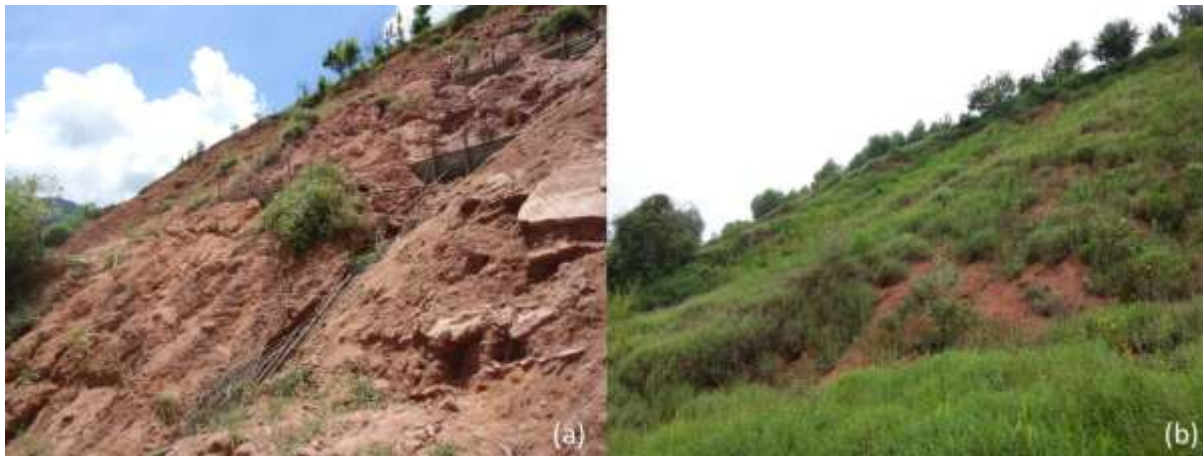


Figure 5: Geotextiles for initial slope stabilization on a roadside in Teresópolis (photo credit: Wolfram Lange)



In rare cases, ecosystem-based measures have been used, but are not yet considered large scale. Reforestation measures for flood protection are carried out sporadically and measures for river restoration are initiated with the creation of retention areas. For protection against landslides, some of the endangered slopes are reforested and partly terraced. For example, the company for agricultural research in RJ state (Pesagro-Rio) constructed a slope stabilizing measure for reducing landslide occurrence in the municipality of Nova Friburgo, which had been highly affected in 2011. After terracing the slope with sediment barriers and stabilizing it with geotextiles, grass and other *leguminosae* were planted to generate a quick soil cover. After a closed vegetation cover had been formed, predominantly indigenous trees were planted, but also some non-native trees with the purpose of generating an economic benefit for the local communities. An agroforestry system was installed in the upper part of the area to improve the soil conditions and to reduce surface drainage. Maize, beans, lychee and palm trees among others are being cultivated as they generate additional income (Nehren et al. 2017; Fig. 6).

Figure 6: During the extreme rainfall event in the Serrana Region in 2011, many slopes collapsed. Shortly after the event, Pesagro-Rio implemented slope stabilization and restoration measures, such as the one shown in the figure above in the municipality of Nova Friburgo. The slope was stabilized using palisades (a); later vetiver (*Chrysopogon zizanioides*) and other grasses and single trees were planted (b) (photo credit: Aluísio Granato de Andrade and Tiago A. Chaves)



Ecosystem-based measures for landslide risk reduction were also considered in the urban areas of RJ state. In RJ, for example, the main measure to date is the Mutirão Reflorestamento, the reforestation program of the Municipal Environmental Agency, which has afforested more than 2,000 ha of degraded land (Lange et al. 2017, Fig. 7). With the support of trained staff on the basis of voluntary community work, particularly steep slopes near informal settlements (*favelas*) were afforested for landslide risk reduction, among many other purposes. However, this program could be better oriented to disaster risk reduction and many actors involved in disaster risk mitigation still focus mainly on gray measures such as protective walls, shotcrete, drainage systems and classic precautionary activities like early warning systems.

Figure 7: After a landslide, this slope bordering an informal settlement in Rio de Janeiro is being terraced and reforested. The measure is part of the program Mutirão Reflorestamento in 2015 (photo credit: Simone Sandholz)



The project Biodiversity and Climate Change in the Atlantic Forest (2013-2018) was proposed by a partnership between the Brazilian and German ministries of the environment (MMA and BMUB), through the International Climate Protection Initiative (IKI), with the technical cooperation of the German International Cooperation Agency (GIZ) and the financial cooperation of the German Development Bank (KfW). It seeks to mainstream EbA into planning at national, state and local levels. The region of the Central Fluminense Protected Areas Mosaic, located in RJ's *Região Serrana*, is one of its demonstration sites. In this context, the staff of the municipality of Duque de Caxias, directly bordering the city of RJ, were contacted in 2015 to implement a pilot project. The territorial planning department was fully aware of climate change and its impacts and sought ways for incorporating these considerations in the revision of its municipal master plan. From this starting point the project and the municipality jointly planned and implemented a series of steps in order to mainstream EbA in urban planning.

The initial step was capacity building. First, the project facilitated the participation of two planning experts of the municipality in a Training-of-Trainers Course on EbA. That was the basis for training additional staff within the department and to create an inter-departmental working group on adaptation to climate change. This resulted in a large success, as climate change became the first topic in years to convene different municipal departments on a regular basis, e.g. the departments of Civil Defense, Planning, and Health, therefore also facilitating inter-departmental dialogue. Secondly, in-depth diagnosis tools were applied using participatory processes. Using land-use maps as a basis, local actors – experts, technicians and local leaders – were interviewed on the relevance of land use and cover types and specific areas in the municipality as well as hotspots for ecosystem services, such as riparian vegetation, mangroves and forests. Also in a participative approach, a vulnerability assessment was performed. Based on previously gathered information and the results of two multi-stakeholder workshops, experts were able to identify vulnerability hotspots and impact chains detailing drivers for vulnerability.

The results of these assessments will help the department of urban planning to review its municipal master plan, manage land use conflicts and discuss different scenarios for resilient and sustainable urban development. Ultimately, the goal is to enhance productive activities while at the same time preserving key natural capital.

## 4.6. The Potential and Limitations of EbA and Eco-DRR in Rio de Janeiro State

Despite the promising cases of ecosystem-based approaches in RJ, these kinds of measures are only isolated cases or pilot studies in geographically limited areas, so their full potential has not been realized. However, at the national level, the government makes efforts for forest protection and restoration. In particular with the implementation of APPs on steep slopes (>45 %), on hilltops, along rivers and in headwater regions, the landscape can be stabilized. This means, that APPs directly contribute to risk reduction and climate change adaptation. Further information and specific data on climate effects and disaster risk could help labelling these efforts as EbA and Eco-DRR measures, therefore supporting conservation and restoration initiatives to gain acceptance also in other sectors in addition to the environment.

Pilot projects such as the one in Duque de Caxias are also key to gaining experiences and evidence on EbA and Eco-DRR, in order to mainstream these topics on a national level. However, to increase the resilience of the landscape, packages of measures are needed which include for example, large-scale reforestation for regulating the regional climate and the restoration of degraded pasture land. The implementation of protection forests against landslides and rockfalls as well as retention areas for reducing flooding should be intensified. Synergies with biodiversity protection should also be used (see Scarano and Ceotto 2015) such as the design of biological corridors in a way that they simultaneously take over DRR functions. However, this requires a better coordination between disaster protection and environmental planning authorities.

A problem that ecosystem-based measures still face is less acceptance among decision-makers because their efficiency and cost-benefit ratio are difficult to determine and most of the measures are only effective in the long-term. As ecosystem-based measures most often require the commitment of the local population, awareness raising campaigns and environmental education should incorporate these concepts to increase community perception for better engagement (Lange et al. 2014). There is also a lack of control mechanisms and appropriate environmental monitoring systems. From this point of view, the implementation and long-term monitoring and evaluation of pilot cases as the one in Duque de Caxias are key in order for EbA to be up-scaled. Finally, change of land use is a major challenge as, for example, floodplains

are intensively used for agriculture and settlements and therefore relocation of settlements to create retention areas are costly and could generate major social and economic conflicts.

Overall, the potential for EbA and Eco-DRR is high in RJ state. Existing projects and initiatives that already consider ecosystem services for CCA and DRR – whether purposefully or as a side benefit – can be strengthened and might serve as best practices to convince more actors and decision makers in the region.

#### 4.7. References

- Barbier EB (2016) The protective service of mangrove ecosystems: A review of valuation methods, *Marine Pollution Bulletin* 109(2):676-681
- Brink E, Aalders T, Adam D et al (2016) Cascades of green: A review of ecosystem-based adaptation in urban areas. *Global Environmental Change* 36:111-123
- CBD - Secretariat of the Convention on Biological Diversity (2009) Connecting biodiversity and climate change mitigation and adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change. Montreal, Canada: Technical Series No. 41
- Daigneault A, Brown P, Gawith D (2016) Dredging versus hedging: Comparing hard infrastructure to ecosystem-based adaptation to flooding. *Ecological Economics* 122:25-35
- Doswald N, Estrella M (2015) Promoting ecosystems for disaster risk reduction and climate change adaptation: Opportunities for Integration. Geneva: United Nations Environment Programme
- Dudley N, Buyck C, Furuta N et al (2015) Protected Areas as Toold for Disaster Risk Reduction, A Handbook for Practitioners. Tokyo and Gland, Switzerland: MOEJ and IUCN
- Dutra CM Cordeiro SHT de C, Cordeiro LA, Deitenbach A (2013) Roteiro para a elaboração dos Planos Municipais de Conservação e Recuperação da Mata Atlântica. Série Biodiversidade 48. Brasília/Brazil: MMA

- Emerton L, Huxham M, Bournazel J, Priyantha Kumara M (2016) Valuing Ecosystems as an Economic Part of Climate-Compatible Development Infrastructure in Coastal Zones of Kenya and Sri Lanka. In: Renaud FK, Sudmeier-Rieux K, Estrella M, Nehren U (eds) Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice. Springer, Advances in Natural and Technological Hazards Research
- Estrella M, Saalismaa N (2013) Ecosystem-based Disaster Risk Reduction (Eco-DRR): An Overview, In: Renaud F, Sudmeier-Rieux K and M. Estrella (eds) The role of ecosystem management in disaster risk reduction. Tokyo: United Nations University Press
- Guannel G, Arkema K, Ruggiero P, Verutes G (2016) The Power of Three: Coral Reefs, Seagrasses and Mangroves Protect Coastal Regions and Increase Their Resilience. Plos One 11(7):1-22
- Heinrich J, Nehren U, Sattler D (2010) Waldfragmente des brasilianischen Küstengebirges – Entwicklungsdynamik und aktuelle räumliche Muster. Geogr Rundsch 9:34-41
- IPCC (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press
- Lange W, Cavalcante L, Dünow L et al (2014) HumaNatureza<sup>2</sup> = Proteção Mútua. Percepção de riscos e adaptação à mudança climática baseada nos ecossistemas na Mata Atlântica, Brasil. SLE publication series – pp 255: Humboldt Universität zu Berlin
- Lange W, Sandholz S, Nehren U (2017) Strengthening urban resilience through nature: The potential of ecosystem-based measures for reduction of landslide risk in Rio de Janeiro. Working Paper. Cambridge, MA: Lincoln Institute of Land Policy (accepted – forthcoming)
- Lo V (2016) Synthesis report on experiences with ecosystem-based approaches to climate change adaptation and disaster risk reduction. Technical Series No.85.

Secretariat of the Convention on Biological Diversity, Montreal.  
<https://www.cbd.int/doc/publications/cbd-ts-85-en.pdf>. Accessed 22 Mar 2017

Marengo JA (2014) O futuro clima do Brasil. *Revista USP* 103:25-32

MMA - Ministério do Meio Ambiente (2011) Áreas de Preservação Permanente e Unidades de Conservação & Áreas de Risco. O que uma coisa tem a ver com a outra? Relatório de Inspeção da área atingida pela tragédia das chuvas na Região Serrana do Rio de Janeiro. Série Biodiversidade 41. Brasília, Brazil: MMA

Munang R, Thiaw I, Alverson K, Liu J, Han Z (2013) The role of ecosystem services in climate change adaptation and disaster risk reduction. *Current Opinion in Environmental Sustainability* 5(1):47-52.

Murti R, Buyck C (eds) (2014) *Safe Havens: Protected Areas for Disaster Risk Reduction and Climate Change Adaptation*. Gland, Switzerland: IUCN

Nehren U, Kirchner A, Sattler D et al (2013) Impact of natural climate change and historical land use on landscape development in the Atlantic Forest of Rio de Janeiro, Brazil. *Anais Acad Brasil Ciênc* 85(2):311–332

Nehren U, Lange W, Kupka S (2017) Ökosystembasierte Maßnahmen zur Risikominderung und Anpassung an den Klimawandel in Südostbrasilien. *Geogr Rundsch* 4:26–31

Renaud F, Sudmeier-Rieux K, Estrella M (2013) *The Role of Ecosystems for Disaster Risk Reduction*, Tokyo, United Nations University Press

Renaud FK, Sudmeier-Rieux K, Estrella M, Nehren U (eds) (2016) *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice*. Springer, *Advances in Natural and Technological Hazards Research*

Scarano FR, Ceotto P (2015) Brazilian Atlantic forest: impact, vulnerability, and adaptation to climate change. *Biodiversity Conservation* 24:2319–2331

UNEP, UNEP-DHI, IUCN, TNC, WRI (2014) *Green Infrastructure Guide for Water Management: Ecosystem-based management approaches for water-related infrastructure projects*. Geneva, UNEP

van Bohemen H (2012) (Eco)System Thinking: Ecological Principles for Buildings, Roads and Industrial and Urban Areas. In: van Bueren, E.M., van Bohemen, H., Itard, L., Visscher, H. (eds) Sustainable Urban Environments. Springer pp 15-70

## 5. Risk Perception for Participatory Ecosystem-Based Adaptation to Climate Change

Lange, W., Pirzer, C., Dünow, L., & Schelchen, A. (2016). Risk Perception for Participatory Ecosystem-Based Adaptation to Climate Change in the Mata Atlântica of Rio de Janeiro State, Brazil. In *Advances in natural and technological hazards research* (pp. 483–506). [https://doi.org/10.1007/978-3-319-43633-3\\_21](https://doi.org/10.1007/978-3-319-43633-3_21)

This is the author's original manuscript of the submitted article.

**Abstract** This article shows that a perception analysis is an important basis to develop adequate sensitization activities and increase the participation of the local population in ecosystem-based disaster risk reduction (eco-DRR) and ecosystem-based adaptation (EbA). The study area is in the mountain region of Rio de Janeiro state where a natural disaster in 2011 showed once more that environmental risks such as landslides and flooding are recurrent. Although degradation of the natural ecosystems is a main reason for the high vulnerability of the local population, ecosystem-based measures to reduce disaster risks and to adapt to climate change are still scarce. Valorizing the benefits of nature through community-based adaptation measures is one promising approach to reduce natural degradation and vulnerability, but it needs a high awareness of the population for active participation in protecting and restoring natural ecosystems. To analyze the degree of awareness and the reasons for the lack in participation, a perception analysis was conducted based on collected quantitative and qualitative data. Results show that people have a high perception of their (a) vulnerability, but miss (b) knowledge on the relation between environmental risks and ecosystem services, do not feel (c) responsible for participating and do not see (d) possibilities for a better engagement in DRR and climate change adaptation (CCA). The article concludes that these three gaps have to be addressed as main contents in a sensitization concept and draws recommendations on how a strategy of sensitization activities for eco-DRR and EbA could look like in the region.

**Keywords** Brazil • Risk • Perception • Vulnerability • Adaptation • Climate change • Ecosystem services • Sensitization • Ecosystem-based adaptation • Extreme weather event

## 5.1. Introduction

### 5.1.1. Objectives

Our main objective is to show a perception analysis that provides a deeper understanding of the awareness and knowledge to enhance local residents' participation in disaster risk management. The interventions recommended are limited exclusively to sensitization activities and exclude other possible interventions such as financial transfers. We analyze the perception of the population in four areas in the municipality of Teresópolis (Rio de Janeiro state) with regard to disaster risks associated with extreme climate events. The perception analysis results identified the drivers and barriers preventing residents from participating more actively and effectively in DRR and CCA. This can serve as a basis for developing a sensitization strategy to enhance local population's participation in disaster risk reduction. The study was undertaken by a team from the German Center for Rural Development (SLE) of the Humboldt University of Berlin within the project "Biodiversity and Climate Change in the Mata Atlântica" which is being implemented by the Brazilian Ministry of Environment (Ministério do Meio Ambiente do Brasil – MMA) with technical support by Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (German Cooperation for Sustainable Development – GIZ) and financial support by KfW Entwicklungsbank (German Development Bank).

### 5.1.2. Disaster Risks and Climate Change in Rio de Janeiro State

Disaster risks associated with extreme events such as torrential rainfall are prevalent in the country's southeast and southern regions. In these areas, disasters caused by natural hazards, namely landslides, mudslides and floods, are recurrent, and their intensity and strength are likely to increase due to climate change (PBMC 2013a). In the Região Serrana (mountain region) of Rio de Janeiro state, yet another disaster occurred in January 2011, with severe consequences (Fig. 8). Torrential rains caused landslides, mudslides and floods that killed more than 900 people and made over

35,000 people homeless. This event put Brazil in third place among countries most affected by catastrophes in 2011 (Guha-Sapir et al. 2012). The World Risk Report of 2012 (Brodbeck 2012) focused on one issue closely linked to many disasters: degradation of the environment. In the case of Brazil, this relationship between environmental degradation and disasters is evident, as changes to nature by humans contribute significantly to the intensity and impacts of disasters.

*Figure 8: Area in Teresópolis affected by the disaster in 2011, 2 years later: flooded area with abandoned houses in the foreground and still visible landslides in the background (Photo: W. Lange)*



The mountain region of Teresópolis is part of the Mata Atlântica biome, the third largest Brazilian vegetation complex and a global biodiversity hotspot. Once encompassing 3500 km along the Brazilian coast and covering 1.0–1.5 million km<sup>2</sup> (Galindo Leal and Gusmão-Câmara 2003), only between 11 and 16% of the original forest cover remains today, found mainly in small fragments (Ribeiro et al. 2009). The Mata Atlântica suffered greatly from exploration for development and large areas of land were converted to different land uses (e.g. agriculture and urban settlements) through various development cycles. Until the nineteenth century, the area was one of the main coffee-producing regions in Brazil. Later, it gained importance for intensive agricultural activities (e.g. producing vegetables such as lettuce, tomato and onions), which remains the main livelihood of the rural population, but also one of the main drivers of environmental degradation (Nehren et al. 2009). Consequently, most of the ecosystems have been destroyed or degraded through industrial and urban expansion, as well as by intensification of land use for agricultural and grazing

purposes (Smyth and Royle 2000). However, nowadays, deforestation has decreased considerably (Fundação SOS Mata Atlântica and Instituto Nacional de Pesquisas Espaciais 2014).

Furthermore, unplanned occupation of slopes and areas close to rivers and streams are other risk factors (Nehren et al. 2009). Once the vegetation cover is removed, these areas become more susceptible to landslides, mudslides and flooding, leading to high risks for residents. Degraded ecosystems cannot efficiently carry out their functions for risk reduction, such as maintaining slope stability, flood control, and the balance of regional climate (Renaud et al. 2013). The existing efforts for ecosystem protection and restoration cannot cope with the high level of degradation in the region. Additionally, the rugged topography and the vulnerable geology (i.e. the basement underneath the soil is of sliding granitic) and soils (i.e. comprised of silty weathering mantle) increase the risks of mudslides, landslides, and floods (CEPED-UFSC 2011; DRM-RJ 2012).

Extreme meteorological events are the main trigger factor for landslides and floods (Fernandes et al. 2004) and are not new to the region. Due to climate change, their frequency and intensity have increased since the middle of the twentieth century (Marengo 2008). Projections for the study region indicate that rainfall will increase by 20% until 2070 and by up to 30% until 2100 (PBMC 2013a). Consequently, climate change will further increase disaster risks and vulnerability (PBMC 2013b) in an already fragile region. Hence, there is an urgent need for efficient measures to adapt to climate change and reduce disaster risk.

### 5.1.3. DRR and CCA in Rio de Janeiro State

Aware of the challenges the country will face due to climate change, the Federal Government of Brazil passed a law establishing the National Politics of Climate Change in 2009. The law was followed by several sectorial plans that focused on mitigation and reduction of carbon emissions. Adaptation to climate change was given more priority in 2013 when an inter-ministerial working group, headed by the Ministry of Environment, was established to develop a National Plan of Adaptation until 2015. In the policy framework of Rio de Janeiro state (SEA 2012), activities related to climate change primarily focus on reducing greenhouse gas emissions. Adaptation is

mentioned in the State Plan of Climate Change, but concrete measures and activities for adaptation still have to be defined and implemented.

After the disaster in 2011, major efforts were made to increase the state's capacity for DRR, but measures mainly focused on engineered infrastructure. Engineered structures such as dredging, dams, embankment restoration and other hydraulic-engineering solutions to control flooding, as well as slope stabilization measures such as use of concrete walls to prevent landslides, were implemented in many parts of the state. These activities involved various actors like the State Government of Rio de Janeiro, the municipalities and the communities (CEPED-UFSC 2011). However, most of these engineered measures are relatively expensive, and do not address the underlying risk factors. Implementation of disaster prevention activities should therefore be supplemented by improving long-term planning procedures including ecosystem-based solutions. Better coordination between the different stakeholders working with adaptation to climate change is also needed, because the activities have failed to integrate with each other.

#### 5.1.4. Effective DRR and CCA Based on Ecosystem Services

An emerging approach to DRR and CCA is based on the sustainable use and management of ecosystem services. Ecosystem-based adaptation (EbA) seeks to integrate the use of ecosystem services and biodiversity into an overall strategy to help people adapt to the adverse impacts of climate change (Colls et al. 2009). Ecosystem-based disaster risk reduction (Eco-DRR) consists in a similar approach that supports healthy, well-managed ecosystems to act as natural infrastructure, reducing physical exposure to many hazards and increasing the socio-economic resilience of people and communities to disasters (Sudmeier-Rieux and Ash 2009). Both approaches have more in common than they are different. Both EbA and Eco-DRR aim to reduce vulnerability to disaster and climate risks by focusing on the sustainable use, management, conservation and restoration of ecosystems (UNEP 2015). The main differences between the two approaches are that EbA is a long-term approach, as the impacts of climate change tend to increase in decades, while Eco-DRR mostly addresses current and recurring hazards. They both address climate- or water-related hazards, although Eco-DRR would also consider other types of hazards, including geological hazards (e.g. earthquakes, tsunamis) as well as technological

hazards (e.g. oil spills impacting on coastal and marine ecosystems). EbA may take into account uncertainties associated with long-term climatic changes, and seek to adapt to the impacts of climate change in vulnerable development sectors, such as agriculture, while Eco-DRR could also be applied to tackle non-climate induced hazards such as tsunamis, landslides, avalanches and rockfall (Venton 2008).

Despite their great potential in the study region, ecosystem-based solutions, such as the conservation (responsible and sustainable use of nature without reducing the services of ecosystems) and restoration (return to its original state) of ecosystems, have been under-estimated by public policymakers, both in the past and present. DRR in Brazil is still mainly focused on the short-term activities of disaster preparedness and response rather than on long-term disaster prevention and mitigation strategies. Compared to technological and engineered infrastructure measures (also commonly referred to as “grey infrastructure”), ecosystem-based solutions (or “green infrastructure”) can provide several co-benefits such as carbon sequestration, climate regulation, and water security (Renaud et al. 2013).

In Brazil, a key policy instrument based on an ecosystem-based approach is the permanent preservation area (Área de Preservação Permanente or APP). Often located on steep slopes and around rivers, APPs are protected by the National Forest Code (Brasil 2012) due to their environmental functions. The high risk of landslides and flooding is explicitly mentioned as one of the reasons why those areas must not be developed. Unfortunately, the lack of law enforcement and land use pressures, such as construction and agricultural development, means the APP instrument is often ineffective. This was apparent in the 2011 disaster where most of the damage occurred in APPs, because people had settled in these areas (SBF 2011). Other activities and measures that are already being implemented, but need more effort, include reforestation, river restoration, and alternative land-use systems such as agroforestry or silvopastoral systems. These solutions consider landscapes and ecosystems as a holistic system and aim to create long-term effects to achieve disaster resilience and support sustainable development. Mainstreaming ecosystem services for DRR and CCA should be improved at all governmental levels as part of the long-term planning process.

Participation by local government and especially local communities in DRR and CCA is vital (Allen 2006). The protection and restoration of ecosystems do not work without the involvement of local people, and their benefits are usually better demonstrated over the medium or long term (Colls et al. 2009).

Participation of the local population is specifically important in Teresópolis, as the human-induced degradation of ecosystem services and unsustainable land use increases disaster risks. One approach of integrating people in EbA or Eco-DRR activities is community-based adaptation (CbA) (IIED 2009; Care 2010). CbA involves participatory processes that increase the local population's awareness and whose primary objective is to improve the capacity of local communities to adapt to climate change (Care 2010). It also aims to protect and sustain ecosystems, not only for livelihoods of people, but also to reduce disaster risks. Participation in CbA primarily depends on the knowledge, needs, and priorities of the local people directly concerned (IIED 2009). CbA can be integrated with Eco-DRR and EbA measures, because it directly engages people affected by disaster risks and supports them to implement activities within their own environment.

#### 5.1.5. Importance of Perception for Participation

In the context of CbA, the perception of local residents affected by disasters or living in high-risk areas plays a significant role. Understanding their perception is important for motivating individuals to actively avoid, mitigate, and reduce risks (Wachinger et al. 2013). Perception may vary depending on several factors such as the type and context of risk, socialization, biases, and social context and is influenced by knowledge, experience, values, attitudes, and emotions. An analysis of the local population's perception allows us to identify how people deal with disaster risks and climate change. These insights assist in the development of a sensitization strategy which considers drivers and barriers, in order to foster enhanced participation in Eco-DRR and EbA activities. For Teresópolis, community participation is analyzed in the context of the protection and restoration of the Mata Atlântica.

#### 5.1.6. Four Key Factors for Active Participation

According to the psychometric paradigm of risk perception, which assumes that the perception of risk leads to a specific behavior (Grothmann and Patt 2005), the response of people to natural hazards is influenced by risk perception, their judgments,

and preferences (Slovic and Weber 2002). Information can lead to behavioral change through adequate educational campaigns (Madajewicz et al. 2007), but the way risk information is formulated has an effect on judgments and vice-versa (Plapp 2003). Both the way information about risks is formulated and the information's availability are extremely important for behavioral response. The individual's decision to act is also determined by how he or she interprets the given information based on previous experiences (Plapp 2003). Depending on the knowledge of alternatives, a decision about whether to take action or not can be made. In order to have the possibility to choose between different alternatives, they have to be available so that possible consequences can be considered (Weber 1997). We can therefore conclude that perception of risk depends greatly on experience, knowledge and judgment. It has an influence on behavior to take up risk-reducing activities and is one of the factors which could serve as a barrier or driver for enhanced participation. Therefore, our analysis consists of four main dimensions:

(a) People's perception of their own vulnerability to disasters, considering exposure, sensitivity, and adaptive capacity as the factors that define vulnerability (IPCC 2001). Exposure is defined as the degree to which a system is exposed to climate-related threats, such as construction of housing on steep slopes which are threatened by landslides, mudslides and floods. Sensitivity is the degree to which the system is affected by the threats, such as direct and indirect damage caused by landslides, mudslides and floods (Messner et al. 2006). Adaptive capacity is the ability of the system to respond successfully to the threat (IPCC 2001; Mytanz 2013), which means for example the knowledge about effective measures to protect and restore ecosystems as well as the financial resources and capacity to implement these measures. If people do not perceive that they are exposed and sensitive to risks, they do not necessarily see the need to act and protect themselves. Furthermore, when they feel overwhelmed and incapable of adapting to risks, there is a high probability that they will not act on those risks.

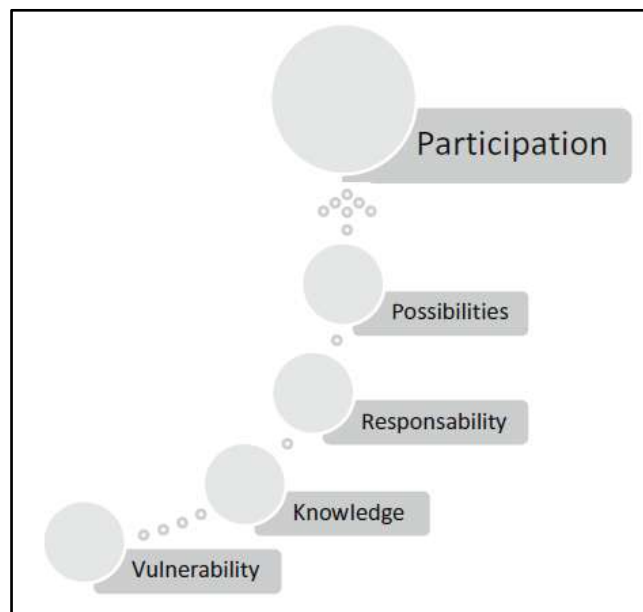
(b) People's knowledge of the relationship between ecosystems and natural hazards: In the context of Teresópolis, this refers to people's knowledge of how ecosystem services can contribute to reducing disaster risks and how ecosystems can be protected and restored.

(c) People's attitudes with regard to their own contribution towards ecosystem protection and restoration: This component refers to people's perception of their responsibility to contribute to the protection and restoration of ecosystems. The main premise is that people accept and assume responsibility for these measures, because ecosystem-based measures will only work if everyone participates over the long term.

(d) People's perception of possibilities and available alternatives to engage more actively in ecosystem-based measures. The main premise is that people must recognize the available opportunities for action in order for them to act and contribute to specific activities.

These four dimensions serve as an analytic scheme to identify barriers in the perception of people that prevent them from participating more actively and effectively in Eco-DRR and EbA (Fig. 9). In order to develop more specific recommendations for an adequate sensitization strategy at local level, it has to be taken into account which mass media is used and what are the experiences with environment sensitization activities that have already been realized in the study region.

Figure 9: Four dimensions as basis for better participation (Own graphic)



### 5.1.7. Methodology

Using a multi-criteria approach, four geographical areas of the municipality of Teresópolis, Caleme, Granja Guarani, Santa Rita and Vieira, were selected for the study. The selection was based on a list of ten potential areas that had been defined

in conjunction with a representative of the environmental department at Teresópolis city hall, where relevant data on the characteristics had been collected in a pre-study. All four selected areas were determined to have a high potential for conservation and/or restoration of ecosystems to reduce disaster risks. To obtain an accurate representation of the whole municipality of Teresópolis, both urban and rural areas as well as those affected and unaffected by the tragedy of 2011 were selected, resulting in a selection of one urban-affected (Caleme), one urban unaffected (Granja Guarani), and two rural-affected (Vieira and Santa Rita) areas (all rural areas had been affected by the 2011 events) (Fig. 10). Additionally, attention was paid to socio-economic criteria (i.e. age and income) to ensure the sample covered the socio-economic characteristics of the entire municipal area.

Figure 10: Research areas within the municipality of Teresópolis (Own graphic)



Three main empirical methods were used for the data collection: semi-structured questionnaires as the main quantitative data collection tool, and focus group

discussions and qualitative interviews with local key actors as additional sources of information. The qualitative empirical instruments aimed to enhance the results obtained from the semi-structured questionnaires and the triangulation of quantitative and qualitative methods allowed a higher validity and more sophisticated interpretation of the results (Flick 2011).

All empirical instruments were pretested and adapted accordingly, before they were applied in the research areas to ensure that appropriate terminology was used and that there were no leading or biased questions. A psychologist in the research team evaluated the research methods to guarantee that they were locally-sensitive, in view of the 2011 tragedy. Additionally, during the training of the researchers, special emphasis was placed on possible negative impacts of the research to avoid harm to the participants (Flick 2007).

During the data collection phase, all research participants were informed briefly about the research topic in order not to distort the results. All agreed to participate, and their anonymity was assured. All methods aimed to gather data regarding the four key factors as well as additional information about existing environmental education activities and the population's extent of using media such as television, newspaper and the internet. The methods have been developed by the research group based on existing literature (Plapp 2003; Mytanz 2013).

The intention was to obtain representative and individual data in order to observe possible variations in people's perceptions. As a unit of analysis, individuals older than 16 years were selected, assuming that perceptions are individually determined (Slovic 1992). Therefore, the semi-structured questionnaire was the principal research method, containing 41 questions (including 17 questions about vulnerability, 9 regarding knowledge of ecosystem services and disasters, 3 on responsibility and 2 about possibilities). Sample questions are given in the results section.<sup>1</sup>

Within the four selected communities, a systematic random sample based on households was applied in order to guarantee that each unit of analysis had the same probability to be chosen for the semi-structured interviews. A monitoring system was

---

<sup>1</sup> All questions and results presented in this article are translations from Portuguese into English. For a list of all questions and results from the semi-structured questionnaire in Portuguese please see Lange et al. (2013).

used to ensure representation by gender and income groups in equal proportions to their composition in the population of each area according to the census (IBGE 2010). Whenever a discrepancy was detected, the sampling strategy was changed in order to specifically reach under-represented groups in the remaining households. A total of 271 semi-structured, face-to-face interviews in Portuguese were conducted (67 in Caleme, 89 in Granja Guarani, 62 in Santa Rita, 53 in Vieira), which is 14.8% of the total population as per the demographic census in the four sample districts (IBGE 2010). This sample size assures representative results with a level of confidence of 90% and a single size error of 5 %. The four research areas were equally represented in the sample.

In addition, focus groups were held to obtain deeper qualitative information on the research issues. Residents older than 16 years were invited to participate. A convenience sample of individuals available and willing to participate in the study was chosen (Collins et al. 2007). Their selection was supported by a “gatekeeper”, a socially engaged and well-known person in the community, to guarantee an adequate composition of the group. There was one focus group discussion in each area. Different participatory methods, such as community mapping and small discussion groups, were used within the focus group to obtain as much information as possible on the different research dimensions. For example, community mapping assessed the perception of disaster risks and understanding of its causes including ecosystem degradation. The focus group methods were facilitated and moderated by two people in Portuguese, and at least three researchers observed the discussion, taking notes on pre-prepared observation sheets. The communities were informed of the results by an information leaflet after the main results were analyzed.

Furthermore, 19 qualitative problem-centered interviews based on an open questionnaire with 27 questions were conducted with local key actors (e.g. representatives of the community association, local NGO leaders, school directors, priests, etc.). The main criteria for their selection were their social engagement in community activities, especially after the 2011 tragedy, and their knowledge about the structure of the community and its problems. In each community, a “gatekeeper” was identified, who supported the research group to make contact with other experts. This was especially important to create a trustworthy and open atmosphere during the interviews. The main objective of the qualitative interviews was to understand the

perception of key protagonists in the communities and their assumptions about the local population's perception of risks. Following the principles of qualitative research, interviews were conducted until saturation level of data was achieved.

The quantitative data obtained from the semi-structured questionnaires were analyzed by quantitative content analysis (Mayring 2010) with the support of the statistical program SPSS. There were categorical and open questions in the questionnaires. The open questions were quantified before the analysis. The quantification of the answers was done by both concept-driven coding, to take into account the results of preliminary research, and open, data-driven coding, to ensure the capture of additional data and phenomenon which were considered of explanatory value for the research (Gibbs 2007). Both the focus group discussions and the qualitative interviews with local key actors were analyzed by qualitative content analysis (Mayring 2010). We used a step model of deductive category application. This means that we worked with coding rules for each category previously developed, determining exactly under what circumstances a text passage can be coded with a category (Mayring 2000). The software ATLAS.ti was used for the analysis.

The indices of perception of vulnerability, exposure, sensitivity and adaptive capacity presented in the results chapter of the article were calculated based on quantitative data from the semi-structured questionnaires. While the index of perception of vulnerability is calculated by adding the perception of exposure and sensitivity and subtracting the perception of adaptive capacity (GIZ 2013), each of these three indices is composed of multiple questions from the questionnaires.<sup>2</sup>

All three empirical research methods were designed with the intention that the methods would also be used in future research on the same and similar topics. Detailed information on all methods, including questionnaires, focus group instructions and interview guidelines are provided in the original study in the form of a perception analysis toolkit (Lange et al. 2013).

To ensure the reliability of the methods and the replicability in other research contexts on disasters, the authors aimed to develop research methods which could be adapted to different disasters and to different levels of affected populations.

---

<sup>2</sup> For the exact composition of each index please see Lange et al. (2013).

## 5.2. Results

### 5.2.1. Perception of Risks and Adaptation Measures in Teresópolis

The results show that three main barriers are impeding the local population from more actively engaging in Eco-DRR and EbA activities. First, while the population has some knowledge of the importance of environmental protection, only a few people have a wider understanding of the role of ecosystem services in reducing disaster risks. Second, although a major part of the population feels responsible for conserving ecosystems, they do not feel responsible for undertaking ecosystem restoration activities. Lastly, a great number of people perceive that the greatest obstacle to better value ecosystems is the lack of resources and options, as well as the lack of opportunities to obtain resources and options. Our results also suggest that people in Teresópolis already have a relatively high perception of their vulnerability to disasters and believe disaster risk will increase in the future. Hence, this important condition for increasing participation in Eco-DRR and EbA is already met. Sensitization activities should therefore primarily focus on the other three barriers: knowledge, perception of responsibility and perception of possibilities.

The following discussion presents the most important insights for each of the four dimensions. This differentiated look at the results is especially important when it comes to developing appropriate sensitization activities and ways to engage the local population in the reduction of disaster risks.

### 5.2.2. Perception of Vulnerability with Respect to Disaster Risks

Our analysis of the perception of vulnerability shows that people in Teresópolis have a relatively high awareness of their exposure and sensitivity and perceive their capacity to adapt to disaster risks as relatively low. This means that most people know that they live in risk-prone areas and realize that they are insufficiently protected against potential disasters. But they are typically not aware of the possibilities to better protect themselves from disasters.

A vivid example that illustrates people's level of awareness of their exposure is that 86% of the population stated that either landslides, mudslides or floods, the most

prevalent hazards in the mountain area of Teresópolis, would pose a direct risk to their life. This high percentage can be explained by the devastating impact of the tragedy of 2011 and the resulting heightened local awareness of disasters. Focus group discussions and interviews with local key actors confirmed that after the events of 2011 the perception of exposure to hazards increased significantly within the community – especially in those areas worst affected. Almost every resident knows at least one family member who was directly harmed by the disaster in 2011. Whilst the tragedy increased local awareness, it also made it hard for people to differentiate between levels of risk across different locations. It even led to an overestimation of risks. For example, more than half of the population (58.5 %) believe that every area in the region has equal probability or risk of experiencing a disaster, not taking into account that some areas could have higher levels of risk than others. This means that, although the awareness of risk is relatively high, many people are not capable of making differentiated judgments about the actual levels of risk of an area. For the perception of sensitivity and adaptive capacity, the results are similar, although less distinct. More than 70% of the population perceive that disasters can cause serious damage to their own lives as well as to their livestock and other assets.

In the case of a disaster, most people feel helpless and incapable of adequately protecting themselves. One-third (34 %) do not even have a basic idea of what they could do to prevent or mitigate the impacts of disasters, and some do not believe actions can be taken at all to protect against disasters. This is mainly due to the lack of knowledge of adequate measures for disaster risk reduction and adaptation, and the perception of a lack of financial resources to take up those measures.

Histogrammes in Fig. 11 shows the distribution among the local population of the perception of (a) vulnerability and factors that define it, (b) exposure, (c) sensitivity and (d) adaptive capacity. While the index of perception of vulnerability is a combination of the other three indices<sup>3</sup>, each of these indices is derived from different questions<sup>4</sup> from

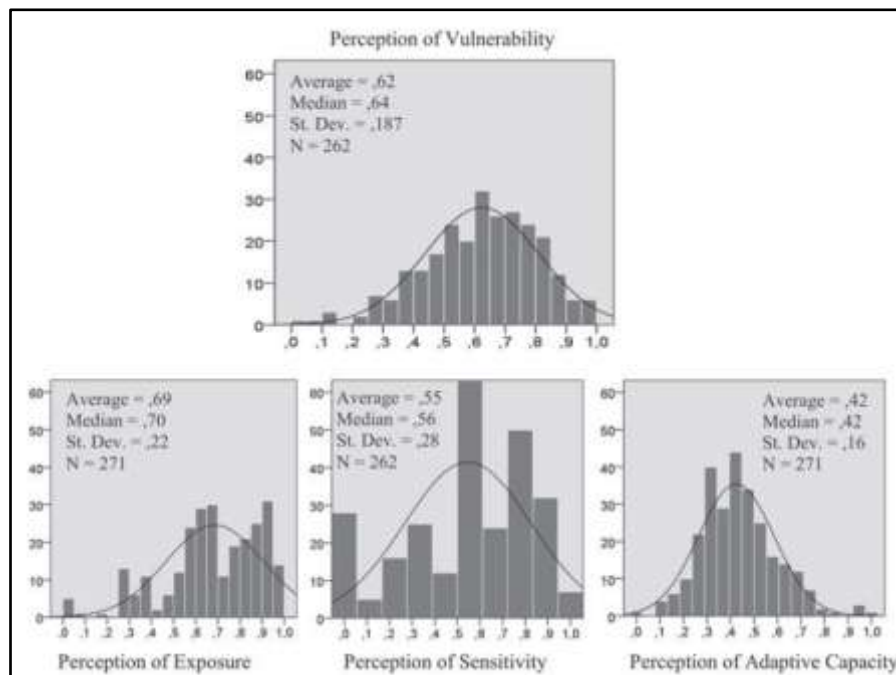
---

<sup>3</sup> The formula used to calculate the index of perception of vulnerability is: perception of Vulnerability = perception of exposure + perception of sensitivity – perception of adaptive capacity (GIZ 2013). To generate a value between 0 and 1 for the vulnerability index, we used the formula “ $1 - ((N_{max} - N_x) / (N_{max} - N_{min}))$ ” (UNDP 1990).

<sup>4</sup> For more information on the composition of each index, including the sets of questions, please see Lange et al. (2013).

the semi-structured interviews. Each histogram shows the distribution of perception from a value of 0 (very low perception) to a value of 1 (very high perception).

Figure 11: Perception of vulnerability and its constituent dimensions (Own graphic)



The histograms show that there is a relatively high average perception of vulnerability of 0.62 with a relatively low standard deviation of 0.19 – that is, the perception of vulnerability deviates quite homogeneously around the average value. For the perception of exposure, this differs slightly. The perception is higher with an average of 0.69 and also deviates more (0.22) with two clusters around the values 0.6 and 0.9. This indicates that one part of the population already has a very high perception of exposure, while the perception of exposure by the rest of the population is far lower. Similar characteristics apply to the perception of sensitivity (high standard deviation of 0.28), although the general perception is lower with an average value of 0.55. The perception of adaptive capacity is generally low with an average of 0.42, deviating homogeneously around this value.

It is also crucial to understand how people perceive their future vulnerability. This knowledge is of special relevance for the planning and design of projects and strategies, especially in the context of Eco-DRR and EbA, because ecosystem-based measures need some time until they can fully yield DRR or CCA benefits and are therefore often undertaken over the medium- or long-term (Renaud et al. 2013).

Of the people surveyed, 76% perceived an increase in frequency and magnitude of rainfall during the last 10 years, and 80% stated that a future increase would have more negative than positive effects on their livelihoods. Also, 68% of the population believed that landslides (compared to 63% for floods) had increased during the last 10 years in frequency and/or magnitude.

These results were confirmed in all four focus groups, especially in the rural areas. Here, people talked comprehensively about the increase in rainfall, landslides, mudslides and floods and more generally about the increase in disaster risks. Although the results are probably also influenced by the 2011 tragedy, people perceive that disaster risks increased during the past few years and, based on this trend, expect that their exposure is likely to increase in the future.

All these results suggest that the perception of vulnerability, as one important driver for enhanced participation in DRR and CCA, already exists in Teresópolis. Sensitization activities should therefore not focus on further increasing awareness of vulnerability. Instead, efforts should focus on more active engagements with the local population to discuss effective measures for DRR and CCA, and enhance local understanding of exposure to disaster risks. A high perception of vulnerability does not automatically mean that people act or even choose adequate measures to reduce risks and/or recognize the value of ecosystems for DRR and CCA. Although disasters could affect everyone, there are certainly areas of high risk and areas of medium or low risk. Finding optimal solutions for each area, on a case-by-case basis, is crucial and requires a well-informed and differentiated perception of risks – especially the perception of exposure to risks. People will need this deeper understanding to choose between risk reduction measures that are most appropriate to their context.

### 5.2.3. Perception of Ecosystem Services and Their Functions to Reduce Disaster Risks

The effectiveness of Eco-DRR and EbA measures depends highly on the acceptance – and ideally the participation – of the local population (IIED 2009), who need to have a good understanding of the risk reduction functions of ecosystems (Borrini-Feyerabend et al. 2007; King and Marfai 2008). For Teresópolis, our results suggest that even though the population has some knowledge about the importance of

ecosystem protection, only a few people have a deeper understanding of the role of ecosystem services in the reduction of disaster risks.

Over 50% of those interviewed explicitly indicated activities in the area of ecosystem degradation as the main cause for the increase of landslides, mudslides and floods in the past 10 years. This basic knowledge of the causality between ecosystem degradation and risk was also confirmed in the focus group discussions. Participants talked about the severe effects of deforestation on increasing the prevalence of landslides, mudslides and floods. However, in addition to recognizing that ecosystem degradation increases disaster risks, people also need to understand how intact ecosystems and the services they provide can contribute to reducing risks, and how ecosystem restoration could therefore be viewed as a key measure for implementing DRR or CCA. In this regard, protected area management can play an essential role.

According to a study on the role of protected areas for risk reduction in the mountain region of Teresópolis, the regions most affected by the catastrophe in 2011 were in APPs (SBF 2011). APPs with intact vegetation were significantly less impacted by the disaster than APPs with degraded vegetation (SBF 2011). This is primarily due to the slope stabilization and water regulation functions of the ecosystems in APPs with intact vegetation (SBF 2011).

When asked how the forests in APPs benefit the population, most interviewees mentioned that forests conserve biodiversity by protecting animals and produce fresh air and clean water. Only 12% spontaneously mentioned that forests can also contribute to reducing the risk of disasters. When specifically asked to elaborate on the risk reduction functions of forests in the focus groups, some participants noted that the roots of the trees would stabilize the soil and thus prevent landmasses from sliding. However, other risk reduction functions of a forest, such as its water absorption capacity and associated flood reduction services, were not mentioned at all.

When asked about the functions of protected areas (including APPs) in general, results were similar. Although 72% of the people surveyed could name at least one protected area in their region, only 5% perceived that protected areas could contribute to reducing disaster risks. Instead, most people understood the functions of protected areas to be mainly for the conservation and restoration of nature in general or for the protection of animals.

When directly asked if protected areas could contribute to the reduction of disaster risks, 65% of the people interviewed agreed. However, only one third (35 %) could afterwards explain at least one concrete example or mechanism how protected areas could reduce disaster risks. These results confirm the observations made during the focus group discussions. Although many participants perceived a certain connection between ecosystem degradation and disaster risks, and some even knew that ecosystems were important to reduce disaster risks, very few people understood the mechanisms by which ecosystems can reduce risks.

This crucial observation shows that people in Teresópolis have a basic understanding but no sophisticated knowledge on the relationship between ecosystems and risk reduction. The limited knowledge is one important factor preventing people to value ecosystem services and participate in risk reduction measures. People need to know that effective conservation and restoration of their surrounding ecosystems can protect them against landslides, mudslides and floods, and they need to know in which areas restoration is especially crucial. If they are not aware of these relationships, why should they be motivated to invest their scarce time to participate in risk reduction measures?

Lack of knowledge about the ecosystem's risk reduction functions is the first barrier to the population's enhanced participation in Eco-DRR and EbA measures identified in our study. As a consequence, sensitization activities in the region should focus on increasing knowledge about the role of local ecosystem services and their functions in reducing disaster risks.

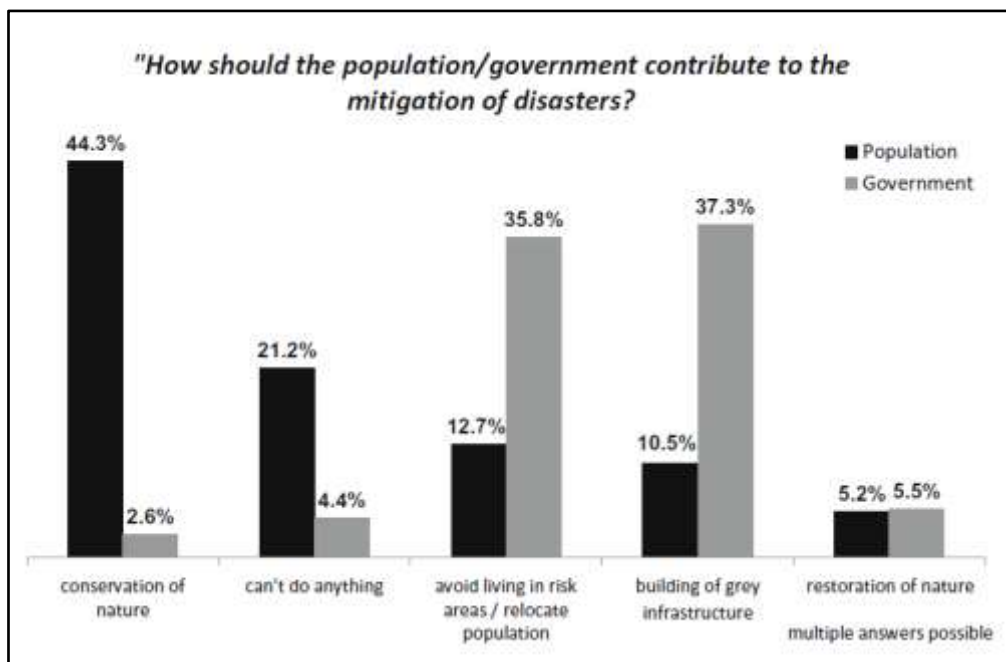
#### 5.2.4. Perception of Responsibility to Protect and Restore Ecosystems

As mentioned above, for Eco-DRR and EbA measures to be effective, the local population should accept and support the measures and ideally, be actively involved (IIED 2009). Another factor that can enhance participation is the population's sense of responsibility to contribute to Eco-DRR and EbA. If people do not have this sense of responsibility, there is little reason why they should be intrinsically motivated to participate (Wachinger et al. 2013). Therefore, we analyzed the local population's perception of its own responsibility to conserve and restore ecosystems. We compared

people’s perceived role of the government in risk reduction with the perception of the responsibilities people see for their community and themselves (see Fig. 12).

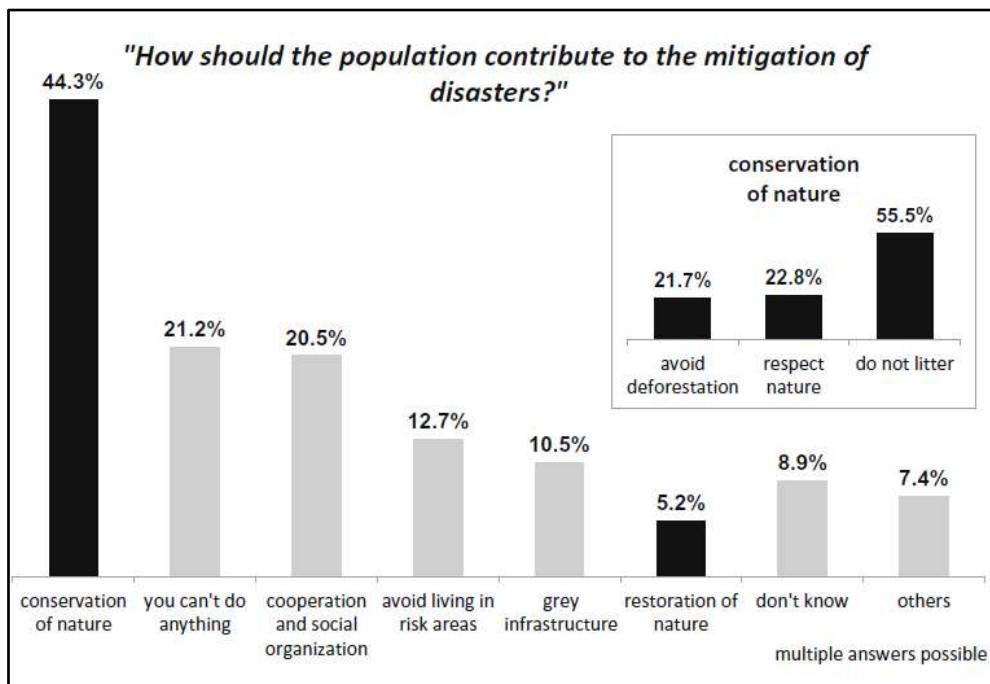
While almost half the people interviewed feel responsible for contributing to the mitigation of disasters by means of conservation of nature, people generally consider the government to be responsible for traditional DRR measures, such as engineered infrastructure (37.3 %). Also, more than one third of the people claimed that the government should force people to leave high risk areas and provide social housing in safe areas. The restoration of ecosystems, by contrast, is neither perceived as a responsibility of the government (5.5 %) nor of the community (5.2 %). This might be explained by the relatively limited knowledge of the effectiveness of ecosystem restoration for risk reduction, as shown above.

Figure 12: Perception of responsibility of the population and of the government (Own graphic). The figure only shows answers that are relevant for EbA and Eco-DRR measures. Other answers, e.g. on governmental inspection or social organization, are excluded to simplify the illustration. For the complete set of answers please see Lange et al. (2013)



When looking in more detail at the responsibilities people see for their community and themselves (Fig. 13), we find that in the area of conservation of ecosystems, those interviewed feel responsible for taking up avoidance behavior (e.g. avoid deforestation, do not litter) rather than undertaking the active implementation of activities (e.g. remove litter from rivers or forests or to actively educate other people).

Figure 13: Perception of responsibility of the population (Own graphic)



Similar observations were made by local community representatives who stressed that after the tragedy of 2011, the main behavioral change in the community was to avoid throwing solid waste into the rivers. Although this activity can certainly reduce the risk of floods (Jha et al. 2012), it cannot effectively reduce the risks of landslides and other hazards. Active ecosystem restoration is also crucial, particularly in the area of Teresópolis where a lot of environmental degradation has already taken place (Smyth and Royle 2000).

At the same time, 21% of the people think that they cannot do anything and another 9% have no idea how to contribute to risk reduction. This means that almost one third of the population do not feel capable of contributing to any DRR measures.

High local awareness of proper waste disposal, however, shows that environmental education could have a significant impact on people's perceptions. Since 2011, there have been various campaigns for proper waste disposal in the Teresópolis area which, according to our interviews, have been well-accepted by the local community.

Lack of the sense of responsibility of the population to effectively conserve, and especially to restore ecosystem services, is the second barrier to enhanced participation in EbA and Eco-DRR identified in our study. Sensitization activities should

therefore also focus on increasing the perception of responsibility among the local population.

Results of our study also suggest that the perception of responsibility is strongly connected to knowledge of the functions of ecosystem services. If people have limited knowledge of the effectiveness of certain measures (e.g. reforestation), it seems less likely that they will feel responsible for implementing them. Therefore, enhancing local knowledge of the effectiveness of ecosystem services for DRR and CCA (the first barrier identified earlier in this paper) seems to be a first step to increasing people's sense of responsibility for implementing effective Eco-DRR or EbA measures.

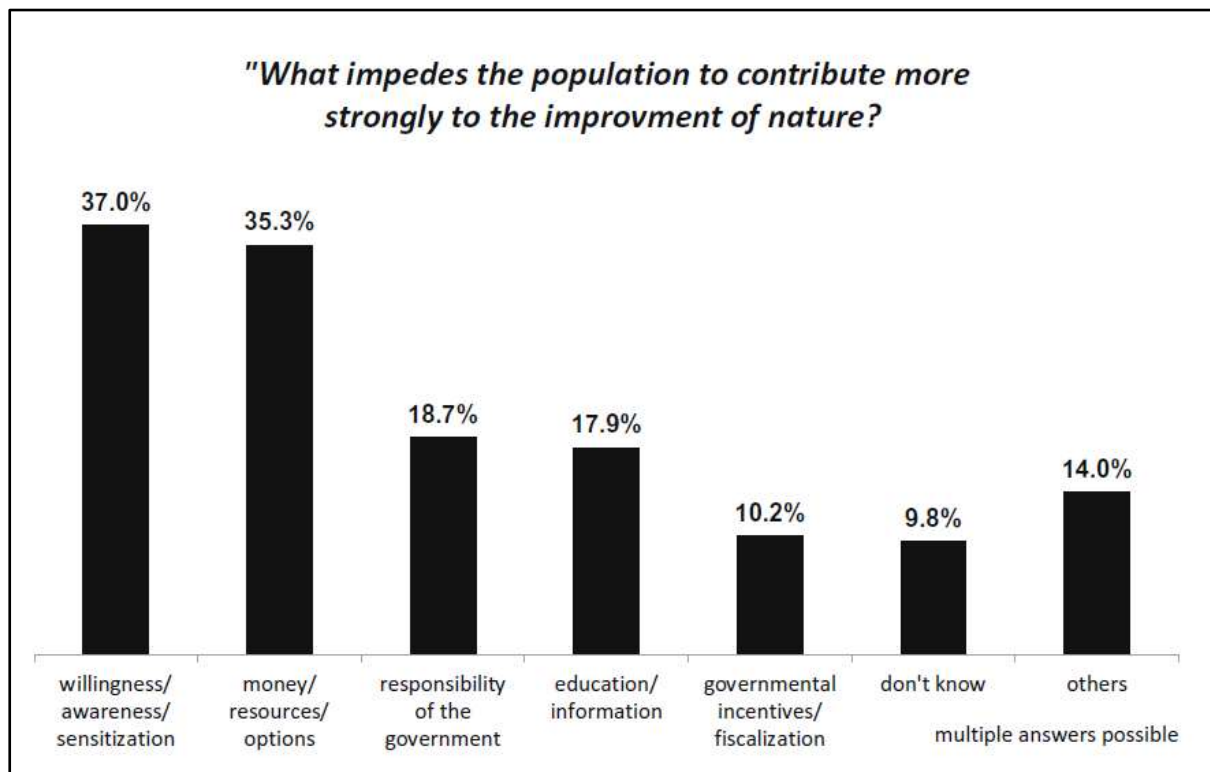
#### 5.2.5. Perception of Possibilities to Conserve and Restore Ecosystems

For people living in low and medium risk areas, the likelihood and the impact of disasters can often be significantly reduced by conserving and restoring the surrounding ecosystems (Nehren et al. 2014). These measures are especially important because in Teresópolis, according to our interviews with local key actors, resettlement capacities are limited and often associated with negative consequences, especially for the most vulnerable and marginalized. Resettled communities run the risk of losing their valuable social networks and supporting infrastructure.

As shown above, a major part of the population is aware of their vulnerability to disasters, and some people also know about the importance of ecosystems for reducing disaster risks. Also, a segment of the population values ecosystems. Why then do so few people actively participate in the protection and restoration of ecosystems?

As shown in Fig. 14, more than one third of the people surveyed in Teresópolis (37 %) perceived a lack of willingness, awareness or sensitization as important factors preventing them from more actively contributing to the protection and restoration of ecosystems. This confirms the above results and the barriers identified.

Figure 14: Perception of obstacles to contribute to conservation and restoration of ecosystems (Own graphic)



While only 18% mentioned a lack of education and information during the interviews, this topic was extensively discussed in the focus groups. Participants identified the lack of knowledge of how to collectively undertake the protection and restoration of ecosystems as equally important as the lack of willingness and awareness. A key outcome of the focus discussions was that people do not feel capable of guiding or instructing others on how to undertake Eco-DRR or EbA activities. Hence, lack of knowledge or training on implementation of Eco-DRR and EbA measures seems to be a major reason why people do not engage more actively in Eco-DRR and EbA.

In addition to knowledge on how to effectively conserve and restore ecosystems, people need to feel they have the resources and capability to do so. Figure 21.7 also shows that more than one third of the population (35.3 %) sees the lack of money and resources and the lack of opportunities to obtain such resources as another great obstacle. Several interviewees also mentioned that the lack of money would result in a lack of time for investing in Eco-DRR and EbA activities, because people would need to work extra hours to earn their income. Thus, particularly time consuming activities like planting trees during weekends would simply not be an option for them. Lack of both resources and knowledge of how to obtain resources is the third gap identified in

this study. Sensitization activities should therefore also focus on increasing knowledge of the local population on how and where to obtain financial resources and options to invest in ecosystem-based measures.

### 5.3. Conclusion

Ecosystem-based measures such as reforestation and protected area management have great potential to reduce disaster risks and adapt to climate change in the mountain area of Teresópolis (Nehren et al. 2014). In many cases, they can complement or even substitute hard engineering measures. However, to be effective, policymakers must design measures sensibly and involve the local community in planning and implementation (Allen 2006).

An analysis of the perceptions of local residents allows us to identify the drivers and barriers for effective participation in EbA and Eco-DRR. The perception analysis is a tool, especially designed to obtain a better understanding of people's awareness of their vulnerability, knowledge of the relationships between environment and disaster risk, perception of self-responsibility and possibilities for action.

Based on the results and additional research regarding environmental education and relevant stakeholders (Lange et al. 2013), a locally adapted sensitization and communication strategy could be developed. In the municipality of Teresópolis, the three barriers identified through our perception analysis need to be addressed. They should constitute the main content of a sensitization strategy and should also be used as a basis for elaborating educational and/or informational materials.

Instead of implementing top-down approaches, perception analyses provide a feasible way to adapt Eco-DRR and EbA strategies to different local needs, thereby increasing their effectiveness and efficiency. A perception analysis, therefore, plays an important role in advising policymakers from national, state, municipal, and local levels on how to implement more effective, ecosystem-based measures for DRR and CCA with strong involvement of the local communities.

It is important to emphasize that a perception analysis serves to complement Eco-DRR and EbA measures at local level. To engage the population and increase their participation, it is especially important to align certain measures bottom-up, although government institutions are foremost responsible for creating the conditions for local

participation, such as providing relevant information about where and how people can contribute effectively. Furthermore, whilst the proposed Eco-DRR or EbA measures might be cost-effective, financial support for their implementation is crucial, such as providing a fund for local communities or even non-governmental organizations to undertake such activities.

We also suggest that public decision makers and other stakeholders in the region use the results and recommendations of our study to develop adequate intervention strategies to increase public participation in disaster risk management. Our methods and data could then be used as a baseline study to measure the impact of their actions.

In addition to the conclusions of our case study, we recommend that the elaborated methods (toolkit)<sup>5</sup> that were successfully applied in this analysis be used by other researchers in similar research areas in order to allow for future comparison of results and to develop bottom-up activities. We strongly recommend that the methodological toolkit is applied, tested and adapted by other researchers in various contexts of disasters in order to contribute to the development of reliable methods for measuring perception of ecosystem services for disaster risk reduction and adaptation. We believe that Eco-DRR and EbA measures can be successfully implemented and will contribute to effective risk reduction strategies.

## 5.4. References

- Allen K (2006) Community-based disaster preparedness and climate adaptation: local capacity building in the Philippines. *Disasters* 30(1):81–101
- Borrini-Feyerabend G, Pimbert M, Farvar T et al (2007) *Sharing power: a global guide to collaborative management of natural resources*. Earthscan, London
- Brasil (2012) Código Florestal: Lei n° 12.651 de 25 de maio de 2012. Presidência da República, Brasília. [http://www.planalto.gov.br/ccivil\\_03/\\_ato2011-2014/2012/lei/l12651.htm](http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm)
- Brodbeck N (ed) (2012) *World risk report*. Bündnis Entwicklung Hilft, Berlin

---

<sup>5</sup> For more information on the toolkit please see Lange et al. (2013).

- Care (2010) Community based adaptation toolkit. Digital toolkit. Care. [http://www.careclimatechange.org/files/toolkit/CARE\\_Integration\\_Toolkit.pdf](http://www.careclimatechange.org/files/toolkit/CARE_Integration_Toolkit.pdf). Accessed 10 Oct 2014
- CEPED-UFSC (2011) Atlas Brasileiro de Desastres Naturais: 1991–2010. Volume Rio de Janeiro. Universidade Federal de Santa Catarina, Florianópolis
- Collins KMT, Onwuegbuzie AJ, Jiao QG (2007) A mixed methods investigation of mixed methods sampling designs in social and health science research. *J Mixed Methods Res* 1(3):267–294
- Colls A, Ash N, Ikkala N (2009) Ecosystem-based Adaptation: a natural response to climate change. IUCN, Gland. 16 pp
- DRM-RJ (2012) Diagnóstico sobre o risco a escorregamentos no estado do Rio de Janeiro e plano de contingencia para atuação do NADE/DRM-RJ no período de dezembro de 2011 a abril de 2012. Governo do Estado do Rio de Janeiro, Rio de Janeiro
- Fernandes NF, Guimaraes RF, Gomes RAT et al (2004) Topographic controls of landslides in Rio de Janeiro: field evidence and modeling. *CATENA* 55(2):163–181
- Flick U (2007) Designing qualitative research. SAGE, London
- Flick U (2011) Triangulation: Eine Einführung. Reihe Qualitative Sozialforschung. VS Verlag für Sozialwissenschaften, Wiesbaden
- Fundação SOS Mata Atlântica, Instituto Nacional de Pesquisas Espaciais (2014) Atlas dos remanescentes florestais da Mata Atlântica, período 2012–2013. São Paulo. [http://mapas.sosma.org.br/site\\_media/download/atlas\\_2012-2013\\_relatorio\\_tecnico\\_2014.pdf](http://mapas.sosma.org.br/site_media/download/atlas_2012-2013_relatorio_tecnico_2014.pdf). Accessed 10 Oct 2014
- Galindo Leal C, Gusmão-Câmara I (2003) The Atlantic Forest of South America: biodiversity status, threats, and outlook, vol 1, State of the Hotspots. Island Press, Washington, DC
- Gibbs GR (2007) Analyzing qualitative data. In: Flick U (ed) The SAGE qualitative research kit. SAGE, Los Angeles

- GIZ (2013) Assessing and monitoring climate vulnerability. Deutsche Gesellschaft für Internationale Zusammenarbeit, Eschborn
- Grothmann T, Patt A (2005) Adaptive capacity and human cognition: the process of individual adaptation to climate change. *Glob Environ Chang* 15:199–213
- Guha-Sapir D, Vos F, Below R, Ponserre S (2012) Annual disaster statistical review 2011 – the numbers and trends. Université catholique de Louvain, Brussels
- IBGE (Instituto Brasileiro de Geografia e Estatística) (2010) Censo Demográfico 2010. <http://censo2010.ibge.gov.br>. Accessed 10 Oct 2014
- IIED (2009) Participatory learning and actions. Community-based adaptation to climate change. IIED, London
- IPCC (2001) 3rd Assessment Report, Working Group II, Appendix I, [www.grida.no/publications/other/ipcc\\_tar/](http://www.grida.no/publications/other/ipcc_tar/). Accessed 10 Oct 2014
- Jha AK, Bloch R, Lamond J (2012) Cities and flooding: a guide to integrated urban flood risk management for the 21st century. The World Bank, Washington, DC. <http://www.gfdr.org/gfdr/sites/gfdr.org/files/urbanfloods/pdf/Cities%20and%20Flooding%20Guidebook.pdf>. Accessed 10 Oct 2014
- King L, Marfai M (2008) Coastal flood management in Semarang, Indonesia. *Environ Geol* 55 (7):1507–1518
- Lange W, Cavalcante L, Dünow L et al (2013) HumaNatureza<sup>2</sup> = Proteção Mútua. Percepção de riscos e adaptação à mudança climática baseada nos ecossistemas na Mata Atlântica, Brasil. Schriftenreihe des Seminars für Ländliche Entwicklung 255 (SLE). Humboldt-Universität zu Berlin, Landwirtschaftlich-Gärtnerische Fakultät, Berlin. <http://edoc.hu-berlin.de/series/sle/255/PDF/255.pdf>. Accessed 11 Nov 2014
- Madajewicz M, Pfaff A, van Geen A et al (2007) Can information alone change behavior? Response to arsenic contamination of groundwater in Bangladesh. *J Dev Econ* 84:731–754
- Marengo JA (2008) Água e Mudanças Climáticas. *Estudos Avançados* 22(63):83–96

- Mayring P (2000) Qualitative content analysis. *Forum Qual Soc Res* 1(2)
- Mayring P (2010) *Qualitative Inhaltsanalyse: Grundlagen und Techniken*. Beltz, Weinheim
- Messner F et al (2006) Flood damage, vulnerability and risk perception – challenges for flood damage research. In: Schanze J, Zeman E, Marsalek J (eds) *Flood risk management: hazards, vulnerability and mitigation measures*, vol 67, NATO Science Series. IV. Earth and Environmental Sciences. Springer, Dordrecht, pp 149–167
- Mytanz C (2013) Indicators for local and regional vulnerability assessment in rural Cameroon. *Climate Protection Programme for Developing Countries*. Eschborn
- Nehren U, Alfonso de Nehren S, Heinrich J (2009) Forest fragmentation in the Serra dos Órgãos: historical and landscape ecological implications. In: Gaese H et al (eds) *Biodiversity and land use systems in the fragmented Mata Atlântica of Rio de Janeiro*. Cuvillier, Göttingen, pp 39–64
- Nehren U, Sudmeier-Rieux K, Sandholz S et al (eds) (2014) *The ecosystem-based disaster risk reduction. Case study and exercise source book*. UNEP and CNRD, Geneva
- PBMC (2013a) *Contribuição do Grupo de Trabalho 1 ao Primeiro Relatório de Avaliação Nacional do Painel Brasileiro de Mudanças Climáticas. Sumário Executivo GT1*. PBMC, Rio de Janeiro
- PBMC (2013b) *Contribuição do Grupo de Trabalho 2 ao Primeiro Relatório de Avaliação Nacional do Painel Brasileiro de Mudanças Climáticas. Sumário Executivo do GT2*. PBMC, Rio de Janeiro
- Plapp S (2003) *Wahrnehmung von Risiken aus Naturkatastrophen. Eine empirische Untersuchung in sechs gefährdeten Gebieten Süd- und Westdeutschlands*. <http://digbib.ubka.uni-karlsruhe.de/volltexte/3542003>
- Renaud FG, Sudmeier-Rieux K, Estrella M (2013) The relevance of ecosystems for disaster risk reduction. In: Renaud F, Sudmeier K, Estrella M (eds) *The role of ecosystems in disaster risk reduction*. UNU Press, Tokyo, pp 3–25

- Ribeiro MC, Metzger JP, Martensen AC et al (2009) The Brazilian Atlantic forest: how much is left, and how is the remaining forest distributed? Implications for conservation. *Biol Conserv* 142(6):1141–1153
- SBF (2011) Áreas de Preservação Permanente e Unidades de Conservação x Áreas de Risco. O que uma coisa tem a ver com a outra?. Série Biodiversidade 41. Ministério do Meio Ambiente, Brasília
- SEA (2012) Plano Estadual sobre Mudança do Clima. Governo do Estado do Rio de Janeiro, Rio de Janeiro. <http://download.rj.gov.br/documentos/10112/1312221/DLFE-56319.pdf/planoEstadualmudclima.pdf>. Accessed 11 Oct 2014
- Slovic P (1992) Perception of risk: reflections on the psychometric paradigm. In: Krimsky S et al (eds) *Social theories of risk*. Praeger, New York, pp 117–152
- Slovic P, Weber EU (2002) Perception of risk posed by extreme events. Working paper. Columbia University, New York. <http://www.rff.org/Documents/Events/Workshops%20and%20Conferences/Climate%20Change%20and%20Extreme%20Events/slovic%20extreme%20events%20final%20geneva.pdf>. Accessed 15 Oct 2014
- Smyth C, Royle S (2000) Urban landslide hazards: incidence and causative factors in Niterói, Rio de Janeiro State, Brazil. *Appl Geogr* 20:95–117
- Sudmeier-Rieux K, Ash N (2009) Environmental guidance note for disaster risk reduction: healthy ecosystems for human security, Revised Edition. IUCN, Gland
- UNDP (1990) Human development report 1990. The concept of measurement of human development. United Nations Development Programme, New York/Oxford

## 6. Nature-Based Solutions for landslide risk reduction in informal settlements of Salvador da Bahia, Brazil

Lange, W., Camarinha, P. I. M., Nehren, U., Andrade, A. & Kraas, F. (submitted, after review currently under revision). Nature-based Solutions for landslide risk reduction in informal settlements of Salvador da Bahia, Brazil. *International Journal of Disaster Risk Reduction*. Submitted

This is the author's original manuscript of the submitted article.

### *Abstract*

Nature-based Solutions (NbS) for climate change adaptation (CCA) and disaster risk reduction (DRR) aim to take advantage of the benefits that nature can provide to cope with potential adverse impacts. The objective of the current study was to identify these NbS and compare them with conventional measures to reduce landslide risk in communities in Salvador da Bahia. We applied mainly qualitative social research methods including semi-structured interviews and participatory workshops in selected communities for data gathering. The results show that NbS are in most cases evaluated by experts as just being as efficient as conventional engineered measures, but are often cheaper and contribute to the sustainable development of the city of Salvador with several co-benefits. However, there is a need for greater awareness of the potential of NbS for better acceptance among the residents of the settlements.

Keywords: shallow landslides, disaster risk reduction (DRR), climate change adaptation (CCA), Nature-based Solutions (NbS), informal settlements, Brazil

### 6.1. Introduction

Shallow landslides triggered by extreme rainfall represent one of the most devastating natural hazards in urban areas of Brazil, particularly affecting informal settlements located on steep slopes (Coelho-Netto et al. 2009, Debortoli et al. 2017, Camarinha et al. 2024, Facadio et al. 2024). In Salvador da Bahia, like in several other Brazilian coastal cities, rapid and unplanned urbanization led to the occupation of exposed areas by socially vulnerable populations, significantly increasing disaster risk (Lange et al. 2017, Ferreira 2023). The informal settlements, known as *favelas*, are

characterized by precarious infrastructure, lack of proper drainage systems, and the removal of natural vegetation, making them highly susceptible to landslides during intense rainfall events. Several buildings in these communities were not constructed in accordance with building regulations, increasing their susceptibility to landslides (Lange et al. 2016, Lange et al. 2018a, Sandholz et al. 2018).

Climate change projections indicate an increase in the frequency and intensity of extreme rainfall events in the coastal regions of Brazil, which will likely exacerbate landslide risk in vulnerable urban areas (Marengo et al. 2021). Historical records show that landslides in informal settlements of Salvador resulted in significant loss of life and property damage, highlighting the urgent need for effective risk reduction strategies and measures. The city experienced several devastating landslide events (e.g., in 2015 and 2022, Barretto & Silva 2023 and Shaughnessy et al. 2024), with a prominent disaster in 2015 claiming 14 lives and destroying numerous hillside homes. Traditional disaster prevention in Salvador predominantly relied on gray infrastructure, such as retaining walls and other engineered solutions. Although these measures offer immediate protection as soon as they are implemented, they can also fail in extreme catastrophic events, are often associated with high costs (Vicarelli et al. 2024), contribute to surface sealing, and are not beneficial ecologically (Sudmeier-Rieux et al. 2019).

While conventional engineering approaches were the predominant response to landslide risk in Brazilian cities, nature-based solutions (NbS) are emerging as promising alternatives that can provide multiple benefits beyond risk reduction (World Bank 2008, Cohen-Shacham 2016, Lange et al. 2018a, Arce-Mojica 2019, Sudmeier-Rieux et al. 2021). These NbS, which include Ecosystem-based Disaster Risk Reduction (Eco-DRR) and Ecosystem-based Adaptation (EbA), integrate sustainable management, conservation, and restoration of ecosystems to reduce disaster risk while supporting community resilience (Nehren et al. 2023).

The potential of NbS for shallow landslide risk reduction lies in their ability to stabilize slopes through reinforcing soil through root systems, which provide mechanical support and increase soil cohesion, improve water infiltration, and reduce surface runoff (Arce-Mojica 2019, Tallaksen & Capobianco 2023, Galeazzi et al. 2024). Additionally, the canopy reduces the splash effect and the vegetation cover decreases

runoff (Nehren et al. 2013; Lann et al. 2024). Compared with those of the conventional engineering measures, NbS provide additional benefits, such as biodiversity conservation, carbon sequestration, and improved quality of life for local communities (World Bank 2008, Cohen-Shacham 2016, Lange et al. 2018a, Sudmeier-Rieux et al. 2021, Nehren et al. 2023). In terms of effectiveness and cost efficiency, studies showed that NbS are just as effective at protecting against natural hazards, such as shallow landslides as conventional technical systems (Sudmeier-Rieux et al. 2019), although they are usually more cost-effective (Vicarelli et al. 2024). NbS were shown to be cost-effective alternatives to traditional engineering approaches, particularly in reducing hydro-meteorological risks, such as floods and landslides. For example, NbS like wetland restoration and slope revegetation can be up to five times cheaper than those by engineered solutions while also providing co-benefits (Ruangpan et al. 2020). Additionally, NbS are resource-efficient and economically viable when designed to adapt to local conditions, ensuring that their implementation and maintenance costs remain proportional to their environmental and social benefits (Sowińska-Świerkosz & García 2022). In the context of NbS, co-benefits refer to the additional positive outcomes generated alongside the primary objective of addressing societal challenges, such as climate change adaptation or disaster risk reduction. These co-benefits include improvements in biodiversity, air and water quality, urban cooling, and human wellbeing, as well as other ecosystem services and social cohesion (Yang et al. 2023, lungman et al. 2025). For example, NbS for flood risk reduction, such as bio-retention basins or green roofs, not only mitigate flooding but also contribute to urban regeneration, increased green space accessibility, and improved mental health (Herranz-Pascual et al. 2025, lungman et al. 2025).

To ensure that NbS are designed and implemented in a proper and effective way, the International Union for Conservation of Nature (IUCN) together with more than 800 practitioners and experts developed a Global Standard for NbS (<https://iucn.org/our-work/topic/iucn-global-standard-nature-based-solutions>). Furthermore, Cohen-Shacham et al. (2019) suggested core principles for successfully implementing and upscaling NbS. Additionally, studies highlight the importance of avoiding the risks of maladaptation (Higuera Roa et al. 2025) and ecosystem disservices (Pereira et al. 2023) when implementing NbS.

Against this backdrop, the main objective of this study was to identify and evaluate NbS for landslide risk reduction in the informal settlements (*favelas*) of Salvador, comparing them with that of conventional engineering measures. This research has specifically focused on:

1. Identifying risk factors for shallow landslides
2. Assessing the potential NbS interventions suitable for Salvador
3. Evaluating and comparing the effectiveness, costs and co-benefits of landslide risk reduction measures
4. Analyzing community perception and acceptance for implementing NbS for landslide risk reduction.

This research addressed a critical gap in understanding the performance of NbS compared with that of the conventional landslide risk reduction measures and their effective implementation in informal urban settings (Arce-Mojica 2019, Tischler 2023). The findings will contribute to the growing body of knowledge on nature- and ecosystem-based approaches for disaster risk reduction and climate change adaptation in vulnerable urban communities.

## 6.2. Background

### 6.2.1. Ecosystem-based Adaptation and Disaster Risk Reduction

Ecosystem-based adaptation (EbA), ecosystem-based disaster risk reduction (Eco-DRR), and nature-based solutions (NbS) represent interconnected approaches harnessing biodiversity and ecosystem services to address societal challenges related to climate change and disaster risks (Brink et al. 2016, Renaud et al. 2016, Walz et al. 2021).

EbA specifically focuses on using biodiversity and ecosystem services to help communities adapt to adverse climate change effects through sustainable ecosystem management, conservation, and restoration (SCBD 2009, Brink et al. 2016). Eco-DRR, while sharing similar principles, primarily addresses current and recurring hazards through sustainable ecosystem management to reduce disaster risk (Estrella & Saalismaa 2013, Renaud et al. 2016). NbS serves as the broader umbrella concept,

encompassing both EbA and Eco-DRR approaches while promoting comprehensive nature-based interventions for multiple societal challenges (Brink et al. 2016, Cohen-Shacham et al. 2016, Cohen-Shacham et al. 2019, Doswald et al. 2021).

Research demonstrates robust evidence for the effectiveness of ecosystem-based approaches in reducing specific climate-related hazards and disaster risks (Doswald et al. 2021, Sudmeier-Rieux et al. 2024). EbA takes a longer-term perspective focused on CCA, while Eco-DRR typically addresses immediate and recurring hazards (Renaud et al. 2016). Both approaches demonstrate high levels of confidence in reducing specific hazards, particularly in urban areas and mountain environments (Sudmeier-Rieux et al. 2021). Research shows robust links between ecosystem functions and disaster risk reduction, especially regarding forests for wildfire management, urban green infrastructure for flood mitigation, and vegetation on steep slopes for reducing mountain hazards (Sudmeier-Rieux et al. 2021).

Economic analyses reveal that NbS can be more cost-effective than that of traditional grey infrastructure, especially when accounting for multiple ecosystem services and long-term benefits (Chausson 2020, Vicarelli et al. 2024). The scientific evidence indicates that these approaches provide numerous co-benefits beyond their primary protective functions, including enhanced biodiversity support, carbon sequestration, improved water quality, strengthened local livelihoods, and community development opportunities (Sudmeier-Rieux et al. 2021, Nehren et al. 2023). Studies consistently demonstrate that ecosystem-based measures can be as effective as conventional engineering approaches while being cheaper and delivering multiple additional benefits (Onuma & Tsuge 2018, Sudmeier-Rieux et al. 2021).

Ecosystem-based approaches demonstrate significant potential for landslide risk reduction, particularly through vegetation management and reforestation of steep slopes. Research shows evidence that existing vegetation plays a crucial role in reducing slope hazards, as landslides become more frequent and extensive following deforestation due to the loss of tree and shrub roots essential for soil stability (Arce-Mojica et al. 2019, Sudmeier-Rieux et al. 2021, Lann et al. 2024). Studies indicate that slope revegetation and forest restoration can effectively stabilize slopes, reduce erosion, and decelerate rainwater runoff (Arce-Mojica et al. 2019). In urban contexts, such as Rio de Janeiro, reforestation programs showed promise in reducing landslide

risk, though their effectiveness needs to be better integrated with formal risk reduction strategies and supported by improved monitoring systems (Lange et al. 2018a). However, ecosystem-based measures cannot completely eliminate landslide risk, and in some cases, hybrid approaches combining both green and grey infrastructure may be the most appropriate (Arce-Mojica et al. 2019, Sudmeier-Rieux et al. 2021).

Implementing NbS in informal settlements presents unique challenges and opportunities requiring careful consideration (Ronchi & Arcidiacono 2019). Research from Rio de Janeiro demonstrates that their implementation faces several distinct challenges. The informal nature of land tenure, dense building structures, and lack of proper infrastructure, such as drainage systems often complicate the establishment of ecosystem-based measures (Lange et al. 2018a, Sandholz et al. 2018). Additionally, a discrepancy between formal urban planning and the reality of informal settlements is observed, requiring novel governance approaches bridging different social groups and institutional scales (Balbim 2023, Alfonsin & Mota Júnior 2024). The implementation process demands extensive community involvement and awareness-raising initiatives, as residents may initially be skeptical of NbS, particularly when forests are perceived as sources of risk rather than as a resource for protection (Lange et al. 2016, Lesser & Brandes 2023). A key success factor is the development of participatory decision-making processes that actively include informal settlers while ensuring coordination between multiple sectors, such as civil defense, geological survey, urban planning, and environmental management (Lange et al. 2018a, Fianoo et al. 2024, Nalumu & Perrotti, 2024). Furthermore, hybrid approaches combining both green and gray infrastructure often prove most practical in these contexts, especially given the immediate protection needs of communities living in high-risk areas, defined by high slope degree and existing cracks, among other risk factors (Lange et al. 2018a, Sandholz et al. 2018).

Research demonstrates that risk perception alone does not sufficiently explain the success or failure of certain risk reduction programs. While communities often show high awareness of their exposure to landslide risks, particularly after experiencing disaster events, this awareness does not automatically translate into appropriate risk-reducing actions (Lange et al. 2016, Zin Mar Than 2023). Studies indicate that people may have difficulty differentiating between risk levels across locations and may

overestimate risks in some areas while underestimate them in others (Lange et al. 2016). Rather than focusing solely on increasing risk awareness, sensitization activities should address as well knowledge gaps about ecosystem services, enhance local understanding of exposure levels, and demonstrate the effectiveness of NbS (Lange et al. 2016). Community participation and local acceptance are crucial factors, as these approaches often require longer implementation timeframes and ongoing maintenance compared with those of traditional engineering solutions (Ruangpan et al. 2020).

### 6.2.2. Risk and climate change profile of Salvador

The Municipality of Salvador is located in the State of Bahia, at the entrance of the Bay of All Saints, and comprises a territorial extension of about 707 km<sup>2</sup> and a population of about 2.4 million inhabitants of which more than 1 million live in informal settlements (*favelas*) (IBGE 2022).

The climate is tropical humid to super-humid, with average annual precipitation and temperature of 1235 mm and 25.6 °C, respectively (climate-Data.org). The rainiest quarter, in the months of April, May, and June, presents an average monthly precipitation varying from 251 to 325 mm and a hydric surplus of more than 100 mm. The months between September and February are the least rainy with precipitation between 111 and 132 mm (Santos et al. 2016). The city of Salvador suffers from extreme weather events, such as heavy rains causing landslides and flooding. According to the analysis of data from the National Institute for Space Research (INPE) climate scenario modeling (Chou et al. 2014), both of the variables of maximum rainfall amount and consecutive rainy days, indicated a potential increase of climate exposure in relation to mass movements as the trend is to have more extreme events of volume and duration.

According to Peixoto (1968) and Nascimento (2008), the compartmentalized block structure and the humid tropical climate favor a deep alteration of the crystalline rocks, the evolution process of which led to the development of several pedological horizons. On one hand, the residual soil and the altered rock constituting the regolith are generally reddish in color, dominantly clayey. On the other hand, soils developed over some types of strata of the Barrier Formation exhibit, in most cases, a sandy and

sandy-silt texture, grayish in color. The contrast often found between the strata of the *Formação Barreiras*, with sandy characteristics, and the residual soil, with clay content, is one of the main factors characterizing the high susceptibility to landslides in the region.

The geomorphological characteristics of Salvador are notably conditioned by the geological components and by the action of the climatic agents. The endogenous force is responsible for the system of faults and fractures existing in the topographic configuration, which implies in the direction of the surface water flow, in the determination of the morphogenetic balance and in the configuration of the modeled relief. The city of Salvador is initially installed on the reverse side of a dissected plateau, with an altitude of about 60 m in the city center, decreasing southeast-south and eastward to the coastal plain bordering the Atlantic. Inland, in a northerly direction, it rises about 110 m (Peixoto 1968).

In relation to slope, the city presents slopes above 18% in a significant portion of its territory, largely due to the fault and fracture systems contributing to the complexity of the topographic compartmentalization of Salvador. Additionally, areas of high population and housing densification exist on slopes with slopes above 100%, highlighting the occupations along the escarpment representing the Salvador Fault, one of the places with the highest number of records of landslides and rockfalls (IPT & CTGeo 2017).

Regarding this aspect, the Municipal Risk Reduction Plan (*Plano Municipal de Redução de Riscos - PMRR*) (IPT & CTGeo 2017) highlights the main causes of landslide episodes, which are: (1) level of fracturing of the scarps and their high slope; (2) absence of surface water channeling; (3) obstruction of natural drainage by the accumulation of debris; (4) destruction of natural flora and impropriety of the species present; and (5) dense and precarious horizontal occupation, with damage to the vegetation cover and the drainage system, among others.

According to the database of the National Center for Monitoring and Disaster Alert (Cemaden), Salvador is among the five Brazilian municipalities with the highest number of alerts sent since 2011 and the third highest number of events with impacts caused by mass movements. Between 2016 and 2024, Cemaden registered 48 events

resulting in at least 151 mass movements (mostly landslides) causing material and human losses in Salvador. The number of landslides, provided by the Flood and Landslide Event Records of Cemaden (*Registros de Eventos de Inundação e Deslizamentos do Cemaden - REINDESC*), in this period may be much higher, although only the cases in which significant impacts were officially reported are included in this statistic (Iwama et al. 2023).

Figure 15 presents the geographic distribution of the aforementioned occurrences, accompanied by a heat map (density of occurrences) facilitating the identification of the regions most affected by landslides. The figure shows that the locations with the highest density of landslide occurrences are in the southwest and west of the municipality, basically in the domains of the Crystalline Complex and where the Barreiras Formation is found, as well as adjacent to the escarpments of the Salvador Fault (Salvador 2004).

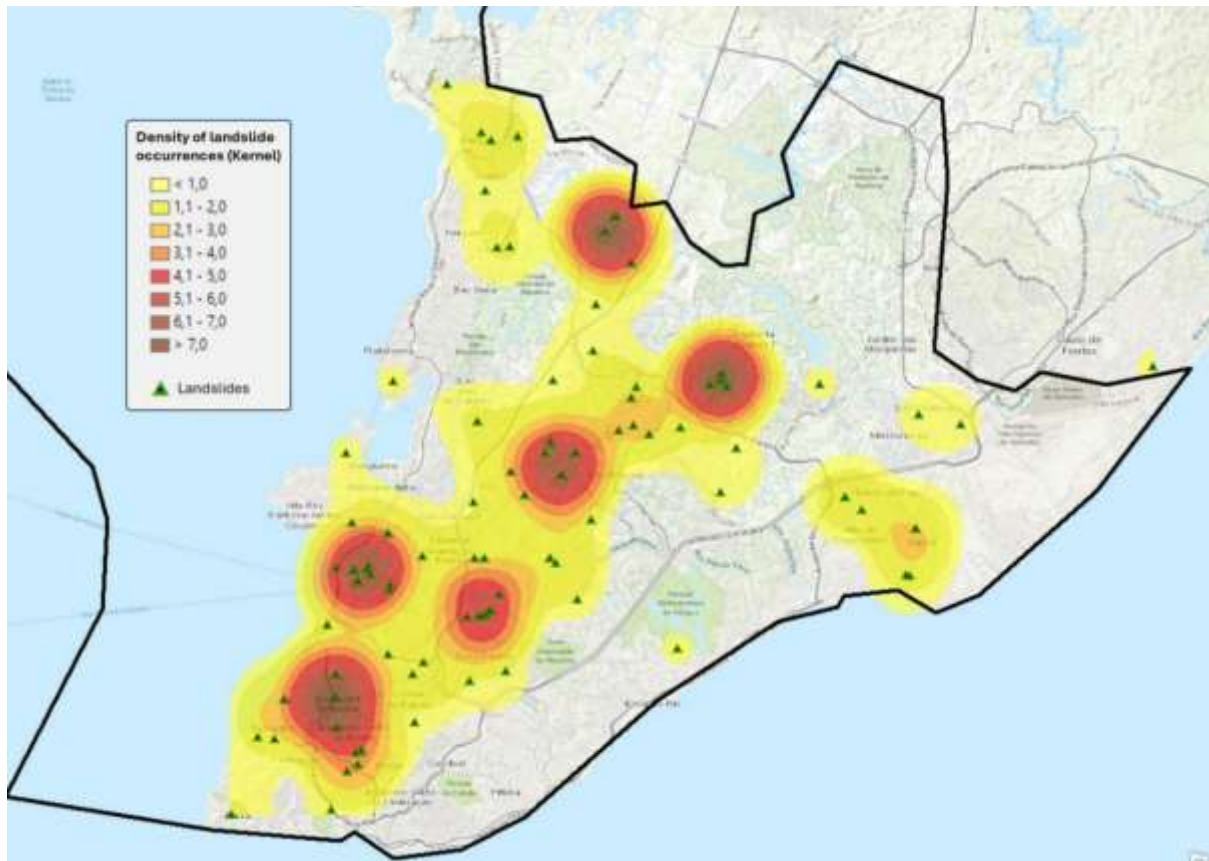
These are regions where a combination of naturally susceptible areas exist from a geological-geotechnical perspective and a high level of anthropogenic interference on the slopes and in their surroundings, which overlap with a large amount of exposed and vulnerable population, and often, with inefficient infrastructure, especially with regard to the drainage network (Salvador 2004).

For analyzing the precipitation patterns in Salvador events exceeding 50 mm within 24 hours, a critical threshold associated with landslide occurrence, was used (Camarinha et al. 2024). This threshold value was adopted by both Salvador Civil Defense (CODESAL) and Cemaden-MCTI as a key parameter for assessing landslide risk conditions. CHIRPS (Climate Hazard Infrared Precipitation with Stations) provides a comprehensive precipitation dataset spanning over 40 years with daily temporal resolution and 0.05° spatial resolution. It shows an increasing trend in precipitation events exceeding the critical threshold for the 1990–2022 period, particularly in recent years.

According to a study conducted by the Brazilian Institute of Geography and Statistics in partnership with the National Center for Monitoring and Alert of Natural Disasters (IBGE & Cemaden 2018), Salvador is the Brazilian city with the largest number of

people living in geohydrological risk areas with a total of approx. 1.2 million people exposed to risks related to landslides.

Figure 15: Density of landslides occurrences based on data provided by REINDESC (Cemaden), referring to the period 2016–2024. Source: Authors.



This high number is a reflection of the urban evolution of the city, which started along the crest of the fault escarpment, and later, directed along the great avenues inserted in the valleys of Salvador, created in the second half of the 20th century, during the period of economic growth of the city. In this evolutionary context, the low-income population was always forced to reside in areas of low added value, such as hilly terrain, valley bottoms, deactivated quarries, and peripheral regions, culminating in complex risk scenarios, especially those related to landslides. This complexity of risk scenarios directly demands complex solutions, not only from a geological-geotechnical perspective, but also urban, and mainly, social perspective (Machado et al. 2019).

### 6.2.3. Materials and methods

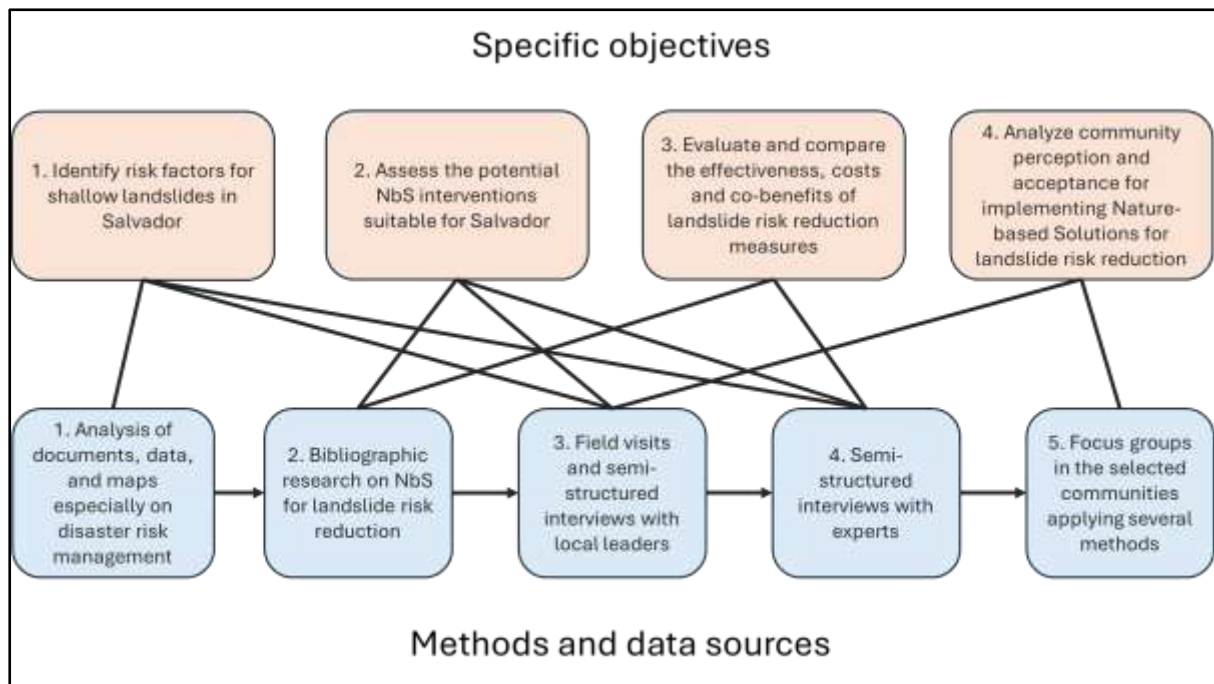
The study sites were selected through a collaborative process with municipal authorities, specifically the Civil Defense of Salvador (CODESAL). Two communities, Beira Dique and Padre Hugo, were identified as suitable research locations based on multiple selection criteria: a) presence of the Community Protection and Civil Defense Center (NUPDEC) of the Civil Defense (CODESAL) and its performance, b) community leadership (capacity of articulation, mobilization, cohesion, and performance), c) current degree of risk, d) DRR/containment/remediation interventions already planned (such as a Structural Action Plan – PAE in the Portuguese abbreviation), e) state of ecosystems (incl. surrounding areas), f) visibility of a potential intervention or of the informal settlement in general within the city and its population (important for CODESAL and the city hall in general for promoting their activities), and g) susceptibility of shallow landslide risk.

This approach to site selection allows for a more holistic evaluation of the opportunities and challenges for the implementation of NbS while considering both social and biophysical factors. The selected communities are examples of representative informal settlements in Salvador, which are prone to landslides and have the necessary institutional framework for intervention implementation.

A comprehensive methodological framework was developed to address the research objectives through a mixed-method design, incorporating both qualitative and quantitative approaches (Fig. 16). This methodological integration was strategically implemented to enhance the validity and reliability of the findings while providing a holistic understanding of NbS for landslide risk reduction in *favelas* of Salvador.

The first objective, identifying risk factors for shallow landslides in Salvador, was approached through the analysis of existing documents (disaster risk management plans, urbanization plans for informal settlements, etc.), data (e.g., demographic data), and maps (especially risk maps), which provide crucial insights into environmental and socio-economic conditions contributing to landslide risks. Additionally, field visits and semi-structured interviews with local leaders supplemented these data, ensuring a comprehensive understanding of the vulnerabilities of the region.

Figure 16: Relation of specific objectives and methods and data sources for operationalization (Source: Authors)



For assessing potential NbS interventions suitable for Salvador, bibliographic research played a key role in identifying best practices and relevant case studies. This was further strengthened by semi-structured interviews with experts in the field selected by expertise, such as academic profile, profession, and knowledge, ensuring that proposed solutions are both scientifically sound and contextually appropriate.

Evaluating and comparing the effectiveness, costs, and co-benefits of various landslide risk reduction measures involved a multi-faceted approach. The combination of expert consultations for opinion and knowledge assessment and document analysis for evaluating different measures enabled a holistic assessment of different strategies, providing valuable insights for decision-makers.

Finally, understanding community perception and acceptance of NbS interventions was crucial for successful implementation. Focus groups conducted in selected communities offered a platform for local stakeholders to express their concerns, expectations, and willingness to adopt these solutions. This participatory approach ensured that the proposed measures aligned with those of the community needs and foster local ownership.

In the semi-structured expert interviews (n = 25, INT-001 to INT-025), a questionnaire was ed with key questions regarding potential impacts and vulnerability (exposure, sensitivity, and adaptive capacity) as well as the identification and evaluation of adaptation measures. The evaluation criteria encompassed cost considerations, effectiveness metrics, feasibility of implementation, co-benefits, and anticipated implementation challenges. These questions were adapted and refined in the course of the interviews. Interviewee selection followed a dual sampling strategy: initial participants were identified through institutional partnerships with the Civil Defense of Salvador (CODESAL), followed by snowball sampling methodology to identify additional relevant experts. The final sample predominantly consisted of municipal technical staff, academic researchers, and private sector engineering professionals with expertise in construction and slope stabilization.

Participatory research methods were employed through three focus group sessions (FGS-01 to FGS-02) conducted within the selected communities. The selection of focus group participants was facilitated through a collaborative process between the community association leadership and the local NUPDEC coordinator, ensuring representative stakeholder engagement from the target community. The research design incorporated multiple participatory techniques, including participatory mapping, facilitated group discussions, and buzz group activities (Lange et al. 2014). These methods were strategically implemented to complement the semi-structured interviews while specifically exploring community perception and knowledge regarding ecosystem services and community participation. The participatory mapping exercises conducted in the community made it easier for the community members to show their perception of the physical features of the land and the resources found in the area thereby helping the community to identify important environmental and socio-cultural features in the area. To assess the adaptive capacity and potential engagement of community members in landslide risk reduction initiatives, a systematic set of semi-structured questions was developed and implemented in two of the focus group discussions. These inquiries were strategically designed to evaluate three fundamental aspects: governmental responsibilities and interventions, community-based adaptive measures, and the integration of ecosystem services in risk reduction strategies.

This methodological approach enabled the collection of rich qualitative and quantitative data from diverse professional and social perspectives while maintaining focus on the technical and practical aspects of nature-based solutions implementation and evaluation.

### 6.3. Results

The detailed identification of the risk factors showed that, apart from the increase in heavy rainfall events, the fact that houses exist and their inhabitants located in landslide risk areas contribute to the exposure as the main risk factor. Additionally, trash on the hillsides and inadequate informal drainage directing water and sewage into the hillsides are factors that can trigger mass movements. Vegetation degradation, particularly the prevalence of unsuitable species, such as banana plants, exacerbates landslide susceptibility due to insufficient root systems for soil stabilization, thereby accelerating surface erosion processes. The sensitivity to landslides is high because the buildings in the communities are in most cases fragile. The potential impacts of landslides are high and can cause loss of life and lead to destruction of buildings and other infrastructure. CODESAL implemented various preparatory and preventive measures, including slope stabilization, early warning systems, evacuation route development, and Community Civil Protection and Defense Centers (NUPEDEC). In the workshops, the population of the surveyed areas primarily pointed to solutions of the public sector to reduce landslide risk and were unsure of their contribution to the solution, indicating a low adaptive capacity of the inhabitants of the communities.

Regarding landslide risk reduction, the slope stabilization and runoff control measures implemented in landslide-prone areas of Salvador encompass various engineering approaches, each with distinct characteristics and effectiveness levels:

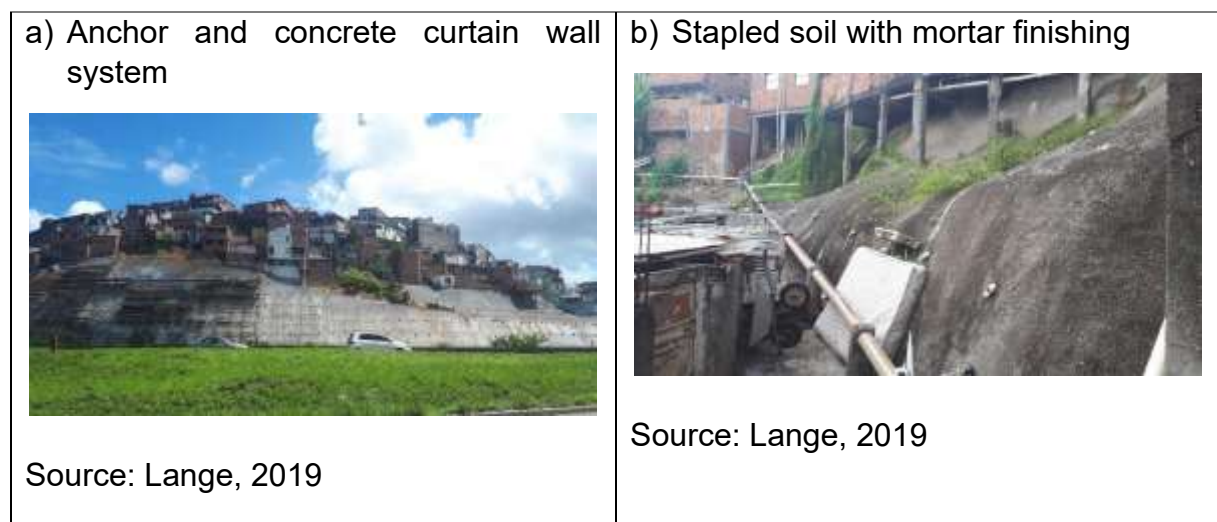
- **Anchor and concrete curtain wall system:** The traditional work applied for decades by the *Companhia de Desenvolvimento Urbano do Estado da Bahia* (CONDER) is a hillside containment with an anchor and concrete curtain wall system (Fig. 17a). This work eliminates with great probability the risk of landslides. On extremely steep slopes and vulnerable soil conditions, it is the most effective option. It is therefore widely accepted by both experts and the local population. However, implementation cost is high. An expert emphasized: *“I make concrete retaining walls, but I don’t like it... the city looks ugly, very gray... There’s also the increase in heat...”* (INT-005).
- **Stapled soil with mortar finishing:** Another containment work traditionally applied by CODESAL and CONDER is the stapled soil with mortar finishing and drainage (Fig.

17b). An interview excerpt is as follows: "The surface coating prevents surface erosion, which is caused by the infiltration of water....The stability of the massif is obtained with the clamp." (INT-005).

- **Geomanta** (a geosynthetic material and concrete used primarily for erosion control and soil stabilization purposes): The **geomanta** is currently the most applied by the City of Salvador, which is a measure solely for waterproofing the slope (Fig. 17c). Low cost is its greatest advantage. Contrarily, **geomanta** has an extremely limited lifespan (up to about 5 years) and requires maintenance or renovation. "The **geomanta** does not stabilize slopes, it is merely a covering." (INT-008). Furthermore, as a measure that only seals the soil, it does not eliminate the risk. Another expert is rigid in his criticism: "Now they've made geomanta, with graffiti to try to see if they can soften it, to make it less bad. This is a scar with a tattoo over it, to try and disguise it. But it's a scar, you could think of doing it the other way around... that's it!" (INT-014). A resident of the *favela* Padre Hugo stated the following at a focus group (FGS-02): "the **geomanta** has brought more water on rainy days, although it has reduced the mud flow" and that "residents pierced the geomanta and are building on top of it" showing some of the challenges of this technology.

These three gray infrastructure measures have no co-benefits for the environment or the local population, apart from reducing the risk of landslides, although they are very impactful interventions for the community and the high visibility of the work shows performance by the public authorities. Additionally, concrete heats up the environment contributing to the heat island and can have a visual impact; as in many cases, concrete is not seen to add to the aesthetic value.

Figure 17: Photos of different solutions for landslide risk reduction



c) *Geomanta*



Source: Lange, 2019

d) Stapled soil retaining structure with green cladding.



Source:

<https://newsba.com.br/2018/03/27/conte-ncao-de-encosta-e-entregue-no-suburbio-ferroviario-de-salvador/>, 2018, modified

e) Staples and wire mesh



Source: Maccaferri, 2019

f) Terracing and Vetiver grass cover



Source: Lange, 2019

g) Reforestation



Source: Lange, 2016

h) Grass cover



Source: Lange, 2019

Hybrid engineering solutions for slope stabilization demonstrate notable advantages through their multifunctional benefits:

- **Stapled soil retaining structure with green cladding:** Figure 17d shows a stapled soil retaining structure with green cladding, which has garnered unanimous support from technical experts due to its dual functionality in soil stabilization and waterproofing, comparable with those of conventional gray infrastructure solutions. These hybrid interventions present favorable cost-effectiveness ratios relative to traditional engineering approaches while offering multiple ecosystem services. In addition to the co-benefits of heat mitigation, increased biodiversity in the city, and contribution to air purification and improvement, it provides superior aesthetic integration within the urban landscape.
- **Staples and wire mesh:** Another hybrid measure that was occasionally implemented on private land is an intervention with staples, wire mesh, and trees or other vegetation (Fig. 17e). This technique stabilizes the soil and lasts as long as other works using gray coating, although it presents all the co-benefits of green infrastructure. The incorporation of larger vegetation, including potential fruit-bearing species, extends the value of intervention beyond slope stabilization to include community benefits and local development opportunities. The economic viability of this approach is particularly noteworthy, as implementation costs remain competitive with traditional engineering solutions.

Regarding green-only measures to reduce the risk of landslides, several promising solutions exist for the City of Salvador:

- **Vetiver grass (*Vetiveria zizanioides*):** While the soil stabilization capacity of Vetiver (Fig. 17f) may not match the structural integrity provided by conventional metal stabilization techniques, its application proves sufficient in specific geotechnical contexts. The system offers multiple ecosystem services and economic benefits, including material utilization potential from its foliage and exceptional cost-effectiveness. However, its implementation in community areas presents challenges regarding informal construction encroachment. However, Vetiver grass comes from Asia and the biodiversity benefits are limited. An expert commented positively on Vetiver: *"I welcome the idea of plant cover, having already worked with students developing protection with the Vetiver species... it has deep roots and can be a solution for green coverings."* (INT-003).
- **Reforestation:** Reforestation (Fig. 17g) initiatives represent another uniquely green measure, offering long-term soil stabilization benefits and environmental durability. The effectiveness of this approach in shallow landslide risk reduction requires site-specific geotechnical assessment, though it provides substantial ecosystem services as the Vetiver grass. *"You have to analyze it case by case. Vegetation helps to keep a slope stable. If you put it on an unstable slope, on soils with discontinuities... sometimes one side of a road is stable, the other is not. You have to be very careful with these solutions... you can't generalize. But in general, slopes of more than 45 degrees are not suitable for vegetation. In principle..."* (INT-008). Native species should be used preferentially and social co-benefits should be generated where possible (such as use of fruit and tree bark).
- **Grass cover:** The implementation of grass cover systems as usually applied on the slopes of Salvador and much different in its characteristics than those of the Vetiver grass (Fig. 17h) demonstrates practical ecological engineering. These systems

provide waterproofing capabilities comparable with those of *geomanta* while offering superior longevity and cost-effectiveness, coupled with enhanced ecosystem services, such as heat reduction and improving air quality. However, their application should be limited to appropriate geotechnical conditions due to their inability to provide structural soil stabilization.

Table 3 summarizes the landslide risk reduction measures in relation to function, co-benefits, costs and challenges. The comparative analysis of landslide risk reduction interventions reveals that NbS and hybrid approaches demonstrate comparable functional effectiveness to that of conventional gray infrastructure while offering enhanced ecosystem services and economic advantages. An expert affirmed that “*the right vegetation plus the right slope plus drainage would also bring the desired benefits. “...”green cover could be enough in many cases.*” (INT-003).

Table 3: Summary of the landslide risk reduction measures in relation to function, co-benefits, costs, and challenges.

Measure	Function	Co-benefits	Costs <sup>6</sup>	Challenges
Anchor and concrete curtain wall system	<ul style="list-style-type: none"> <li>Stabilization</li> <li>Impermeabilization</li> </ul>	-	Up to 520 USD/m <sup>2</sup>	<ul style="list-style-type: none"> <li>Major construction works to implement the intervention</li> <li>Visual impact</li> <li>Heating of the surroundings</li> </ul>
Stapled Soil with Mortar Finishing	<ul style="list-style-type: none"> <li>Stabilization</li> <li>Impermeabilization</li> </ul>	-	Ca. 312 USD/m <sup>2</sup>	<ul style="list-style-type: none"> <li>Major construction works to implement the intervention</li> <li>Visual impact</li> <li>Heating of the surroundings</li> </ul>
<i>Geomanta</i>	<ul style="list-style-type: none"> <li>Impermeabilization</li> </ul>	-	Ca. 39 USD/m <sup>2</sup>	<ul style="list-style-type: none"> <li>Impact of the intervention</li> <li>Visual impact</li> <li>Heating of the surroundings</li> <li>Durability</li> <li>No stabilization</li> </ul>
Stapled soil retaining structure with green cladding	<ul style="list-style-type: none"> <li>Stabilization</li> <li>Impermeabilization</li> </ul>	<ul style="list-style-type: none"> <li>Heat reduction</li> <li>Improving air quality</li> <li>Low visual impact</li> </ul>	Ca. 208 USD/m <sup>2</sup>	<ul style="list-style-type: none"> <li>Impact of the intervention</li> </ul>
Staples and wire mesh	<ul style="list-style-type: none"> <li>Stabilization</li> </ul>	<ul style="list-style-type: none"> <li>Heat reduction</li> <li>Improving air quality</li> <li>Increased urban biodiversity</li> <li>Low visual impact</li> <li>Planting of fruit trees possible</li> </ul>	Ca. 208-234 USD/m <sup>2</sup>	-
Vetiver grass	<ul style="list-style-type: none"> <li>Superficial stabilization</li> <li>Impermeabilization</li> </ul>	<ul style="list-style-type: none"> <li>Heat reduction</li> <li>Improving air quality</li> <li>Low visual impact</li> <li>Use of the material</li> </ul>	Ca. 5-10 USD/m <sup>2</sup>	<ul style="list-style-type: none"> <li>Risk of new occupation with houses</li> <li>Low stabilization of slope</li> </ul>
Reforestation	<ul style="list-style-type: none"> <li>Stabilization</li> </ul>	<ul style="list-style-type: none"> <li>Heat reduction</li> <li>Improved air quality</li> <li>Increased urban biodiversity</li> <li>Low visual impact</li> </ul>	Ca. 5.195 USD/ha or 0,5 USD/m <sup>2</sup>	<ul style="list-style-type: none"> <li>Feasibility depends on situation</li> </ul>

<sup>6</sup> Conversion rate from Brazilian Real (BRL) to US-Dollar (USD) as of July 1, 2019 on <http://www.oanda.com>

		<ul style="list-style-type: none"> <li>• Planting of fruit trees and thus added value possible</li> </ul>		
Grass cover	<ul style="list-style-type: none"> <li>• Impermeabilization</li> </ul>	<ul style="list-style-type: none"> <li>• Heat reduction</li> <li>• Improved air quality</li> <li>• Low visual impact</li> </ul>	Ca. 10-20 R\$/m <sup>2</sup>	<ul style="list-style-type: none"> <li>• Less accepted by local population</li> <li>• Risk of new occupation with houses</li> <li>• No stabilization of slope</li> </ul>

The empirical analysis of expert interviews reveals a strong consensus regarding the efficacy of NbS for landslide risk reduction. Technical specialists emphasized the multifunctional benefits and cost-effectiveness of these interventions while highlighting critical implementation considerations. Contrarily, they stressed the importance of community awareness so that the population participates and values green measures (including not to occupy these green spaces) and highlighted the need to analyze the situation well in which those kind of measures are feasible. The major concern stated is related to the type of vegetation to be used and the circumstances (vertical roots, water consumption, canopy size, potential use for the community, impermeability of the plantation) that offer the best protection results.

Initial community preferences demonstrate a predisposition toward conventional gray infrastructure interventions from public authorities. An expert emphasized: *“They feel like they “exist” when a state team is carrying out actions, works, even if these works don't bring the necessary benefit. Often the garbage they throw out will cause problems down the line. It is necessary to show the causal relationship.”* (INT-018) However, following explanations regarding ecosystem functions and services and NbS, community members expressed willingness to participate in both implementation and maintenance of green measures. Therefore, the successful implementation of NbS requires comprehensive community sensitization programs. An expert confirmed: *“The point is, number one in this whole process, is awareness raising, the social issue. We do a lot of things and turn our backs, thinking that people will cope... it's not like that.”* (INT-010). Evidence from Salvador demonstrates that when residents understand the multifunctional benefits of ecosystem-based approaches, their engagement in environmental stewardship could increase significantly. The fieldwork revealed the following: the selection of vegetation species plays a crucial role in community acceptance and long-term sustainability. Two key considerations emerge: First, a functional value should exist. Species selection should prioritize plants providing direct community benefits, such as fruit-bearing trees for increasing food security, species with cultural or religious significance, and vegetation offering immediate ecosystem services, such as shade and temperature regulation. An excerpt states *“there is also the possibility that the community garden will help to contain invasion [with new houses] in the cultivated area, as long as it represents a value for the residents and thus contains the occupation.”* (INT-018). Second, species selection

should increase community integration. The integration of culturally significant and productive species enhances community ownership and ensures sustained maintenance of green infrastructure interventions.

The vulnerability assessment showed that other risk factors should also be addressed, which can limit the effectiveness of NbS. These include the following measures (which are not necessarily based on ecosystem services) aiming in particular at reducing shallow landslide triggers:

- Improved trash collection: The accumulation of trash in inappropriate places, such as slopes is a recurring challenge known to be a trigger for mass movements.
- Adequate drainage: In several cases, informal or surface drainage, both rainwater and sewage, is directed to the slopes, increasing the volume of infiltrated water and consequently the potential saturation of the soil.
- Reduction of soil impermeability: Related to the previous point, favoring the infiltration of water into the soil in places away from the slopes can reduce the volume of water directed onto the slopes.

The need to sensitize and raise awareness was a unanimous opinion of the experts interviewed, which was reinforced by the participants from the communities. Without knowing the benefits of ecosystem-based measures, the mobilization and consequent participation of the community, both in the implementation and maintenance of the measures, seems hardly feasible. The most relevant topics thus to be addressed in awareness campaigns should be:

- Waste collection and proper disposal
- Education on functions and services of vegetation (slope stabilization, water retention and infiltration, shade, etc.)
- Their own responsibility of residents and their possibility to contribute to the establishment and maintenance of ecosystem services
- Vegetation and green area management techniques

Apart from in-person awareness raising activities, it is recommended that a green areas management manual should be developed in communities, which is useful for the landslide risk reduction measures. The big challenge of awareness campaigns is to achieve durability and elucidate, which measures will actually be accepted and maintained in the long term. Co-benefits include general awareness raising on environmental and sustainability issues.

Throughout the study, several knowledge gaps appeared that are recommended to fill:

- What are the most concrete interpretations of climate scenarios and their consequences?
- What is the cost-benefit ratio for green or hybrid measures?
- Which type of vegetation is best, most appropriate, and beneficial, and in which situation?
- Which knowledge and perception gaps of the people in the communities need to be addressed in detail?

Finally, the spatial distribution of informal settlements in landslide prone areas represents a significant socio-environmental vulnerability, exposing populations to heightened risks. While the relocation of residents from high-risk zones theoretically would be an absolute risk elimination strategy, such interventions are characterized by complex socio-economic implications and substantial financial constraints. The implementation of resettlement programs encounters considerable challenges regarding social equity, community cohesion, and economic feasibility. Given these multifaceted constraints and the potential negative impacts on community structures, population relocation was deliberately excluded from the analytical framework of this study.

## 6.4. Discussion

The findings of this study significantly advance our understanding of NbS for landslide risk reduction in informal urban settlements. We reveal the potential of a paradigm shift in disaster risk management, moving from purely engineered solutions toward integrated approaches harnessing ecosystem services while addressing socio-economic challenges. This aligns with that of the broader discussions in the literature, which highlight the effectiveness of NbS in addressing climate risks and providing co-benefits, such as biodiversity conservation and social resilience (Arce Mojica et al. 2019, Chausson et al., 2020).

The demonstrated effectiveness of NbS compared with that of conventional engineering measures represents important findings in urban resilience strategies. The successful implementation of hybrid solutions, particularly the combination of staples with wire mesh and vegetation, challenges the traditional reliance on purely gray infrastructure (Renaud et al., 2016). This finding is particularly significant as it

provides empirical evidence that green solutions can achieve comparable stability while delivering additional ecosystem services (Wolff et al., 2022).

The cost-effectiveness of NbS compared with that of traditional gray measures presents a compelling argument for their widespread adoption, especially in resource-constrained environments typical of developing countries. Studies consistently showed that NbS can be more affordable while offering long-term benefits, such as reduced maintenance costs and enhanced community resilience (Chausson et al., 2020; Ruangpan et al., 2020). This economic advantage could potentially revolutionize the approach to slope stabilization projects in cities, making risk reduction more accessible to vulnerable communities (Renaud et al., 2016).

A critical insight emerges regarding the initial community preference for conventional infrastructure, which transforms into support for NbS following proper education, sensitization, and engagement. This transformation highlights the fundamental importance of knowledge transfer and community participation in sustainable urban development. Participatory methods, such as citizen science and co-design practices, were shown to increase community acceptance and ensure that projects align with local needs (Wolff et al., 2022). The emphasis of the study on selecting vegetation with direct community benefits represents an innovative approach to ensuring long-term project sustainability through socio-economic integration.

Additionally, we uncovered significant barriers to NbS implementation, particularly regarding technical expertise in vegetation selection and site-specific applications, i.e. in informal settlement. These challenges emphasize the need for comprehensive capacity building within municipal authorities and technical staff. The identified knowledge gaps regarding root systems, water consumption, and canopy size indicate critical areas for future research and technical guidance development resonates with Ruangpan et al. (2020). Additionally, when implementing NbS or hybrid solutions, the IUCN Global Standard for NbS and the Core Principles for NbS Implementation (Cohen-Shacham et al. 2019) should be considered to avoid maladaptation and unintended ecosystem disservices.

While NbS offer significant benefits for landslide risk reduction in urban informal settlements, one should be cautious regarding potential ecosystem disservices and maladaptation. Inappropriate selection or management of vegetation - such as

introducing species with shallow root systems, high water demand, or invasive tendencies - can inadvertently destabilize slopes, alter hydrological cycles, or outcompete native flora, thereby reducing the intended protective function and possibly increasing landslide risk (Nehren et al. 2023, Sandholz et al. 2018). Furthermore, poorly adapted NbS may lead to unintended consequences, such as increased maintenance burdens, the proliferation of pests, or the exclusion of community use, ultimately undermining both ecological integrity and social acceptance (Nehren et al. 2023).

The findings point toward several crucial areas for future development. The need for mainstreaming NbS into urban planning frameworks and municipal guidelines emerges as a priority as emphasized by Cohen-Shacham et al. (2016). Additionally, we suggest that pilot projects could serve as valuable demonstrations for scaling up NbS implementation across similar urban contexts. The use of pilot projects as demonstrations for wider adoption is supported by Ruangpan et al. (2020), who emphasized their role in showcasing the efficacy and replicability of NbS interventions. The research also highlights the necessity of developing integrated assessment frameworks considering both the technical performance and social acceptance of NbS mirroring Chausson et al. (2020) call for integrated frameworks. The demonstrated success of community engagement strategies suggests that future projects should incorporate participatory approaches from their inception.

We contribute significantly to the growing body of evidence-supporting NbS to disaster risk reduction in urban environments. The findings challenge the traditional dichotomy between environmental conservation and urban development, suggesting that NbS can effectively serve both purposes while providing additional societal benefits. Our implications extend beyond Salvador, offering valuable insights for other cities facing similar challenges of informal settlements in landslide-prone areas. The demonstrated success of NbS and hybrid solutions and the importance of community engagement provide a replicable framework for implementing NbS in various urban contexts, not only in developing countries, while addressing both technical and social aspects of risk reduction.

## 6.5. Conclusions

This interdisciplinary analysis of the study of Nature-based Solutions (NbS) in Salvador/Bahia reveals transformative potential for landslide risk reduction, grounded in empirical evidence. The following conclusions emerge as critical pathways for sustainable urban climate resilience:

**Untapped NbS Potential:** Salvador shows significant potential for Nature-based Solutions (NbS) in landslide risk reduction, particularly in vulnerable urban areas. Expert interviews and field assessments confirm NbS match traditional engineering effectiveness while offering greater cost-efficiency and ecosystem services.

**Effective Ecosystem-Based Measures:** Vetiver grass systems, reforestation, and hybrid solutions (combining vegetation with structural elements) stabilize slopes and reduce landslide risks in suitable geotechnical contexts. These enhance soil reinforcement via root systems, improve water infiltration, and reduce surface runoff.

**Socio-Economic Advantages:** NbS implementations demonstrate better cost-benefit ratios than conventional methods, alongside co-benefits like biodiversity enhancement, carbon sequestration, and community well-being. Hybrid approaches (e.g., stapled soil structures with green cladding) receive strong expert endorsement for dual soil stabilization and waterproofing.

**Implementation Requirements:** Critical success factors include community engagement, awareness programs, species selection, and site-specific geotechnical assessments. Integration into urban planning frameworks, sectoral plans, and environmental education programs is essential for long-term sustainability.

**Strategic Integration:** NbS should be systematically incorporated into Salvador's urban development strategy, combining technical expertise, institutional support, and community participation to maximize disaster risk reduction and sustainable development outcomes.

## 6.6. References

Alfonsin B. de M. & Mota Júnior R. J. C. (2024). Challenges in the Implementation of the City Statute's Instruments for Promoting the Social Function of Property.

RGSA: Revista de Gestão Social e Ambiental, 18(10), e8497.  
<https://doi.org/10.24857/rgsa.v18n10-032>

Arce-Mojica T. de J., Nehren U., Sudmeier-Rieux K., Miranda P. J., & Anhuf D. (2019). Nature-based solutions (NbS) for reducing the risk of shallow landslides: Where do we stand? *International Journal of Disaster Risk Reduction*, 41, 101293. <https://doi.org/10.1016/j.ijdr.2019.101293>

Balbim R. N. (2023). Produção Internacional da Informalidade Urbana e os “Núcleos Urbanos Informais” no Brasil. [https://doi.org/10.33148/cetropicov47n1\(2023\)art1](https://doi.org/10.33148/cetropicov47n1(2023)art1)

Barreto A., & Silva A. (2023). Os impactos socioambientais das fortes chuvas de Salvador-BA associados à sua expansão urbana. <https://doi.org/10.46943/VIII.CONEDU.2022.GT14.019>

Brink E., Aalders T., Ádám D., Feller R., Henselek Y., Hoffmann A., Ibe K., Matthey-Doret A., Meyer M., Negrut N. L., Rau A.-L., Riewerts B., von Schuckmann L., Törnros S., von Wehrden H., Abson D. J., & Wamsler C. (2016). Cascades of green: A review of ecosystem-based adaptation in urban areas. *Global Environmental Change*, 36, 111–123. <https://doi.org/10.1016/j.gloenvcha.2015.11.003>

Camarinha P. I., Seki, Y., Souza, D., & Patrício, L. (2024). Quantitative analysis of rainfall events for potential rapid landslides and flashfloods in Brazilian municipalities. *International Journal of Science and Research Archive*. <https://doi.org/10.30574/ijsra.2024.11.2.0433>

Chausson A., Turner B., Seddon D., Chabaneix N., Girardin C. A. J., Kapos V., Key I., Roe D., Smith A., Woroniecki S. & Seddon N. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, 26(12), 6134–6155. <https://doi.org/10.1111/gcb.15310>

Coelho-Netto A.L., Avelar A.d.S. & Lacerda W.A. (2009). Landslides and Disasters in Southeastern and Southern Brazil. *Developments in Earth Surface Processes*, 13(C), pp. 223–243.

- Cohen-Shacham E., Walters G., Janzen C. & Maginnis S. (eds.) (2016). Nature-based Solutions to address global societal challenges. Gland, Switzerland: IUCN. xiii + 97pp
- Cohen-Shacham E., Andrade A., Dalton J., Dudley N., Jones M., Kumar C., Maginnis S., Maynard S., Nelson C. R., F. G. Renaud, Welling R. & Walters G. (2019). Core principles for successfully implementing and upscaling Nature-based Solutions. *Environmental Science & Policy* 98, 20-29.
- Debortoli N., Camarinha P. I. M., Marengo J. A. & Rodrigues, R. (2017). An index of Brazil's vulnerability to expected increases in natural flash flooding and landslide disasters in the context of climate change. *Natural Hazards*, 86(2), 557–582. <https://doi.org/10.1007/S11069-016-2705-2>
- Doswald N., Janzen S., Nehren U., Santamaria K., Vervest M.-J., Sans J., Edbauer L., Chavda S., Sandholz S., Renaud F., Ruiz V., Narvaez L., Yang S., Mohil D., Uzoski D., Gerner N. & Grey C. (2021). Words into action: Nature-based solutions for disaster risk reduction. UN Office for Disaster Risk Reduction, Engaging for resilience in support of the Sendai Framework for Disaster Risk Reduction 2015-2030.
- Estrella M. & Saalismaa N., (2013). Ecosystem-based DRR: an overview. In Renaud F. et al.: *The role of ecosystems in disaster risk reduction*. pp. 483–506. Springer.
- Facadio A.C., Coelho-Netto A.L., Macario K.D., Ishimine K. M., Barth O.M. & Jou R. (2024). Holocene hillslope evolution through extreme rainfall induced landslides in the mountainous region of Rio de Janeiro, Brazil: Geochronology and paleoenvironmental evidence. *Earth Surface Processes and Landforms*, 49(13), pp. 4388–4403.
- Ferreira M. L. (2023). Extreme rain event highlights the lack of governance to face climate change in the Southeastern coast of Brazil. *Geography and Sustainability* 5 (1). <https://doi.org/10.1016/j.geosus.2023.11.001>
- Fianoo I. N., Mensah S. L., Okyere S. A., Boadie-Ampong M., & Jirjiri J. (2024). Linking Informal Settler Practices and Circular Principles in Global South: Lessons from

- Asian and Latin American Cities. pp. 11–25. Springer Nature. [https://doi.org/10.1007/978-981-99-9025-2\\_2](https://doi.org/10.1007/978-981-99-9025-2_2)
- Galeazzi S., Ciabatta L., Brocca L., & Salciarini D. (2024). A probabilistic model for slope stability analysis including the root reinforcement effects. EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-5565, <https://doi.org/10.5194/egusphere-egu24-5565>
- Herranz-Pascual K., Anchustegui P., Cantergiani C., & Iraurgi I. (2025). Tool Used to Assess Co-Benefits of Nature-Based Solutions in Urban Ecosystems for Human Wellbeing: Second Validation via Measurement Application. Land.
- Higuera Roa O., Walz Y. & Nehren U. (2025). How to avoid the risk of maladaptation? From a conceptual understanding to a systematic approach for analyzing potential adverse effects in adaptation actions. *Mitigation and Adaptation Strategies for Global Change*, 30, 27. <https://doi.org/10.1007/s11027-025-10217-w>
- Instituto Brasileiro de Geografia e Estatística (IBGE) & Centro Nacional de Monitoramento e Alertas de Desastres Naturais (CEMADEN-MCTI) (2018a). População em áreas de risco no Brasil. CEMADEN.
- Instituto Brasileiro de Geografia e Estatística (IBGE) (2022) Censo Demográfico 2022. Rio de Janeiro, Brazil.
- lungman T., Caballé S.V., Segura-Barrero R., Cirach M., Mueller N., Daher C., Villalba G., Barboza E.P. & Nieuwenhuijsen M. (2025). Co-benefits of nature-based solutions: A health impact assessment of the Barcelona Green Corridor (Eixos Verds) plan. *Environ Int.* 2025 Feb;196:109313. doi: 10.1016/j.envint.2025.109313. Epub 2025 Feb 1. PMID: 39919507; PMCID: PMC11839897.
- Iwama A. Y., Aguilar-Muñoz V., & Seleguim F. B. (Eds.). (2023). Riscos ao Sul: Diversidade de riscos de desastres no Brasil [PDF eBook]. Isso dá um Livro. ISBN 978-65-994944-3-7
- Instituto de Pesquisas Tecnológicas (IPT) & Centro de Tecnologias Geoambientais (CTGeo). (2017). Assessoria técnica especializada para elaboração de Plano

Municipal de Redução de Riscos de Salvador, BA (Technical report).  
<http://www.codesal.salvador.ba.gov.br/images/pdf/Manuais/PMRR.pdf>  
(Accessed: May 24, 2023).

Lange W., Cavalcante L., Dünow L., Medeiros R., Pirzer C., Schelchen A., & Valverde Y. (2014). *HumaNatureza<sup>2</sup> = Proteção Mútua – Percepção de riscos e adaptação à mudança climática baseada nos ecossistemas na Mata Atlântica, Brasil* (Schriftenreihe des Seminars für Ländliche Entwicklung No. 255). SLE.

Lange W., Pirzer C., Dünow L., & Schelchen A. (2016). Risk perception for participatory ecosystem-based adaptation to climate change in the Mata Atlântica, Brazil. In F. Renaud et al. (Eds.), *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice*. pp. 483–506. Springer.

Lange W., Sandholz S., & Nehren U. (2018a). Strengthening urban resilience through nature: The potential of ecosystem-based measures for reduction of landslide risk in Rio de Janeiro. Working Paper. Lincoln Institute of Land Policy. 63 pages.  
[https://www.lincolninst.edu/sites/default/files/pubfiles/lange\\_wp18wl1.pdf](https://www.lincolninst.edu/sites/default/files/pubfiles/lange_wp18wl1.pdf)

Lange W., Sandholz S., Viezzar J., Becher M., & Nehren U. (2018b). Ecosystem-based approaches for disaster risk reduction and climate change adaptation in Rio de Janeiro State. In U. Nehren, S. Schlüter, C. Raedig, D. Sattler, & H. Hissa (Eds.), *Strategies and tools for a sustainable rural Rio de Janeiro* (Series on Environmental Management). pp. 345-359. Springer.

Lann T., Bao H., Lan H., Zheng H., Yan C. & Peng J. (2024). Hydro-mechanical effects of vegetation on slope stability: A review. *Science of the Total Environment* 926, 171691

Lesser C. N., & Brandes A. F. das N. (2023). Against the grain: environmental laws, local botanical knowledge, and housing access in Rio de Janeiro. *Journal of Environmental Studies and Sciences*, 13, 439–452.  
<https://doi.org/10.1007/s13412-023-00828-7>

Machado R.A.S., Oliveira A.G. & Lois-González R.C. (2019). Urban ecological infrastructure: The importance of vegetation cover in the control of floods and landslides in Salvador / Bahia, Brazil. *Land Use Policy* 89: 104180

- Marengo J. A., Camarinha P. I. M., Alves L. M., Diniz F. L. R., & Betts, R. (2021). Extreme rainfall and hydro-geo-meteorological disaster risk in 1.5, 2.0, and 4.0°C global warming scenarios: An analysis for Brazil. *Frontiers in Climate*, 3, 610433. <https://doi.org/10.3389/FCLIM.2021.610433>
- Nalumu D. J. & Perrotti D. (2024). A review of the contribution of nature-based solutions to the urban metabolism of the informal settlements. *IOP Conference Series*, 1363(1), 012083. <https://doi.org/10.1088/1755-1315/1363/1/012083>
- Nascimento S. A. de M. (2008). Diagnóstico hidrogeológico, hidroquímico e da qualidade da água do aquífero freático do Alto Cristalino de Salvador – Bahia (Doctoral thesis). Instituto de Geociências, Universidade Federal da Bahia.
- Nehren U., Kirchner A., Sattler D., Turetta A.P. & Heinrich J. (2013). Impact of natural climate change and historical land use on landscape development in the Atlantic Forest of Rio de Janeiro, Brazil. *Anais da Academia Brasileira de Ciências*, 2013, 85(2), pp. 497–518.
- Nehren U., Arce-Mojica T., Cara Barrett A., Cueto J., Doswald N., Janzen S., Lange W., Ortiz Vargas A., Pirazan-Palomar L., Renaud F.G., Sandholz S., Sebesvari Z., Sudmeier-Rieux K. & Walz Y. (2023). Towards a typology of nature-based solutions for disaster risk reduction. *Nature-based Solutions*, 3, 100014.
- Onuma A. & Tsuge, T. (2018). Comparing green infrastructure as ecosystem-based disaster risk reduction with grey infrastructure in terms of costs and benefits under uncertainty: A theoretical approach. *International Journal of Disaster Risk Reduction*, 32, 22–28. <https://doi.org/10.1016/j.ijdr.2018.01.025>
- Pereira P., Yin C. & Hua T. (2023). Nature-based solutions, ecosystem services, disservices, and impacts on well-being in urban environments, *Current Opinion in Environmental Science & Health*, Volume 33, ISSN 2468-5844, <https://doi.org/10.1016/j.coesh.2023.100465>.
- Peixoto C. S. (1968). Os fatores físicos condicionantes dos problemas da cidade de Salvador (Livro Docência thesis). Faculdade de Filosofia, Universidade Federal da Bahia.

- Renaud F.G., Sudmeier-Rieux K., Estrella M. & Nehren U. (Eds.) (2016). Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice. pp. 483–506. Springer.
- Ronchi S. & Arcidiacono A. (2019). Adopting an ecosystem services-based approach for flood resilient strategies: The case of Rocinha Favela (Brazil). *Sustainability* 11(1): 4
- Ruangpan L., Vojinovic Z., Di Sabatino S., Leo L. S., Capobianco V., Oen A. M. P., McClain M. E., & Lopez-Gunn E. (2020). Nature-based solutions for hydro-meteorological risk reduction: A state-of-the-art review of the research area. *Natural Hazards and Earth System Sciences*, 20, 243–270. <https://doi.org/10.5194/nhess-20-243-2020>
- Salvador (2004). Plano Diretor de Encostas. Prefeitura Municipal de Salvador. Secretaria Municipal do Saneamento e Infraestrutura Urbana. Coordenadoria de Áreas de Risco Geológico. Módulo II – Diagnóstico, TOMO I/III, pp. 10-173
- Sandholz S., Lange W. & Nehren U. (2018). Governing green change: Ecosystem-based measures for reducing landslide risk in Rio de Janeiro. *International Journal for Disaster Risk Reduction*, 28, 115–124. <https://doi.org/10.1016/j.ijdr.2018.01.020>
- Santos A. P. P. dos, Silva M. R. da, Aragão J. G. M. dos, Lima F. J. L. de, Quadro S. R. dos & Correia, M. de F. (2016). Mecanismos dinâmicos associados à ocorrência de um evento climático extremo de precipitação na cidade de Salvador-BA. *Revista Brasileira de Meteorologia*, 9(7), 2196–2212. <https://doi.org/10.5935/1984-2295.20160156>
- Secretariat of the Convention on Biological Diversity (SCBD) (2009). Connecting biodiversity and climate change mitigation and adaptation: Report of the second ad hoc technical expert group on biodiversity and climate change. Technical Series No. 41. Montreal, Canada: SCBD.
- Shaughnessy C., Santiago D., Donoso P., Perkins R. & Lisboa T. (2024). Creative health in the urban Global South: barriers and facilitators in the cases of Cochabamba and Salvador. *Perspectives in Public Health*. 144(5):297-303. [doi:10.1177/17579139241288678](https://doi.org/10.1177/17579139241288678)

- Sowińska-Świerkosz B. & García J. (2022). What are Nature-based solutions (NBS)? Setting core ideas for concept clarification, *Nature-Based Solutions*, Volume 2, 100009, ISSN 2772-4115, <https://doi.org/10.1016/j.nbsj.2022.100009>.
- Sudmeier-Rieux K., Nehren U., Sandholz S. & Doswald N. (2019). *Disasters and ecosystems, Resilience in a changing climate - Source Book*. Geneva: UNEP; and Cologne: TH Köln - University of Applied Sciences.
- Sudmeier-Rieux K., Arce-Mojica T., Boehmer H.J., Doswald N., Emerton L., Friess D.A., Galvin S., Hagenlocher M., James H., Laban P., Lacambra C., Lange W., McAdoo B.G., Moos C., Mysiak J., Narvaez L., Nehren U., Peduzzi P., Renaud F.G., Sandholz S., Schreyers L., Sebesvari Z., Tom T., Triyanti A., van Eijk P., van Staveren M., Vicarelli M. & Walz Y. (2021). Scientific evidence for ecosystem-based disaster risk reduction. *Nature Sustainability*. <https://doi.org/10.1038/s41893-021-00732-4>
- Sudmeier-Rieux K., Galvin S., Nehren U., Moos C., Vicarelli M., Walz Y., Emerton L., Triyanti A. & Doswald N. (2024). Editorial: Special issue: Nature-based Solutions for reducing disaster risk. What is the evidence? *Nature-based Solutions* 100207. [doi.org/10.1016/j.nbsj.2024.100207](https://doi.org/10.1016/j.nbsj.2024.100207)
- Tallaksen L. M., & Capobianco, V. (2023). Governing equations of slope stability models that consider hydrological and mechanical effects of root reinforcement: A review EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-9214, <https://doi.org/10.5194/egusphere-egu23-9214>
- Tischler O. (2023). Designing and evaluating robust nature-based solutions for hydro-meteorological risk reduction. *International Journal of Disaster Risk Reduction*, 93, 103787. <https://doi.org/10.1016/j.ijdr.2023.103787>
- Vicarelli M., Sudmeier-Rieux K., Alsadadi A., Shrestha A., Schütze S., Kang M. M., Leue M., Wasielewski D. & Mysiak, J. (2024). On the cost-effectiveness of Nature-based Solutions for reducing disaster risk. *Science of The Total Environment*, 947, 174524. <https://doi.org/10.1016/j.scitotenv.2024.174524>
- Walz Y., Nick F., Higuera Roa O., Nehren U. & Sebesvari Z. (2021). Coherence and Alignment among Sustainable Land Management, Ecosystem-based

Adaptation, Ecosystem-based Disaster Risk Reduction and Nature-based Solutions. United Nations University (UNU-EHS) Report 28

Wolff E., Rauf H.A., Diep L., Natakun B., Kelly K. & Hamel P. (2022). Implementing participatory nature-based solutions in the Global South. *Front. Sustain. Cities* 4:956534. doi: 10.3389/frsc.2022.956534

World Bank (2008). *Biodiversity, Climate Change, and Adaptation : Nature-based Solutions from the World Bank Portfolio*. © World Bank. <http://hdl.handle.net/10986/6216> License: CC BY 3.0 IGO.

Yang S., Ruangpan L., Torres A.S. & Vojinovic Z. (2023). Multi-objective Optimisation Framework for Assessment of Trade-Offs between Benefits and Co-benefits of Nature-based Solutions. *Water Resour Manage* 37, 2325–2345 (2023). <https://doi.org/10.1007/s11269-023-03470-8>

Zin Mar Than, Hlaing Maw Oo, Toe Aung, Tin Tin Kyi, Saw Sandar Oo, Win Lei Mar, Willkomm, M., Miller, C., Martini, S., Zin Nwe Myint, Khin Khin Soe, Win Maung, Heinkel, S.-B., Thiebes, B., Spohner, R., & Kraas, F. (2023). Disaster risk perception and preparedness of households in Yangon, Myanmar: Disaster experiences, socio-demographic factors and spatial variation. *ERDKUNDE*, 77(4), 303–321. <https://doi.org/10.3112/erdkunde.2023.04.04>

## 7. Synthesis

### 7.1. Summary of Key Findings

Through its three interconnected studies and the overarching framework, this thesis comprehensively examined the role of NBS in addressing CCA and DRR in Brazil, particularly highlighting vulnerable urban environments. The collective empirical findings underscored the escalating urgency for resilient approaches to reduce the impacts of hydro-meteorological hazards. The latter are exacerbated by a confluence of geophysical vulnerabilities, anthropogenic landscape degradation, and the intensifying effects of climate change.

Paper 1, “Ecosystem-Based Approaches for Disaster Risk Reduction and Climate Change Adaptation in Rio de Janeiro State” (Chapter 4; Lange et al., 2018a), investigated the macro-level policy and institutional landscape governing NBS mainstreaming. A significant finding from this study was the persistent disconnect between progressive national legislative frameworks, such as the Forest Code and the National Policy of Civil Protection and Defense (PNPDEC), and their effective implementation at the state and local levels. The research revealed that Permanent Preservation Areas (APPs), despite their legal mandate for environmental protection and risk reduction, often fail at their intended purpose due to enforcement gaps and competing land-use priorities. Therefore, this paper critically contrasted the prevalent reliance on technical DRR measures with the underutilization of EbA/Eco-DRR interventions, advocating for the urgent adoption of cross-sectoral governance models. This study concluded with a compelling critique of Brazil’s fragmented (or “siloe”) risk management paradigm, proposing the integration of NBS within broader planning frameworks that align with SDGs and national climate resilience agendas (Chapter 4; Lange et al., 2018a).

Paper 2, “Risk Perception for Participatory Ecosystem-Based Adaptation to Climate Change” (Chapter 5; Lange et al., 2016) shifted the focus to the human dimension of NBS adoption. Specifically, this work investigated community perceptions in Teresópolis, a region profoundly affected by past landslide and flood disasters. The study uncovered critical barriers to community engagement in EbA/Eco-DRR

initiatives. Although residents exhibit a high awareness of their vulnerability to disasters, a significant knowledge gap regarding the intrinsic link between ecosystem health and risk reduction still existed. Building on this, the study identified a limited sense of personal responsibility among community members for CCA/DRR efforts and a perceived lack of meaningful avenues for participation. These crucial findings highlighted that the biophysical efficacy of NBS alone is insufficient for successful implementation. Rather, success of this process hinges on culturally resonant education campaigns, robust trust-building between communities and institutions, and creating genuine participatory opportunities. The paper challenges traditional top-down CCA/DRR models, advocating for co-designed interventions that effectively leverage local knowledge and address socio-economic inequities (Chapter 5; Lange et al., 2016).

Paper 3, “Nature-Based Solutions for Landslide Risk Reduction in Informal Settlements of Salvador da Bahia, Brazil” (Chapter 6; Lange et al., submitted, after review currently under revision) closely examined NBS application within the complex, challenging context of informal urban settlements. This research compared the efficacy and benefits of NBS with conventional engineering approaches in Salvador da Bahia. A key insight from this study was the expert consensus that NBS are often perceived as equally effective as traditional structural measures, yet they frequently offer greater cost-efficiency and a broader spectrum of co-benefits, including enhanced ecological resilience and support for sustainable urban development. However, the paper also identified a critical deficit in public awareness of the potential of NBS, underscoring the need for targeted community education to foster greater acceptance and facilitate successful implementation in informal settlements. Ultimately, the study reinforced the necessity of hybrid strategies, which blend green and grey infrastructure, as the most viable and effective solutions in high-risk urban zones characterized by precarious conditions.

Overall, the three manuscripts reveal five aspects that are central to understanding the challenges and opportunities for mainstreaming NBS in Brazil.

- First, this thesis provides empirical evidence for the escalating urgency of NBS adoption in Brazil, driven by increasing climate-induced hazards and the demonstrated limitations of conventional grey infrastructure approaches. The

research quantified the practical benefits and cost-effectiveness of NBS in real-world Brazilian contexts. These findings help close a crucial gap in the literature by providing concrete evidence that NBS consistently offer multifaceted co-benefits beyond mere risk reduction, including biodiversity conservation, carbon sequestration, and enhanced public health outcomes.

- Second, persistent policy and governance gaps, characterized by fragmented approaches and a historical preference for grey infrastructure, significantly impede the widespread adoption of NBS. This fact necessitates a concerted effort toward cross-sectoral coordination and integrated planning. This finding advances the state of the art by explaining how cross-sectoral coordination failures manifest in practice, contributing to the growing literature on multi-level governance models for environmental management.
- Third, this thesis established the centrality of community engagement and perception as a pivotal factor in NBS success, providing empirical evidence that ecological literacy, sense of ownership, and inclusive participatory mechanisms are not merely desirable but essential for long-term sustainability. This finding challenges the predominantly technical focus of existing NBS literature and contributes to emerging research on the social dimensions of environmental interventions.
- Fourth, the research provided evidence for the economic viability and extensive co-benefits of NBS, including quantified assessments of cost-effectiveness compared with traditional approaches. This contribution addresses a significant gap in the literature, where economic analyses of NBS have been limited and often theoretical.
- Fifth, the unique challenges posed by informal settlements necessitate tailored approaches, often involving hybrid green-grey infrastructure solutions to promote long-term resilience.

These findings are likely applicable beyond Brazil to comparable countries facing similar challenges of rapid urbanization, climate vulnerability, and governance capacity constraints. Therefore, this research enhanced the global understanding of how socio-economic, political, and environmental contexts shape NBS implementation outcomes, providing a framework that can inform policy and practice across the Global South.

## 7.2. Discussion

The findings presented in this thesis illuminated the complex interplay between vulnerability, risk perception and ecosystem services in Brazil, simultaneously positioning NBS as a resilient pathway toward enhanced resilience. According to the literature, this synthesis enhances existing research by providing empirical evidence for conceptual frameworks that have dominated the field (Cohen-Shacham et al., 2016; Sudmeier-Rieux et al., 2021). This discussion synthesizes the insights gleaned from the introductory chapters and the three empirical papers, critically examining the implications of their findings for policy, practice, and future research while explicitly positioning these contributions within the current state of the art.

### *Governance and Policy: Bridging the Implementation Gap*

The policy analysis by Lange et al. (2018a) revealed a critical implementation gap in Brazil's NBS agenda extending beyond simple regulatory deficiencies to encompass deeper structural challenges in environmental governance. This research indicated that despite the existence of progressive national policies, these measures' effectiveness is often undermined by fragmented governance structures, inadequate enforcement mechanisms, and competing land-use priorities (Chapter 4; Lange et al., 2018a). The case of Permanent Protection Areas (APPs) is particularly illustrative, demonstrating how legal mandates can be rendered ineffective without robust institutional support and cross-sectoral coordination. According to the literature, this fragmentation produces a lack of integrated planning, where environmental conservation, urban development, and disaster management often operate in isolation, hindering the holistic application of NBS (Sandholz et al., 2018).

Building on the empirical findings from this thesis, the research emphasized the urgent need for multi-level governance models that foster collaboration across different scales and sectors, echoing the broader theoretical frameworks developed by Kabisch & van den Bosch (2017). Such models are essential for reconciling diverse stakeholder interests, streamlining regulatory frameworks, and ensuring the effective mainstreaming of NBS into urban planning and DRR policies. Furthermore, the thesis implicitly argues for a shift from a purely regulatory approach to one that incentivizes

and supports NBS implementation through financial mechanisms and capacity building.

Researchers found that overcoming path dependencies that favor traditional grey infrastructure requires both policy reform and a concerted effort to demonstrating the tangible benefits and cost-effectiveness of NBS to decision-makers and investors (Johnson et al., 2022; Vicarelli et al., 2024). The empirical evidence provided by this thesis, particularly the comparative cost–benefit analyses and expert assessments from Salvador da Bahia, contributes directly to this demonstration by providing concrete data that can inform policy decisions. These findings are likely applicable to other developing countries with similar governance challenges and institutional capacity constraints.

### *The Human Dimension: Perception, Participation, and Empowerment*

Lange et al. (2016) highlighted the critical role of the human dimension in the success of NBS, providing empirical evidence to advance beyond theoretical discussions of participation to examine actual barriers and opportunities in vulnerable communities. The study in Teresópolis demonstrated that even in highly vulnerable communities with a strong awareness of disaster risks, a significant gap exists in understanding the link between ecosystem health and risk reduction (Chapter 5; Lange et al., 2016). Research has indicated that this ecological illiteracy, coupled with a limited sense of personal responsibility and insufficient avenues for participation, has created substantial barriers to the adoption and long-term sustainability of NBS.

According to the literature, these findings challenge the conventional top-down approaches to CCA and DRR, which frequently overlook the importance of local knowledge, cultural contexts, and community ownership. However, this thesis extended beyond identifying these challenges to provide specific insights into how these issues manifest in Brazilian contexts and what interventions might address them effectively. Building on the empirical findings, the thesis strongly advocates for a participatory approach to NBS implementation, where communities are not merely beneficiaries but active co-designers and co-managers of interventions.

Findings indicate that this requires culturally resonant education campaigns that translate complex ecological concepts into accessible language, fostering a deeper

appreciation for ecosystem services. Furthermore, building trust between communities and institutions is paramount because historical experiences of marginalization and top-down decision-making can breed skepticism and disengagement. Following this logic, the research findings from Teresópolis provided specific evidence of how these dynamics play out in practice, contributing to the growing literature on meaningful participation in environmental management. Empowering local communities by providing capacity building, information access, and opportunities for involvement can unlock these communities' potential as agents of change, leveraging their traditional ecological knowledge and fostering responsibility for resilience building (Kibii et al., 2025).

### *The Imperative for a Paradigm Shift: Beyond Grey Infrastructure*

Research has indicated that Brazil's historical reliance on conventional, technical-centric approaches to DRR has been insufficient in addressing escalating hydro-meteorological hazards (Alcántara et al., 2023). Specifically, the catastrophic events in the *Região Serrana* and Petrópolis have been poignant reminders that structural measures alone cannot fully address the multifaceted drivers of vulnerability. The latter include extensive deforestation, unplanned urbanization, and the pervasive impacts of climate change. Building on the empirical findings from this thesis, particularly the cost-effectiveness analyses presented by Lange et al. (submitted, after review currently under revision), this research demonstrated that NBS offer a more sustainable, holistic alternative that addresses both immediate risk reduction needs and long-term resilience building.

Researchers found that by integrating conservation, restoration, and sustainable management of ecosystems, NBS not only reduce disaster risks but also provide multiple co-benefits as the latter include biodiversity conservation, carbon sequestration, and improved human well-being (Cohen-Shacham et al., 2016; Ruangpan et al., 2020; Sudmeier-Rieux et al., 2021). However, this thesis explored beyond these general assertions by providing specific empirical evidence from Brazilian contexts. The comparative analyses presented by Lange et al. (submitted, after review currently under revision) strengthened this argument by indicating that NBS are frequently more cost-efficient than traditional grey infrastructure, particularly when accounting for long-term benefits and multifunctionality of NBS. This finding

helps to close a crucial gap in research and subsequent advocacy because previous studies have often lacked the quantitative economic data needed to convince decision-makers and investors (Johnson et al., 2022; Vicarelli et al., 2024).

According to the literature, the continued preference for grey infrastructure, despite its limitations, can be attributed to several factors, including established institutional frameworks, entrenched engineering practices, and a perceived immediate efficacy (Kabisch & van den Bosch, 2017). However, building on the governance analysis findings from Lange et al. (2018a), this thesis argued that such a preference perpetuates a siloed approach to risk management, which fails to address the systemic and interconnected nature of environmental and social vulnerabilities. Therefore, a fundamental paradigm shift is imperative, moving away from a reactive, engineering-dominated response toward a proactive, integrated, and ecosystem-based strategy that recognizes the intrinsic value of natural systems in building resilience. This finding is transferable to countries of the Global South comparable to Brazil where similar institutional path dependencies favor conventional infrastructure approaches over innovative NBS implementations.

However, a critical examination revealed several limitations challenging the widespread adoption and effectiveness of NBS. First, the evidence base for the reliability and cost-effectiveness of NBS, especially compared to engineered alternatives, has remained limited, and their resilience under future climate scenarios is uncertain (Seddon et al., 2020). In this vein, there are risks of maladaptation, such as when afforestation with non-native monocultures undermines biodiversity and ecosystem resilience (Seddon et al., 2020; Seddon et al., 2021). Methodologically, the lack of standardized tools for evaluating the performance, efficiency, and cost–benefit of NBS hinders robust impact assessment and upscaling, with most available models adapted from other fields and not tailored to the multifunctional nature of NBS (Kumar et al., 2021). Beyond this, social and governance barriers—including insufficient stakeholder engagement, unclear property rights, and limited institutional capacity—further constrain implementation, particularly in urban and developing contexts (Nelson et al., 2020; Sarabi et al., 2020). Additionally, the political appeal of NBS could distract from the urgent need to reduce fossil fuel emissions and protect intact ecosystems, and poorly designed interventions might threaten local resource rights or

fail to deliver intended co-benefits (Osaka et al., 2021; Seddon et al., 2021). Consequently, realizing the full potential of NBS requires addressing these scientific, technical, and social limitations through more rigorous evaluation, inclusive governance, and integration with broader sustainability strategies.

### *NBS in Informal Settlements: Challenges and Hybrid Solutions*

Lange et al. (submitted, after review currently under revision) provided a nuanced explanation of the challenges and opportunities related to the implementation of NBS in informal urban settlements, particularly in Salvador da Bahia, contributing novel insights to a relatively understudied area of NBS research. Research has indicated that these environments are characterized by precarious land tenure, high population density, inadequate infrastructure, and a complex socio-economic fabric that creates distinct implementation challenges (Lange et al., submitted, after review currently under revision; Sandholz et al., 2018). As observed in some communities, the perception of natural vegetation as a source of hazard rather than protection, as observed in some communities, further complicates the adoption of NBS (Lange et al., 2016; Lesser & Brandes, 2023).

According to the literature, these factors necessitate tailored approaches that are sensitive to the specific realities of informal settlements, moving beyond one-size-fits-all NBS implementation (Sandholz et al., 2018). Building on the empirical findings from Salvador da Bahia, this study's emphasis on hybrid infrastructure solutions is particularly relevant in this context. Although pure NBS might be ideal in theory, the immediate safety needs and existing structural vulnerabilities in informal settlements frequently demand a pragmatic combination of NBS and engineered approaches (Chapter 6; Lange et al., submitted, after review currently under revision). Studies have shown that this integrated approach can provide immediate protection while simultaneously fostering long-term ecological resilience and delivering co-benefits (Vicarelli et al., 2024).

However, the success of such hybrid solutions, still hinges on robust community engagement and cross-sectoral coordination to ensure that interventions are culturally appropriate, socially equitable, and effectively maintained, following the participatory principles identified by Lange et al. (2016). The findings from Salvador da Bahia

reinforce the idea that successful NBS implementation in these challenging contexts requires a flexible and adaptive strategy that acknowledges both biophysical and socio-economic realities.

### *Toward a Resilient Future: Integrating NBS into Broader Development Agendas*

The overarching message of this thesis is that NBS are not merely environmental interventions but fundamental components of a broader sustainable development agenda that aligns with multiple international frameworks. Research has revealed that the multifunctionality and capacity to deliver multiple co-benefits of NBS align seamlessly both with the SDGs (particularly those related to climate action, sustainable cities and communities, and life on land), with the Paris Agreement's goals for climate mitigation and adaptation and the Sendai Framework's priorities for DRR (UNEP, 2021; UNFCCC, 2015; UNISDR, 2015).

According to the literature, integrating NBS into national and sub-national development plans rather than treating them as standalone projects, is crucial for achieving systemic change and long-term resilience (Cohen-Shacham et al., 2016). Developing the empirical findings from this thesis, this integration represents a significant departure from standard approaches in the literature. The latter often treat environmental, development, and disaster risk concerns as separate domains. In this vein, the research demonstrates that NBS can serve as a bridge between these traditionally siloed areas, providing a framework for integrated planning and implementation.

Research has demonstrated that this integration requires a shift in investment priorities, moving beyond short-term returns and valuing the long-term ecological and social dividends of NBS (Johnson et al., 2022; Vicarelli et al., 2024). The economic analyses presented in this thesis provide concrete evidence to support such investment shifts, contributing to the growing body of literature that quantifies the economic benefits of NBS. Moreover, the research necessitates enhanced interdisciplinary collaboration to further quantify the cost-effectiveness and co-benefits of NBS across diverse contexts, strengthening the evidence base for policy and investment decisions (Chausson et al., 2020; Vicarelli et al., 2024).

However, this thesis differs from other literature in that its comprehensive examination of how these theoretical benefits manifest in practice across different scales and contexts within Brazil. The research provides empirical evidence for the transformative potential of NBS while simultaneously identifying the specific barriers and enablers that determine implementation success. Furthermore, fostering knowledge exchange and international collaboration can increase the adoption of best practices and innovative solutions in Brazil. Ultimately, this thesis posits that by embracing NBS as a cornerstone of DRR and CCA, Brazil can not only reduce the devastating impacts of climate change but also foster more equitable, sustainable, and resilient communities for the future.

### 7.3. Conclusions

This thesis has explored the critical role of NBS in enhancing CCA and DRR within the Brazilian context, particularly examining the challenges and opportunities arising from vulnerable urban landscapes. The research was structured around three fundamental questions that address key gaps in the existing literature: (1) How do policy and governance frameworks influence NBS implementation at different scales? (2) What role do community perceptions and participation play in the success of ecosystem-based interventions? and (3) How do NBS compare to conventional engineering measures in reducing landslide risks in informal settlements?

Answering Question 1, the investigation of policy and governance frameworks revealed that although Brazil possesses progressive national legislation supporting NBS, significant implementation gaps have persisted due to fragmented governance structures and inadequate cross-sectoral coordination. The research demonstrates that effective NBS mainstreaming requires polycentric governance models that can bridge the divide between policy formulation and practical implementation. This finding contributes to the literature by providing specific evidence of how governance failures manifest in practice and what institutional arrangements might address these challenges.

Addressing Question 2, examining community perceptions and participation established that technical efficacy alone is insufficient for NBS success. The research

provided empirical evidence that ecological literacy, trust building, and meaningful participatory opportunities are essential prerequisites for sustainable NBS implementation. This finding advances the literature by moving beyond theoretical discussions of participation to examine actual barriers and enablers in vulnerable communities, providing concrete insights for practitioners and policymakers.

Responding to Question 3, the analysis of NBS implementation in informal settlements demonstrated that hybrid green-grey approaches offer viable solutions in contexts characterized by immediate safety needs and complex socio-economic challenges. The research contributed novel insights to an understudied area of NBS literature, providing evidence-based recommendations for addressing the unique challenges of informal urban environments.

### *Theoretical and Practical Contributions*

This thesis makes several significant contributions to both conceptual understanding and practical application of NBS. Conceptually, the research advances the field by providing a comprehensive analytical framework integrating governance, social, and technical dimensions of NBS implementation. This framework demonstrates how these dimensions interact to influence implementation outcomes, transcending beyond single-factor explanations to embrace the complexity of real-world contexts.

Practically, this thesis provides evidence-based recommendations for policymakers, practitioners, and communities seeking to implement NBS in the Global South. These suggestions include prioritizing participatory co-design approaches where communities are active partners rather than passive beneficiaries. These approaches emphasize on hybrid green-grey solutions with biodiversity conservation and enhance interdisciplinary research to strengthen evidence through quantified assessments and context-specific monitoring frameworks. Furthermore, the research explores how to design governance arrangements, engagement strategies, and technical solutions respond to local conditions and constraints. Overall, governance arrangements should establish cross-sectoral coordination mechanisms that bridge environmental conservation, urban development, and disaster management while accommodating diverse stakeholder interests and competing land-use priorities. Additionally, engagement strategies should prioritize culturally resonant education campaigns that

translate complex ecological concepts into accessible language. Finally, these strategies should provide with trust-building initiatives addressing historical marginalization and creating genuine participatory opportunities for co-design and co-management.

## 8. References for chapters 1, 2, 3 and 7

- Alcântara, E., Marengo, J. A., Mantovani, J., Londe, L. R., San, R. L. Y., Park, E., Lin, Y. N., Wang, J., Mendes, T., Cunha, A. P., Pampuch, L., Seluchi, M., Simões, S., Cuartas, L. A., Goncalves, D., Massi, K., Alvalá, R., Moraes, O., Filho, C. S., . . . Nobre, C. (2023). Deadly disasters in southeastern South America: flash floods and landslides of February 2022 in Petrópolis, Rio de Janeiro. *Natural Hazards and Earth System Sciences*, 23(3), 1157–1175. <https://doi.org/10.5194/nhess-23-1157-2023>
- Alfonsin, B., & Júnior, R. J. C. M. (2024). Challenges in the implementation of the City Statute's instruments for promoting the social function of property. *Revista De Gestão Social E Ambiental*, 18(10), e8497. <https://doi.org/10.24857/rgsa.v18n10-032>
- Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., & Sanchez, A. (2019). Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *Journal of Environmental Management*, 239, 244–254. <https://doi.org/10.1016/j.jenvman.2019.03.036>
- Anderson, C. C., Renaud, F. G., Hanscomb, S., & Gonzalez-Ollauri, A. (2022b). Green, hybrid, or grey disaster risk reduction measures: What shapes public preferences for nature-based solutions? *Journal of Environmental Management*, 310, 114727. <https://doi.org/10.1016/j.jenvman.2022.114727>
- Anderson, C., & Renaud, F. (2021). A review of public acceptance of nature-based solutions: The 'why,' 'when,' and 'how' of success for disaster risk reduction measures. *Ambio*, 50, 1552–1573.
- Apostolaki, S. (2025). Nature-based solutions: from flood defense to addressing water scarcity and climate change risks. *Nature-Based Solutions*, 100233. <https://doi.org/10.1016/j.nbsj.2025.100233>
- Arce-Mojica, T., Nehren, U., Sudmeier-Rieux, K., Miranda, P. J., & Anhof, D. (2019). Nature-based solutions (NbS) for reducing the risk of shallow landslides: Where do we stand? *International Journal of Disaster Risk Reduction*, 41, 101293. <https://doi.org/10.1016/j.ijdr.2019.101293>

- Aslam, A., & Rana, I. A. (2021). Impact of the built environment on climate change risk perception and psychological distancing: Empirical evidence from Islamabad, Pakistan. *Environmental Science & Policy*, 127, 228–240. <https://doi.org/10.1016/j.envsci.2021.10.024>
- Balbim, R. N. (2023b). Produção Internacional da Informalidade Urbana e os “Núcleos Urbanos Informais” no Brasil. *Ciência & Trópico*, 47(1). [https://doi.org/10.33148/cetropicov47n1\(2023\)art1](https://doi.org/10.33148/cetropicov47n1(2023)art1)
- Barretto, A., & Silva, A. (2023). Os impactos socioambientais das fortes chuvas de Salvador-BA associados à sua expansão urbana [The socio-environmental impacts of heavy rains in Salvador-BA associated with its urban expansion]. VIII CONEDU, GT14.019. doi: 10.46943.VIII.CONEDU.2022.GT14.019
- Browder, G., Ozment, S., Bescos, I., Gartner, T., & Lange, G. (2019). Integrating green and gray: Creating next generation infrastructure. World Resources Institute. <https://doi.org/10.46830/wrirpt.18.00028>
- Bowyer, P., Alfieri, S. M., Basu, B., Cremin, E., Debele, S., Kumar, P., Lechner, V., Loupis, M., Menenti, M., Mickovski, S., Gonzalez-Ollauri, A., Pfeiffer, J., Pilla, F., Pulvirenti, B., Ruggieri, P., Basu, A. S., Spyrou, C., Unguendoli, S., Zieher, T., & Di Sabatino, S. (2024). Modelled effectiveness of NbS in reducing disaster risk: evidence from the OPERANDUM project. *Nature-Based Solutions*, 5, 100127. <https://doi.org/10.1016/j.nbsj.2024.100127>
- Calil, J., Reguero, B. G., Zamora, A. R., Losada, I. J., & Méndez, F. J. (2017). Comparative Coastal Risk Index (CCRI): A multidisciplinary risk index for Latin America and the Caribbean. *PLoS ONE*, 12(11), e0187011. <https://doi.org/10.1371/journal.pone.0187011>
- Calliari, E., Castellari, S., Davis, M., Linnerooth-Bayer, J., Martin, J., Mysiak, J., Pastor, T., Ramieri, E., Scolobig, A., Sterk, M., Veerkamp, C., Wendling, L., & Zandersen, M. (2022). Building climate resilience through nature-based solutions in Europe: A review of enabling knowledge, finance and governance frameworks. *Climate Risk Management*, 37, 100450. <https://doi.org/10.1016/j.crm.2022.100450>

- Caro, C., Marques, J. C., Cunha, P. P., & Teixeira, Z. (2020). Ecosystem services as a resilience descriptor in habitat risk assessment using the InVEST model. *Ecological Indicators*, 115, 106426. <https://doi.org/10.1016/j.ecolind.2020.106426>
- CBD—Secretariat of the Convention on Biological Diversity (2009). *Connecting biodiversity and climate change mitigation and adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change*. Montreal, Canada: Technical Series No. 41, 126 pages. <https://www.cbd.int/doc/publications/cbd-ts-41-en.pdf>
- Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. a. J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., & Seddon, N. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, 26(11), 6134–6155. <https://doi.org/10.1111/gcb.15310>
- Cipriani, E., Gemignani, A., & Menicucci, D. (2024). Awareness of everyday effects of climate change: The Climate Change Perceptual Awareness Scale (CCPAS). *Heliyon*, 10(19), e38461. <https://doi.org/10.1016/j.heliyon.2024.e38461>
- Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2016). *Nature-based solutions to address global societal challenges*. Gland, Switzerland: International Union for Conservation of Nature. <https://portals.iucn.org/library/sites/library/files/documents/2016-036.pdf>
- Coelho-Netto, A. L., De Souza Avelar, A., & Lacerda, W. A. (2009). Landslides and disasters in southeastern and southern Brazil. In *Developments in earth surface processes* (pp. 223–243). [https://doi.org/10.1016/s0928-2025\(08\)10012-8](https://doi.org/10.1016/s0928-2025(08)10012-8)
- Depietri, Y., & McPhearson, T. (2017). Integrating the Grey, green, and blue in Cities: Nature-Based Solutions for Climate Change adaptation and Risk Reduction. In *Theory and practice of urban sustainability transitions* (pp. 91–109). [https://doi.org/10.1007/978-3-319-56091-5\\_6](https://doi.org/10.1007/978-3-319-56091-5_6)
- Doswald, N., & Estrella, M. (2015 December 1). *Promoting ecosystems for disaster risk reduction and climate change adaptation*. United Nations Environment Programme. <https://www.unep.org/resources/report/promoting-ecosystems-disaster-risk-reduction-and-climate-change-adaptation>

- Doswald, N., Janzen, S., Nehren, U., Santamaria, K., Vervest, M., Sans, J., Edbauer, L., Chavda, S., Sandholz, S., Renaud, F., Ruiz, V., Narvaez, L., Yang, S., Mohil, D., Uzoski, D., Gerner, N. & Grey, C. (2021). Words into action: Nature-based solutions for disaster risk reduction. United Nations Office for Disaster Risk Reduction, Geneva-Switzerland. Engaging for resilience in support of the Sendai Framework for Disaster Risk Reduction 2015–2030. [https://www.preventionweb.net/files/74082\\_naturebasedsolutionsfordrr20210624c.pdf](https://www.preventionweb.net/files/74082_naturebasedsolutionsfordrr20210624c.pdf)
- Duffaut, C., Versini, P. & Frascaria-Lacoste, N. (2022). Are really Nature-Based Solutions sustainable solutions to design future cities in a context of global change? Discussion about the vulnerability of these new solutions and their probable unsustainable implementation. *The Science Of The Total Environment*, 853, 158535. <https://doi.org/10.1016/j.scitotenv.2022.158535>
- European Commission. (2020). Bringing nature back into our lives: EU Biodiversity Strategy for 2030. Brussels: European Commission. [https://ec.europa.eu/commission/presscorner/api/files/attachment/865560/fact-sheet-EU-biodiversity-strategy\\_en.pdf](https://ec.europa.eu/commission/presscorner/api/files/attachment/865560/fact-sheet-EU-biodiversity-strategy_en.pdf)
- Eggermont, H., Balian, E., Azevedo, J. M. N., Beumer, V., Brodin, T., Claudet, J., Fady, B., Grube, M., Keune, H., Lamarque, P., Reuter, K., Smith, M., Van Ham, C., Weisser, W. W., & Roux, X. L. (2015). Nature-based solutions: new influence for environmental management and research in Europe. *GAIA - Ecological Perspectives for Science and Society*, 24(4), 243–248. <https://doi.org/10.14512/gaia.24.4.9>
- Faivre, N., Fritz, M., Freitas, T., De Boissezon, B., & Vandewoestijne, S. (2017). Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. *Environmental Research*, 159, 509–518. <https://doi.org/10.1016/j.envres.2017.08.032>
- Fernandes, N. F., Guimarães, R. F., Gomes, R. A., Vieira, B. C., Montgomery, D. R., & Greenberg, H. (2003). Topographic controls of landslides in Rio de Janeiro: field evidence and modeling. *CATENA*, 55(2), 163–181. [https://doi.org/10.1016/s0341-8162\(03\)00115-2](https://doi.org/10.1016/s0341-8162(03)00115-2)

- Fianoo, I. N., Mensah, S. L., Okyere, S. A., Boadie-Ampong, M., & Jirjiri, J. (2024). Linking Informal Settler Practices and Circular Principles in Global South: Lessons from Asian and Latin American Cities. In *Advances in 21st century human settlements* (pp. 11–25). [https://doi.org/10.1007/978-981-99-9025-2\\_2](https://doi.org/10.1007/978-981-99-9025-2_2)
- Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2014). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525–542. <https://doi.org/10.1080/1573062x.2014.916314>
- Gonzalez-Ollauri, A., Munro, K., Mickovski, S. B., Thomson, C. S., & Emmanuel, R. (2021). The ‘Rocket Framework’: a novel framework to define key performance indicators for nature-based solutions against shallow landslides and erosion. *Frontiers in Earth Science*, 9. <https://doi.org/10.3389/feart.2021.676059>
- Handzic, K. (2009). Is legalized land tenure necessary in slum upgrading? Learning from Rio’s land tenure policies in the Favela Bairro Program. *Habitat International*, 34(1), 11–17. <https://doi.org/10.1016/j.habitatint.2009.04.001>
- IBGE -Instituto Brasileiro de Geografia e Estatística. (2025) Base nacional de dados geográficos. <http://www.ibge.gov.br>
- IPBES—Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, & H. T. Ngo (Eds.). IPBES secretariat, Bonn, Germany. 1,148 pages. <https://www.ipbes.net/global-assessment>
- IPCC—Intergovernmental Panel on Climate Change. (2014). Climate change 2014: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 1,132 pages. [https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-FrontMatterA\\_FINAL.pdf](https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-FrontMatterA_FINAL.pdf)

- IPCC—Intergovernmental Panel on Climate Change. (2023). Climate change 2023: Synthesis report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. <https://www.ipcc.ch/report/ar6/syr/>
- Jang, W. M., Kim, U., Jang, D. H., Jung, H., Cho, S., Eun, S. J., & Lee, J. Y. (2020). Influence of trust on two different risk perceptions as an affective and cognitive dimension during Middle East respiratory syndrome coronavirus (MERS-CoV) outbreak in South Korea: serial cross-sectional surveys. *BMJ Open*, 10(3), e033026. <https://doi.org/10.1136/bmjopen-2019-033026>
- Johnson, B. A., Kumar, P., Okano, N., Dasgupta, R., & Shivakoti, B. R. (2022). Nature-based solutions for climate change adaptation: A systematic review of systematic reviews. *Nature-Based Solutions*, 2, 100042. <https://doi.org/10.1016/j.nbsj.2022.100042>
- Kabisch, N. & van den Bosch, M. (2017). Urban green spaces and the potential for health improvement and environmental justice in a changing climate. In: N. Kabisch, H. Korn, J. Stadler, A. Bonn [Eds.], *Nature-based solutions to climate change in urban areas—Linkages of science, policy and practice*. Springer. [https://link.springer.com/chapter/10.1007/978-3-319-56091-5\\_12](https://link.springer.com/chapter/10.1007/978-3-319-56091-5_12)
- Ke, Y., Bai, Y., Ali, M., Ashraf, A., Li, M., & Li, B. (2024). Exploring residents' perceptions of ecosystem services in nature reserves to guide protection and management. *Ecological Indicators*, 158, 111535. <https://doi.org/10.1016/j.ecolind.2023.111535>
- Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., & Cerdà, A. (2017). The superior effect of nature based solutions in land management for enhancing ecosystem services. *The Science of the Total Environment*, 610–611, 997–1009. <https://doi.org/10.1016/j.scitotenv.2017.08.077>
- Kibii, C., Guerra, F., Bananayo, P., & Sandholz, S. (2025). Nature-Based Solutions for Climate Change Adaptation and Resilience in Urban Informal Settlements: insights from Kibera, Kenya and Villa 20, Argentina. *Nature-Based Solutions*, 100216. <https://doi.org/10.1016/j.nbsj.2025.100216>

- Kumar, P., Debele, S. E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S. M., Basu, B., Basu, A. S., Bowyer, P., Charizopoulos, N., Jaakko, J., Loupis, M., Menenti, M., Mickovski, S. B., Pfeiffer, J., Pilla, F., Pröll, J., Pulvirenti, B., Rutzinger, M., . . . Zieher, T. (2021). An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. *Earth-Science Reviews*, 217, 103603. <https://doi.org/10.1016/j.earscirev.2021.103603>
- Lange, W., Pirzer, C., Dünow, L., & Schelchen, A. (2016). Risk Perception for Participatory Ecosystem-Based Adaptation to Climate Change in the Mata Atlântica of Rio de Janeiro State, Brazil. In *Advances in natural and technological hazards research* (pp. 483–506). [https://doi.org/10.1007/978-3-319-43633-3\\_21](https://doi.org/10.1007/978-3-319-43633-3_21)
- Lange, W., Sandholz, S., Viezzer, J., Becher, M., & Nehren, U. (2018a). Ecosystem-Based Approaches for Disaster Risk Reduction and Climate Change Adaptation in Rio de Janeiro State. In *Springer series on environmental management* (pp. 345–359). [https://doi.org/10.1007/978-3-319-89644-1\\_22](https://doi.org/10.1007/978-3-319-89644-1_22)
- Lange, W., Sandholz, S., & Nehren, U. (2018b). Strengthening urban resilience through nature: The potential of ecosystem-based measures for reduction of landslide risk in Rio de Janeiro. Working Paper. Lincoln Institute of Land Policy. <https://www.lincolninst.edu/publications/working-papers/strengthening-urban-resilience-through-nature/>
- Lange, W., Camarinha, P. I. M., Nehren, U., Andrade, A. & Kraas, F. (submitted, after review currently under revision). Nature-based Solutions for landslide risk reduction in informal settlements of Salvador da Bahia, Brazil. *International Journal of Disaster Risk Reduction*.
- Lann, J., Bao, H., Lan, H., Zheng, H., Yan, C., & Peng, J. (2024). Hydro-mechanical effects of vegetation on slope stability: A review. *Science of the Total Environment*, 926, 171691. <https://www.sciencedirect.com/science/article/pii/S0048969724018333>
- Lele, S. (2009). Watershed services of tropical forests: from hydrology to economic valuation to integrated analysis. *Current Opinion in Environmental Sustainability*, 1(2), 148–155. <https://doi.org/10.1016/j.cosust.2009.10.007>

- Lesser, C. N., & Brandes, A. F. N. (2023). Against the grain: environmental laws, local botanical knowledge, and housing access in Rio de Janeiro. *Journal of Environmental Studies and Sciences*, 13(3), 439–452. <https://doi.org/10.1007/s13412-023-00828-7>
- Lourenço, I. B., Guimarães, L. F., Alves, M. B., & Miguez, M. G. (2020). Land as a sustainable resource in city planning: The use of open spaces and drainage systems to structure environmental and urban needs. *Journal of Cleaner Production*, 276, 123096. <https://doi.org/10.1016/j.jclepro.2020.123096>
- Machado, R. A., Oliveira, A. G., & Lois-González, R. C. (2019). Urban ecological infrastructure: The importance of vegetation cover in the control of floods and landslides in Salvador / Bahia, Brazil. *Land Use Policy*, 89, 104180. <https://doi.org/10.1016/j.landusepol.2019.104180>
- Marengo, J. A., Camarinha, P. I., Alves, L. M., Diniz, F., & Betts, R. A. (2021). Extreme rainfall and Hydro-Geo-Meteorological disaster risk in 1.5, 2.0, and 4.0°C global warming scenarios: An analysis for Brazil. *Frontiers in Climate*, 3. <https://doi.org/10.3389/fclim.2021.610433>
- Martin, J.G.C., Scolobig, A., Linnerooth-Bayer, J., Irshaid, J., Aguilera Rodriguez, J. A., Fresolone-Caparrós, A., & Oen, A. (2025). The nature-based solution implementation gap: A review of nature-based solution governance barriers and enablers. *Journal of Environmental Management*, 388, 126007. <https://doi.org/10.1016/j.jenvman.2025.126007>
- Maund, P. R., Irvine, K. N., Dallimer, M., Fish, R., Austen, G. E., & Davies, Z. G. (2020). Do ecosystem service frameworks represent people's values? *Ecosystem Services*, 46, 101221. <https://doi.org/10.1016/j.ecoser.2020.101221>
- MMA - Ministério do Meio Ambiente (2011) Áreas de Preservação Permanente e Unidades de Conservação & Áreas de Risco. O que uma coisa tem a ver com a outra? Relatório de Inspeção da área atingida pela tragédia das chuvas na Região Serrana do Rio de Janeiro. Série Biodiversidade 41. Brasília, Brazil: MMA
- Munns, W. R., Poulsen, V., Gala, W. R., Marshall, S. J., Rea, A. W., Sorensen, M. T., & Von Stackelberg, K. (2016). Ecosystem services in risk assessment and

- management. *Integrated Environmental Assessment and Management*, 13(1), 62–73. <https://doi.org/10.1002/ieam.1835>
- Nalumu, D. J., & Perrotti, D. (2024). A review of the contribution of nature-based solutions to the urban metabolism of the informal settlements. *IOP Conference Series Earth and Environmental Science*, 1363(1), 012083. <https://doi.org/10.1088/1755-1315/1363/1/012083>
- Nehren, U., Arce-Mojica, T., Barrett, A. C., Cueto, J., Doswald, N., Janzen, S., Lange, W., Vargas, A. O., Pirazan-Palomar, L., Renaud, F., Sandholz, S., Sebesvari, Z., Sudmeier-Rieux, K., & Walz, Y. (2023). Towards a typology of nature-based solutions for disaster risk reduction. *Nature-Based Solutions*, 3, 100057. <https://doi.org/10.1016/j.nbsj.2023.100057>
- Nehren, U., Kirchner, A., Sattler, D., Turetta, A. P., & Heinrich, J. (2013). Impact of natural climate change and historical land use on landscape development in the Atlantic Forest of Rio de Janeiro, Brazil. *Anais Da Academia Brasileira De Ciências*, 85(2), 497–518. <https://doi.org/10.1590/s0001-37652013000200004>
- Nelson, D. R., Bledsoe, B. P., Ferreira, S., & Nibbelink, N. P. (2020). Challenges to realizing the potential of nature-based solutions. *Current Opinion in Environmental Sustainability*, 45, 49–55. <https://doi.org/10.1016/j.cosust.2020.09.001>
- Osaka, S., Bellamy, R., & Castree, N. (2021). Framing “nature-based” solutions to climate change. *Wiley Interdisciplinary Reviews Climate Change*, 12(5). <https://doi.org/10.1002/wcc.729>
- Pan, Y., & Qu, Y. (2024). Cultural Ecosystem Services in Land Use/Land Cover Change: A Literature Review and Prospects for Future research. *Land*, 13(12), 2027. <https://doi.org/10.3390/land13122027>
- Pearlmutter, D., Theochari, D., Nehls, T., Pinho, P., Piro, P., Korolova, A., Papaefthimiou, S., Mateo, M. C. G., Calheiros, C., Zluwa, I., Pitha, U., Schosseler, P., Florentin, Y., Ouannou, S., Gal, E., Aicher, A., Arnold, K., Igondová, E. & Pucher, B. (2019). Enhancing the circular economy with nature-based solutions in the built urban environment: green building materials,

- systems and sites. *Blue-Green Systems*, 2(1), 46–72. <https://doi.org/10.2166/bgs.2019.928>
- Pereira, P., Yin, C. & Hua, T. (2023). Nature-based solutions, ecosystem services, disservices, and impacts on well-being in urban environments. *Current Opinion in Environmental Science & Health*, 33, 100465. <https://doi.org/10.1016/j.coesh.2023.100465>
- Peter, S. (2020). Integrating Key Insights of Sociological Risk Theory into the Ecosystem Services Framework. *Sustainability*, 12(16), 6437. <https://doi.org/10.3390/su12166437>
- Phuong, T. T., Tan, N. Q., Dinh, N. C., Linh, N. H. K., & Ty, P. H. (2023). Flood Vulnerability-Rural Poverty Nexus: Implications for disaster risk reduction and sustainable rural development in Vietnam. *Environment and Ecology Research*, 11(2), 362–377. <https://doi.org/10.13189/eer.2023.110210>
- Quintas-Soriano, C., Brandt, J. S., Running, K., Baxter, C. V., Gibson, D. M., Narducci, J., & Castro, A. J. (2018). Social-ecological systems influence ecosystem service perception: a Programme on Ecosystem Change and Society (PECS) analysis. *Ecology and Society*, 23(3). <https://doi.org/10.5751/es-10226-230303>
- Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., Geneletti, D., & Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science & Policy*, 77, 15–24. <https://doi.org/10.1016/j.envsci.2017.07.008>
- Renaud, F. G., Sudmeier-Rieux, K., Estrella, M., & Nehren, U. (2016). Ecosystem-Based Disaster Risk Reduction and Adaptation in practice. In *Advances in natural and technological hazards research*. <https://doi.org/10.1007/978-3-319-43633-3>
- Ronchi, S., & Arcidiacono, A. (2018). Adopting an Ecosystem Services-Based approach for flood resilient strategies: the case of Rocinha Favela (Brazil). *Sustainability*, 11(1), 4. <https://doi.org/10.3390/su11010004>

- Ruangpan, L., Vojinovic, Z., Di Sabatino, S., Leo, L. S., Capobianco, V., Oen, A. M. P., McClain, M. E., and Lopez-Gunn, E. (2020). Nature-based solutions for hydro-meteorological risk reduction. *Natural Hazards and Earth System Sciences*, 20(1), 243–270. <https://nhess.copernicus.org/articles/20/243/2020/>
- Sandholz, S., Lange, W., & Nehren, U. (2018). Governing green change: Ecosystem-based measures for reducing landslide risk in Rio de Janeiro. *International Journal of Disaster Risk Reduction*, 32, 75–86. <https://doi.org/10.1016/j.ijdr.2018.01.020>
- Sarabi, S., Han, Q., Romme, A. G. L., De Vries, B., Valkenburg, R., & Ouden, E. D. (2020). Uptake and implementation of Nature-Based Solutions: An analysis of barriers using Interpretive Structural Modeling. *Journal of Environmental Management*, 270, 110749. <https://doi.org/10.1016/j.jenvman.2020.110749>
- Seddon, N., Chausson, A., Berry, P., Girardin, C. a. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B Biological Sciences*, 375(1794), 20190120. <https://doi.org/10.1098/rstb.2019.0120>
- Seddon, N., Smith, A., Smith, P., Key, I., Chausson, A., Girardin, C., House, J., Srivastava, S., & Turner, B. (2021). Getting the message right on nature-based solutions to climate change. *Global Change Biology*, 27(8), 1518–1546. <https://doi.org/10.1111/gcb.15513>
- Seleguim, F. B., Weins, N. W., Gutierrez, E. P., Soeira, M. R. C., Nichi, J., & Da Costa Ferreira, L. (2024). Nature-based solutions to adapt to local climate change: political strategies in Brazilian cities. *Brazilian Political Science Review*, 18(1). <https://doi.org/10.1590/1981-3821202400010004>
- Serra-Llobet, A., Jähnig, S. C., Geist, J., Kondolf, G. M., Damm, C., Scholz, M., Lund, J., Opperman, J. J., Yarnell, S. M., Pawley, A., Shader, E., Cain, J., Zingraff-Hamed, A., Grantham, T. E., Eisenstein, W., & Schmitt, R. (2022). Restoring rivers and floodplains for habitat and flood risk reduction: Experiences in Multi-Benefit Floodplain Management from California and Germany. *Frontiers in Environmental Science*, 9. <https://doi.org/10.3389/fenvs.2021.778568>

- Slovic, P., & Weber, E. U. (2013). Perception of risk posed by extreme events. SSRN Electronic Journal. [https://papers.ssrn.com/sol3/Delivery.cfm/SSRN\\_ID2293086\\_code46495.pdf?abstractid=2293086&mirid=1](https://papers.ssrn.com/sol3/Delivery.cfm/SSRN_ID2293086_code46495.pdf?abstractid=2293086&mirid=1)
- Sudmeier-Rieux, K., Arce-Mojica, T., Boehmer, H. J., Doswald, N., Emerton, L., Friess, D. A., Galvin, S., Hagenlocher, M., James, H., Laban, P., Lacambra, C., Lange, W., McAdoo, B. G., Moos, C., Mysiak, J., Narvaez, L., Nehren, U., Peduzzi, P., Renaud, F. G., . . . Walz, Y. (2021). Scientific evidence for ecosystem-based disaster risk reduction. *Nature Sustainability*, 4(9), 803–810. <https://doi.org/10.1038/s41893-021-00732-4>
- Thiault, L., Jupiter, S. D., Johnson, J. E., Cinner, J. E., Jarvis, R. M., Heron, S. F., Maina, J. M., Marshall, N. A., Marshall, P. A., & Claudet, J. (2021). Harnessing the potential of vulnerability assessments for managing social-ecological systems. *Ecology and Society*, 26(2). <https://doi.org/10.5751/es-12167-260201>
- Thorslund, J., Jarsjo, J., Jaramillo, F., Jawitz, J. W., Manzoni, S., Basu, N. B., Chalov, S. R., Cohen, M. J., Creed, I. F., Goldenberg, R., Hylin, A., Kalantari, Z., Koussis, A. D., Lyon, S. W., Mazi, K., Mard, J., Persson, K., Pietro, J., Prieto, C., . . . Destouni, G. (2017). Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management. *Ecological Engineering*, 108, 489–497. <https://doi.org/10.1016/j.ecoleng.2017.07.012>
- Torres, P. H. C., De Souza, D. T. P., Momm, S., Travassos, L., Picarelli, S. B., Jacobi, P. R., & Da Silva Moreno, R. (2023). Just cities and nature-based solutions in the Global South: A diagnostic approach to move beyond panaceas in Brazil. *Environmental Science & Policy*, 143, 24–34. <https://doi.org/10.1016/j.envsci.2023.02.017>
- Toxopeus, H., Kotsila, P., Conde, M., Katona, A., Van Der Jagt, A. P., & Polzin, F. (2020). How ‘just’ is hybrid governance of urban nature-based solutions? *Cities*, 105, 102839. <https://doi.org/10.1016/j.cities.2020.102839>
- Tozer, L., Hörschelmann, K., Anguelovski, I., Bulkeley, H., & Lazova, Y. (2020). Whose city? Whose nature? Towards inclusive nature-based solution governance. *Cities*, 107, 102892. <https://doi.org/10.1016/j.cities.2020.102892>

- UNEA—United Nations Environment Assembly. (2022). Nature-based solutions for supporting sustainable development (Resolution UNEP/EA.5/Res.5). United Nations Environment Programme.
- UNEP—United Nations Environment Programme. (2021). The UN decade on ecosystem restoration. United Nations Environment Programme.
- UNFCCC—United Nations Framework Convention on Climate Change. (2015). Paris Agreement to the United Nations Framework Convention on Climate Change. United Nations. <https://unfccc.int/process-and-meetings/the-paris-agreement>
- UNISDR – United Nations Office for Disaster Risk Reduction. (2015). Sendai Framework for Disaster Risk Reduction 2015-2030. Geneva, Switzerland.
- Vicarelli, M., Sudmeier-Rieux, K., Alsadadi, A., Shrestha, A., Schütze, S., Kang, M. M., Leue, M., Wasielewski, D., & Mysiak, J. (2024). On the cost-effectiveness of Nature-based Solutions for reducing disaster risk. *The Science of the Total Environment*, 947, 174524. <https://doi.org/10.1016/j.scitotenv.2024.174524>
- Walz, Y., Nick, F., Roa, O. H., Nehren, U., & Sebesvari, Z. (2021). Coherence and Alignment among Sustainable Land Management, Ecosystem-based Adaptation, Ecosystem-based Disaster Risk Reduction and Nature-based Solutions. <https://doi.org/10.53324/mwgp9896>
- Welden, E. A., Chausson, A., & Melanidis, M. S. (2021). Leveraging Nature-based Solutions for transformation: Reconnecting people and nature. *People and Nature*, 3(5), 966–977. <https://doi.org/10.1002/pan3.10212>
- Wong-Parodi, G., Relihan, D. P., & Garfin, D. R. (2024). A longitudinal investigation of risk perceptions and adaptation behavior in the US Gulf Coast. *PNAS Nexus*, 3(4). <https://doi.org/10.1093/pnasnexus/pgae099>
- Yang, L., Wang, K., Yi, J., Guo, J., & Ou, M. (2024). Socio-ecological risk analysis framework coupled with ecosystem services. *PubMed*, 35(5), 1419–1425. <https://doi.org/10.13287/j.1001-9332.202405.0>