THE NATURE-BASED SOLUTIONS OPPORTUNITY SCAN

LEVERAGING EARTH OBSERVATION DATA TO IDENTIFY INVESTMENT OPPORTUNITIES IN NBS FOR CLIMATE RESILIENCE IN CITIES AND COASTS ACROSS THE WORLD

GLOBAL PROGRAM ON NATURE-BASED SOLUTIONS FOR CLIMATE RESILIENCE

PROBLUE
HEALTHY OCEAN · HEALTHY ECONOMIES · HEALTHY COMMUNITIES

GFDRR
Global Facility for Disaster Reduction and Recovery

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GLOBAL WATER SECURITY & SANITATION PARTNERSHIP

NBS INVEST
Accelerating Nature Based Solutions in Least Developed Countries

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ACKNOWLEDGMENTS

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The report was designed by Estudio Relativo and edited by Hope Steele.

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ABBREVIATIONS AND ACRONYMS

API	Application Programming Interface
AOI	area of interest
ASAs	advisory services and analytics
CCDRs	Country Climate and Development Reports
CIF	Climate Investment Funds
CO_2/ha/year	carbon dioxide per hectare per year
CSOs	civil society organizations
DEM	Digital Elevation Model
ENB	Environment, Natural Resources and the Blue Economy
EO	Earth observation
GCS	Google Cloud Storage
GEE	Google Earth Engine
GFDRR	Global Facility for Disaster Reduction and Recovery
GIS	geographic information systems
GP	Global Practice
GPNBS	Global Program on Nature-Based Solutions for Climate Resilience
GPURL	Urban, Disaster Risk Management, Resilience and Land
IBAT	Integrated Biodiversity Assessment Tool
IDA	International Development Association
IPF	investment project financing
LAC SD	Latin America and the Caribbean Sustainable Development Practice Group
MDBs	multilateral development banks
NBS	nature-based solutions
NBSOS	Nature-Based Solutions Opportunity Scan
NDVI	normalized difference vegetation index
PG	Practice Group
RETF	recipient-executed trust fund
SCC	social cost of carbon
SD	Sustainable Development Practice Group
SFINCS	Super-Fast INundation of CoastS

All dollar amounts are US dollars unless otherwise indicated.

ES

EXECUTIVE SUMMARY

Mangrove 2
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THE CHALLENGE

Countries are facing rising climate-related challenges that are making them more vulnerable to climate-related disasters.

These problems are especially relevant in cities and coastal areas, where climate risks emerge because of sea-level rise, increasing intensity of rainfall, and extreme heat. Investing in nature-based solutions (NBS) for climate resilience can be effective in reducing climate risks while also bringing other important benefits for communities and the environment. These investments can utilize a variety of natural features by, for instance, creating urban green spaces and corridors, restoring watercourses and coastlines, and preserving natural wetlands and mangroves. Often, the optimization of benefits is achieved through the integration of natural and gray infrastructure, thereby minimizing life-cycle costs and enhancing environmental outcomes.

Even though the World Bank's NBS for climate resilience lending portfolio is steadily growing, governments and Task Teams face challenges in the identification, design, and implementation of investment projects.

The integration of NBS for climate resilience into the World Bank portfolio has increased substantially. Between fiscal years 2012 and 2023, the World Bank approved over 200 projects with NBS components. The financing committed to NBS components in these projects combined exceeds $10 billion. A significant share of these lending operations has received technical support from the Global Program on Nature-Based Solutions for Climate Resilience (GPNBS),[1] which is housed at the Global Facility for Disaster Reduction and Recovery (GFDRR). While interest in NBS for climate resilience has increased at the World Bank and among clients, technical barriers persist and investments in NBS remain a modest share of total financing going toward infrastructure and climate resilience.

Actionable information is needed at the right time to support the scaling up of NBS investments.

A common challenge is that identifying potential NBS investments is hindered by a lack of data and technical expertise on NBS. Having the right information to understand opportunities for NBS investment at the identification stage is critical for enabling further greening of infrastructure and climate-resilience projects. Without rapid and accurate information on NBS opportunities, and without the right technical expertise throughout the project cycle, projects often fall back on more traditional gray infrastructure investments.

THE OBJECTIVE

The Nature-Based Solutions Opportunity Scan (NBSOS) supports the World Bank, its clients, and its development partners in identifying NBS investment opportunities, understanding the benefits that these may bring for communities and the environment, and integrating these NBS interventions into investment programming.

The development of the NBSOS responds directly to the demand from project teams and government decision-makers who are interested in integrating NBS in investment planning but do not have the necessary information to understand investment typologies, geographic priorities, and the expected costs and benefits. The NBSOS is therefore primarily developed for use in the early phase of project investment planning, where it provides clear indications of potential NBS interventions and their benefits for a city or coastline. In addition, the NBSOS is applied for strategic diagnosis—including Country Climate and Development Reports (CCDRs) and climate adaptation planning—where cross-sectoral investment prioritization is important.

NBSOS is a geospatial analysis and participatory process offered by GFDRR as an on-demand service in cities and coastal areas worldwide. The NBSOS is applied at the request of and in collaboration with World Bank project teams and their clients, and it is tailored to each specific case in order to provide the

1 For more information about GPNBS, see https://naturebasedsolutions.org/.

most useful advice. NBSOS relies on an array of openly available global geospatial data sets that are complemented with local data where available. The tool provides a starting point in understanding NBS investment opportunities. Following the NBSOS, the GPNBS team provides additional capacity building and technical support to help ensure that its outcomes inform the development of more detailed analyses, such as pre-feasibility and design studies and, eventually, investments.

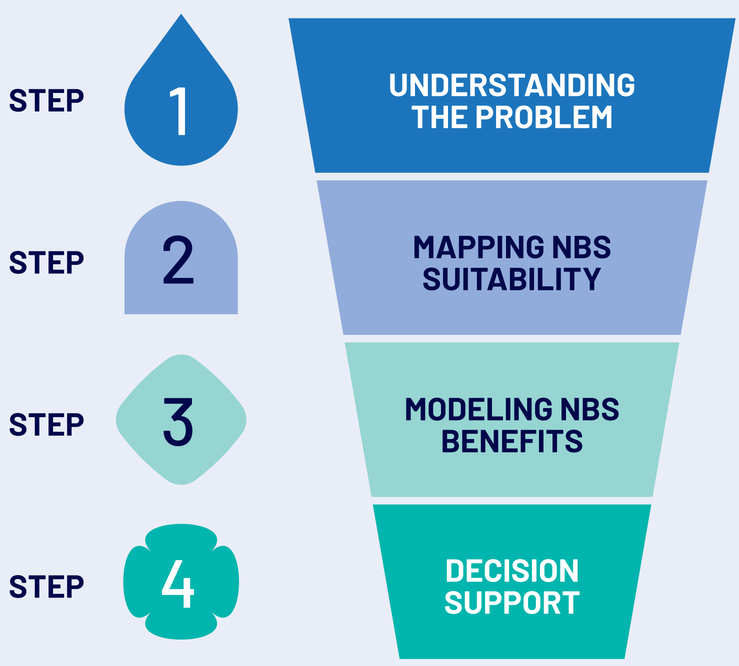
THE APPROACH

The NBSOS uses 10- to 30-meter resolution global geospatial data and a sophisticated methodology to map the potential benefits of NBS and identify investment opportunities in cities and along coastlines anywhere in the world.

The methodology and the software are designed in such a way that its deliverables—including results, interpretation, recommendations, and a full package of geospatial data—can be prepared in approximately four to six weeks. The NBSOS is tailored to the local context prior to implementation in an inception meeting with the Task Team, in some cases also involving the client.

The NBSOS analysis consists of four methodological steps (see figure ES-1): problem analysis, suitability mapping, benefit modeling, and decision support. The first step entails understanding the magnitude and spatial variation of climate resilience challenges and natural hazards in the area of interest. The second step consists of mapping suitable areas for protection and creation of the NBS types considered. The third step models and estimates the positive impact of NBS in addressing the identified climate resilience challenges and natural hazards. Finally, the fourth step consists of finding the optimal distribution of NBS investments to maximize benefits, through multicriteria or cost-benefit analysis, providing relevant information to decision-makers.

FIGURE ES-1: NATURE-BASED SOLUTIONS OPPORTUNITY SCAN METHODOLOGY



SOURCE: Original figure for this publication.

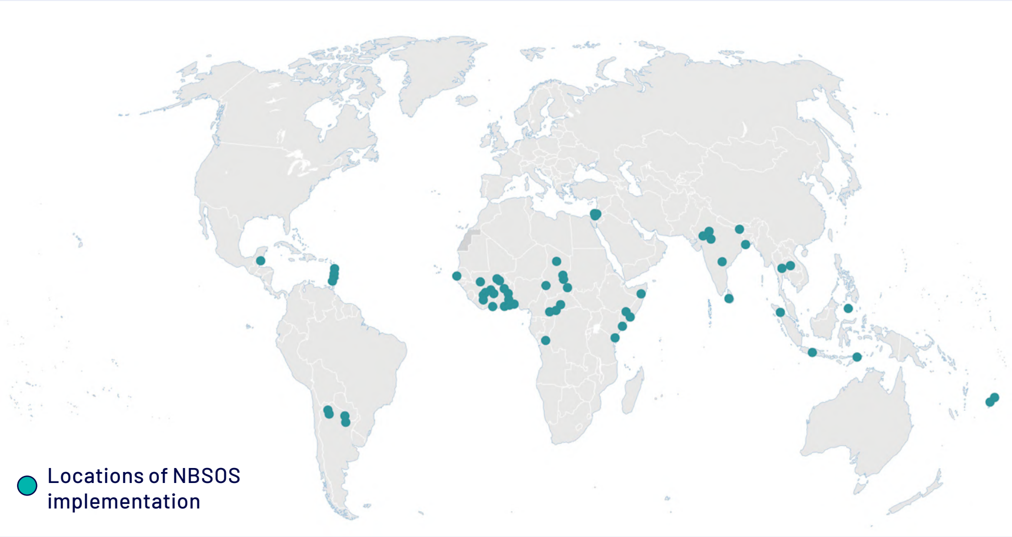
THE IMPACT

The NBSOS was successfully implemented in 20 countries between mid-2022 and early 2024, including 8 coastal landscapes and 51 cities, informing an estimated $2.3 billion in development financing as well as key strategic assessments (see map ES-1).

Most projects informed are investment project financing (IPF) engagements that use the NBSOS to identify potential NBS interventions as part of the project. In addition, the NBSOS has been used to identify NBS for adaptation investment needs for CCDRs. The NBSOS has been applied in different regions (map ES-1)—such as Africa, South Asia, and Latin America and the Caribbean—and across Global Practices such as the Urban, Disaster Risk Management, Resilience and Land (GPURL); Environment, Natural Resources and the Blue Economy (ENB); Water; and Transport Global Practices.

Experience shows that the NBSOS has a higher project-level impact if GPNBS supports Task Teams by presenting and interpreting results, and by integrating results in (pre-)feasibility and design studies. Through early identification of potential NBS investment locations and by estimating the potential benefits of NBS reducing climate risk and providing ecosystem services, the NBSOS has been instrumental for project identification and design. Experience also shows the need to provide guidance to Task Teams, thus ensuring the correct interpretation of results and clarifying limitations of the methodology. The NBSOS is a first and rapid assessment that can provide useful indication of areas and types of NBS investments and their benefits (and costs), but it cannot replace a full feasibility and design study, which is often a next step. The role of an NBSOS assessment in the investment process should be clear to the task team and government clients.

MAP ES-1: LOCATIONS WHERE INVESTMENT OPPORTUNITY MAPPING USING THE NBSOS WAS USED TO INFORM WORLD BANK-FINANCED OPERATIONS AND CORE DIAGNOSTICS



SOURCE: Original map for this publication based on coordinates of NBSOS study sites.
NOTE: NBSOS = Nature-Based Solutions Opportunity Scan.

THE WAY FORWARD

Most projects financing climate resilience, water, or other public infrastructure in urban and coastal settings can benefit from applying the NBSOS at an early stage to identify opportunities for NBS investments.

In addition to highlighting specific opportunities for NBS investments, NBSOS results demonstrate the advantages of having a more holistic approach to NBS, integrating multiple benefits, and planning multifunctional solutions. This is, for example, relevant for strategic engagements such as CCDRs, especially for countries with vulnerable coastlines, big cities, or rapid urban expansion. In this type of engagement, the NBSOS has proven itself to be an effective tool to inform development finance.

Analytical capabilities of the NBSOS are—and will be—continuously updated. Incremental science-based improvements are continually tested and implemented during applications. More fundamental analytical improvements will focus on expanding the capability of the NBSOS estimating biodiversity impact and quantifying pluvial flood reduction by NBS in urban areas. In addition, a growing body of research and practice will increase the ability to estimate unit costs of NBS adjusted to the landscape or country context as part of the NBSOS. As more NBS for climate resilience projects are studied and implemented globally, more data points on costs become available. In collaboration with GFDRR and PROGREEN,[2] GPNBS is developing rapid costing tools to inform and improve unit cost estimations used in the NBSOS.

Within the current operational model, it is possible to further increase capacity to deliver NBSOS to Task Teams by about 25–50 percent.

Increased efficiency as a result of standardization, along with a larger pool of expert consultants to run the analyses, can expand its capacity up to about 70–80 cities and 15 coastal landscapes per year, but if the demand exceeds this capacity, it will lead to a longer response time to the requests of Task Teams. Additional capacity could be created either by developing a webtool with graphical user interface for nonexpert users, or by stimulating industry (that is, World Bank vendors) to adopt the NBSOS methods by opening the source code and enabling knowledge transfer. The latter option seems favorable, since 20 external partners—including multilateral development banks (MDBs), other development partners, private sector firms, and leading civil society organizations (CSOs)—have requested access to the NBSOS. Hence, the source code of the urban NBSOS will become available on request upon publication of this report for a selected number of external partners (see https://naturebasedsolutions.org/opportunity-scan).

2 Details about PROGREEN, which is "a global partnership for sustainable and resilient landscapes," can be found at https://www.progreen.info/.

Urban streams
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1 BACKGROUND

Cities and coastal areas are increasingly exposed to climate change impacts.

From the 1970s to the period 2010–20, the frequency of extreme heat and dry events increased across cities globally, and the frequency of extreme wet events has increased since the 1990s. Global sea-level rise of about 0.125 millimeters per year is also increasing the risk of flooding for coastal cities. More than half of the world's population lives in cities, while about 10 percent live along low elevation coastal zones. Urban areas are becoming more crowded, with the resultant loss of greenspace affecting biodiversity and with climate and disaster impacts such as extreme heat and flooding having a greater effect on a greater number of people. By protecting natural systems and investing in nature-based solutions (NBS), infrastructure projects can build resilience and protect development gains for future generations (see Mukim and Roberts 2023).

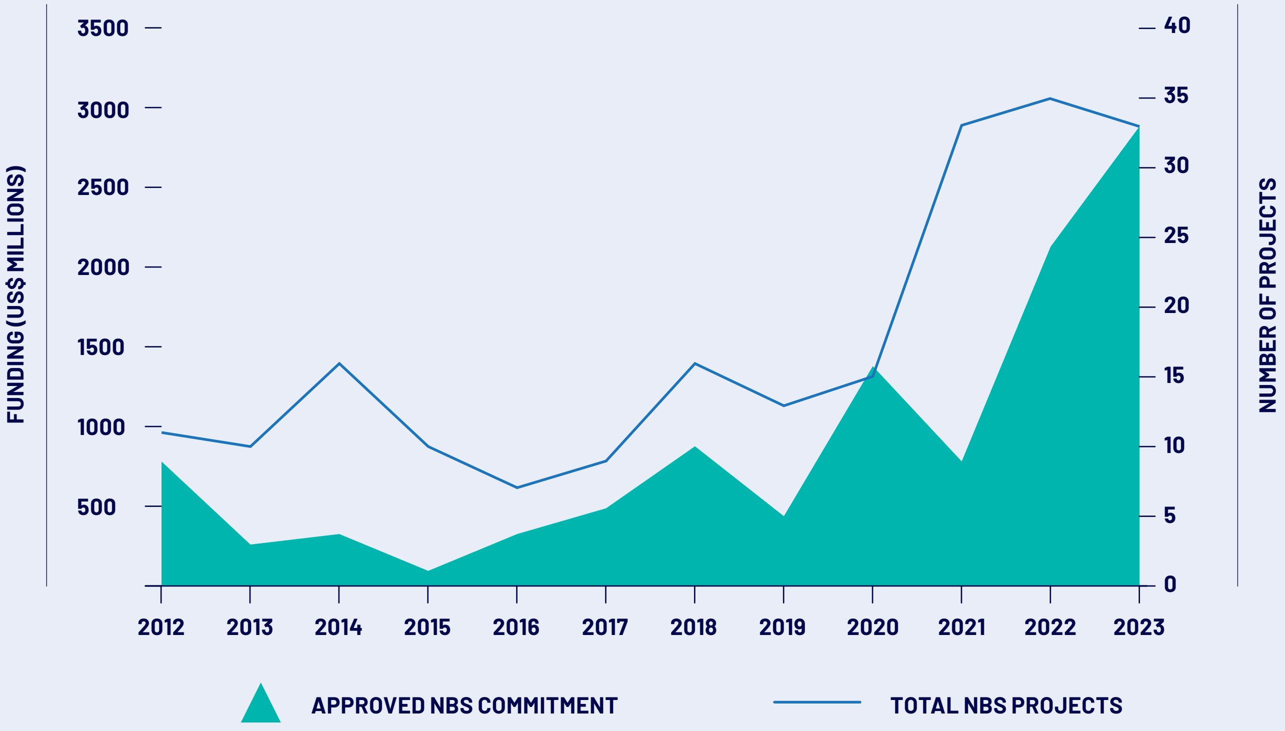
NBS for climate resilience are multifunctional solutions to meet the rising challenge of climate resilience.

NBS can provide a range of benefits such as reducing disaster risks, restoring biodiversity, creating opportunities for recreation, improving human health, ensuring water and food security, and supporting community well-being and livelihoods (van Zanten et al. 2023). Examples include the strategic design of urban parks to combat flooding, the rehabilitation of coastal wetlands to reduce erosion, and planned urban afforestation initiatives to alleviate and mitigate urban heat stress. NBS are often integrated into larger infrastructure investment projects and can complement gray infrastructure to reduce disaster risk and build resilience, while bringing additional benefits.

Despite the multiple benefits of NBS, it remains difficult to bring these solutions to scale as part of development, environmental, and climate resilience projects.

Even though the integration of NBS for climate resilience investment has been growing, investments in NBS are still a minor share of total financing of the World Bank's sustainable development and infrastructure portfolios. Between fiscal years 2012 and 2023, the Bank approved 200 projects that include an NBS component. The total committed financing for project components that include NBS exceeds $10 billion (figure 1) (World Bank 2023; the numbers from this report have been complemented with World Bank fiscal year 2022 and 2023 committed financing). Since 2021, the Global Program on Nature-Based Solutions for Climate Resilience (GPNBS) supported 31 of these projects, with $2.4 billion financing committed to NBS components. GPNBS-supported projects benefitted over 24 million people, afforested/reforested or restored more than 2.8 million hectares of degraded ecosystems, protected nearly 35,000 kilometers of coastal areas, and brought 14 million hectares of land under sustainable land management or enhanced biodiversity protection. Despite these results, several implementation barriers persist, and there is an opportunity to increase the integration of NBS as part of projects investing in urban development, coastal management and the blue economy, water management, transport, landscape restoration, and climate mitigation.

FIGURE 1: WORLD BANK PROJECTS WITH NATURE-BASED COMPONENTS BETWEEN FISCAL YEARS 2012 AND 2023



SOURCE: Original figure for this publication based on NBSOS data.
NOTE: NBS = Natured-Based Solutions.

©Alec Douglas Unsplash

One of the challenges to integrating NBS in development finance is the early identification of investment opportunity areas, particularly in data-poor environments.

In the project identification phase, with limited time and resources at hand, there is a need for a quick and robust analytical approach that can support the initial identification of opportunity areas for investment in NBS, relying on globally available geospatial data. Such investment opportunity mapping can inform projects in different ways:

It supports project identification and is a starting point of an investment plan.

It provides a baseline for local stakeholder and community dialogue.

And it informs (pre-) feasibility studies, design, and implementation.

Responding to this need, the Global Program on Nature-Based Solutions for Climate Resilience (GPNBS) and the World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) have developed the NBS Opportunity Scan (NBSOS).[3]

3 For details about the GPNBS see https://www.naturebasedsolutions.org/; see also GFDRR 2023.

2 WHAT IS THE NBSOS?

The primary objective of employing the NBSOS is to identify priorities for potential NBS investments in projects that are in preparation or in the early implementation stage.

This ensures that its outcomes can inform the development of more detailed analyses, such as pre-feasibility studies. By identifying opportunities for NBS during preliminary assessments and project inception, it becomes more feasible to seamlessly integrate nature-based infrastructure into final solutions and investment strategies.

NBSOS is a standardized geospatial methodology and a participatory process offered as an on-demand service to Task Teams for NBS investment opportunity mapping in cities and coastal areas worldwide.

It aims to support World Bank teams, governments, and other investors to understand which NBS types have most potential in a particular city, what potential project sites are, what their potential benefits are, and how NBS can complement gray infrastructure. The NBSOS methodology is designed in a way that its deliverables—including results, interpretation, and recommendations, and geospatial data package—can be prepared in approximately four to six weeks.

NBSOS relies on an array of openly available 10- to 30-meter resolution Earth observation data and other geospatial data sets. The analysis consists of four methodological steps, as shown in figure 2.

1

First, understanding the problem and mapping hazards: what are the spatial distribution and magnitude of resilience and sustainability challenges and what are the solutions considered to cope with these challenges?

2

The **second** step consists of mapping suitable areas for implementing the NBS types considered. To achieve this, the physical conditions (for example, soil type, slope) required for each NBS type are ascertained.

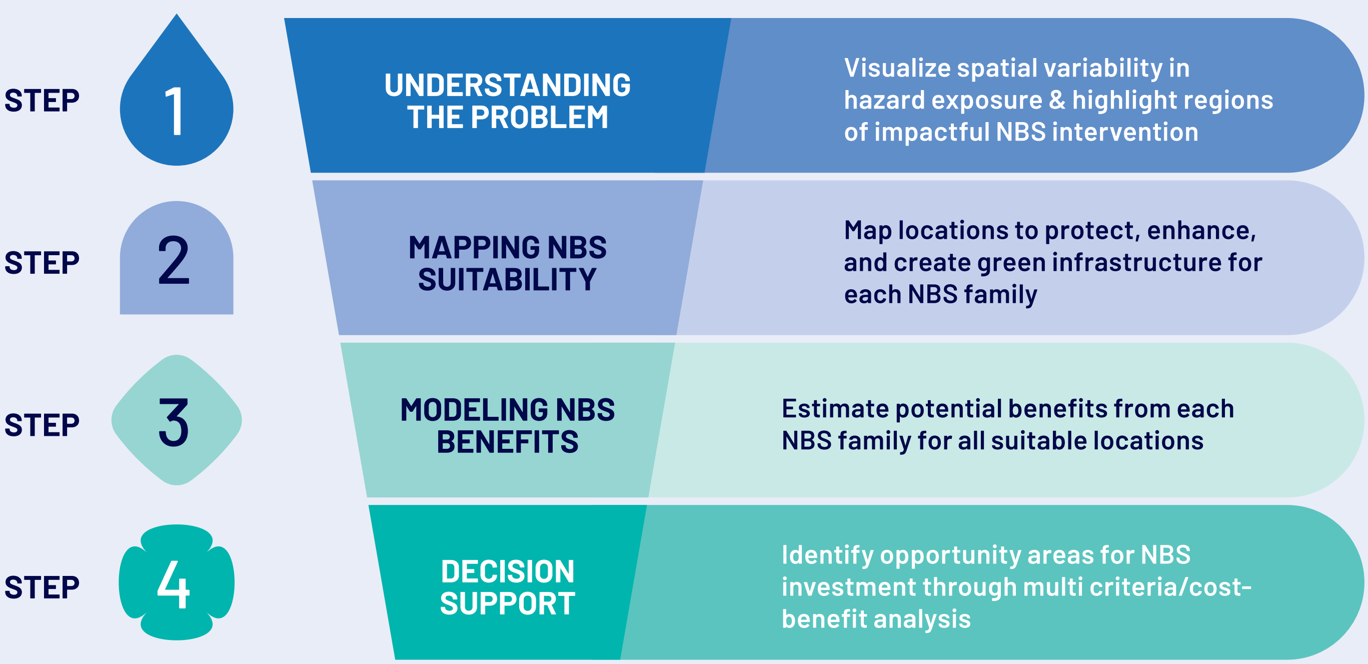
3

The **third** step models and estimates the positive socioeconomic impact (that is, the benefits) NBS has in addressing the identified resilience and sustainability challenges.

4

Fourth, the decision support step consists of finding the optimal distribution of NBS to maximize benefits, which is accomplished through multicriteria and cost-benefit analysis.

FIGURE 2: NATURE-BASED SOLUTIONS OPPORTUNITY SCAN METHODOLOGY



SOURCE: Original figure for this publication.
NOTE: An NBS family is a group of nature-based solutions, such as urban farming or mangrove forests. See figure 3 and World Bank 2021.

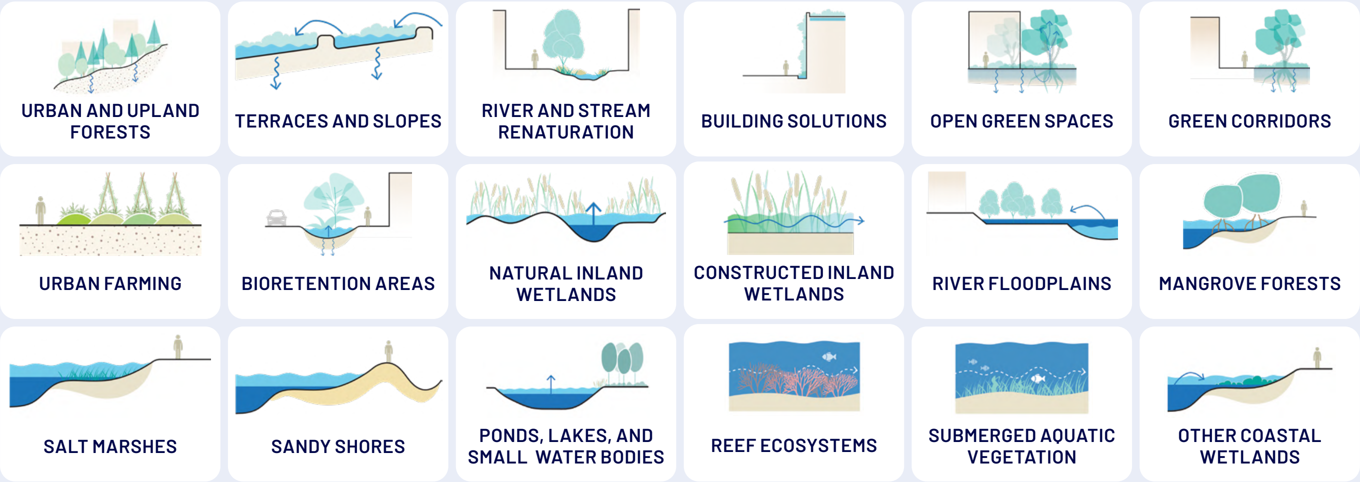
3

HOW IS THE NBSOS APPLIED?

Before the analysis starts, the NBSOS is tailored to the needs of the Task Team.

In this process, the area of interest is determined: in the urban case, this can vary from a small settlement area to a large catchment of several hundred kilometers squared; in the coastal case, it can vary from few hundred kilometers to the entire coast of a small country. Moreover, through consultation with the Task Team, the most important NBS benefits linked to the climate resilience and sustainability challenges in the area are identified and relevant NBS types are selected. The NBS are selected from the 14 different NBS families that are described in the *Catalogue of Nature-Based Solutions for Urban Resilience* (World Bank 2021)(figure 3).

FIGURE 3: FAMILIES OF NATURE-BASED SOLUTIONS



SOURCE: World Bank 2021.

NOTE: NBS = nature-based solutions.

Next, each of the four steps followed to implement the NBSOS is described separately for the urban and coastal analyses.

3.1 THE URBAN NBS OPPORTUNITY SCAN

The different components, data, processes, and results of the four methodological steps for applying the NBSOS in urban areas are summarized in figure 4. Each of these steps is explained in the sections below. A detailed description of the methodology is provided in appendix A. The urban NBSOS is described in this section using the example of Dakar, Senegal.

FIGURE 4: COMPONENTS, DATA, PROCESSES, AND RESULTS COMPRISING THE FOUR STEPS FOR APPLYING THE NBSOS IN URBAN AREAS

STEP 1 UNDERSTANDING THE PROBLEM

HAZARDS	INPUT DATA	GIS PROCESSING	OUTPUT RESULT
PLUVIAL FLOODING	• DEM • Flood Model • Population Density	Flood Exposure & Reduction Potential Mapping	Pluvial Flood Exposure & Priority Area Maps
HEAT STRESS	• Air temperature Model • Population Density	Air Temperature Exposure Mapping	Heat Stress Priority Area Maps
LACK OF GREEN SPACE	• Existing Green Space Map • Population Density	Recreation Opportunity Mapping	Health/Recreation Priority Area Maps

STEP 2 MAPPING NBS SUITABILITY

NBS FAMILIES	INPUT DATA	GIS PROCESSING	OUTPUT RESULT
	• Soil Properties • Climate Trends • Terrain • Land Cover • Land Use • Greenness • Bare Soil Frequency	NBS Suitability Mapping	NBS Suitability Maps

STEP 3 MODELING NBS BENEFITS

BENEFITS	INPUT DATA	GIS PROCESSING	OUTPUT RESULT
Pluvial Flood Reduction	• Pluvial Flood Priority Maps • NBS Suitability Maps	Runoff Reduction & Storage Model	Pluvial Flood Benefits Maps
Heat Stress Reduction	• Heat Stress Priority Maps • NBS Suitability Maps	Air Temperature Reduction Model	Heat Stress Benefits Maps
Improved Access to Green Space	• Heath/Recreation Priority Maps • NBS Suitability Maps	Distance from Green Space Model	Health/ Recreation Benefits Maps

STEP 4 DECISION SUPPORT

BENEFITS	INPUT DATA	GIS PROCESSING	OUTPUT RESULT
Pluvial Flood Importance	• Pluvial Flood Benefits Maps	Combined Weighted Benefits Mapping	Optimal NBS Maps
Heat Stress Importance	• Heat Stress Benefits Maps		
Access to Green Space Importance	• Health/Recreation Benefits Maps		

SOURCE: Original figure for this publication.
NOTE: DEM = Digital Elevation Model; GIS = geographic information systems; NBS = nature-based solutions; NBSOS = Nature-Based Solutions Opportunity Scan.

3.1.1

1 STEP 1: UNDERSTANDING URBAN RESILIENCE CHALLENGES

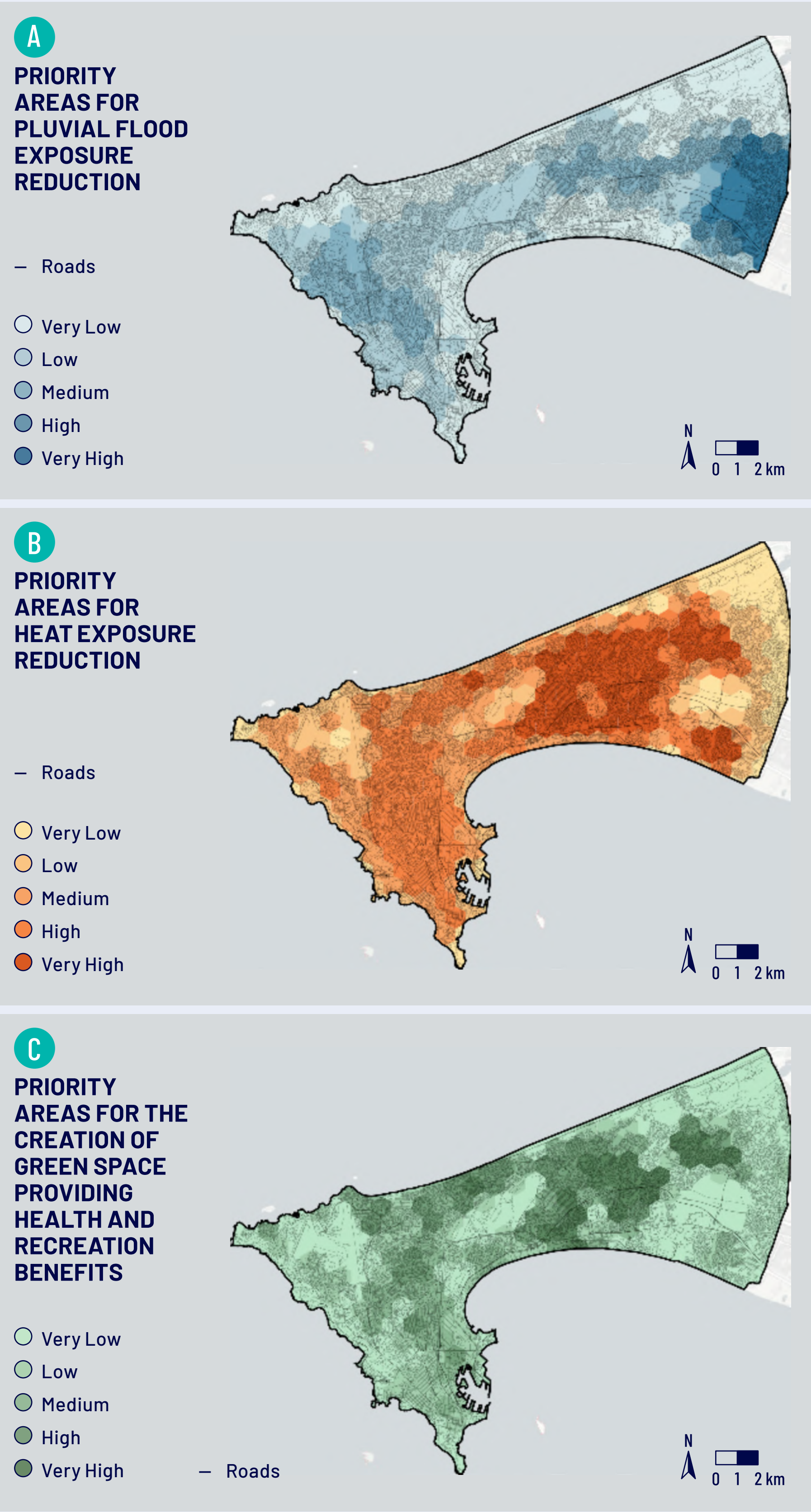
Priority areas for investment within the city are identified by looking at where the resilience and sustainability challenges are most prevalent.

The urban NBSOS assesses where to implement NBS to reduce pluvial flooding; where to mitigate extreme heat; and where there is a need to increase access to green space, which is assumed to provide health, recreation, and social cohesion benefits to communities (map 1).

Exposure to flooding is calculated as a product of population density[4] and annual flood probability based on the Fathom global pluvial flood model (Sampson et al. 2015). Using a 30-meter resolution Digital Elevation Model (FABDEM, no date), a downstream catchment area is determined for each potential NBS location to prioritize areas with the highest flood exposure in its downstream catchment. In the case of heat stress, heat exposure is calculated as the product of population and average annual air temperature based on a global temperature model

4 Population density is calculated using Meta's Resources and tools for advancing AI, available at https://ai.meta.com/resources/.

MAP 1: MAPPING OF PRIORITY AREAS: EXAMPLE MAPS OF NBS PRIORITY AREA IDENTIFICATION ACROSS THE URBAN AREA OF DAKAR, SENEGAL



SOURCE: Original maps for this publication based on NBSOS data.

(Hooker, Duveiller, and Cescatti. 2018). Finally, to define areas lacking green spaces that provide health and recreation benefits, the NBSOS estimates the number of people within each sub-neighborhood that are not within 300 meters of a green space larger than 1 hectare (Konijnendijk 2023), based on the remote sensing derived normalized difference vegetation index (NDVI).

3.1.2

2 STEP 2: MAPPING URBAN NBS SUITABILITY

Suitability maps are created to identify areas for protecting existing greenspaces and areas suitable for creating or constructing new NBS (map 2)

For example, the NBSOS can identify areas with degraded vegetation and determine to what extent that area can be restored by implementing NBS such as green corridors, urban forests, or open green spaces. Areas suitable for creating new NBS are mapped for each NBS type, allowing visualization of each of the selected NBS types at the city level (map 3). The NBSOS looks for opportunities in non-built-up areas. However, box 1 shows an example of a customized NBSOS application in which recommendations of preferred areas for building solutions implementation were provided.

BOX 1

MAPPING POTENTIAL OPPORTUNITIES FOR BUILDING SOLUTIONS

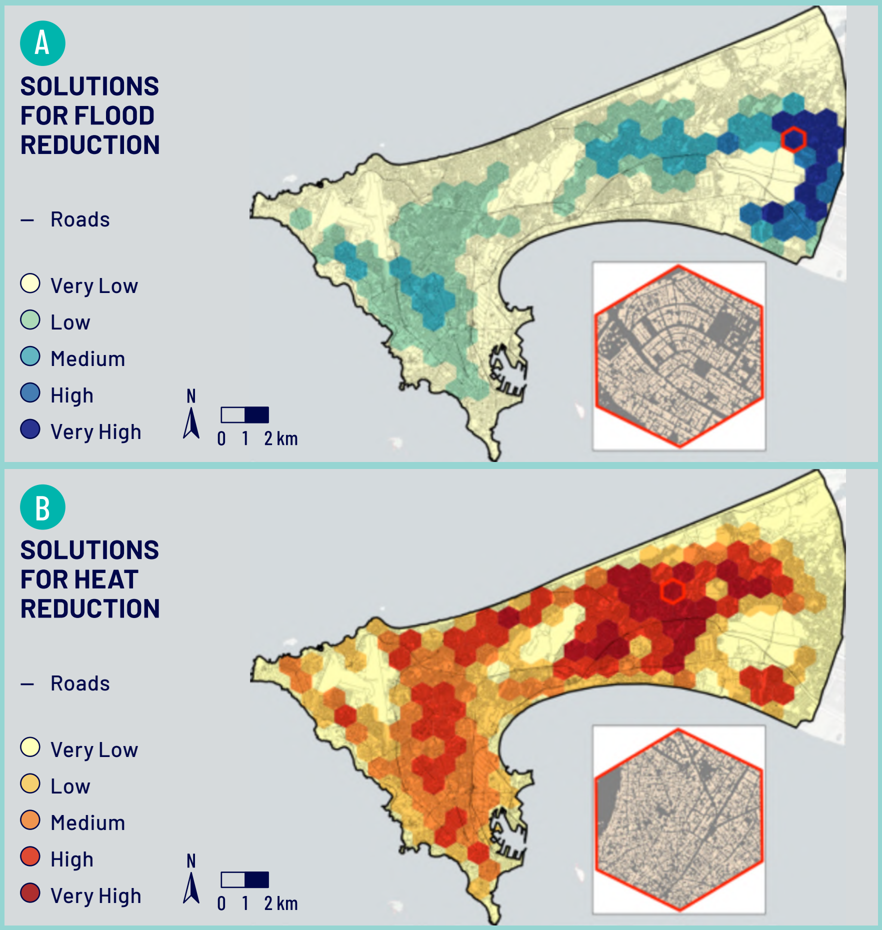
Because of very high urban density and low space availability for other NBS, opportunities for solutions in buildings were studied for the city of Dakar. This is an example of the possibilities of customization when using the NBSOS.

Recommended areas for building solutions are identified combining three criteria: areas with high building density, areas with low opportunities for creating other NBS, and areas with high priority for applying NBS for either flood or heat reduction.

Green roofs and rain barrels are effective to reduce runoff and mitigate flooding downstream. In the "very high" flood reduction potential hexagons (East Dakar), buildings cover, on average, 79 percent of the area. Green roofs and green walls are effective to mitigate heat stress, impacting mutually in the public space and inside buildings. In the "very high" heat potential hexagons (central urban area, buildings cover on average 89 percent of the area.

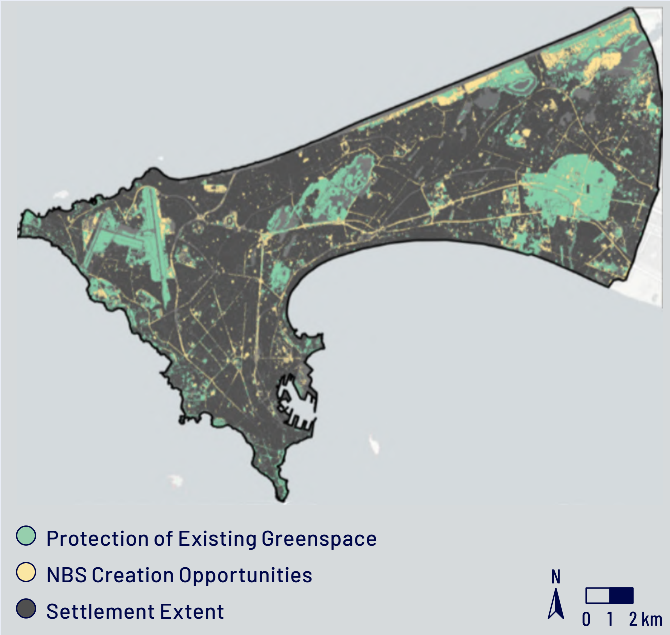
This information can aid decision -makers to decide where to focus incentive programs and engagement campaigns to encourage the development of this type of NBS.

MAP B1: RECOMMENDED AREAS FOR BUILDING SOLUTIONS IN DAKAR, SENEGAL



SOURCE: Original maps for this publication based on NBSOS data.

MAP 2: MAPPING OF NBS SUITABILITY: DAKAR, SENEGAL



SOURCE: Original map for this publication based on NBSOS data.
NOTE: This is an example spatial delineation of currently vegetated regions to protect and suitable areas for the creation of NBS within the urban area of Dakar, Senegal.

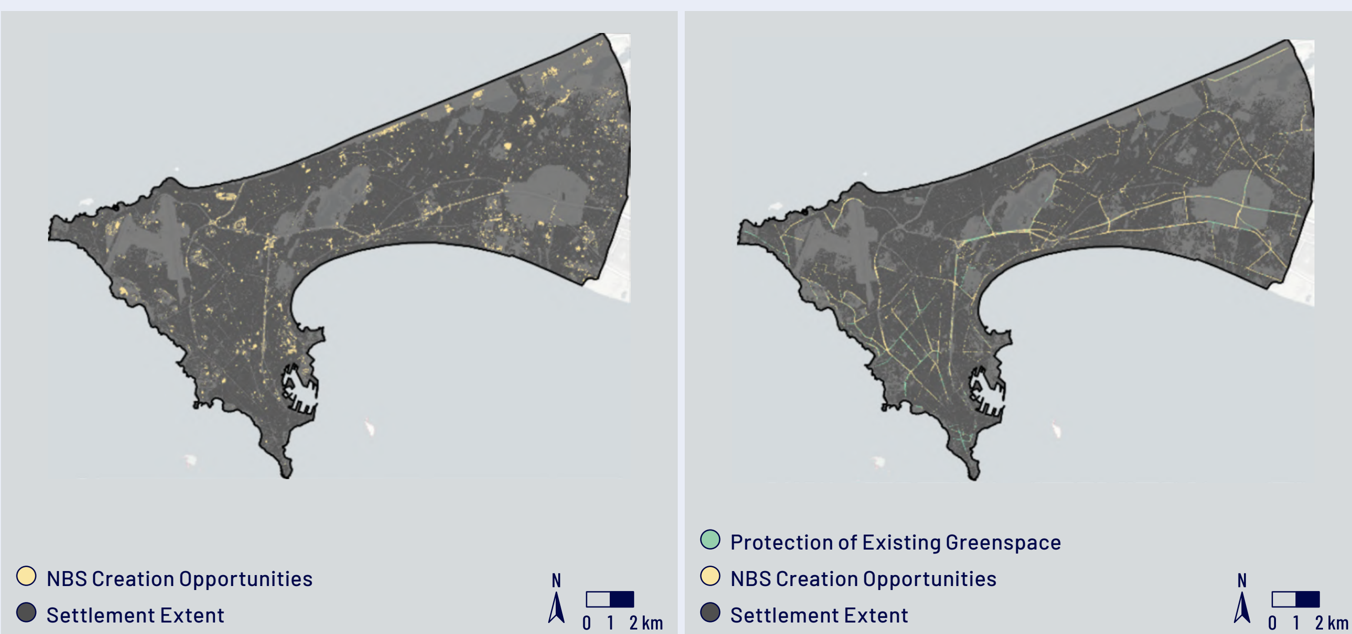
NBS suitability is determined by NBS-type specific rule sets using a diverse set of Earth observation indicators that rely on publicly available data sets with global coverage.

The rule sets are based on indicators that describe soil properties (Earth Engine Data Catalog, no date-f, no date-g); bare soil frequency (Earth Engine Data Catalog, no date-e); surface water frequency (Earth Engine Data Catalog, no date-d); precipitation (Earth Engine Data Catalog, no date-a); slope (FABDEM, no date); land capability (Sentinel-2 timeseries) (Earth Engine Data Catalog, no date-e, no date-c); land cover (Earth Engine Data Catalog, no date-b, no date-c) and distance to roads; buildings, and water bodies (OpenStreetMap contributors 2024).

MAP 3: MAPPING OF NBS SUITABILITY, DAKAR, SENEGAL

A OPEN GREEN SPACES

B GREEN CORRIDORS



SOURCE: Original map for this publication based on NBSOS data.
NOTE: Example of suitable areas for creating new NBS are mapped for open green spaces and green corridors within the urban area of Dakar.

3.1.3

3 STEP 3:
MODELING NBS BENEFITS IN CITIES

The NBSOS applies index-based valuation of flood reduction benefits, heat reduction benefits, and health and recreation benefits that are expected when the NBS is implemented.

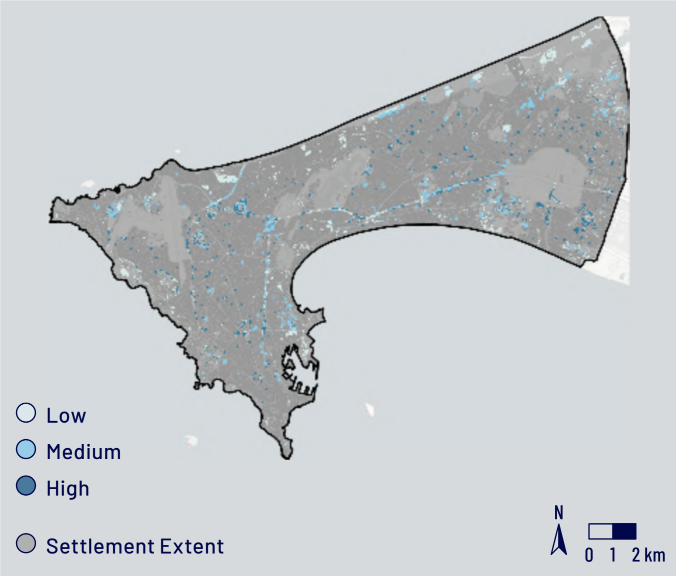
Optionally, these benefits can be complemented with a qualitative score (high-medium-low) for other benefits as defined in the *Catalogue of Nature-Based Solutions for Urban Resilience* (World Bank 2021). These benefits describe the positive impact of the selected types of NBS interventions addressing climate resilience and sustainability challenges in the specific city being considered. The NBSOS estimates these benefits for all the suitable areas and for each NBS family, as identified in Step 2.

To demonstrate the benefits in a spatially explicit way, the models described in Step 1 are utilized to estimate the three main benefits. For instance, the spatial flood mitigation model is used to measure the area in the city where NBS have the highest potential to reduce the exposure of people to stormwater flooding. The heat model estimates the effect of NBS families on air temperature and how many people near the NBS benefit from this cooling effect. Finally, the health, recreation, and social interaction benefits of the NBS are estimated by counting the additional population that has access to green space within 300 meters of their homes. The results are presented per NBS as the number of hectares providing high, medium, and low levels of benefit, and are displayed on the map (map 4). This helps to demonstrate which NBS families will yield the most benefits and where to implement them to maximize those benefits.

MAP 4: MAPPING OF OPEN GREEN SPACE BENEFITS, DAKAR, SENEGAL

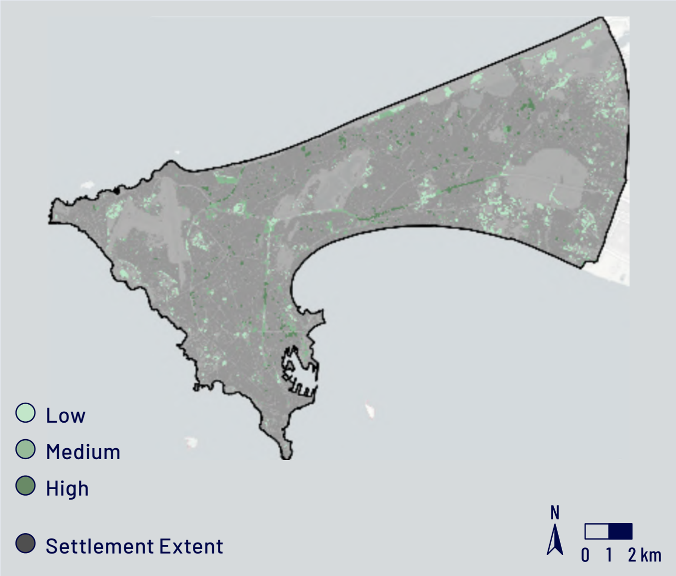
A

REDUCING PLUVIAL FLOOD EXPOSURE



B

IMPROVING RECREATION/HEALTH VIA ACCESS TO GREEN SPACES

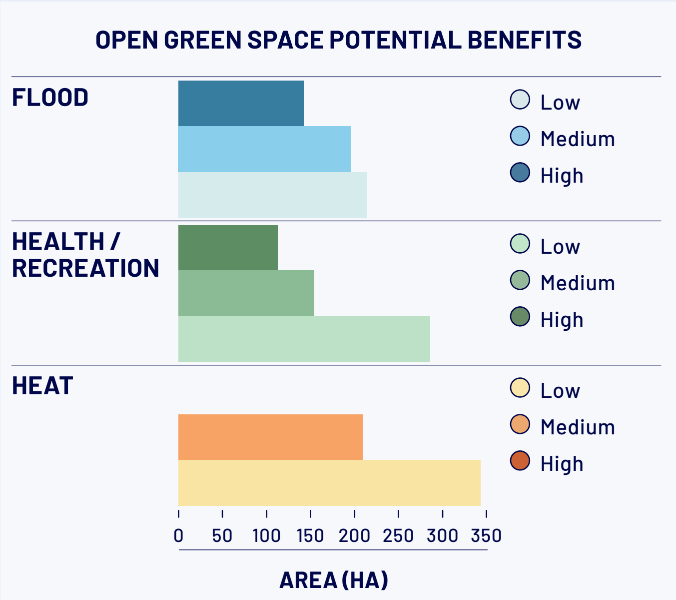


C

REDUCING HEAT STRESS EXPOSURE

D

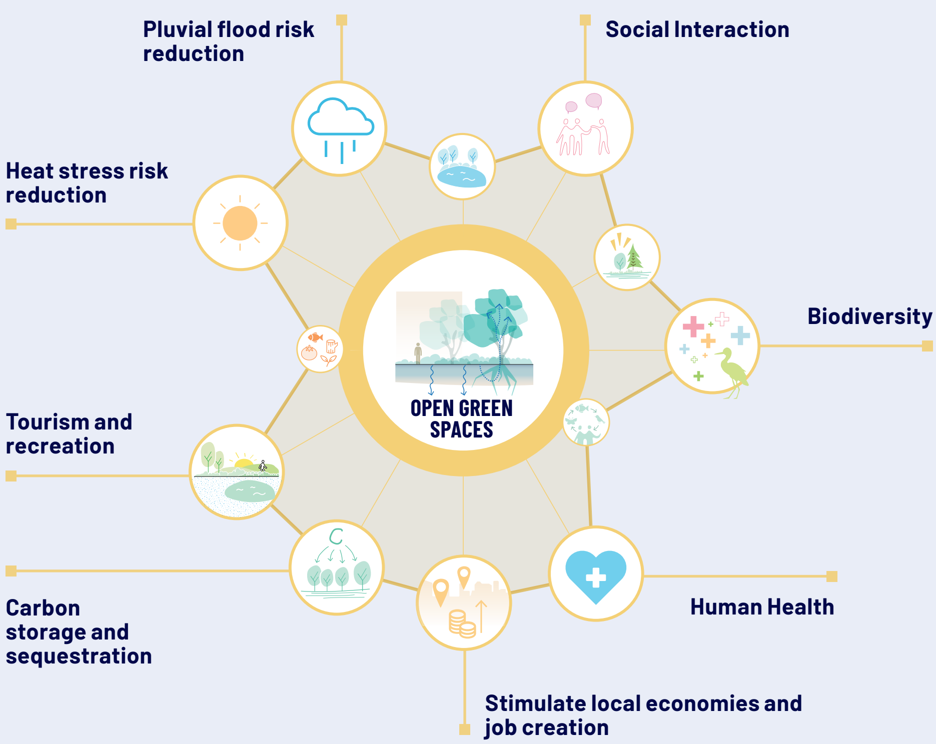
OPEN GREEN SPACE POTENTIAL BENEFITS



SOURCE: Original maps and figure for this publication based on NBSOS data.
NOTE: This is an example of spatial variability in the potential benefits from the creation of open green spaces for reducing pluvial flood exposure, improving recreation/health via access to open green spaces, and reducing heat stress across the city.

Other benefits of NBS—such as resources production and biodiversity (figure 5)—can be valued using a land use matrix-based valuation approach (Burkhard et al. 2012), linking NBS families defined in the *Catalogue of Nature-Based Solutions for Urban Resilience* to a qualitative score of 1 (low) to 3 (high). These benefits are added to the three spatially modeled benefits (flood reduction, heat reduction, and health and recreation/social interaction) on a case-by-case basis, depending on their local relevance.

FIGURE 5: BENEFITS PROVIDED BY OPEN GREEN SPACES



SOURCE: World Bank 2021.

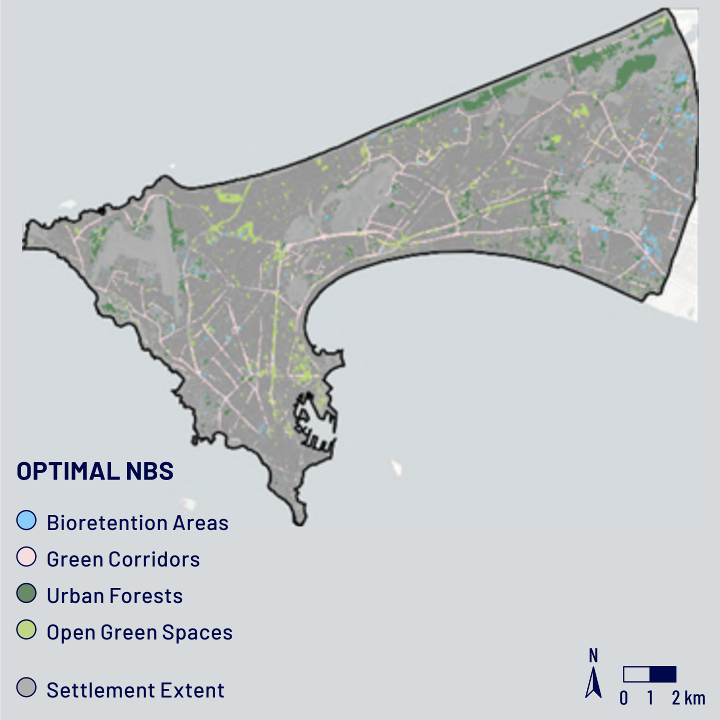
3.1.4

4 STEP 4:
DECISION SUPPORT FOR URBAN NBS

As a final step, NBS investment opportunity areas, based on a spatial multicriteria analysis, are suggested.

In practice, areas suitable for creating or constructing NBS interventions—such as urban forests, open green spaces, and urban agriculture—overlap. However, each of these NBS interventions will provide different benefits. Urban forests have a high canopy density and will be effective in reducing heat, while open green spaces can be designed for water storage and reduce flooding. By assigning weights to the different benefits (for example, assigning a higher weight to the flood reduction potential when that is more important than reducing heat), NBS that compete for space can be prioritized in areas that are exposed to multiple hazards and resilience challenges. The NBSOS prioritizes those areas that are most effective in delivering the selected benefits (map 5). Potential investment scenarios can be developed from this optimization exercise—for instance, by choosing the NBS delivering the highest 20 or 10 percent of combined benefits.

MAP 5: OPTIMIZATION USING MULTICRITERIA ANALYSIS, DAKAR, SENEGAL



SOURCE: Original map for this publication based on data from the NBSOS.
NOTE: This is an example of scan outputs describing the spatial variability in optimal NBS solutions. Optimal solutions were determined by combining weighted normalized benefits from pluvial flood exposure reduction (60 percent), heat stress reduction (20 percent), and improved health/recreation (20 percent). The optimal solution describes the NBS type providing the highest level of combined benefits for each pixel.

3.1.5
URBAN NBSOS VALIDATION

A validation exercise was performed to validate inputs and outputs of the NBSOS pluvial flood assessment and related recommendations.

The NBSOS uses flood hazard from a global model (Sampson et al. 2015) to define where urban areas get flooded and, based on this, where to implement NBS to reduce pluvial flooding. Flood hazard data have a high impact on the definition of priority areas for NBS implementation for flood reduction and on the assessment of the level of benefits obtained from the proposed solutions. Therefore, it was essential to understand the agreement between the Fathom flood maps (Fathom 2019, 2023; Sampson et al. 2014) and flood hazard maps prepared using locally sourced data. In addition, a key issue for the NBSOS was to verify the priority areas for flood reduction

NBS through comparison with a local high-resolution flood modeling study. Finally, the NBSOS estimated degradation levels of urban greenspaces to classify areas as protection areas (low degradation) and creation areas (high degradation). The last validation objective was to compare NBSOS results on protection and creation with solutions proposed by the local study.

The results from the validation exercise showed that, despite some difference in accuracy between the global model and the local one, the main hazard characteristics are captured and factored in the NBSOS. Moreover, the use of an updated version of this model (Fathom v3; see Fathom 2023) shows great improvement in resolution and accuracy, which will be reflected in the accuracy of future NBSOSs.

Regarding NBSOS outputs, despite the huge difference in terms of resolution and accuracy between the inputs used by the NBSOS (global and low-resolution data) and those used by the local study (in-situ and high-resolution data), the NBSOS can correctly identify the main hotspots for implementing NBS for flood risk reduction, and it is also able to make recommendations for NBS creation and protection similar to those of the local study. The NBSOS is able to provide a direction early on, before the application of more expensive and time-consuming studies, which could deliver more accurate results.

River renaturation
©Arun antony on Unsplash

3.2
THE COASTAL NBS OPPORTUNITY SCAN

The different components, data, processes, and results of the four methodological steps for applying the NBSOS in coastal areas are summarized in figure 6.

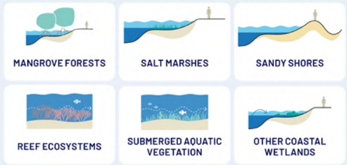
Each of these steps is explained in the sections below. A detailed description of the methodology is provided in appendix B. The coastal NBSOS is described in this section uses the example of Viti Levu, the largest island in Fiji. The main methodological differences between the urban and the coastal NBSOSs are that the coastal version assesses coastal NBS over a 30-year period, considering ecosystem degradation, climate change and socioeconomic development, while the urban NBSOS does not consider the evolution of benefits over time. Also, in contrast to the urban NBSOS, the coastal version presents a cost-benefit analysis for the interventions, while the urban NBSOS assesses trade-offs between NBS types using multicriteria analysis.

FIGURE 6: COMPONENTS, DATA, PROCESSES, AND RESULTS COMPRISING THE FOUR STEPS FOR APPLYING THE NBSOS IN COASTAL AREAS

STEP 1 UNDERSTANDING THE PROBLEM

HAZARDS	INPUT DATA	GIS PROCESSING	OUTPUT RESULT
COASTAL FLOODING	• Bathymetry • Topography • Land Use • Sea Level Rise • Waves • ESLs • Population Density • Building Footprint	SFINCS Coastal Flood Modeling	Coastal Flood Exposure Maps

STEP 2 MAPPING NBS SUITABILITY

NBS FAMILIES	INPUT DATA	GIS PROCESSING	OUTPUT RESULT
	• Currents NBS Extent • Bathymetry • Climate Trends • Land Cover • Land Use • Greenness • Bare Soil Frequency	NBS Suitability Mapping	NBS Suitability Maps

STEP 3 MODELING NBS BENEFITS

BENEFITS	INPUT DATA	GIS PROCESSING	OUTPUT RESULT
Coastal Flood Reduction	• Coastal Flood Exposure Maps • NBS Suitability Maps	Flood Exposure Reduction Model	Avoided Damage from NBS Maps
Carbon Sequestration and Storage	• Mangrove C Emission Factor • Mangrove Suitability Maps	Mangrove Extent Carbon Cost Model	Carbon Storage & Sequestration Benefits Maps
Tourism and Recreation	• Annual Tourism Data • Beach and Hotel Location	Economic Beach Valuation Model	Tourism Benefits Maps
Fisheries and Raw Materials	• Ecosystem Service Database • NBS Suitability Maps	Ecosystem Extent Valuation Model	Fisheries/Materials Benefits Maps

STEP 4 DECISION SUPPORT

BENEFITS	INPUT DATA	GIS PROCESSING	OUTPUT RESULT
Restoration Costs	• Cost Databases NBS Suitability Maps	Calculation of Benefit-to-Cost ratio for Each Project	Benefit-to-Cost Ratio Maps
Ecosystem Benefits	• Benefits from Step 3 NBS Suitability Maps		

SOURCE: Original figure for this publication.
NOTE: GIS = geographic information systems; NBS = nature-based solutions; NBSOS = Nature-Based Solutions Opportunity Scan; SFINCS = Super-Fast INundation of CoastS.

ES
1
2
3
4
5
6
A1
A2

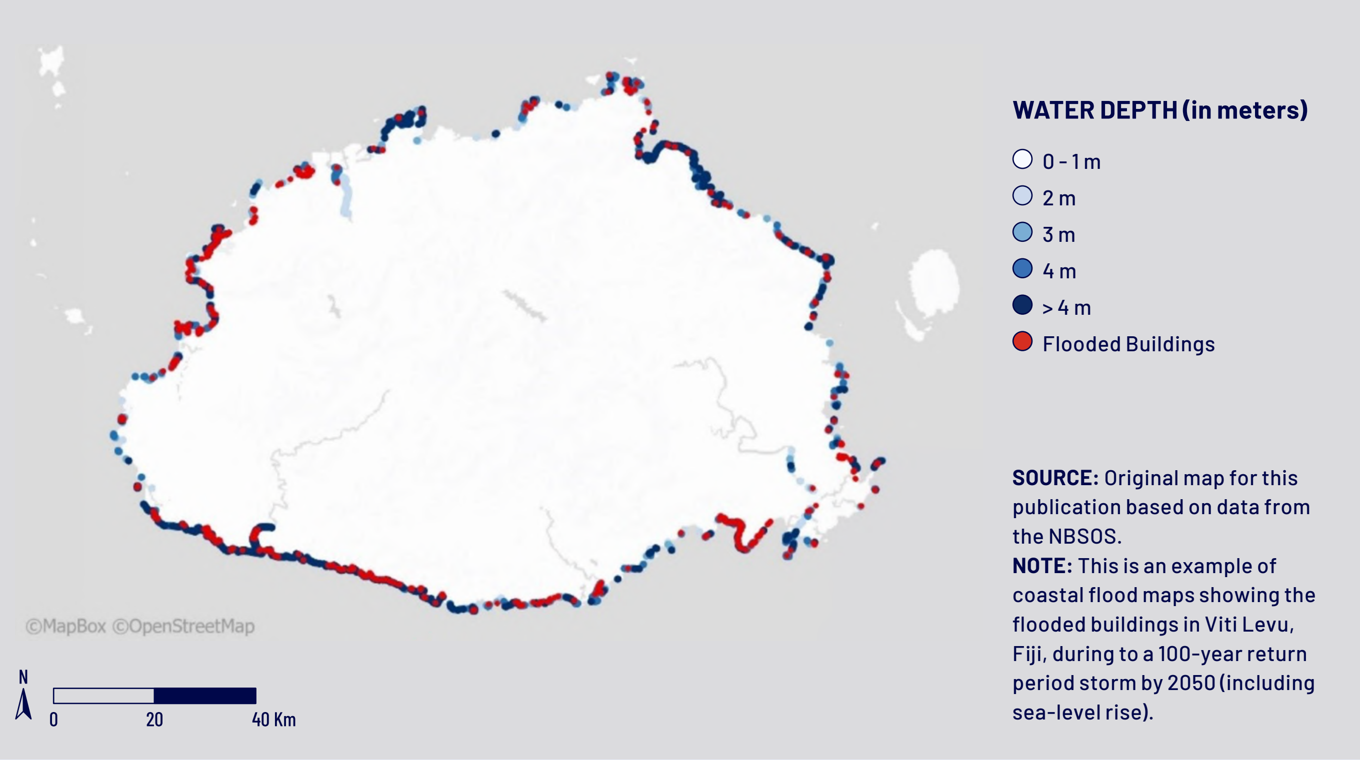
3.2.1

1 STEP 1:
UNDERSTANDING COASTAL RESILIENCE CHALLENGES

Using the hydraulic model Super-Fast Inundation of CoastS (SFINCS; Leijnse et al. 2021), coastal flood extent and flood depth is modeled for the baseline scenario and for a 2050 scenario, which considers sea-level rise and increasing storm intensity due to climate change. The hydraulic model accounts for several effects: extreme surge levels, wave set-up, run-up for different return periods (10, 50, 100 and 500 years), and the increase in water level due to sea-level rise (by 2050). The model uses as input a digital elevation model (Hawker et al. 2022);[5] land use, extreme waves, and water levels (Hersbach et al. 2018); and the rates of sea-level rise for future scenarios (IPCC 2021). The model output is a flood map showing inundated locations and the local water depth with a spatial resolution of 30 meters.

Structural flood damages to buildings are estimated overlaying flood extent and depth overlaying flood maps with datasets of population (FCL and CIESIN 2016) and building footprints (Google Research, no date; Sirko et al. 2021) for each return period. This step returns maps with flooded population and assets during coastal storm events, now and in future scenarios, considering sea-level rise. To illustrate areas most exposed to coastal flooding, the NBSOS shows the exposure of coastal buildings to a 100-year return period coastal flood event under 2050 conditions. An example for Viti Levu, Fiji, is displayed in map 6.

MAP 6: MAPPING COASTAL FLOODING, VITI LEVU, FIJI



SOURCE: Original map for this publication based on data from the NBSOS.
NOTE: This is an example of coastal flood maps showing the flooded buildings in Viti Levu, Fiji, during to a 100-year return period storm by 2050 (including sea-level rise).

5 The database used for the Digital Elevation Model is available at https://data.bris.ac.uk/data/dataset/s5hqmjcdj8yo2ibzi9b4ew3sn.

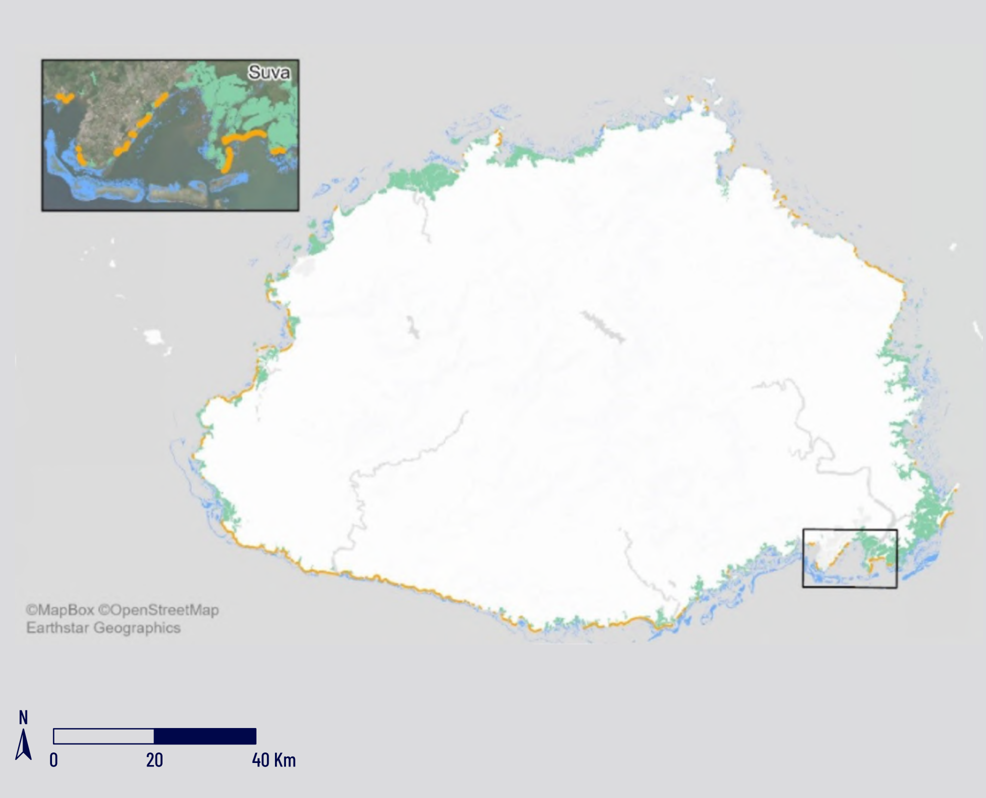
3.2.2

2 STEP 2: MAPPING COASTAL NBS SUITABILITY

Globally available geospatial data sets are used to map the baseline extent of coastal ecosystems, such as mangroves (Bunting et al. 2022), coral reefs (Lyons et al. 2020), and beaches (Google Earth 2023).

The result shows the current extent of key coastal ecosystems that function as nature-based solutions for climate resilience (the example of Viti Levu is shown in map 7). The coastal NBSOS uses a specific subset of coastal NBS types derived from the long list provided in figure 3.

MAP 7: EXTENT OF COASTAL ECOSYSTEMS, VITI LEVU, FIJI



NBS CURRENT EXTENT

- Mangroves
- Coral reefs
- Beaches

SOURCE: Original map for this publication based on data from the NBSOS.
NOTE: This is an example of the baseline extent of key coastal ecosystems that function as nature-based solutions for climate resilience as of 2022 in Viti Levu, Fiji.

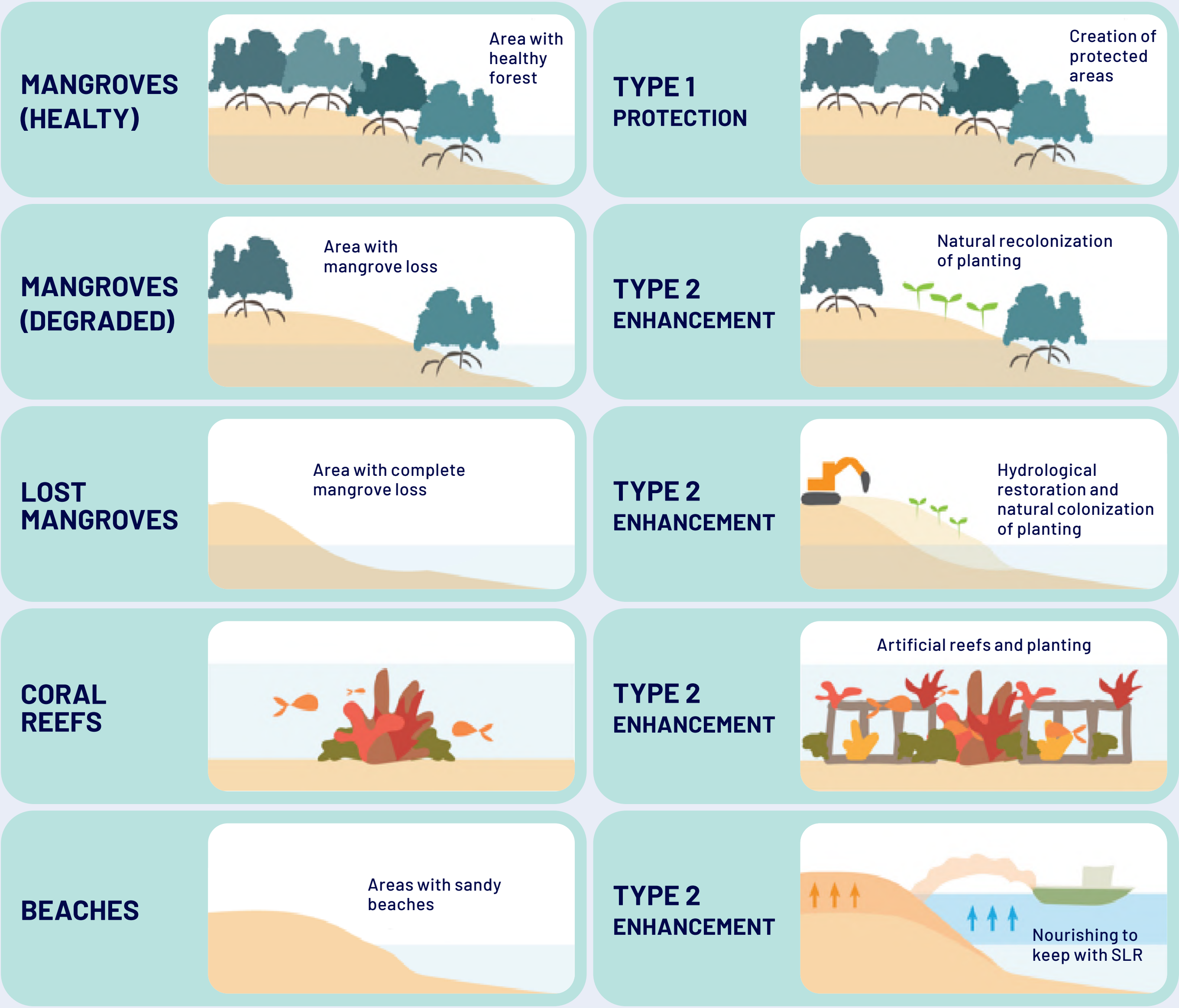
For mangroves, the NBSOS identifies two types of interventions: (1) protection of mangroves by protecting areas where they exist today and remain healthy, and (2) enhancement of mangroves (figure 7). Protection is preventing degradation or loss of mangrove extent. Enhancement could occur at locations where mangroves exist at present but are sparse, or at locations where mangroves may have existed in the past but do not at present, and where environmental conditions may be favorable for their restoration. These interventions could occur at sites within 100 meters of existing mangroves and at most 100 meters inland from the coastline, capturing intertidal areas currently without mangrove cover.

For coral reefs, potential enhancement sites are identified based on the presence of coral reefs in shallow water areas close to shore—between the shoreline and a water depth of 3 meters—since these areas are most effective for flood reduction

purposes. Coral reef enhancement interventions in NBSOS should have a measurable coastal protection or adaptation outcome. They are understood as interventions that reduce the water levels on the reef and attenuate waves, thereby protecting coastal assets. In most cases, such coral reef interventions would be hybrid solutions, combining artificial structures with reef restoration (Jongman et al. 2021). Coral reef presence is identified using global coral reef extent data from the Allen Coral Atlas.

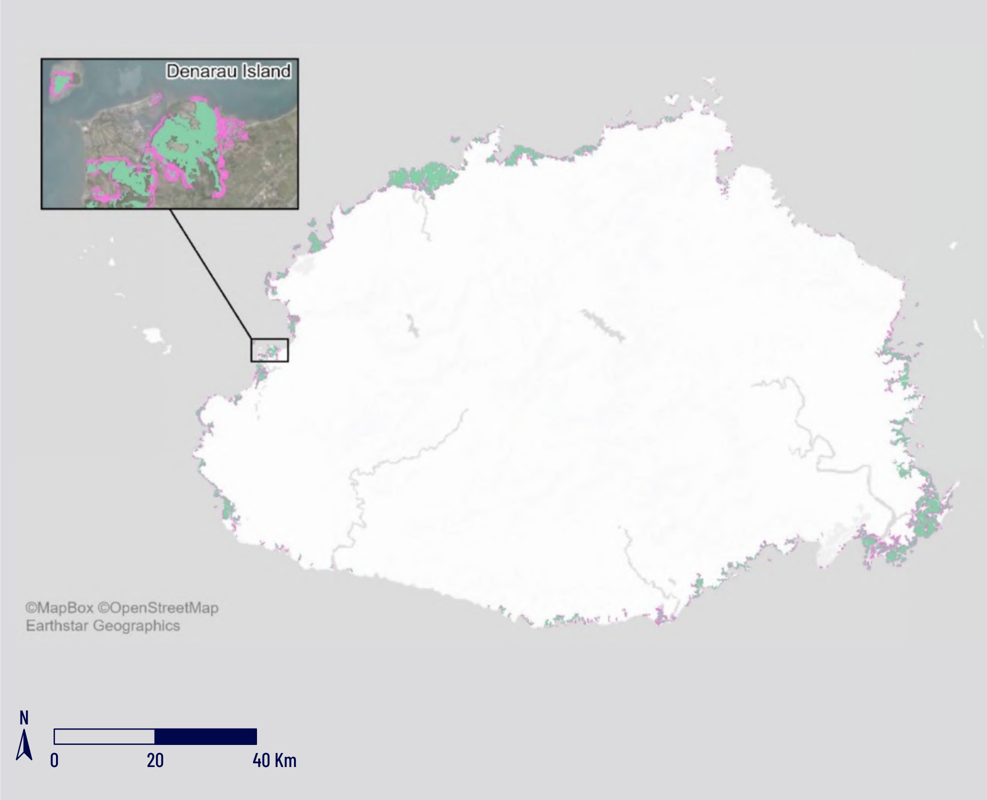
For the NBSOS, the GPNBS team manually interprets and digitizes sandy beaches based on the Google Earth imagery as a comprehensive globally available data set is not available. NBS interventions on beaches include the conservation of beaches so that they can keep their relative height with respect to rising sea levels, thus protecting their function for coastal protection and for tourism. In practice, this intervention will often require beach nourishments, which should be conducted in a sustainable way to avoid negative environmental impact (figure 7).

FIGURE 7: NBS TYPES AND INTERVENTIONS CONSIDERED IN THE COASTAL NBSOS



SOURCE: Original figure for this publication.

MAP 8: OPPORTUNITIES FOR MANGROVES, VITI LEVU, FIJI



SOURCE: Original map for this publication based on data from the NBSOS.
NOTE: This is an example map of possible NBS interventions for mangrove ecosystems (mangrove areas to protect and potential areas for mangroves rehabilitation) in Viti Levu, Fiji.

3.2.3

3 STEP 3:
MODELING NBS BENEFITS AND ESTIMATING COSTS IN COASTAL AREAS

The benefits and costs of coastal NBS are valued by comparing the baseline situation to future scenarios in which the extent and condition of NBS is expected to change as a result either of degradation by anthropogenic action or of enhancement by NBS interventions (map 8).

In those future scenarios, looking at the situation in 2050, the NBSOS accounts for projected sea-level rise, anticipated economic and demographic growth in coastal zones, expected ecosystem degradation, and potential effect of ecosystem enhancement by NBS. To value each coastal NBS individually, there is a comparison of scenarios where only one type of ecosystem is enhanced while the others degrade.


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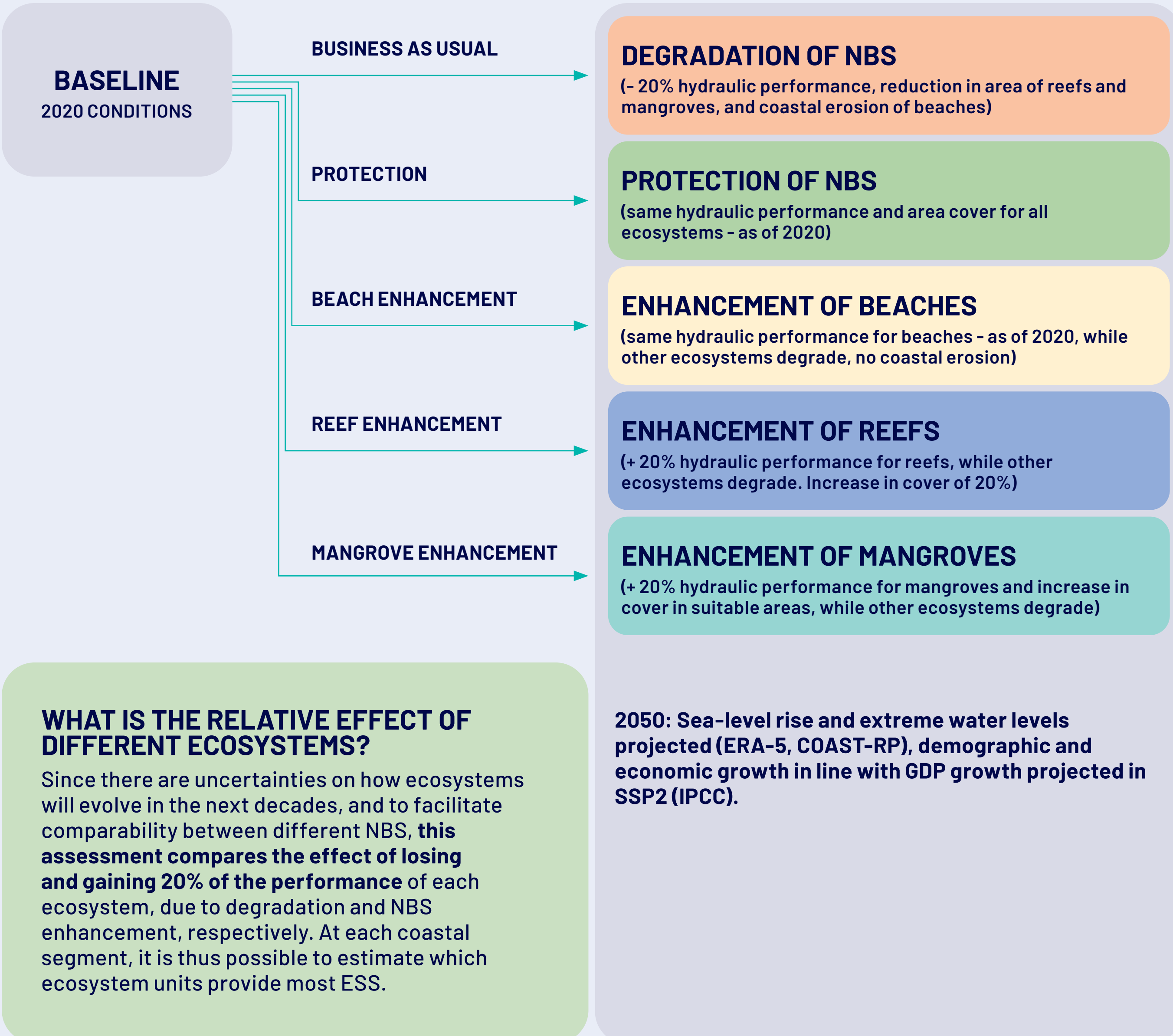
FIGURE 8: DESCRIPTION OF NBS SCENARIOS USED IN THE BENEFITS ASSESSMENT



WHAT IS THE RELATIVE EFFECT OF DIFFERENT ECOSYSTEMS?

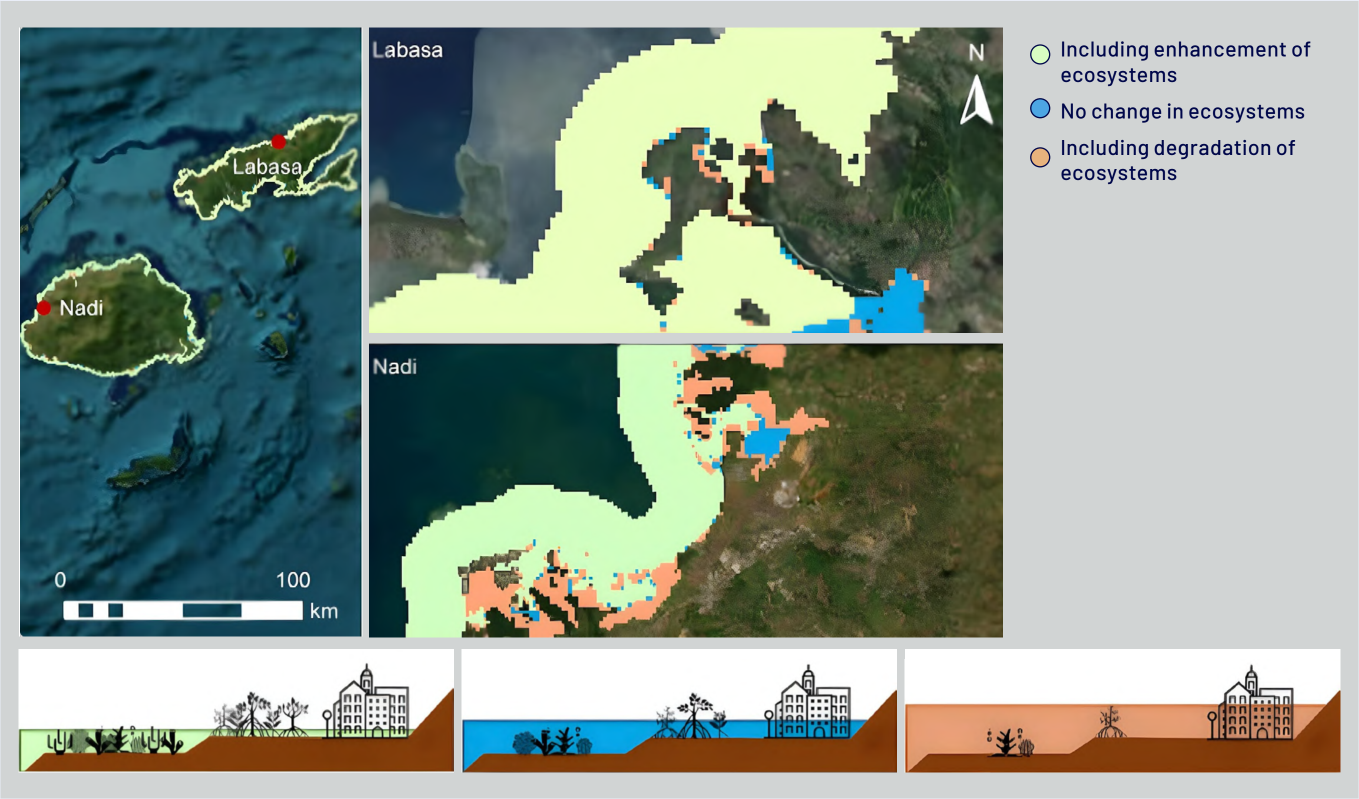
Since there are uncertainties on how ecosystems will evolve in the next decades, and to facilitate comparability between different NBS, **this assessment compares the effect of losing and gaining 20% of the performance** of each ecosystem, due to degradation and NBS enhancement, respectively. At each coastal segment, it is thus possible to estimate which ecosystem units provide most ESS.

SOURCE: Original figure for this publication.

FLOOD RISK REDUCTION BENEFITS

Annual expected damages from coastal flooding are estimated using a probabilistic flood risk assessment. Building on the inundation maps developed with the SFINCS model and building on the flood exposure analysis described in Step 1, annual direct damages to buildings are calculated (see appendix B for specifications) due to coastal flooding. Avoided damages as a result of the presence of coastal NBS are estimated for the scenarios presented in figure 8, expected damages between the scenarios. Map 9 shows a graphical representation of the modeled inundation of coastal areas for different NBS scenarios.

MAP 9: COASTAL FLOOD RISK REDUCTION OF NBS, VITI LEVU AND VANUA LEVU, FIJI



SOURCE: Original map for this publication based on data from the NBSOS.
NOTE: This is an example map of a flood event caused by a 100-year storm in 2050 for different scenarios of landscape change between 2020 and 2050 in Viti Levu and Vanua Levu, Fiji.

TOURISM, LIVELIHOODS, AND CLIMATE MITIGATION BENEFITS

In addition to the flood and climate risk reduction benefits of coastal NBS, they provide other critical benefits for development, including solid contributions to nature-based tourism, food security, and climate mitigation. For coral reefs and mangroves, estimations from the Ecosystem Services Valuation Database (Brander et al. 2023; ESVD, no date) are used in regression analyses to estimate functions that relate the value of fisheries (for mangroves and tourism) and tourism (only for coral reefs) services to the characteristics and context of the site. These functions are applied to predict location-specific benefits while considering size of the ecosystem, the population density of the area, and the income of the beneficiaries.

The value of beach conservation for tourism is estimated using the sum of tourists' willingness to pay for beach nourishment, plus a share of the added value of hotel and accommodation revenues. The NBSOS distributes the tourism value of beaches using the beach visitation function, based on the distance of beaches to hotels. The hotel locations are obtained from Booking.com. For the NBSOS, beach tourism values are quantified using local tourism data on number of tourists and average duration of stay; these data usually come from the country's department of tourism.

Blue carbon sequestration benefits are estimated for enhanced or restored mangrove areas. Computation of additional carbon sequestration from NBS multiplies the cumulative additional mangrove area by a representative carbon sequestration rate per unit area of 6.3 tonnes of carbon dioxide per hectare per year (CO_2/ha/year). Carbon stored per year are valued economically using the social cost of carbon (SCC), which is the monetary value of damages caused by emitting 1 more tonne of CO_2 in a given year.

Estimations of the per hectare costs of mangrove restoration are obtained from Bayraktarov et al. (2016) and Su, Friess, and Gasparatos (2021); estimations of the costs of coral reef restoration are obtained from Bayraktarov et al. (2016). For both coral reef restoration and mangrove restoration, regression analysis is used to adjust cost estimations of restoration per unit area to local PPP per capita GDP. The cost of beach nourishment is obtained from Spencer, Strobl, and Campbell (2022).

3.2.4

4 STEP 4: DECISION SUPPORT FOR COASTAL NBS

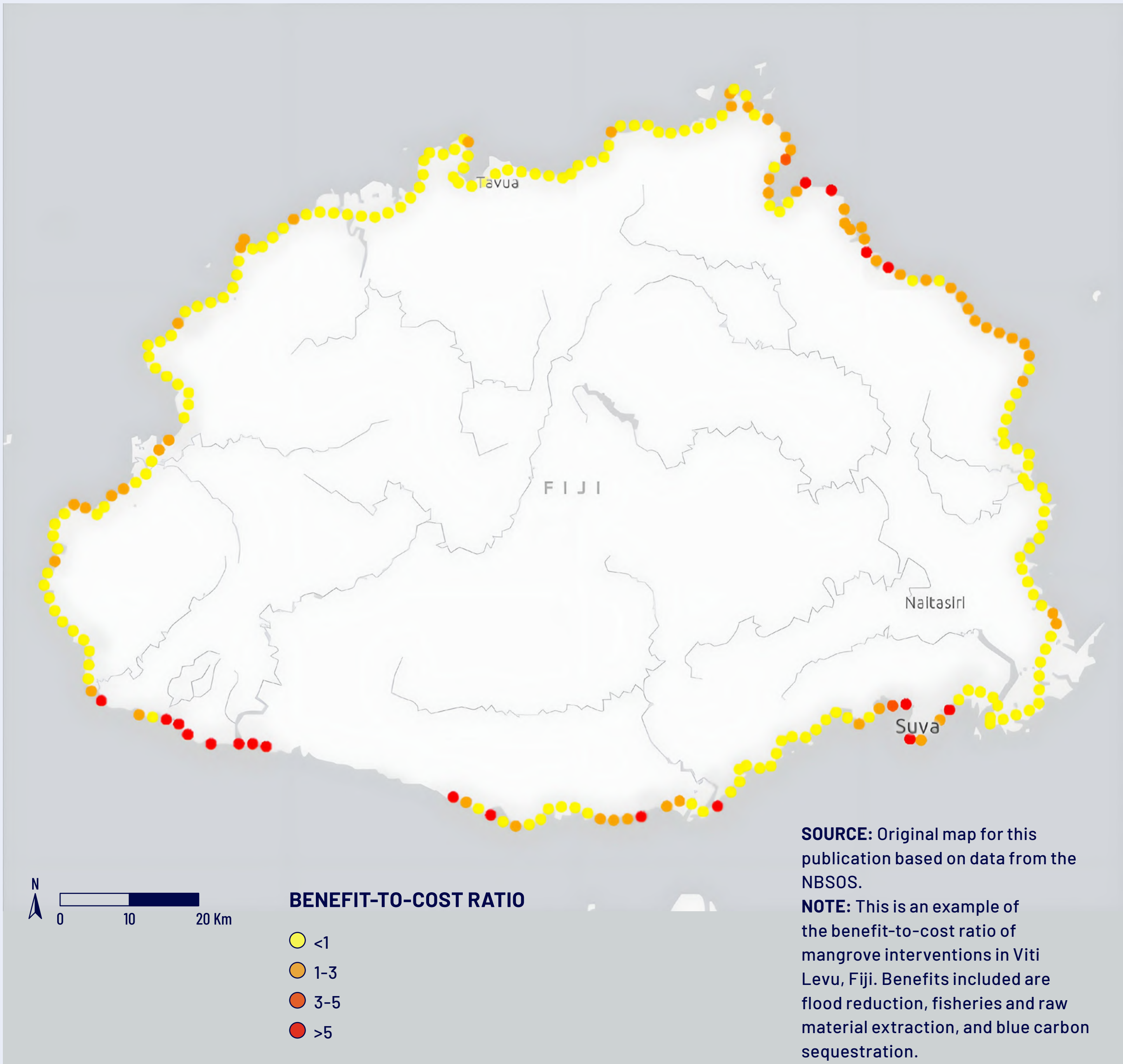
The cost-benefit analysis gives a first indication of the economic viability of investing in NBS for coastal climate resilience and its spatial variation across the area of interest.

In the cost-benefit analysis, all benefits and costs are expressed as present value, discounted over a 28-year project lifetime. In the output of the NBSOS, the costs and benefits are expressed per hectare for mangroves, per square meter for beach conservation, and per linear meter for coral reef interventions.

Seychelles
©Hashimoto

The NBSOS shows the results of the cost-benefit analysis in a spatially explicit way to guide Task Teams and clients what are potentially viable locations to invest. Benefit-to-cost ratios, which are obtained by dividing the sum of all benefits by the costs, are calculated and mapped per 2-kilometer coastal section. A benefit-to-cost ratio of >1 indicates a positive return on investment. This, as shown in map 9, helps to identify the most viable interventions within a country considering the integrated value of flood reduction and other benefits such as increases to fisheries, carbon sequestration, and tourism.

MAP 9: BENEFITS AND COSTS OF NBS, VITI LEVU, FIJI

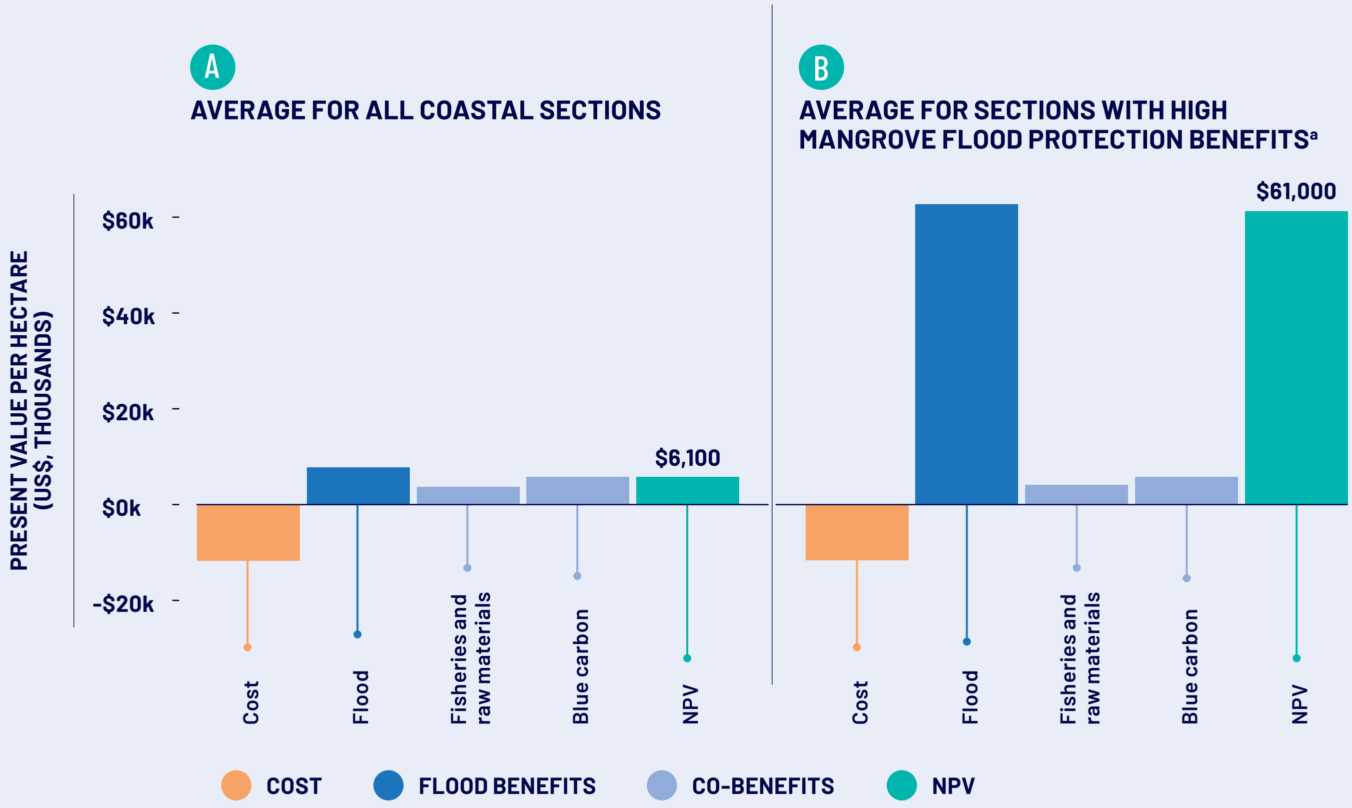


SOURCE: Original map for this publication based on data from the NBSOS.
NOTE: This is an example of the benefit-to-cost ratio of mangrove interventions in Viti Levu, Fiji. Benefits included are flood reduction, fisheries and raw material extraction, and blue carbon sequestration.

The contribution of flood protection, fisheries, and carbon sequestration benefits to the overall benefit-cost ratio varies across coastal sections (figure 9).

Figure 9 panel b shows that, on average, mangrove restoration has a positive net present value, but that most of the flood protection value is concentrated in 46 sites with a high coastal flood risk reduction value. At these sites, most flood damage can potentially be avoided, while other benefits or ecosystem services are also provided.

FIGURE 9: BENEFITS AND COSTS OF MANGROVE INTERVENTIONS PER HECTARE (PRESENT VALUE) IN VITI LEVU



SOURCE: Original figure for this publication.
NOTE: NPV = net present value.
a. These are the 46 sections in Viti Levu with 20 percent highest flood protection.

This cost-benefit analysis represents the first screening to support strategic planning and site prioritization.

As the NBSOS runs on global data sets, there is uncertainty in both cost and benefit estimations at different levels. Hence, further studies are needed to test concept designs and to understand the feasibility of potential investments in coastal NBS for climate resilience.

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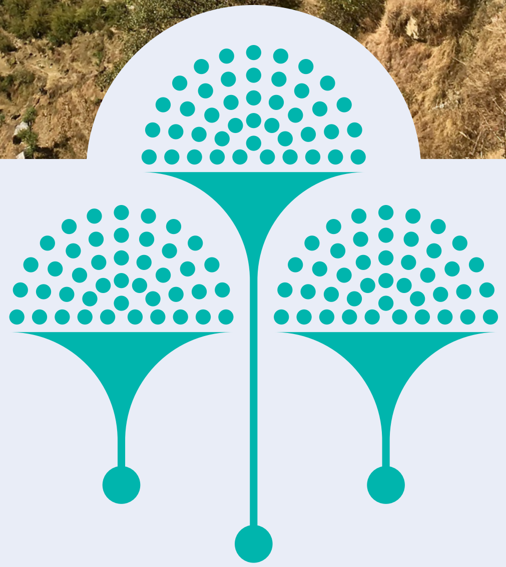
4

HOW IS THE NBSOS INFORMING DEVELOPMENT FINANCE?



The NBSOS was successfully implemented in 20 countries between 2022 and April 1, 2024, including in coastal landscapes in 8 countries and in 51 cities across 14 countries

(table 1).

In 14 of the applications, the NBSOS was used to identify investments in NBS for climate resilience for an IPF operation. The combined financing committed to these 14 operations amounts to $2.3 billion; a share of this financing amount will likely be allocated to NBS for climate resilience. In several other countries—such as India, Sri Lanka, Thailand, and Timor-Leste—the NBSOS has been used to inform the dialogue on NBS with the government upstream through advisory services and analytics (ASAs). In addition, in Belize, the Eastern Caribbean countries, Senegal, Sri Lanka, and the West-Bank and Gaza, the NBSOS was used to estimate investment needs in NBS for adaptation for their respective Country Climate and Development Reports (CCDRs),[6] integrating NBS in the economies' long-term strategies for climate adaptation.

6 Information about the Country Climate and Development Reports can be found at https://www.worldbank.org/en/publication/country-climate-development-reports.

In May 2022, the urban NBSOS was used to inform the N'Djamena Urban Resilience Project—a $150 million International Development Association (IDA) investment project—by identifying the areas in which NBS contribute to climate resilience and reduce exposure of vulnerable populations to flooding and extreme heat. The NBSOS estimated NBS investment opportunity areas for urban parks and forests, urban agriculture, green corridors, and river floodplain measures. For urban parks and forests, the NBSOS identified nearly 400 hectares of investment opportunity areas contributing to a reduction of pluvial flood exposure, while 285 hectares were identified where urban parks and forests would reduce exposure to extreme heat. The findings of the NBSOS in N'Djamena have been integrated as investment options in (pre-)feasibility studies for drainage infrastructure and solid waste investment. Furthermore, the project will aim to expand and consolidate a virtuous cycle for the resilience of green local initiatives already present in the city, such as urban agriculture, local food markets, production organic composting, and tree nurseries. Finally, following the NBSOS, the project is measuring its results in terms of successful NBS, tracking the percentage of the population living within a 2-kilometer radius of an effective NBS for climate resilience.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In St. Lucia, an integrated coastal and urban NBSOS was used to assess investment needs in NBS for adaptation for the CCDR and to support the identification of NBS investments options for the forthcoming St. Lucia Flood Risk Project (table 1). The NBSOS identified potential investments in NBS to mitigate pluvial and fluvial food as well as extreme heat in the towns Castries and Anse La Raye, the area of interest of a new IPF $20 million operation. Forty hectares were found to be potentially suitable for a flood detention area or as an urban park with a water storage function, while 50 hectares of green corridors were mapped with the potential to highly reduce the exposure of people to extreme heat. After GPNBS held an NBS workshop in September 2023, the World Bank received a request to finance a new investment operation on flood risk reduction in St. Lucia, likely with a component on nature-based flood management interventions complementing gray infrastructure investment. The coastal NBS, which informed the CCDR, estimated spatially explicit benefit-cost ratios of potential investment in beach conservation and nourishment, mangroves, and coral reefs to protect St. Lucia against coastal flooding, sea-level rise, and increasing extreme water levels.

TABLE 1: DETAILS OF NBSOS DELIVERED BETWEEN MID-2022 AND APRIL 1, 2024

COUNTRY	PROJECT CODE	NBSOS APPLICATION	GP/PG	TYPE OF ENGAGEMENT	FINANCING OF IPF (US$, MILLIONS)	FINANCING SOURCE IPF
Argentina	P178534	NBSOS in 4 secondary cities	Water	IPF	200	IBRD
Belize	P181064	NBSOS in Belize City and country's coastline	ENB, GPURL	IPF	16.5	IBRD/RETF
	P501812	NBSOS Belize coastline	ENB	CCDR		
Burkina Faso	P177918	NBSOS in 3 secondary cities	Transport, GPURL	IPF	200	IDA
Central African Republic	P178774	NBSOS in Bangui and 3 secondary cities	GPURL	IPF	70	IDA
Chad	P177044	NBSOS in N'Djamena	GPURL	IPF	150	IDA
	P177163	NBSOS in 3 secondary cities	GPURL	IPF	140	IDA
Côte d'Ivoire	P168308,	NBSOS in Abidjan	GPURL	IPF	315	IDA
	P177062	NBSOS and 8 secondary cities	GPURL	IPF	300	IDA
Eastern Caribbean Countries	P179742	NBSOS in coastal areas	LAC SD front office	CCDR	n.a.	n.a.
Fiji	P181433	NBSOS in coastal areas in Viti Levu and Vanua Levu	ENB	IPF	37	CIF/RETF/ IDA
India	P502683	NBSOS in 5 cities	GPURL	ASA	n.a.	n.a.
Mali	P171658	NBSOS in Bamako	GPURL	IPF	250	IDA

Continues in the next page →

SOURCE: Original table for this publication.
NOTE: The pipeline beyond April 1, 2024, is not included in this table. ASA = advisory services and analytics; CCDR = Country Climate and Development Reports; CIF = Climate Investment Funds; ENB = Environment, Natural Resources and the Blue Economy Global Practice; GPURL = Urban, Disaster Risk Management, Resilience and Land Global Practice; IDA = International Development Association; IPF = investment project financing; LAC SD = Latin America and the Caribbean Sustainable Development Practice Group; n.a. = not applicable; NBSOS = Nature-Based Solutions Opportunity Scan; RETF = recipient-executed trust fund; SD = Sustainable Development Practice Group.
a. Eastern Caribbean Countries in this analysis include Dominica, Grenada, St. Lucia, and St. Vincent and the Grenadines.

COUNTRY	PROJECT CODE	NBSOS APPLICATION	GP/PG	TYPE OF ENGAGEMENT	FINANCING OF IPF (US$, MILLIONS)	FINANCING SOURCE IPF
Nepal	P163418	NBSOS in Itahari	GPURL	IPF	116	IDA
St. Lucia	P503961	NBSOS in 2 cities and in the island's coastal areas	GPURL	IPF	20	IDA
Senegal	P175830	NBSOS in Dakar and Thies	GPURL	IPF	290	IDA
	P180943	NBSOS in Dakar and Thies	ENB, SD	CCDR	n.a.	n.a.
Somalia	P170922	NBSOS in 4 cities	GPURL	IPF	154	IDA/RETF
Sri Lanka	P176456	NBSOS in coastal areas	ENB	ASA	n.a.	n.a.
	P500980	NBSOS in coastal areas	ENB	CCDR	n.a.	n.a.
Thailand	P178093	NBSOS in 4 cities	Water	ASA	n.a.	n.a.
Timor-Leste	P178790	NBSOS in coastal areas	ENB	ASA	n.a.	n.a.
West Bank and Gaza	P179452	NBSOS in 7 cities	GPURL	CCDR	n.a.	n.a.

SOURCE: Original table for this publication.
NOTE: The pipeline beyond April 1, 2024, is not included in this table. ASA = advisory services and analytics; CCDR = Country Climate and Development Reports; CIF = Climate Investment Funds; ENB = Environment, Natural Resources and the Blue Economy Global Practice; GPURL = Urban, Disaster Risk Management, Resilience and Land Global Practice; IDA = International Development Association; IPF = investment project financing; LAC SD = Latin America and the Caribbean Sustainable Development Practice Group; n.a. = not applicable; NBSOS = Nature-Based Solutions Opportunity Scan; RETF = recipient-executed trust fund; SD = Sustainable Development Practice Group.
a. Eastern Caribbean Countries in this analysis include Dominica, Grenada, St. Lucia, and St. Vincent and the Grenadines.

5

SUSTAINABILITY AND OPERATIONAL MODEL

Urban farming 2
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The NBSOS is a service offered to Task Teams to identify opportunities for NBS investments in the early stages of projects, using a small core team of staff and consultants in GFDRR.

Currently, the NBSOS team has the capacity to deliver the NBSOS in about **50 cities** and **10 coastal landscapes** per fiscal year. The application follows a streamlined process:

1. Following a request from a Task Team, a **two-page proposal is prepared.** This includes tasks, deliverables, and level of effort/budget.

2. The proposal is fine-tuned in an **inception meeting** to determine the precise area of interest, climate resilience challenges of interest, the NBS types of interest, and the potential integration of locally collected data. A short inception note is prepared based on the meeting.

3. Once the inception note is cleared by the Task Team, the **NBSOS analysis is conducted** by the GPNBS team and deliverables are prepared.

4. **Results are presented** to the Task Team and final deliverables—a PowerPoint deck and a geospatial data package that is available upon request—are shared.

The demand for the NBSOS is increasing rapidly, and developments are continually being made to increase the efficiency and quality of the service.

Among these developments is the increased automatization of the process to reduce the number of input hours required for each application. Furthermore, sustainability risks are mitigated by the good archiving of data, by documentation, and by having multiple consultants in the team who can perform the tasks needed to obtain coastal and urban NBSOS results. The team also collaborates with a wider team of GPNBS experts who can support Task Teams on the use of these results for project design and implementation. Nonetheless, the capacity for deployment is not limitless, and NBSOS applications need to be planned carefully to ensure timely delivery for effective operational use of the outcomes.

The NBSOS runs primarily in Python,[7] with data and end products stored in Google Cloud Storage (GCS). The NBSOS input data sets are characterized by globally comprehensive spatial coverage, allowing the NBSOS to be implemented in any region of the world. Global data sets are processed for an area of interest (AOI) representing the spatial extent of analysis, which is defined with Task Teams for each case. As the availability, detail, and breadth of global data sets continue to increase, so will the functionality of the NBSOS.

To ensure access to both recent and historical Earth observation (EO) data, the EO data is obtained with Google Earth Engine (GEE). GEE provides access to a multi-petabyte catalogue of EO data, ranging from raw satellite observation bands to analysis-ready land cover products. GEE's Python Application Programming Interface (API) allows seamless integration of data acquisition in the NBSOS Python framework. Most of the analysis in NBSOS is done in Python, except the heat module and map visualization, which run in R software.[8] The use of open data and open software makes it possible to turn the NBSOS into an open-source tool in the future. GPNBS has the ambition to make parts of the source code available on GitHub upon publication of the methodology in a peer-reviewed academic journal.[9]

7 Python is a programming language. It allows you to work quickly and lets you integrate systems effectively. For more information about Python, see https://www.python.org/.

8 R is a free software environment appropriate for statistical computing and graphics. More information can be found at https://www.r-project.org/.

9 More details about GitHub can be found at https://github.com/.

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6

NEXT STEPS AND EVOLUTION OF THE NBSOS

There are two main areas for next steps for the NBSOS. The first involves the improvement of NBSOS' analytical capability; the second involves increasing its capacity. This section looks briefly at each.

6.1 THE DEVELOPMENT OF ANALYTICAL CAPABILITIES

Analytical capabilities of the NBSOS are—and will continue to be—constantly improved and tested during NBSOS applications. Such incremental ongoing improvements include remote sensing-based observations of coastal erosion, erosion modeling along inland water bodies, and suitability mapping of green roofs in dense urban areas. Such improvements rely on existing scientific approaches and are typically tested in two or three applications before being integrated into the main workflow.

More fundamental analytical improvements will focus on expanding the capability of the NBSOS estimating biodiversity impact and quantifying pluvial flood reduction by NBS. Combining spatial species diversity data from tools such as the Integrated Biodiversity Assessment Tool (IBAT) and habitat connectivity models,[10] the GPNBS team is working with partners to design a biodiversity module for the NBSOS. In addition, the GPNBS team is developing a model that can provide a quantitative estimate of flood hazard and exposure reduction as a result of NBS investment options. The current model identifies in which areas NBS have the highest potential of reducing flood exposure, whereas the updated model will calculate flood extent and flood depth both with and without NBS.

10 More information about IBAT can be found at https://www.ibat-alliance.org/.

A growing body of research and practice will increase the ability to estimate unit costs of NBS adjusted to the landscape or country context as part of the NBSOS.

As more NBS for climate resilience are studied and implemented globally, more data points on costs become available. In collaboration with GFDRR and PROGREEN, GPNBS is developing rapid costing tools to inform and improve unit cost estimations used in the NBSOS.

6.2 TOWARD MORE CAPACITY FOR DELIVERY

Within the current operational model, it is possible to further increase capacity responding to additional demand from World Bank Task Teams and beyond. Increased efficiency due to standardization, along with a larger pool of expert consultants to run the analyses, can expand the capacity for coastal and urban NBSOS in fiscal year 2025 by 25–50 percent of current capacity, which might be sufficient to meet demand in the World Bank. If the demand exceeds this capacity, it will lead to the requests of Task Teams needing a longer response time. Several options can be considered to further expand capacity to deliver NBS investment opportunity recommendations.

Capacity could be increased even more by developing a webtool with graphical user interface for nonexpert users. It could also be increased by stimulating development partners and industry (that is, World Bank vendors) to adopt the NBSOS methods by opening the code and enabling knowledge transfer.

The former option comes with risks, including the sustainability of maintaining such a webtool with graphical user interface as well as a potential lack of expertise among users to interpret and use the results to identify investments. The latter option—stimulating industry—might be a more promising avenue. Since a pre-publication on the NBSOS was released in July 2023 (GFDRR and ESA 2023), about 20 external partners—including multilateral development banks (MDBs), other development partners, private sector firms, and leading civil society organizations (CSOs)—have requested access to the NBSOS source code to adopt the methodology for investment identification. Piloting external dissemination, the World Bank aims to start sharing the source code of the urban NBSOS on request with a limited number of external partners upon publication of this report.

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THE NATURE-BASED SOLUTIONS OPPORTUNITY SCAN

APPENDIX A: DETAILED METHODOLOGY OF THE URBAN NBSOS

GLOBAL PROGRAM ON NATURE-BASED SOLUTIONS FOR CLIMATE RESILIENCE
PROBLUE
HEALTHY OCEAN • HEALTHY ECONOMIES • HEALTHY COMMUNITIES
GFDRR
Global Facility for Disaster Reduction and Recovery
Administered by THE WORLD BANK
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ABBREVIATIONS AND ACRONYMS

ACP	Africa Caribbean Pacific
AOI	area of interest
API	Application Programming Interface
CAPEX	capital expenditure
COG	Cloud Optimized GeoTIFF
CN	Curve Number
CPI	Consumer Price Index
DEM	Digital Elevation Model
EO	Earth observation
ESA	European Space Agency
GBA	Greater Banjul Area, The Gambia
GCS	Google Clouse Storage
GEE	Google Earth Engine
GFDRR	Global Facility for Disaster Reduction and Recovery
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
LCC	Land Capability Classification
LST	land surface temperature
MODIS	Moderate Resolution Imaging Spectroradiometer
NBS	nature-based solutions
NBSOS	Nature-Based Solutions Opportunity Scan
NDRR	Natural Disaster Risk Reduction
NDVI	Normalized Difference Vegetation Index
OSM	OpenStreetMap
PPT	PowerPoint
RP	return period
RUSLE	Revised Universal Soil Loss Equation
SUDS	sustainable urban drainage systems
TA	technical assistance
UFRMM	Urban Flood Risk Mitigation Model

OVERVIEW OF PRODUCT, APPLICATION, AND METHODOLOGY

Urban forest
©Vickry Alvian_Unsplash

A.1.1 OVERVIEW

The Nature-Based Solutions Opportunity Scan (NBSOS) is a geospatial analysis and a participatory process that is offered as an on-demand service for nature-based solutions (NBS) investment opportunity mapping in cities around the world. It aims to support World Bank Task Teams, governments, and other investors to understand which NBS families have the most potential in a city, what potential project sites are, what their potential benefits are, and how NBS can complement gray infrastructure. The NBSOS methodology is designed in such a way that its deliverables—including results, interpretation, recommendations, and a geospatial data package—can be prepared in approximately six weeks.

The NBSOS utilizes an array of openly available medium resolution (10- to 30-meter) Earth observation (EO) data and other geospatial data sets as inputs into an analytical workflow consisting of four methodological steps (see figure 4 in the main text for an overview of the NBSOS methodology). The first step is to understand the problem: what is the spatial distribution and magnitude of urban resilience and sustainability challenges and what are the solutions considered? The second step consists of mapping suitable areas for the NBS families considered. The third step models and estimates the positive impact of NBS to address the identified resilience and sustainability challenges. In the fourth step, optimal solutions are identified using multicriteria analysis to highlight solutions that maximize NBS co-benefits. The next section of this appendix describes the geospatial data sets and models that constitute the NBSOS (section A.2). It then outlines the participatory process and deliverables of the NBSOS as a service to World Bank Task Teams (section A.3). The last section describes a validation exercise for the NBSOS flood module (section A.4).

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A.2 METHODOLOGY

A.2.1 SOFTWARE/CODING SCHEME

The NBSOS runs primarily in Python, with data and end products stored in Google Cloud Storage (GCS). In summary, the geospatial modeling component of the NBSOS compiles environmental indicators from global, publicly available EO and geospatial data sets to (1) prioritize regions of NBS implementation as a function of population exposure to pluvial flooding, extreme heat, and lack of access to green spaces; (2) identify NBS creation opportunities for the NBS families described in the World Bank's *Catalogue of Nature-Based Solutions for Urban Resilience* by applying conditional suitability rulesets on environmental indicators; (3) estimate the potential for NBS creation to provide flood mitigation, extreme heat mitigation, health/recreation benefits, and other benefits; and (4) provide decision support by identifying optimal NBS families through a multicriteria analysis. The NBSOS input data sets are characterized by globally comprehensive spatial coverage, allowing the urban NBSOS to be implemented in any urban region of the world. Global data sets are subset and processed for an area of interest (AOI) defining the spatial extent of analysis.

A.2.1.1 GOOGLE EARTH ENGINE

The NBSOS highlights priority intervention areas, identifies land suitable to support NBS creation, and quantifies potential benefits of NBS in cities by synthesizing publicly available EO data. To ensure access to both recent and historical EO data, EO data were obtained with Google Earth Engine (GEE). GEE provides access to a multi-petabyte catalogue of EO data, ranging from raw satellite observation bands to analysis-ready land cover products. GEE's Python Application Programming Interface (API) allows seamless integration of data acquisition in the NBSOS Python framework.

A.2.1.2
DATA PROCESSING

The EO data derived from GEE are used in the development of spatial raster layers describing environmental indicators that form the basis of NBSOS' subsequent modules. Examples of environmental indicators are the Land Capability Classification Index (Quant et al. 2020), tree canopy cover (Brandt et al. 2023), and bare soil frequency (Demattê et al. 2020) (further described in section A.2.3 on mapping NBS suitability). Analysis-ready indicators are centrally stored as Cloud Optimized GeoTIFF (COG) spatial raster format files in GCS, where data can be accessed via Python by each benefit module of NBSOS. All further analysis in NBSOS is done in Python, except for the heat module and map visualization, which run in R software.

A.2.2
MAPPING PRIORITY AREAS

Priority area mapping consists of identifying high-impact areas for NBS investment within the AOI guided by two questions: (1) Where are hazard exposures highest? And (2) Where can NBS be implemented to reduce the exposure to the hazard most effectively? Therefore, this first step focuses on identifying where the problems are (figure A.1).

FIGURE A.1: IDENTIFYING PRIORITY AREAS

Determine where people have the highest exposure to the hazard.

Determine where to apply NBS to solve it more effectively.

Identifying priority areas helps to understand where to act first to have the highest impact, helping to make a strategic long-term plan.

SOURCE: Original figure for this publication.
NOTE: NBS = nature-based solutions.

A.2.2.1
PLUVIAL FLOODING

To identify pluvial flood exposure, the annual flood probability per neighborhood, derived from Fathom Global Flood Model (Fathom, no date), is multiplied by the number of people living in each neighborhood of the AOI. Subsequently, the NBSOS implements a basic hydrological model to identify neighborhoods where NBS investment could have the highest impact in reducing pluvial flood exposure. Pluvial flood mitigation by NBS is operationalized in the NBSOS as the combination of runoff reduction through surface cover changes and storage potential of NBS.

A.2.2.1.1 INPUT DATA AND PROCESSING

Table A.1 describes elements of the input data used to model pluvial flood mitigation.

TABLE A.1: INPUT DATA FOR PLUVIAL FLOOD MITIGATION MODELING

DATA TYPE	DATA SET NAME AND SOURCE	RESOLUTION
Flood hazard data	Fathom Pluvial Flood Risk (Fathom, no date)	30 meters
Population data	High Resolution Settlement Layer (FCL and CIESIN 2016)	30 meters
Digital Elevation Model	FABDEM (Hawker et al. 2022)	30 meters

SOURCE: Original table for this publication.

The NBSOS uses Fathom Global Flood Maps v2 to estimate annual flood probability per neighborhood in the target city. Fathom Global Flood Maps V2 is a proprietary global flood model that provides spatially explicit flood simulations for 10 different return periods at a 90-meter resolution. Fathom modeled flood outputs of flood depth in millimeters are simplified into a binary outcome per pixel of either flooded (> 0) or not flooded (0). Annual flood risk per pixel ($F_{a,i}$) is calculated as

$$F_{a,i} = \sum \frac{1}{R} \cdot F_{R,i},$$

where R is the return period in years and ($F_{R,i}$) is the binary flood outcome for pixel i for return period R. The mean annual flood probability for each neighborhood is then multiplied by the total population of each neighborhood to estimate a neighborhood annual flood exposure value. Neighborhood population is determined by summing the rasterized population using High Resolution Settlement Layer population data per neighborhood (FCL and CIESIN 2016). Unless relevant neighborhood administrative boundaries are provided by Task Teams, neighborhood subregions of the AOI are created using the Hexagonal Hierarchical Geospatial Indexing System (Sahr 2020), which produces hexagonal grids of approximately 0.75 square kilometers per subregion.

A.2.2.1.2 ESTIMATION OF FLOOD PRIORITY AREAS

To account for the downstream effect of runoff reduction, the NBSOS uses a series of watershed delineations. Using the Python library Pysheds (Bartos 2020), first the flow accumulation per pixel is determined, describing the number of additional pixels directly upstream of that pixel. For each pixel with an accumulation flow greater than 500 pixels, the watershed (that is, the area that accumulates to that pixel) is calculated. To account for the inaccuracies of flood hazard data in urban areas, watersheds are generalized per neighborhood by combining the watersheds of each pixel per neighborhood to create a spatially explicit neighborhood watershed that gets assigned the flood hazard exposure value of its original neighborhood. Finally, the flood hazard exposure values of all neighborhood watersheds are summed up to obtain a raster that shows a relative distribution of population that can be affected per pixel accounting for flood probability. This raster is averaged over neighborhoods to estimate the flood priority areas, representing high-impact regions to apply NBS to reduce downstream hazard exposure (see map 1 of the main text for an example).

A.2.2.2
HEAT STRESS

A.2.2.2.1 INPUT DATA DESCRIPTION AND PROCESSING

Table A.2 describes the data sets used for modeling extreme heat mitigation.

TABLE A.2: INPUT DATA FOR EXTREME HEAT MITIGATION MODELING

DATA TYPE	DATA SET NAME AND SOURCE	RESOLUTION
Land surface temperature data	MODIS Land Surface Temperature (Wan, Hook, and Hulley 2021)	1 kilometer
Ambient air temperature data	A global data set of air temperature derived from remote sensing and weather stations (Hooker, Duveiller, and Cescatti 2018)	1 kilometer
Population data	High Resolution Settlement Layer (FCL and CIESIN 2016)	30 meters

SOURCE: Original table for this publication.

To estimate spatial variability in heat exposure within the AOI, global spatial data sets on average annual air temperature and population density are combined. Average annual air temperature at 10-meter spatial resolution is estimated using the methodologies presented in Hooker, Duveiller, and Cescatti (2018), who describe a statistical model derived by comparing remotely sensed land surface temperature (LST) and ambient air temperature observed at weather stations at two meters above the land surface that incorporates information on geographic and climatic similarity. First, the five most recent years of daily daytime and nighttime LST rasters at a 1-kilometer spatial resolution from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Wan, Hook, and Hulley 2021) are acquired and aggregated to a monthly timestep for a 5-kilometer buffered region around the AOI using GEE. The 1-kilometer monthly LST rasters are used as inputs in the geographically weighted and climate space weighted regression models described in Hooker, Duveiller, and Cescatti (2018), resulting in two distinct data sets of 1-kilometer resolution monthly air temperature. To obtain more accurate air temperature predictions, the two regression model outputs are combined using the stacked generalization weighting coefficients presented in Table 1 of Hooker, Duveiller, and Cescatti (2018), resulting in 12 rasters of estimated average monthly air temperature. Average annual air temperature is estimated by taking the mean value for each pixel across the 12 monthly air temperature rasters. To match the spatial resolution of the NBSOS, the average annual air temperature raster is resampled to 10-meter spatial resolution using cubic interpolation and cropped to the AOI.

Population density is estimated using the High Resolution Settlement Layer (FCL and CIESIN 2016), which provides estimates of global human population distribution at approximately 30-meter spatial resolution by combining recent census data with high-resolution satellite imagery. After resampling the population data to the 10-meter native resolution of the NBSOS, a moving window Gaussian spatial weighting function is applied to each pixel within the AOI such that each pixel value represents the weighted population count within 1 kilometer of the pixel, where per pixel population counts closer to each focal pixel are weighed more heavily than per pixel population counts further from each focal pixel.

To capture spatial variability within the AOI, mean annual air temperature and population density rasters are aggregated to neighborhood subregions within the AOI. For each subregion, the mean annual air temperature and sum of the population count for all raster pixels within the subregion are used to determine priority areas.

A.2.2.2.2 ESTIMATION OF HEAT PRIORITY AREAS

Heat priority areas are estimated at the subregion scale using an index calculated as:

$$Priority_{heat,i} = AirT_i(°C) \times Population_i,$$

where $AirT_i$ represents the mean annual air temperature within each subregion *i* and $Population_i$ represents the spatially weighted population count within each subregion i (see map 1 in the main text).

A.2.2.3
HEALTH, RECREATION, AND SOCIAL COHESION

A.2.2.3.1 INPUT DATA AND PROCESSING

Table A.3 describes the data sets used as inputs for modeling health, recreation, and social cohesion benefits.

TABLE A.3: INPUT DATA FOR HEALTH, RECREATION, AND SOCIAL COHESION MODELING

DATA TYPE	DATA SET NAME AND SOURCE	RESOLUTION
Existing green space data	Derived from bare soil frequency (Demattê et al. 2020) and productivity performance indicator (Quandt et al. 2020) (see sections 2.3.2.1 and 2.3.3.1)	10 meters
Population data	High Resolution Settlement Layer (FCL and CIESIN 2016)	30 meters

SOURCE: Original table for this publication.

The health, recreation, and social cohesion benefits of urban nature relate to the proximity of nature to residents. Novel, evidence-based guidelines for greener, healthier cities suggest that all urban residents should be within 300 meters of an open green space (Konijnendijk 2023). Thus, neighborhoods with less green space and a high population of residents greater than 300 meters from the nearest open green space represent high-priority regions for NBS implementation. To identify spatial variability in priority areas for health, recreation, and social cohesion benefits from NBS creation, data on population density are combined with the size and location of existing green spaces.

Population density is estimated using the High Resolution Settlement Layer (FCL and CIESIN 2016), which provides estimates of global human population distribution at approximately 30-meter spatial resolution by combining recent census data with high-resolution satellite imagery. Data on the size and location of existing green spaces come from the "protection" layer described in sections 2.3.2.1 and 2.3.3.1, where existing green spaces are identified based on recent trends in bare soil frequency and Earth observation greenness indexes. Existing green spaces providing health and recreation benefits are defined as contiguous green spaces greater than 1 hectare in area. Existing green spaces providing social cohesion benefits are defined as contiguous green spaces greater than 0.5 hectare in area (WHO 2016).

To estimate the number of residents farther than 300 meters from existing green spaces, the existing green spaces greater than 1 hectare and those greater 0.5 hectares are vectorized and buffered by 300 meters. The sum of the population counts falling outside of the 300-meter buffered existing green space vectors is calculated for each subregion within the AOI to identify priority areas.

A.2.2.3.2 ESTIMATION OF HEALTH, RECREATION, AND SOCIAL COHESION PRIORITY AREAS

The health and recreation priority areas correspond to the number of residents who are more than 300 meters from contiguous green spaces greater than 1 hectare in area. The social cohesion priority areas correspond to the number of residents who are more than 300 meters from contiguous green spaces with an area greater than 0.5 hectares. In both cases, higher population counts that are more than 300 meters from an existing green space correspond to a higher-priority area value (see map 1 in the main text).

A.2.2.4
VISUALIZATION AND MAPPING

Priority areas for each hazard are provided in a series of maps created using R. Priority index values for each hazard of interest and subregion *i* are normalized by the equation:

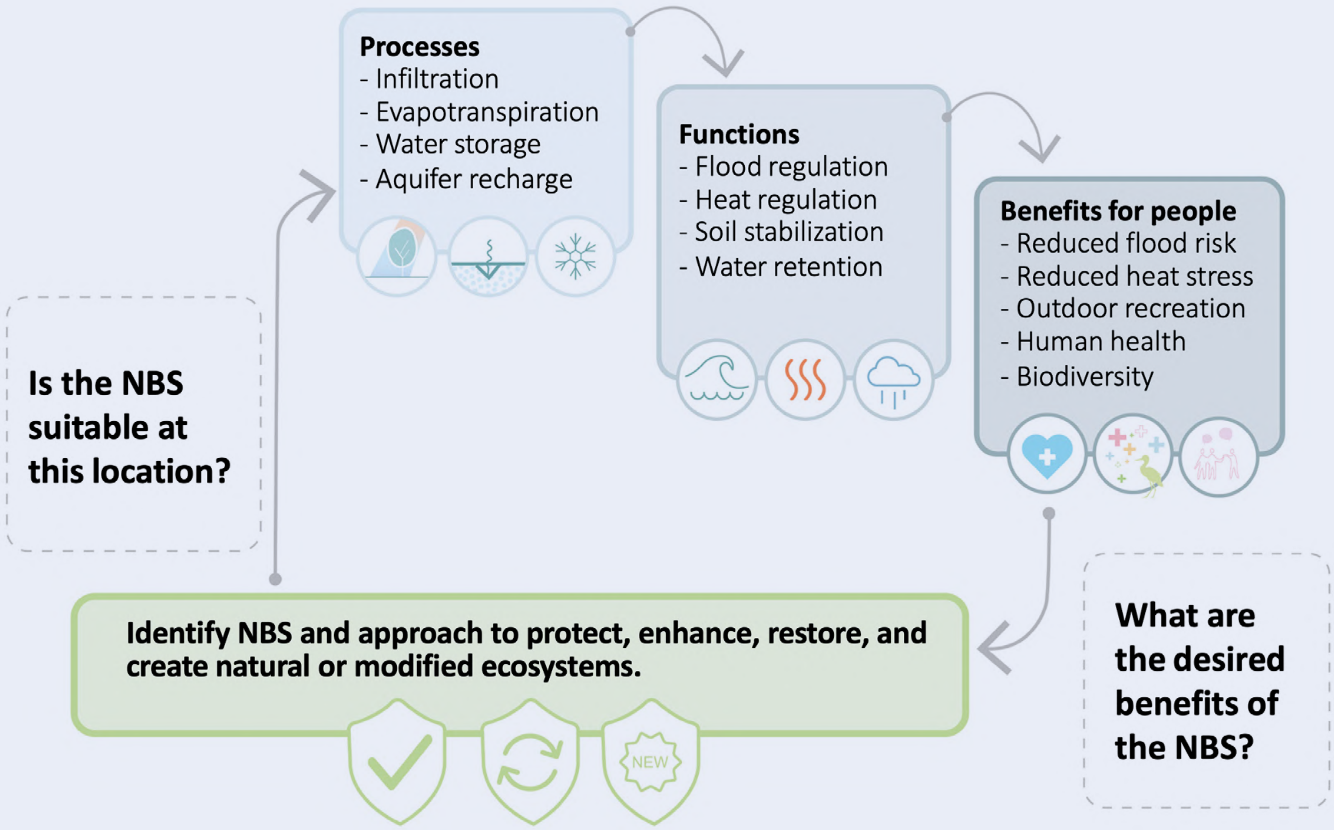
$$Normalized\ Priority_{hazard,i} = \frac{Priority_{hazard,i} - \min\left(Priority_{hazard}\right)}{\max(Priority_{hazard}) - \min\left(Priority_{hazard}\right)},$$

such that the index describes values from 0 to 1, where higher values correspond to neighborhood subregions with a higher-priority index value. The AOI subregions are then categorized into five groups (Very Low, Low, Medium, High, Very High) using the Jenks natural breaks clustering algorithm to minimize variability within priority categories and maximize variability across priority categories. The priority map for each benefit depicts the categorical index values ranging from Very Low to Very High for each subregion within the AOI (see map 1 of the main text for an example of mapping priority areas).

A.2.3 MAPPING NBS SUITABILITY

The NBSOS suitability mapping is a two-stage analysis to isolate regions within the AOI where NBS could be implemented. First, areas within the AOI deemed suitable for supporting NBS based on environmental properties (for example, slope, soil properties, land cover) are identified (section A.2.3.1) (figure A.2). Second, the areas with the capacity to support NBS are further analyzed using EO data on bare soil frequency and greenness to categorize areas as existing greenery to protect or degraded land representing opportunities for the creation of new NBS (see section A.2.3.2).

FIGURE A.2: A FRAMEWORK TO SUPPORT THE FIRST IDENTIFICATION OF POTENTIAL INVESTMENTS IN NBS



SOURCE: Original figure for this publication.
NOTE: NBS = nature-based solutions.

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A.2.3.1
SUITABILITY RULESETS

The spatial identification of NBS suitability is done through a ruleset of Earth observation biophysical indicators, which represent the state of perviousness and topology of a given location. For each type of NBS, a specific ruleset to identify suitability was developed, as shown in table A.4.

TABLE A.4: NBS SUITABILITY RULESET

NBS FAMILY	BUILD.	ELEV. MAX	SLOPE MAX	SOIL DEPTH MIN	SOIL PH	SOIL BULK DENSITY MAX	SOIL TEXTURE	HYDRO SOIL CLASS	SURFACE WATER	ROADS	LCC	HEAVY PREC. DAYS
River Renaturation	No	1,500	35	100	>4	1.6	n.a.	n.a.	50m	No	n.a.	n.a.
Green Corridors	No	1,500	35	150	4–7	1.6	n.a.	n.a.	No	10m	n.a.	n.a.
Urban Forest	No	1,500	35	150	4–7	1.6	n.a.	n.a.	No	No	n.a.	n.a.
Bioretention Area	No	1,500	5	100	n.a.	n.a.	n.a.	≤3	No	No	n.a.	n.a.
Urban Farming	No	1,500	20	n.a.	n.a.	n.a.	not 1 or 12	n.a.	No	No	≤7	n.a.
Open Green Space	No	1,500	35	150	4-7	1.6	n.a.	n.a.	No	No	n.a.	≥2

SOURCE: Original table for this publication.
NOTE: Build. = building footprint; Elev. max = maximum elevation; Slope max = maximum slope; Soil min = minimum soil depth; Soil bulk density max = maximum soil bulk density; Heavy prec. days = Heavy precipitation days; LCC = Land Capability Classification; n.a. = not applicable.

A description of how each indicator of table A.4 was generated follows. All input data layers used to calculate the indicators of table A.4 are listed in table A.5.

Building footprint (build.): To distinguish built-up area from pervious area, we merged the World Settlement Footprint (Marconcini et al. 2020) with Google Open buildings (Sirko et al. 2021). Every location identified as a settlement or building in either data set is classified as a building.

Elevation (Elev. max): To map global elevation, FABDEM (Hawker et al. 2022) was used: a 30-meter resolution global digital elevation model (DEM) with removed buildings and tree cover.

Slope (Slope max.): The elevation data described above were used to calculate a slope in degrees using the slope function of GEE.

Soil data (Soil depth min., Soil PH, Soil bulk density max., Soil texture, Hydro soil class): For soil data in Africa, ISDA estimated soil properties were used, mapped at 30-meter resolution for the entire continent of Africa (Hengl et al. 2021). For other regions, the global soil texture classes at a 250-meter resolution were used (Hengl 2018), and SoilGrids soil properties for other soil characteristics (Poggio et al. 2021). Hydrological soil groups were calculated using the method of Ross et al. (2018) using soil properties described above.

Land Capability Classification (LCC): LCC is a global land evaluation ranking that groups soils based on their potential for agricultural and other uses. LCC can help determine whether land is suitable for certain uses and whether there are risks for degradation. LCC is calculated using the LCC method described in Quandt et al. (2020). Input data for the LCC algorithm are the soil properties and slope described above.

Surface water: To identify surface water, a surface water layer prepared by the EU Joint Research Centre (JRC) (Pekel et al. 2016) was merged with water bodies in OpenStreetMap (OSM) (OpenStreetMap Contributors 2023) and ESA World Cover (Earth Engine Data Catalog, no date-b).

Roads: Roads were identified using OSM data (OpenStreetMap Contributors 2023). For green corridors, suitability was only identified within 10 meters of roads classified as "motorway," "primary," "primary_link," "road," "secondary," "secondary_link," "tertiary," "tertiary_link," "trunk," and "trunk_link."

Heavy precipitation (Heavy prec. days): To identify the number of days with heavy precipitation, daily precipitation values from the CHIRPS data set (Earth Engine Catalog, no date-a.) of the five most recent years were used and the number of days with precipitation over 10 millimeters were counted.

TABLE A.5: INPUT DATA FOR NBS SUITABILITY MODELING

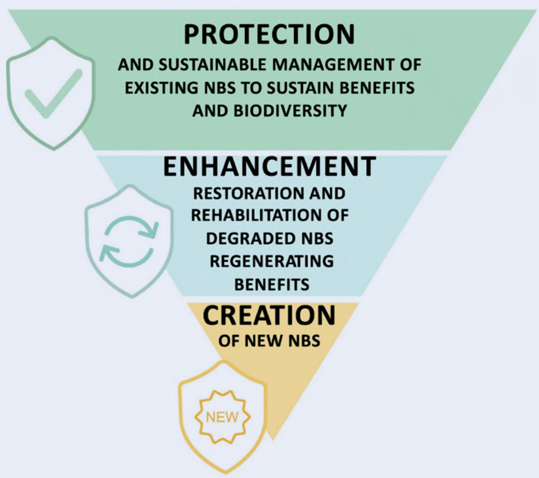
DATA LAYER	SOURCE
Land cover	ESA World Cover (Earth Engine Data Catalog, no date-b)
Elevation	FABDEM (Hawker et al. 2022)
Soil properties	ISDA Soil Properties (Africa) (Hengl et al. 2021)
	Open Land Soil Texture (Hengl 2018)
	SoilGrids (Poggio et al. 2021)
Precipitation	CHIRPS precipitation data set (Earth Engine Catalog, no date-a)
Settlements	Google Open Buildings (Sirko et al. 2021)
	World Settlement Footprint (Marconcini et al. 2020)
Water	Global Water Surface Layer (Pekel et al. 2016)
	OpenStreetMap Water (OpenStreetMap Contributors 2023)
Roads	OpenStreetMap Roads (OpenStreetMap Contributors 2023).

SOURCE: Original table for this publication.

A.2.3.2 CLASSIFICATION OF CREATION AND PROTECTION OPPORTUNITIES

The World Bank *Catalogue of Nature-Based Solutions for Urban Resilience* describes a hierarchical approach to NBS implementation in urban ecosystems (World Bank 2021) (figure A.3). The first element in the hierarchy, referred to here as "protection," describes the sustainable management of existing NBS to sustain benefits and biodiversity. The second element, referred to as "enhancement," represents the restoration and rehabilitation of degraded NBS. The third element, referred to as "creation," points to the implementation of new natural or green infrastructure in cities. Following the NBSOS suitability analysis to identify land that can support NBS within cities, the suitable land identified for each NBS family is further classified as areas to protect existing green space (combining the elements of protection and enhancement) and areas that represent opportunities for the creation of new NBS.

FIGURE A.3: A HIERARCHY OF APPROACHES UNDER THE NATURE-BASED SOLUTIONS UMBRELLA



SOURCE: World Bank 2021.

A.2.3.2.1 CLUSTERING AND CLASSIFICATION METHOD FOR EARTH OBSERVATION INDICATORS

To categorize suitable land into areas for protection or creation, the NBSOS used two EO indicators: (1) the bare soil frequency and (2) the productivity performance indicator. The *bare soil frequency indicator* is calculated as the number of bare soil observations from Sentinel-2 imagery divided by the number of cloud-free Sentinel-2 observations for each pixel within the two most recent years of data (Demattê et al. 2020). The *productivity performance indicator* aims to describe the vigor of existing vegetation in the city. The performance productivity indicator is calculated for each unique combination of landcover and soil texture within the AOI. For pixels within each unique landcover and soil texture combination, the mean Normalized Difference Vegetation Index (NDVI) is calculated for each pixel for the most recent year of Sentinel-2 observations and is divided by the 95^{th} percentile of mean NDVI across all pixels in the landcover/soil texture class such that higher values represent greener vegetation. The three layers of input data for the two indicators are listed in table A.6.

For each indicator of bare soil frequency and productivity performance, we apply a Jenks natural breaks clustering algorithm to create rasters categorizing pixels into five integer classes (1–5), where values equal to 1 represent the most degraded land within the AOI (high bare soil frequency or low productivity performance) and values equal to 5 represent the greenest regions within the AOI (low bare soil frequency or high productivity performance). The respective clustered rasters are added together to create a new raster with values ranging from 2 to 10, with lower values representing more degraded land and higher values representing existing green space to protect.

TABLE A.6: INPUT DATA FOR NBS OPPORTUNITY CLASSIFICATION

DATA LAYER	DATA SET NAME AND SOURCE
Land cover	ESA World Cover (Earth Engine Data Catalog, no date-b)
Soil properties	ISDA Soil Properties (Africa) (Hengl et al. 2021)
	Open Land Soil Texture (Hengl 2018)
	SoilGrids (Poggio et al. 2021)
Surface reflectance	Sentinel-2 (Earth Engine Data Catalog, no date-c)

SOURCE: Original table for this publication.

The combined bare soil frequency/productivity performance cluster raster is manually inspected to identify a threshold integer value where values higher than or equal to the threshold represent regions of existing green space to protect. For all clusters with a value less than the manually determined threshold, the cluster spatial extent is intersected with the suitability extent of each NBS family to identify degraded land suitable for the creation of NBS. The resulting product is a categorical raster with three categories representing (1) the protection of existing green space, (2) NBS creation opportunities, and (3) regions without existing vegetation that are not suitable for NBS creation.

A.2.3.3
NBS SUITABILITY MAPPING

The NBSOS outputs include categorized maps of the AOI highlighting regions representing the protection of existing green space and all opportunities for NBS creation (see map 2 in the main text). Additionally, the NBSOS provides individual maps demarcating the creation opportunities for individual NBS families, as regions suitable for creation of some NBS families may not be suitable for others (see map 3 in the main text).

Opportunities for NBS protection and creation are presented using a set of maps created using the R software environment. First, NBS opportunities for the entire AOI are provided highlighting regions for NBS protection, creation, and the extent of existing human settlement. As the AOI often extends beyond the limits of densely populated city centers, a second map of NBS opportunities is frequently provided for the core city area, where NBS creation opportunities are often concentrated. Lastly, several maps are provided highlighting regions within the core city area representing NBS creation opportunities for each NBS family of interest.

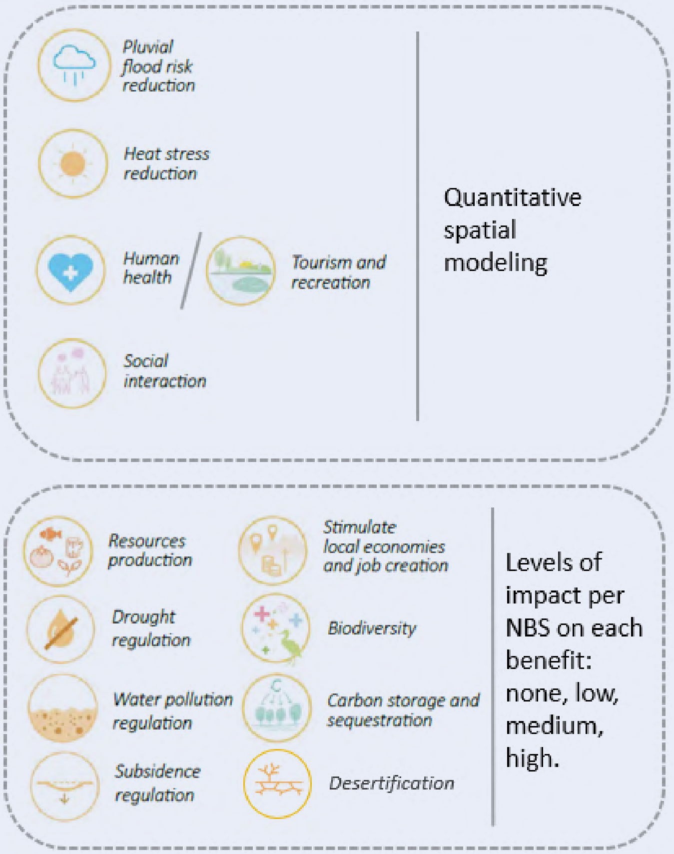
A.2.4
MAPPING BENEFITS

The modeling of benefits follows two different methodologies (figure A.4). Some benefits are modeled using spatial analysis, while others are estimated using a more qualitative analysis.

In the case of pluvial flood risk reduction, the NBSOS quantifies the impact by calculating the effect of NBS on runoff reduction through spatial analysis, estimating flood risk reduction in different areas. Regarding heat stress reduction, the NBSOS also uses spatial analysis to reduce the exposure to hazards in places where NBS are implemented. For health, a proxy for health and recreation benefits is used, and accessibility to green spaces is considered to estimate the benefit. A similar approach is followed for social interaction.

For other benefits considered in the NBSOS, the impact of each NBS on each benefit is defined as none, low, medium, or high. This is based on the *Catalogue of Nature-Based Solutions for Urban Resilience* (World Bank 2021). In this case, the benefits are not spatially modeled; rather it is assumed that they are delivered where the NBS is located.

FIGURE A.4: NBSOS BENEFITS AND IMPACTS



SOURCE: Original figure for this publication.

A.2.4.1
PLUVIAL FLOOD BENEFITS

The NBSOS utilizes a spatial flood mitigation model to estimate flood exposure reduction potential from NBS by calculating the reduced flood risk from NBS implementation as the product of annual flood probability, exposed population, and NBS-specific runoff reduction. For each neighborhood, flood risk is calculated as the product of annual flood probability and exposed population as explained in section A.2.2.1. Runoff reduction potential is calculated as the difference between runoff in the current scenario and runoff in an NBS scenario where each pixel that is identified as suitable for NBS creation is converted to the respective NBS family. The runoff reduction potential of every pixel is linked to neighborhoods through a basic spatial hydrological model explained in section A.2.2.1.2. Data sources for this module are listed in table A.7. All modeling is carried out in Python.

TABLE A.7: INPUT DATA FOR FLOOD MITIGATION BENEFIT MODELING

DATA LAYER	DATA SET NAME AND SOURCE
Land cover	ESA World Cover (Earth Engine Data Catalog, no date-b)
Soil properties	ISDA Soil Properties (Africa) (Hengl et al. 2021)
	Open Land Soil Texture (Hengl 2018)
	SoilGrids (Poggio et al. 2021)
Surface reflectance	Sentinel-2 (Earth Engine Data Catalog, no date-c)
Elevation	FABDEM (Hawker et al. 2022)

SOURCE: Original table for this publication.

A.2.4.1.1 RUNOFF REDUCTION THROUGH SURFACE COVER CHANGES

The NBSOS estimates the runoff reduction associated with surface cover changes due to the creation of an NBS family though the Curve Number (CN) method following the InVEST Urban Flood Risk Mitigation Model (UFRMM) (Hamel et al. 2021). A pixel-based runoff is calculated for a given storm depth based on a CN associated with each combination of soil type and land use class.

Following UFRMM, runoff Q is estimated in millimeters as:

$$Q_{p,i} = \frac{\left(P - \lambda S_{\max_i}\right)^2}{P + (1-\lambda) S_{\max_i}},$$

where P is the storm depth in millimeters, S_{max} is the potential retention at pixel i, and λS_{max} is the rainfall depth needed to start runoff at pixel i. If $P < \lambda \times S_{max}$, Q is 0. λ is a parameter that is set by default at 0.2. S_{max} is a function of CN and is calculated as

$$S_{\max_i} = \frac{25400}{CN_i} - 254.$$

For each NBS family, runoff reduction per pixel of the current situation is compared with a curve number calculated with all pixels converted to the respective NBS family. Curve numbers were derived following Jaafar, Ahmad, and El Beyrouthy (2019), using SoilGrids (Poggio et al. 2021) and ISDA soil properties data (Hengl et al. 2021) to derive hydrological soil groups (Ross et al. 2018). Hydrological soil groups, in combination with the WorldCover 2020 land cover data (Earth Engine Data Catalog, no date-b) are used to derive a land cover/hydrological soil group–specific curve number. Additionally, bare soil frequency (Demattê et al. 2020) is used to differentiate three hydrologic conditions (poor, fair, and good) for each hydrological soil group/land cover combination. Changes in land cover and bare soil percentage are shown in table A.8.

TABLE A.8: LAND COVER CONVERSION AND BARE SOIL PERCENTAGE CHANGE ASSOCIATED WITH EACH NBS FAMILY

NBS FAMILY	LAND COVER TYPE CONVERSION	BARE SOIL (% DECREASE)
Open green space	Grassland	20
Urban forest	Trees	40
Green corridors	Trees	30
Urban farming	Agriculture	10
Inland wetland	Wetland	50
River floodplain	Wetland	40
River renaturation	Grassland	20
Terrace slope	Agriculture	10
Bioretention area	Wetland	40
Green roof	Grassland	20

SOURCE: Original table for this publication.
NOTE: *Bare soil percentage decrease* is a proxy for the hydrologic condition of the given pixel. Indeed, the establishment of a new NBS assumes an improvement in the hydrologic condition of the given pixel (that is, a reduction in bare soil percentage).

The CN-based runoff reduction of each pixel is multiplied with the flood hazard mitigation potential calculated in paragraph A.2.2.1 to yield a final flood mitigation potential value for each pixel that accounts for downstream flood exposure reduction.

A.2.4.1.2 RUNOFF REDUCTION THROUGH STORAGE

Bioretention areas and open green spaces can also mitigate flood exposure through storage, which is based on the equations below (Reig et al. 2019):

$$SV = R \times A \times C$$

$$VC = SV \times RR,$$

where *SV* is the supply runoff volume entering the NBS (in cubic meters), *R* is the rainfall (in meters), *A* is the drainage area (in square meters), *C* is the runoff coefficient, *VC* is the runoff volume captured by the NBS (in cubic meters), and *RRF* is the runoff reduction factor, specific for each NBS.

To simulate this process, compatible with the runoff reduction method described in the previous section, the NBSOS incorporates a storage model based on curve numbers by calculating a runoff coefficient (McCuen and Bondelid 1981).

For each contiguous area identified as suitable for creation of bioretention areas or open green spaces, the total area is represented by *S*. The area (*A*) sent to this potential NBS patch *j* is calculated as

$$A_j = \frac{S_j}{F},$$

where *F* is an NBS-specific factor (0.05 for bioretention areas and 0.03 for open greens pace (ARC 2016; McCuen and Bondelid 1981). Moreover, *A* is capped at 1 hectare for bioretention areas and 4 hectares for open green spaces (ARC 2016; Woods Ballard et al. 2015). Using the average CN value of area *A*, a runoff coefficient *C* is calculated as

$$C = -0.4586 + 0.0138 \times CN.$$

Subsequently, a new *C* value (C_a) is calculated:

$$C_a = C_b \times (1 - RRF),$$

where C_b is the original *C* value and *RRF* is an NBS-specific coefficient with 0.4 for bioretention and 0.2 for open green spaces (Battiata et al. 2010; Hirschman et al. 2018). To estimate the storage effect, new average *CN* value for area A (McCuen and Bondelid 1981) is simulated as

$$CN = 34.457 + 69.908 \times C_b.$$

In a last step, the storage effect is simulated by calculating the runoff reduction using the new CN values for each modeled bioretention or open green space patch. The difference between runoff in the baseline scenario and the new CN scenario is assigned as the storage effect expressed in the same unit as the runoff reduction value calculated for the other NBS families.

A.2.4.2
HEAT STRESS BENEFITS

Heat stress describes the suite of conditions that can occur in the human body when environmental conditions preclude the shedding of excess heat. Projected increases in global temperatures are expected to intensify heat stress throughout the twenty-first century, with extreme heat conditions endangering human health, impairing economic growth, reducing agricultural yields, and compromising ecosystems. Cities, characterized by warmer temperatures, higher population densities, and increased economic activity, are particularly susceptible to the consequences of extreme heat. NBS, however, have the potential to mitigate local temperatures by providing shade and consuming solar radiation for evapotranspiration. The NBSOS includes a module to estimate spatial variability in NBS heat stress benefits based on the priority areas described in section A.2.2.2 and statistical relationships between landcover composition and air temperature.

A.2.4.2.1 SPATIAL REGRESSION MODEL OF LANDCOVER IMPACTS ON AIR TEMPERATURE

The NBSOS heat stress module estimates spatial variability in potential heat stress mitigation across the AOI through relationships between landcover composition and average annual air temperature (air temperature data processing is described in section A.2.2.2). For each neighborhood subregion within the AOI, the landcover composition is determined by estimating the percent landcover of eight different landcover types mapped as part of the European Space Agency (ESA) WorldCover data set, which includes built-up land, trees, grass, shrubs, wetlands, croplands, bare land, and water. The landcover composition of subregions is compared with modeled average annual air temperature in a spatial regression analysis to estimate the local sensitivity of air temperature to landcover types that can be manipulated via NBS implementation. Typically, the model estimates only the impacts of built-up land and tree cover; however, any of the eight landcover types described above could be included in the analysis. The spatial regression modeling framework includes spatial lag effects on the independent variables and model error to estimate both local and "spillover" effects of NBS implementation across the AOI. The heat benefits module utilizes a spatial autoregressive framework because of spatial autocorrelation in the temperature data, which might bias coefficient estimates from a traditional ordinary least squares regression modeling framework. The model is estimated as:

$$y = X\beta + WX\theta + u,$$

$$u = \lambda W u + \varepsilon,$$

$$\varepsilon \sim N(0, \sigma^2),$$

where y is the dependent variable vector (average annual air temperature (°C)), X is the independent variable matrix (for example, tree cover (%), built-up cover (%)), β is the regression parameter vector, W is a spatial weighting matrix, θ is the spatial lag parameter vector, u is the spatial error, λ is the spatial coefficient of the error, and ε is the error vector of the model.

Using the estimated coefficients describing the sensitivity of air temperature to land cover compositions (that is, β and θ), average air temperature is predicted under scenarios for each NBS family that assumes NBS creation in all pixels deemed suitable for its creation, resulting in a spatially variable data set of potential ambient air temperature reductions from NBS creation. To account for the importance of temperature reduction in priority areas characterized by a higher population density and average annual air temperature, spatial data on potential temperature reductions are combined with heat stress priority areas to estimate heat stress benefits as:

$$Benefits_{heat,i,j} = Priority_{heat,k} \times abs(TemperatureReduction_{i,j}) \times Suitability_{i,j},$$

where the heat stress benefits for pixel *i* and NBS family *j* are equal to the product of heat stress priority within the subregion *k*, the absolute value of the estimated potential temperature reduction from NBS implementation for pixel *i* and NBS family *j*, and a binary suitability indicator for pixel *i* and NBS family *j*.

A.2.4.3
HEALTH, RECREATION, AND SOCIAL COHESION BENEFITS

NBS can promote and/or improve health, recreation, and social cohesion by providing opportunities for social activities, such as walking and cycling, especially in proximity to residential areas. Urbanization results in a higher demand for recreation opportunities and increased visitor numbers in NBS such as urban forests, open green spaces, or green corridors. Recreation/social benefit potential is calculated by assuming that benefits of urban green spaces are provided in areas where residents live within 300 meters of an urban green space (Konijnendijk 2023).

To estimate the potential health/recreation benefits of areas identified as suitable for the creation of open green spaces or urban forests, calculations are made of the number of people within a radius of 300 meters of contiguous potential patches larger than 1 hectare who would gain access to this green space and who did not already have access to such an urban green space within 300 meters. Effectively, a location suitable for urban forest or open green space creation larger than 1 hectare in an area with few nearby urban green spaces and high population counts would yield a higher potential benefit than a suitable location with lower population counts or a greater abundance of existing urban green space. To estimate social cohesion benefits, the NBSOS utilizes a methodology similar to that for the health/recreation benefits but reduces the minimum green space threshold to 0.5 hectares to account for green spaces that may not be large enough for recreation but are large enough to support social interaction.

A.2.3.4
JOBS AND RESOURCES PRODUCTION BENEFITS

NBS investment in cities represents an opportunity for the creation of new jobs through the implementation of NBS and the potential for resources production once established. For example, a community-based reforestation project in Freetown, Sierra Leone, has created more than 550 jobs to support local economies (World Bank 2021). Bioretention areas can improve the image and market value of real estate to promote economic development, generate green jobs, and increase productivity for workers with access to green areas (World Bank 2021). Urban farming increases food supply and production, reduces the distance that food must travel from the producer to the consumer, and creates jobs for agricultural entrepreneurs and workers (World Bank 2021). The NBSOS estimates potential jobs and resources production benefits by combing a spatially weighted population distribution model to capture variability in population density with proximity to NBS creation with a weighting matrix estimating variability in the provision of jobs and resources production benefits across different types of NBS.

A.2.3.4.1 SPATIALLY WEIGHTED POPULATION MODEL

Population density is estimated using the High Resolution Settlement Layer (FCL and CIESIN 2016), following the same methodology as the population density in the heat stress module.

For each NBS family, jobs and resources production benefits are estimated as:

$$Benefits_{jobs\,resources,i,j} = Population_i \times Suitability_{i,j} \times Weight_j,$$

where the benefits for pixel *i* and NBS family *j* are a function of the weighted population value of pixel *i*, the suitability of pixel *i* to support NBS family *j*, and the weighting value for NBS family *j* that defines the ability of the NBS family to provide benefits relative to others. Example jobs and resources production weights for a subset of NBS families are provided in table A.9.

TABLE A.9: EXAMPLE JOBS AND RESOURCES PRODUCTION WEIGHTS FOR A SUBSET OF NBS FAMILIES

NBS FAMILY	JOBS AND RESOURCES PRODUCTION WEIGHT
Bioretention area	1
Open green space	2
Green corridor	1
Urban farming	3
Urban forest	2

SOURCE: Original table for this publication.

A.2.4.5
SOIL EROSION BENEFITS

Urban NBS can be implemented to stabilize slopes and soils, particularly in mountainous or hilly cities characterized by loose soils or cities with seasonal streambeds susceptible to erosion from water. The NBSOS estimates the potential for NBS creation to mitigate soil erosion by combining annual soil erosion rates with NBS-specific weights characterizing the relative potential for each NBS family to reduce soil erosion.

Annual soil erosion rates are estimated with the Revised Universal Soil Loss Equation (RUSLE). The RUSLE estimates long-term annual soil erosion rates (tonnes $ha^{-1}\,yr^{-1}$) from water as:

$$A = \frac{R}{V} \times K \times \frac{LS}{L},$$

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where *A* is the soil erosion rate, *R* is the rainfall erosivity factor, *K* is the soil erodibility factor, *L* is the slope-length factor, *S* is the slope-steepness factor, and *V* is the vegetation factor. Soil erosion rates are then combined with the NBS-specific weights as:

$$Benefits_{erosion,i,j} = A_i \times Weight_j,$$

where the soil erosion benefits for pixel *i* and NBS family *j* are the product of the soil erosion rate in pixel *i* and the weighting values for NBS family *j*.

A.2.4.6 OTHER BENEFITS

Benefits from the implementation of NBS in cities that do not have dedicated modules within the NBSOS, such as water quality improvement and subsidence regulation, are estimated using matrix weighting models. In these models, relative benefits across NBS families are estimated as a function of NBS suitability and the potential for benefit provision across NBS families, where weights of benefit provision are informed by the World Bank's *Catalogue of Nature-Based Solutions for Urban Resilience* (World Bank 2021). The modular structure of the NBSOS, however, allows for the constant development of additional benefits modules, with new benefits modules regularly developed and implemented to improve benefit estimation.

A.2.4.7 VISUALIZATION AND MAPPING

For each analyzed benefit and NBS family of interest, the benefit values are normalized for pixel *i* and NBS family *j* by the equation:

$$NormalizedBenefit_{i,j} = \frac{Benefit_{i,j} - \min(Benefit)}{\max(Benefit) - \min(Benefit)},$$

such that the normalized benefit index describes values from 0 to 1, where higher values correspond to pixels with a greater potential benefit. The benefits of interest are presented through (1) a series of maps created with the R software environment describing spatial variability in the provision of each benefit across the AOI and (2) a bar graph characterizing the area of feasible NBS creation with the potential to provide low, medium, and high benefit levels (both are available in map 4 in the main report).

Low, medium, and high thresholds are determined for each benefit of interest by first computing the maximum potential benefit level per pixel across all NBS families. The distribution of maximum potential benefits across pixels is then further divided into the 0 to 25th percentile (low benefits), the 25th to 75th percentile (medium benefits), and the 75th to 100th percentile (high benefits).

A.2.5 MAPPING OPTIMAL ALLOCATION OF NBS

In the fourth analysis step, the NBSOS implements a multicriteria analysis to identify spatial variability in optimal NBS families, which can be used to inform an NBS investment plan (see box A.1 for an example of decision support). In practice, creation opportunities for the implementation of NBS interventions such as urban forests, open green spaces, and urban agriculture overlap. However, these NBS interventions will provide different benefits. The multicriteria optimization analysis assigns weights to the different benefits of interest (for example, pluvial flood reduction is more important than heat stress mitigation). These weights are used to estimate variability in combined benefits provision across NBS families with overlapping suitability. The result is a map depicting the optimal allocation of NBS families that maximize combined benefits. The total area of each NBS family in the map of optimal solutions can subsequently be combined with cost estimates of NBS family-specific implementation to estimate a total cost of investment (section A.2.5.2.2).

A.2.5.1 BENEFIT WEIGHTING AND COMBINATION

Benefit weights are determined considering the local context and as a part of task team consultation to choose which benefits are most important in the AOI. Sometimes more than one scenario is proposed (for example, equal benefit weights and heat mitigation with highest weight). Each benefit of interest is assigned a weight (as a percentage) corresponding to its project importance such that all benefits' weight sum to 100 percent. For example, in a project primarily targeting pluvial flood reduction, while also interested in co-benefits of heat stress reduction and improved health/recreation, a flood-heavy weighting scheme may be applied such that flood benefits are assigned a weight of 60 percent and heat stress/health benefits are each assigned weights of 20 percent.

To compute the combined benefits across the AOI for each NBS family, normalized benefit values for each benefit are multiplied by the corresponding weighting value and summed together. For example, in the flood-heavy weighting scheme described above, the normalized combined benefits for NBS family j and pixel i are calculated as:

$$\begin{aligned} &NormalizedCombinedBenefit_{i,j} \\ &\quad = 0.6 \times NormalizedBenefit_{flood,i,j} + 0.2 \times NormalizedBenefit_{heat,i,j} \\ &\quad +0.2 \times NormalizedBenefit_{health,i,j}, \end{aligned}$$

resulting in a combined benefits map for each NBS family of interest.

A.2.5.1.1 MAPPING MAXIMUM POTENTIAL BENEFITS PER PIXEL

The combined benefits maps for the NBS families of interest are merged into a multiband raster for the AOI. To quantify spatial variability in the maximum potential benefits per pixel, the maximum value is calculated across all bands for each pixel in the multiband combined benefits raster.

A.2.5.1.2 SELECTION OF NBS FAMILIES PROVIDING MAXIMUM POTENTIAL BENEFITS

A categorical raster depicting the optimal NBS family per pixel is produced by combining the maximum potential benefits raster with each NBS family-specific combined benefits raster. The optimal NBS family per pixel is defined as the NBS typology providing combined benefits equal to the maximum potential benefits (see map 5 in the main text for an example).

A.2.5.2
ESTIMATE PROJECT INVESTMENT

A.2.5.2.1 REDUCE OPTIMAL NBS MAP TO PERCENTILE DEFINING GREATEST BENEFITS

In most cases, it is not feasible to implement all optimal NBS interventions identified by the NBSOS. The optimal NBS map can be restricted to depict only regions providing the highest level of benefits, defined in consultation with task teams according to budget constraints. Thresholds are assigned based on the distribution of maximum combined benefits, where optimal NBS families and locations providing benefits that fall below the threshold are removed from the map. For example, in the case of identifying the most beneficial 10 percent NBS opportunities, pixels falling below the 90th percentile of values in the maximum potential benefits raster are removed from the analysis prior to selecting NBS families providing maximum potential benefits (section A.2.5.1.2).

A.2.5.2.2 COST ESTIMATION

To estimate the investment cost, unit cost values from previous projects in the region are used for each NBS and converted to US dollars. These values are updated to current values using the Consumer Price Index (CPI). This means that price values for earlier years are corrected for inflation using the cost to the average consumer of acquiring a basket of goods and services that may change yearly.

The correction is performed using the following equation:

$$Cost_{current\ year} = Cost_{project\ year} \times \frac{CPI_{project\ year}}{CPI_{project\ year}},$$

where *project year* is the year of the reference project that provides the reference unit cost values.

The NBS cost estimated considers only capital expenditure (CAPEX) values for each NBS per unit of area or length. The final value is obtained multiplying unit implementation costs and the coverage values corresponding to the percentage of most beneficial NBS opportunities.

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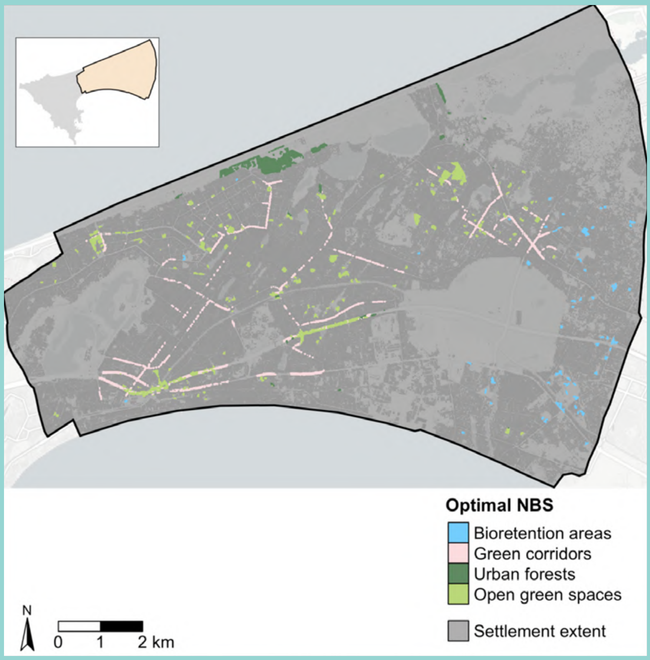
BOX **A.1**

DECISION SUPPORT FOR NBS INVESTMENTS IN URBAN AREAS

Some NBS are suitable for the same space. Multicriteria analysis is applied to select the most effective combination of NBS to maximize the targeted benefits. The distribution in this example corresponds to the case of 60 percent weight for pluvial flood benefits and equal weight of 20 percent for heat stress reduction and improved access to green spaces.

The scenario shown below corresponds to the optimal NBS delivering the 20 percent highest level of combined benefits or, put another way, NBS that provide benefits corresponding to the highest 80th percentile. The needed investment was estimated using unit costs from other projects in the region.



SOURCE: Original map for this publication.
NOTE: The optimal solution comprise the NBS providing the 20 percent highest level of combined benefits. Investment costs were estimated using unit costs from other projects in the same region.

TABLE A.1.1: BREAKDOWN OF NBS INVESTMENT IN GREATER DAKAR

GREATER DAKAR (EAST)	NBS WITH 20% HIGHEST BENEFITS	
	OPPORTUNITY	CAPEX (US$, MILLIONS)
Urban forest	45 hectares	$2.8
Green corridors	50 kilometers	$6.3
Open green spaces	61 hectares	$28.3
Bioretention areas	13 hectares	$31.4
TOTAL INVESTMENT		**$68.8**

SOURCE: Original table for this publication.
NOTE: CAPEX = capital expenditure.

Some recommendations to maximize benefits in this case include:

- The design of multifunctional open green spaces designed for both stormwater detention and recreation.
- The design of multifunctional green corridors, offering opportunities for both social interaction and heat mitigation.

A.3

APPLICATION OF THE NBSOS AS A SERVICE TO WORLD BANK TASK TEAMS

A.3.1 TASK TEAM CONSULTATION

Consultations with Task Teams are held at the beginning of each NBSOS application. During these meetings, different types of relevant information are collected. This helps to provide a customized service, considering local characteristics, necessities, and data.

A.3.1.1 DETERMINATION OF THE AREA OF INTEREST

The AOI usually covers the built-up area, or core city area, along with an extra area defined by the Task Team. If the focus is on flood mitigation, for instance, the AOI might be extended to cover the upper part of the catchment to identify opportunities for NBS to reduce runoff going into the city. When there is an interest in exploring opportunities around the city, a buffer around the urbanized area is defined with the local Task Team to determine the AOI.

A.3.1.2 IDENTIFICATION OF RELEVANT ENVIRONMENTAL HAZARDS AND ASSOCIATED WEIGHTS

The main urban challenges are identified by the local Task Team. Usually, between three and five challenges are selected; the most common are flood reduction, heat stress mitigation, health/recreation improvements, social cohesion enhancement, and the creation of local jobs and resources production.

A.3.1.3
SELECTION OF RELEVANT NBS FAMILIES

Relevant NBS families for each case are also discussed with local Task Teams. Frequently, the definition of local challenges to be addressed determines the main NBS to be studied. For instance, if one main challenge is pluvial flood risk, bioretention areas and open green spaces will be considered among the NBS studied. When heat stress reduction is targeted, urban forests and green corridors are included in the analysis. In some cases, a further discussion about local preferences or characteristics may lead to the identification of specific solutions not identified a priori. For example, the existence of urban streams as part of the urban fabric would lead to a study of opportunities for stream renaturation.

A.3.1.4
AVAILABILITY OF SUPPLEMENTAL LOCAL DATA SETS

The availability of local data to enhance and customize the NBSOS analysis is also discussed with the local Task Team. Even though the analysis can be performed using available global data, the addition of local data can improve some results or their visualization. For instance, population vulnerability data, which usually are not available as open data, can improve flood and heat risk analyses. Administrative divisions data can help to present results per neighborhood or district, helping to better communicate the NBSOS's outputs.

A.3.2
INTERPRETATION, PRESENTATION, AND RECOMMENDATIONS

A.3.2.1
DELIVERABLES

The NBSOS results are delivered as a PowerPoint (PPT) presentation deck, including a summary of NBSOS methodology, context analysis with indices regarding local hazards, and NBSOS results. These results include the identification of priority areas from hazard-exposure analysis, opportunity maps of different NBS, and potential benefits levels obtained from their implementation. Finally, the PPT deck also includes an interpretation of results and recommendations, along with design and implementation considerations for the NBS studied. In addition to the deck, geospatial raster data of suitability of NBS families (such as GeoTIFF), shapefiles describing climate resilience and environmental challenges (flooding, heat, lack of public green space), and indexes that describe the impact of NBS-types mitigating these challenges are also delivered.

A.3.2.2
PRESENTATION TO TASK TEAMS AND CLIENTS

The PPT deck is presented to the Task Team during an online meeting. During this meeting, feedback about the results obtained, their interpretation, and recommendations are collected. These suggestions are integrated into the final files for submission.

A.3.2.3
PARTICIPATORY MODELS FOR CLIENT AND STAKEHOLDER ENGAGEMENT

In some cases, further engagements with local Task Teams include activities to help the use of NBSOS results with local stakeholders. These activities include the presentation of results, interactive activities to facilitate discussions among local actors, support during pre-feasibility studies, and so on.

A.3.2.4
COSTED INVESTMENT PLANS TO INFORM PROJECT APPRAISAL

Optimal NBS maps for highest benefits and estimations of costs can be used to inform project appraisal phases. The main limitation is usually the nonavailability of local data on NBS costs. In many cases, unit cost data from other countries in the region are used, but even this type of data sometimes presents a challenge.

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A.4 NBSOS VALIDATION: NBS FOR FLOOD REDUCTION

A.4.1 INTRODUCTION

The NBSOS uses input flood hazard from Fathom to assess where urban spaces get flooded (Fathom, no date) and, based on this, to determine where to implement NBS to reduce pluvial flooding. Therefore, the input data on flood hazard have a high impact on the definition of priority areas for NBS implementation for flood reduction and on the assessment of the level of benefits obtained from the proposed solutions. One way to validate the exercise's objectives is to evaluate the accuracy of the flood hazard data used.

Using data on flood hazards, the NBSOS estimates catchment areas contributing to flooded areas to establish where the implementation of NBS for runoff reduction could have a high impact on reducing this problem (priority area). Another objective of this validation exercise is to assess whether the areas identified as priority areas by the NBSOS are also seen as priority areas for NBS implementation by a local in-depth study.

Finally, the NBSOS estimated degradation levels of urban green spaces to classify areas as protection areas (low degradation) and creation areas (high degradation). There is a third category implicitly included in the NBSOS results—sometimes green spaces classified as protection areas have room for enhancement. This means that green spaces with low degradation level can still be enhanced by designs to, for instance, increase storage capacity and recreation opportunities. The last objective of the validation is to compare NBSOS results on protection and creation with solutions proposed by the local study.

A.4.2 OBJECTIVES

This validation comprises three parts:

1. One of the main factors driving the output of the NBSOS is the input flood maps employed in the analysis. For this reason, this part of the validation focuses on assessing how the input flood hazard areas, which are Fathom flood maps version 2 (Fathom, no date), compare to the flood maps obtained from a locally calibrated hydrodynamic model with higher resolution and accuracy.

2. The second part of the validation compares areas identified by the NBSOS as being of high priority to allocate NBS for flood reduction with areas where the local study recommends the implementation of sustainable urban drainage.

3. The third part focuses on evaluating the NBS suitability obtained using the NBSOS by comparing protection and creation recommendations with recommendations from the local study regarding flood reduction solutions.

The second and third parts aim to assess the accuracy of the output produced by the NBSOS. The comparison is performed against the outputs obtained from an analysis that used higher resolution data, exploited in-situ data, and elicited local stakeholders' knowledge to calibrate and validate the results.

A.4.3 DESCRIPTION OF LOCAL STUDY USED FOR COMPARISON

The project Flood and Coastal Risk Assessment and Priority Investment Planning for Greater Banjul was part of a technical assistance (TA) to the government of The Gambia led by the World Bank and funded by the Africa Caribbean Pacific (ACP) – EU Natural Disaster Risk Reduction (NDRR) Program through the World Bank Global Facility for Disaster Reduction and Recovery (GFDRR). The overall objective of the TA was to deliver an assessment of the flood and coastal risks in the Greater Banjul Area (GBA) and the Kombo North/Saint Mary district and to identify and prioritize, in a participatory way, measures and infrastructure investments, including NBS.

To accomplish the goals of the project, the Dutch firm Royal Haskoning DHV was hired by the World Bank's Task Team to conduct the necessary assessments. Flood and coastal erosion hazard were assessed through advanced inundation modeling and analysis of satellite images and validated with the stakeholders. Future natural hazards were estimated by extrapolation of trends in combination with the recent climate change projections from the Intergovernmental Panel on Climate Change (IPCC) 5th assessment report for time horizons 2040 and 2070. The resulting hazard maps were combined with the land use maps and damage functions to estimate the vulnerability and risk (economic and social) related to these hazards. The mapped risks were used as input to the development of investment options: packages of strategic measures that were prioritized through a multicriteria analysis and a cost-benefit analysis. Finally, recommendations for selected investments and their priorities were prepared.

Flood model simulations were run for different recurrence periods ranging from 0.4-year to 200-year and for different time horizons (2020, 2040, 2070) to get a full picture of inundation extents and depths. The results of hazard and risk assessment were used to identify hotspot areas (where the risk level is the highest) for which an integrated strategy with a corresponding package of risk mitigating measures was developed (including structural, nonstructural, and nature-based options).

Despite certain limitations—in particular, the fact that the area has a flat topography constitutes a challenge for the flood model—the outputs of this assessment can be considered to be of high accuracy given the accuracy and high resolution of the data employed and the validation steps employed in the overall process. Moreover, the goal of the study overlaps with the scope of the NBSOS. Therefore, we used these outputs as a benchmark to assess the quality of the NBSOS.

A.4.4 RESULTS

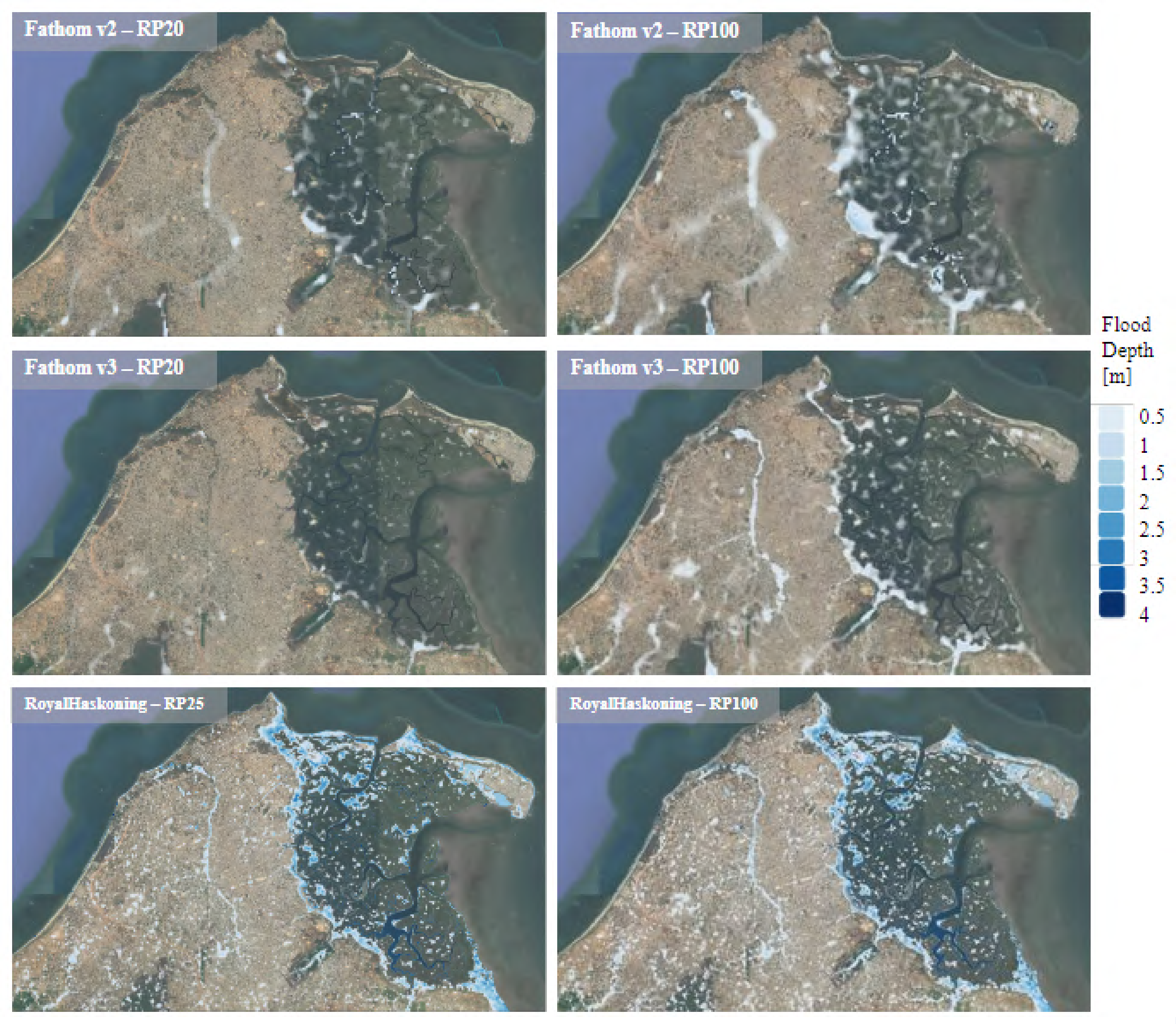
A.4.4.1 FLOOD HAZARD VALIDATION

In this assessment, different return period (RP) flood maps for the Greater Banjul Area, The Gambia, obtained from Fathom v2, Fathom v3, and a calibrated hydrodynamic model (see section A.4.3 are compared (map A.1). Results for both 20- and 100-year return periods show that Fathom data accurately represents flood areas along the main drainage system, not fully representing smaller surfaces of decentralized flooding. This is an expected result due to resolution differences in the models, while Fathom has a resolution of 90 meters and 30 meters, respectively, for versions 2 and 3, the case-specific model uses a 2.5-meter resolution. For this case, better accuracy is shown by Fathom v3 in the case of RP100. However, Fathom v2 shows better results for the case of the 20-year return period.

A.4.4.2 PRIORITY AREAS FOR NBS CREATION

Another result obtained from the NBSOS is the identification of priority areas where it would be most effective to allocate NBS for flood reduction. These areas are shown by the hexagons in shades of green in map A.2, where the darker the green the higher the priority. The map also shows areas recommended by the local study where to implement sustainable urban drainage systems (SUDS), which is another name given to NBS specifically applied for urban drainage. Comparing both recommendations, the NBSOS recommends implementing NBS mainly in areas also identified by the local study. It is important to note that the local study looks at the availability of spaces, resulting in more precise recommendations.

MAP A.1: FLOODED AREAS IN BANJUL, THE GAMBIA, BY FATHOM V2 (UPPER MAPS), FATHOM V3 (MIDDLE MAPS), AND LOCAL HYDRODYNAMIC MODEL (LOWER MAPS), FOR THE CASES OF 20 YEARS (LEFT) AND 100 YEARS (RIGHT) RETURN PERIODS



SOURCE: Original maps for this publication based on Fathom v2 and v3 data and local model data.
NOTE: SUDS = sustainable urban drainage systems.

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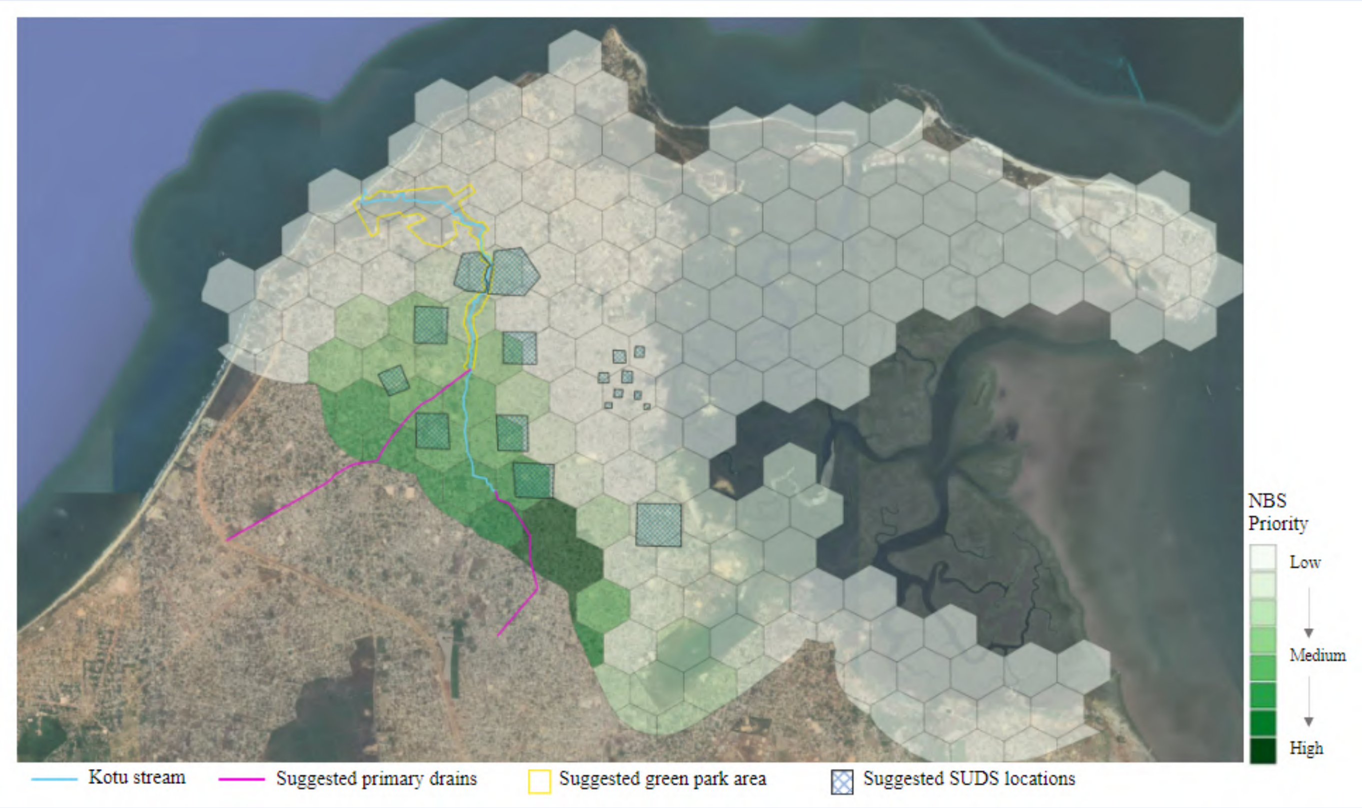
MAP A.2: COMPARISON BETWEEN AREAS IN BANJUL, THE GAMBIA, IDENTIFIED BY THE NBSOS AS HIGH PRIORITY FOR NBS IMPLEMENTATION (GREEN) AND AREAS FOR SUDS IMPLEMENTATION RECOMMENDED BY THE LOCAL STUDY

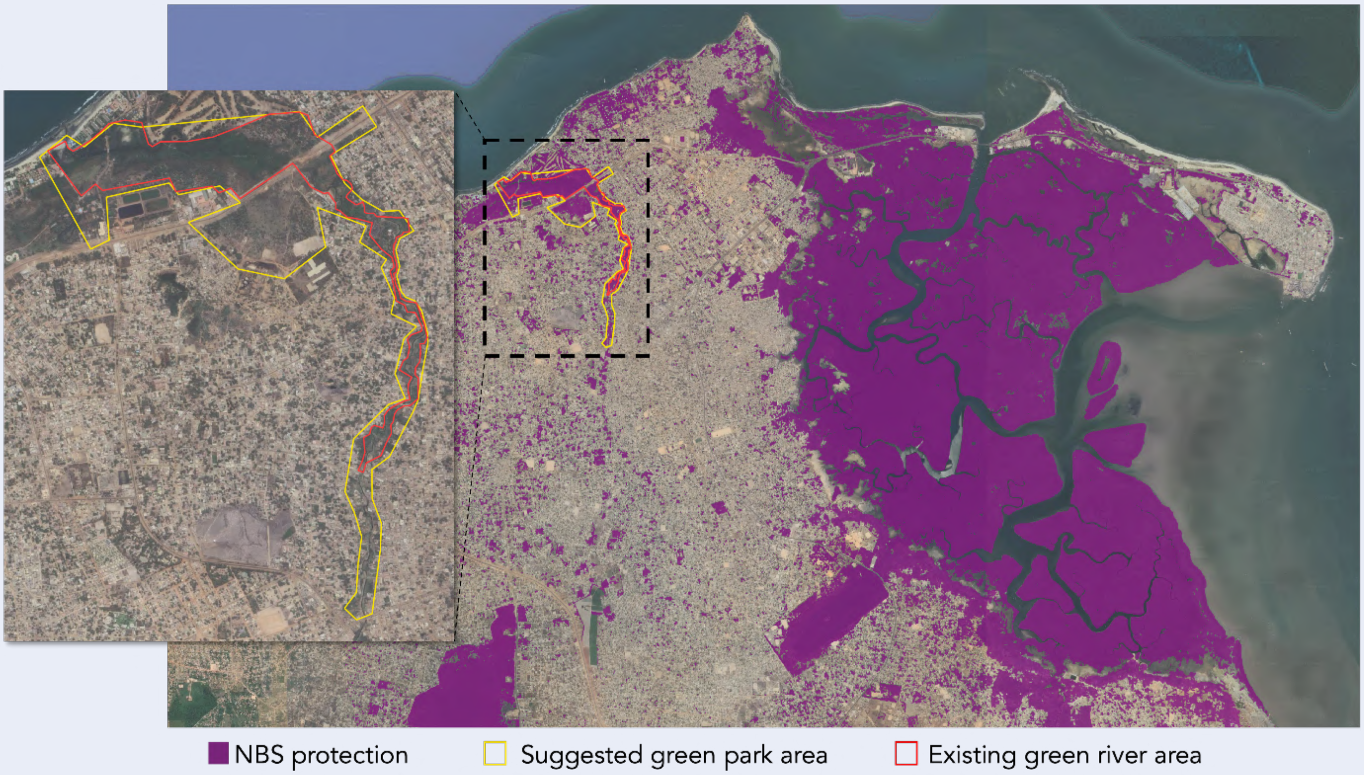


SOURCE: Original map for this publication based on NBSOS data and local study data.
NOTE: NBS = nature-based solutions; NBSOS = Nature-Based Solutions Opportunity Scan; SUDS = sustainable urban drainage systems.

A.4.4.3 SUITABILITY FOR NBS PROTECTION AND CREATION

Finally, an output from the NBSOS suitability analysis is the identification of areas for NBS protection, which have existing green spaces in good condition. The NBSOS also identifies areas for NBS creation, which are bare areas or areas with green spaces in bad condition. Map A.3 shows green space areas (depicted in purple) identified as opportunities for NBS protection. The map also shows (in red) the area identified by the local in-depth study as an opportunity for creating a green park along the river. Even though the NBSOS identifies this area as suitable for protection and not creation, the results are comparable. The area is a green space in good condition, and creating a park would protect it from being urbanized or degraded and enhance it to provide more benefits than it currently does.

MAP A.3: NBS PROTECTION AREAS IN BANJUL, THE GAMBIA, DEFINED BY THE NBSOS (PURPLE), AND IN YELLOW, THE GREEN PARK SUGGESTED BY THE LOCAL STUDY



SOURCE: Original map for this publication based on NBSOS data and local study data.

A.4.5 CONCLUSIONS

The flood model validation exercise provides evidence supporting the use of global flood maps in the NBSOS to identify high-priority areas to target flood mitigation through NBS.

- Flood maps: Despite the difference in accuracy between the Fathom global model and the local one, the main hazard characteristics are captured and factored in the NBSOS. Fathom v3 shows a great improvement in resolution and accuracy, which will be reflected in the accuracy of future NBSOS.

- NBSOS high-priority areas: Despite the huge difference in terms of resolution and accuracy between the inputs used by the NBSOS (global and low-resolution data) and the ones used by the local study (in-situ and high-resolution data), the NBSOS can correctly identify the main hotspots for risk reduction, and it is able to suggest similar recommendations regarding NBS creation, protection, or enhancement.

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THE NATURE-BASED SOLUTIONS OPPORTUNITY SCAN

APPENDIX B: DETAILED METHODOLOGY OF THE COASTAL NBSOS REPORT

GLOBAL PROGRAM ON NATURE-BASED SOLUTIONS FOR CLIMATE RESILIENCE
PROBLUE
HEALTHY OCEAN · HEALTHY ECONOMIES · HEALTHY COMMUNITIES
GFDRR
Global Facility for Disaster Reduction and Recovery
Administered by THE WORLD BANK
IBRD · IDA | WORLD BANK GROUP

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ABBREVIATIONS AND ACRONYMS

AOI area of interest
API Application Programming Interface
BCR benefit-to-cost ratio
CBA cost-benefit analysis
CMIP6 Coupled Model Intercomparison Project Phase 6
COG Cloud-Optimized GeoTIFF
EAAD expected average annual damage
EAAP expected annual affected population
EO Earth observation
ESVD Ecosystem Services Valuation Database
GCS Google Cloud Storage
GDP gross domestic product
GEE Google Earth Engine
HyCreWW Hybrid Coral Reef Wave and Water level
MPA marine protection areas
NBS nature-based solutions
NBSOS Nature-Based Solutions Opportunity Scan
NDVI Normalized Difference Vegetation Index
PPP purchasing power parity
RCP Representative Concentration Pathways
SCC social cost of carbon
SFINCS Super-Fast INundation of CoastS
SSP2 Shared Socioeconomic Pathways 2
tCO_2/ha/year tonnes of carbon dioxide per hectare per year
WTP willingness to pay

All dollar amounts are US dollars unless otherwise specified.

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B.1 OVERVIEW OF PRODUCT, APPLICATION, AND METHODOLOGY

B.1.1 OVERVIEW

The coastal Nature-Based Solutions Opportunity Scan (NBSOS) identifies investment opportunities for protecting and enhancing mangroves, coral reefs, and beaches. This scanning tool highlights locations with high potential for coastal nature-based solutions (NBS) and quantifies the benefits of NBS in terms of climate change–exacerbated flood-risk reduction, tourism, blue carbon, and fisheries, among other ecosystem services. By estimating benefit-to-cost ratios (BCRs), the tool can support World Bank Task Teams, governments, and other investors to understand which NBS families have the most potential, identify potential project sites, and determine which ones provide the highest benefits. The NBSOS outputs and deliverables—including results, interpretation, recommendations, and a geospatial data package—can be prepared in approximately six weeks.

The coastal NBSOS utilizes an array of openly available medium resolution (10- to 30-meter) Earth observation data and other geospatial data sets as inputs into an analytical workflow consisting of four methodological steps (see figure 2 in the main text for a graphic representation of the steps). The first step is understanding the problem: what is the spatial distribution and magnitude of coastal flood risks due to storms, surges, and climate change? The second step maps suitable areas for NBS (mangroves, coral reefs, and beaches) and the third step models and estimates benefits and costs of the possible NBS intervention to quantify BCRs. Finally, in the fourth step, it provides decision support through multicriteria and cost-benefit analyses. This appendix describes the geospatial data sets and models that constitute the coastal NBSOS (section 2) and outlines the deliverables of the coastal NBSOS as a service to World Bank Task Teams (section 3). The coastal NBSOS runs primarily in Python, with data and end products stored in Google Cloud Storage (GCS).

B.1.2

NBS SCENARIOS

The benefits and costs of coastal NBSOS are valued by comparing the present-day situation to future scenarios that account for sea-level rise, economic and demographic growth, expected ecosystem degradation, and potential effect of ecosystem protection and ecosystem enhancement by NBS. The NBS scenarios include changes in extent and condition of ecosystems, from degradation by anthropogenic action or, alternatively, from enhancement through NBS interventions. Those future scenarios consider a timeframe up to the year 2050.

Given the uncertainties about how ecosystems could evolve in the future as a result of environmental and anthropogenic factors, and to facilitate comparability between different NBS, the approach compares the effect of losing and gaining 20 percent of the performance of each ecosystem through degradation and NBS enhancement, respectively. Furthermore, each typology of NBS is modeled independently, allowing a spatially explicit valuation of the services of each NBS and ecosystem at each coastal segment (see the example in map B.5 for coral reefs in Mombasa, Kenya).

Nacala
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B.2 METHODOLOGY

B.2.1 SUMMARY OF THE METHODOLOGY

To understand the problem, the increase in coastal flood risks due to climate change and growing socioeconomic exposure is calculated for coastal areas by modeling the flood extent during coastal storms with the SFINCS (Super-Fast INundation of CoastS) hydraulic model) (Leijnse et al. 2021). The resulting flood maps are overlaid with data sets of population and building footprint to quantify population and residential buildings affected by flooding during storm events.

To map NBS suitability, potential NBS sites are identified via geospatial modeling of publicly available Earth observation (EO) and geospatial data sets. These data sets provide information about the current ecosystem cover, land cover, topographic, and bathymetric data. The NBS suitability assessment generates maps showing potential sites for NBS protection and enhancement.

To model NBS benefits, the flood benefits of potential NBS sites are modeled in SFINCS, while the other co-benefits (tourism, blue carbon, and sustainable resource extraction, among others) are calculated using regression functions fitted to NBS benefit estimations from other projects. BCRs are estimated to identify locations where NBS investment would have the highest economic returns; the full methodology of the scanning tool is illustrated in figure 6 in the main text. In that figure, Step 1 is to understand and quantify the extent of coastal flood hazards in the baseline situation; the hydraulic model SFINCS is used to predict flood extent reduction using climate forcing (waves, extreme water levels, and scenarios of sea-level rise). Step 2 maps NBS suitability for mangroves, coral reefs, and beaches; data sets of the spatial domain (showing current topography, bathymetry, land uses, ecosystem presence) are used as input of the NBS suitability. Step 3 models NBS benefits, and SFINCS is applied to quantify coastal flood reduction by NBS interventions.

Additional co-benefits are calculated using regression functions fitted to NBS estimations from other projects. Step 4 supports decisions, and BCRs are calculated and mapped for scenarios with NBS.

To support decisions, maps showing the potential location of different NBS projects and illustrating their BCRs are provided.

B.2.2 OVERVIEW OF SOFTWARE/CODING SCHEME

The coastal NBSOS steps have been implemented in a pseudo-automatic framework in Python that streamlines the sourcing of input data, flood model setup and simulations, assessment of scenarios, and the spatial distribution of co-benefits and BCRs of NBS opportunities. The steps are described below.

B.2.2.1 DOWNLOADING INPUT DATA

The coastal NBSOS first identifies suitable land to support NBS protection and enhancement to assess potential NBS and their benefits by synthesizing publicly available EO data. To ensure access to both recent and historical EO data, EO data are obtained through the Google Earth Engine (GEE), which provides access to a multi-petabyte catalogue of remote sensing data that ranges from raw satellite observation bands to analysis-ready land cover products. The GEE's Python Application Programming Interface (API) is used for a seamless integration of data acquisition in the coastal NBSOS Python framework. The tool uses a custom area of interest (AOI) that extends at least 4 kilometers into the ocean and an area inland defined by the user (for example, administrative boundaries). All data layers (table B.1) are downloaded from GEE except for three OpenStreetMap data layers, which are downloaded using the OSMnx Python library (Boeing 2024).

TABLE B.1: DATA LAYERS OF THE COASTAL NBSOS FROM GOOGLE EARTH ENGINE

DATA LAYER	DATA SET NAME AND SOURCE
Coral reef extent	Allen Coral Atlas (Allen Coral Atlas 2022)
Mangrove extent	Global Mangrove Watch (Bunting et al. 2022)
Land cover	ESA World Cover (Earth Engine Data Catalog, no date-a)
Surface water	JRC Global Surface Water (Pekel et al. 2016)
	OpenStreetMap (OpenStreetMap Contributors 2023)
Built-up land	Google Buildings (Sirko et al. 2021)
	World Settlement Footprint (Marconcini et al. 2020)
Soil characteristics	ISDA Soil Properties (Africa) (Hengl et al. 2021)
	Open Land Soil Texture (Hengl 2018)
	SoilGrids (Poggio et al. 2021)
Elevation	FABDEM (Hawker et al. 2022)
Roads	OpenStreetMap (OpenStreetMap Contributors 2023)
Population	High Resolution Settlement Layer (FCL and CIESIN 2016)

SOURCE: Original table for this publication.

B.2.2.2
EO INDICATORS

The EO data derived from GEE are used in the development of spatial raster layers describing environmental indicators that form the basis of the NBSOS' subsequent modules. Examples of environmental indicators are the Land Capability Classification Index (Quandt et al. 2020), tree canopy cover, and bare soil frequency (see section 2.3). Analysis-ready indicators are centrally stored as Cloud-Optimized GeoTIFF (COG) spatial raster format files in GCS, where data can be accessed via Python by each module in the coastal NBSOS.

B.2.3
MAPPING PRIORITY AREAS

The mapping of priority areas consists of identifying high-impact areas for NBS investment within the AOI, which is guided by two main questions: (1) Where is hazard risk highest? and (2) Where could NBS be implemented to reduce hazard risks most effectively? In other words, this step focuses on characterizing the flood and erosion hazards and building and infrastructure exposed.

B.2.3.1
COASTAL FLOODING

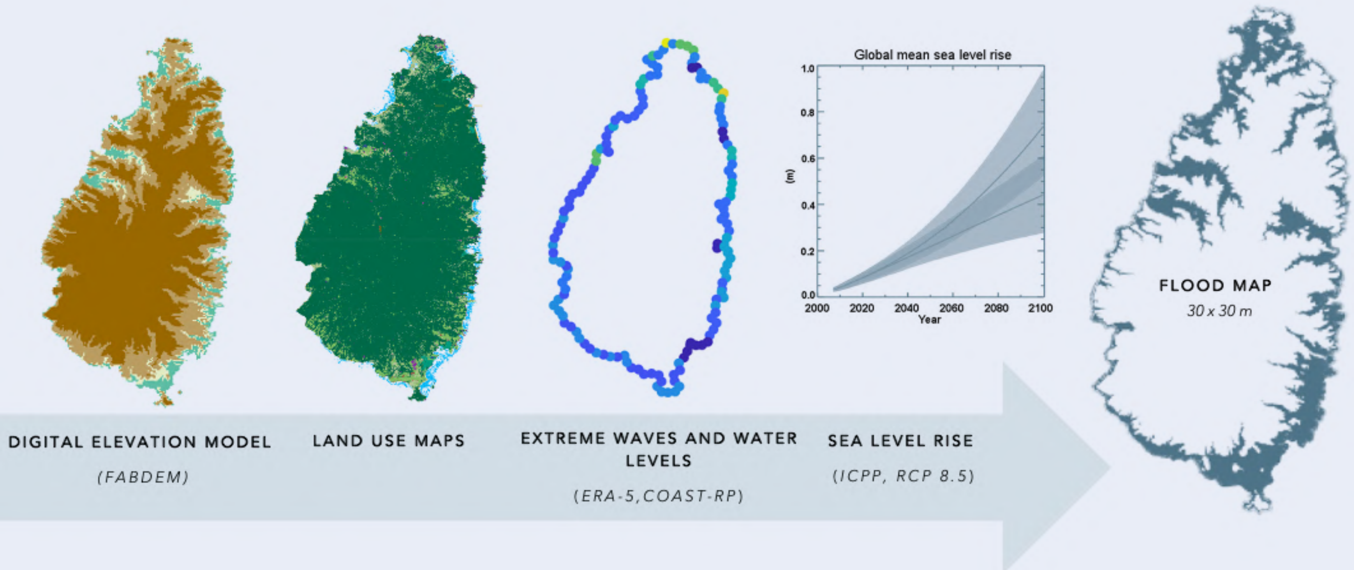
Coastal flooding is characterized by the combination of storm surges, wave action, and sea-level rise. Flooding in the coastal NBSOS is simulated using the hydraulic model SFINCS, a reduced-physics solver that can simulate 2D compound flooding in coastal regions accurately but with low computational time (Leijnse et al. 2021). SFINCS has been applied and validated across various geographies, research studies, and projects (Deltares 2020; Röbke et al. 2021; Sebastian et al. 2021). In the NBSOS, the model is run for different climate forcing scenarios (for example, climate change) and geospatial scenarios (for example, NBS options). The resulting flood maps for each scenario are overlaid with population and building exposure, which allows a spatial identification of exposed population and buildings.

B.2.3.2
INPUT DATA DESCRIPTION AND PROCESSING

The flood model domain is defined using FABDEM (Hawker et al. 2022) topographic data and bathymetric data calculated from Sentinel-2 imagery. Extreme waves are obtained from the ERA-5 climate reanalysis (Hersbach et al. 2018) and water levels from the COAST-RP data set (Dullaart et al. 2022) that provides extreme sea levels associated with return periods between 1 and 100 years. Future scenarios in the tool include water levels that contain local sea-level rise estimates and changes in extreme water levels associated with the Representative Concentration Pathway (RCP) 8.5 scenario (Solomon et al. 2007).

The flood model factors in different ground roughness values associated with existing land uses. The effects of these land uses, including ecosystems, modify the flood propagation inland by changing the bottom (ground) friction, hydraulic flows, and inundation patterns. Furthermore, coastal ecosystems can also reduce wave-driven water levels through wave breaking and frictional effects. These effects are included in the model by decreasing the input water levels applied in SFINCS based on specific parameterizations described below. In the baseline scenario, the effect of existing coastal ecosystems on coastal flooding is included through additional ground roughness (that is, flood reduction) and by decreasing the wave-driven water levels according to estimates based in literature (Medeiros 2023; Zhang et al. 2012) and detailed hydrodynamic studies. An example of the input data sets for modeling in SFINCS is shown in map B.1.

MAP B.1: SUMMARY OF THE METHODOLOGICAL STEPS TO ASSESS FLOODING IN THE COASTAL NBSOS TOOL IN SAINT LUCIA

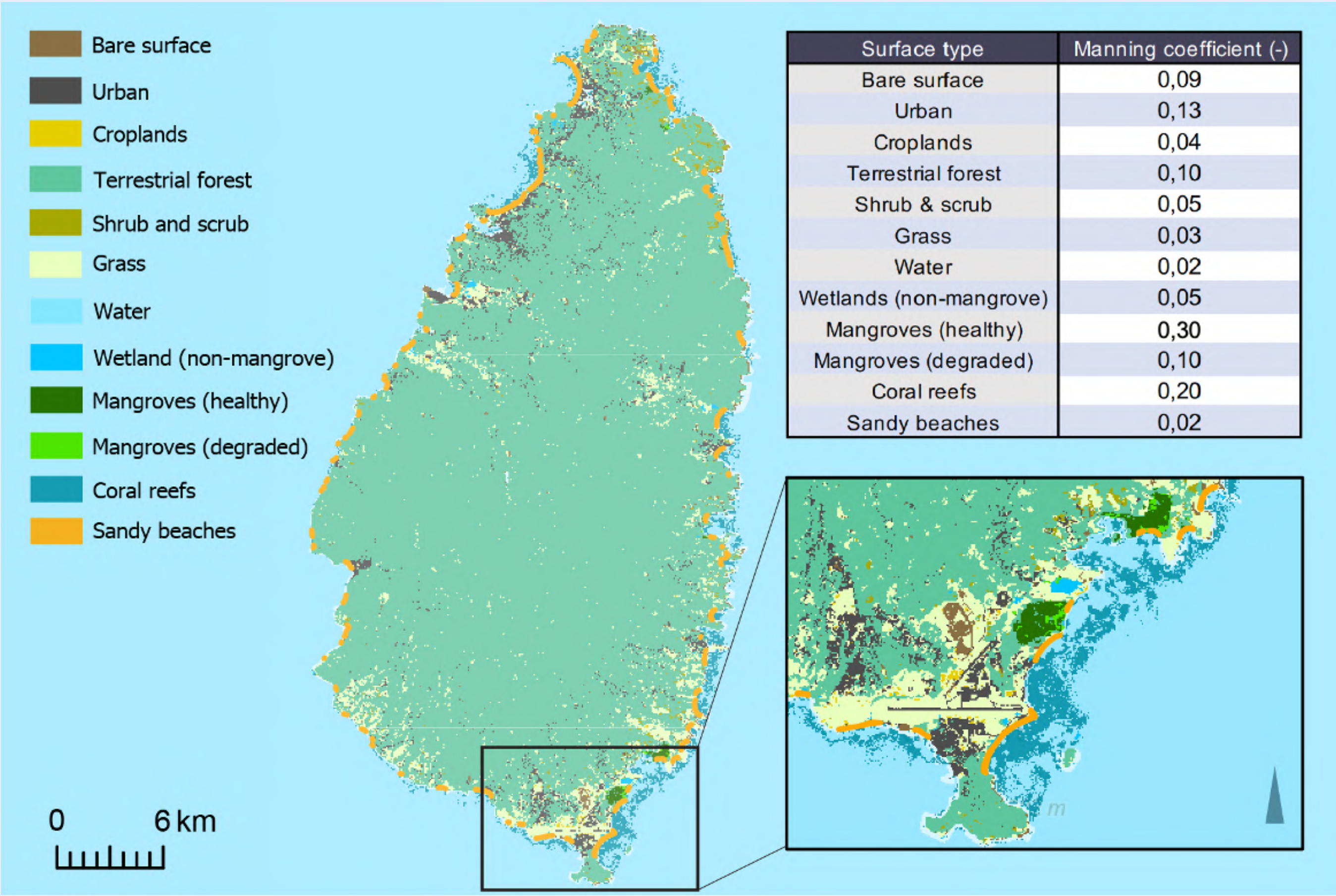


SOURCE: Original map for this publication, based on NBSOS data.
NOTE: Inputs to the flood model are a digital elevation model, spatial distribution of land uses, information on waves and water levels, and projections of sea-level rise and storm surge for future climate scenarios. The model output consists of a flood map with water depths at a horizontal resolution of 30 × 30 meters.

B.2.3.3
EFFECT OF COASTAL ECOSYSTEMS ON BOTTOM FRICTION

When modeling flood inland, water flows will experience more resistance at locations with many obstacles or relatively more bottom roughness (for example, a dense mangrove forest) but will face less resistance in areas with bare ground (lower bottom roughness) and channels, where the flow is unobstructed and the water deeper. For this reason, the effect of coastal ecosystems on bottom friction is implemented through different values of the land use roughness using Manning friction coefficients, based on the literature (Zhang et al. 2012) (see the table in map B.2). In the scenarios of the baseline situation, existing ecosystems are given Manning friction coefficients based on present-day land use maps (year 2020), which correspond to values of 0.3 for healthy mangroves (Medeiros 2023); 0.1 for degraded mangroves; 0.2 for coral reefs; and 0.02 for sandy beaches (see map B.2 for an example).

MAP B.2: **EXAMPLE OF A LAND USE MAP FOR THE BASELINE SITUATION IN 2020 AND MANNING COEFFICIENT FOR THE DIFFERENT LAND USES IN THE BASELINE SITUATION IN SAINT LUCIA**



Surface type	Manning coefficient (-)
Bare surface	0,09
Urban	0,13
Croplands	0,04
Terrestrial forest	0,10
Shrub & scrub	0,05
Grass	0,03
Water	0,02
Wetlands (non-mangrove)	0,05
Mangroves (healthy)	0,30
Mangroves (degraded)	0,10
Coral reefs	0,20
Sandy beaches	0,02

SOURCE: Original map for this publication, based on NBSOS data.

B.2.3.4
EFFECT OF COASTAL ECOSYSTEMS ON WAVE RUN-UP

Although SFINCS is a reduced-complexity model capable of estimating flooding inland, the model is based on the shallow-water equations (similar to Delft3D and other flood physics-based models) and it is unable to simulate wave hydrodynamics in the surf zone and swash processes that are critically influenced by ecosystems such as reefs, mangroves, and beach and dune systems. To address this, the NBSOS represents wave effects on water levels using formulations that estimate wave run-up (defined as an increase in the mean water level from wave processes, which depends on the magnitude of offshore wave parameters, the topography of the coast, and wave propagation in the surf zone). Wave effects on the water levels by coral reefs and beaches are calculated using two separate methods.

For coral reefs, the NBSOS uses the Hybrid Coral Reef Wave and Water level (HyCreWW) metamodel (Rueda et al. 2019), which was built based on a large set of run-up estimations for different reef morphologies, beach slopes, and wave and water-level conditions (Pearson et al. 2017). The metamodel calculates the top 2 percent of wave run-up ($R_{2\%}$), including the effects of wave setup, very low frequency waves, and infragravity waves. Run-up estimates are calculated as a function of several input parameters (offshore water level, offshore wave height, offshore wavelength, fore reef slope, reef flat width, beach slope and coefficient of friction). To assess the impact of corals on predicted run-up, two computations are performed: one with the current width of the reef intact and another where the reef disappears, reducing its width to zero due to degradation. This comparison enables the calculation of run-up reduction attributed to the reef. Subsequently, this reduction is adjusted based on the NBS scenario and the assumed condition of coral health.

Differently, for beaches, the Stockdon formula is applied (Stockdon et al. 2006. This formula was derived through field measurements and empirical data and is widely applied in coastal engineering. It computes the elevation exceeded by only 2 percent of all run-up or swash events ($R_{2\%}$) as a function of offshore wave height, offshore wavelength, and beach slope.

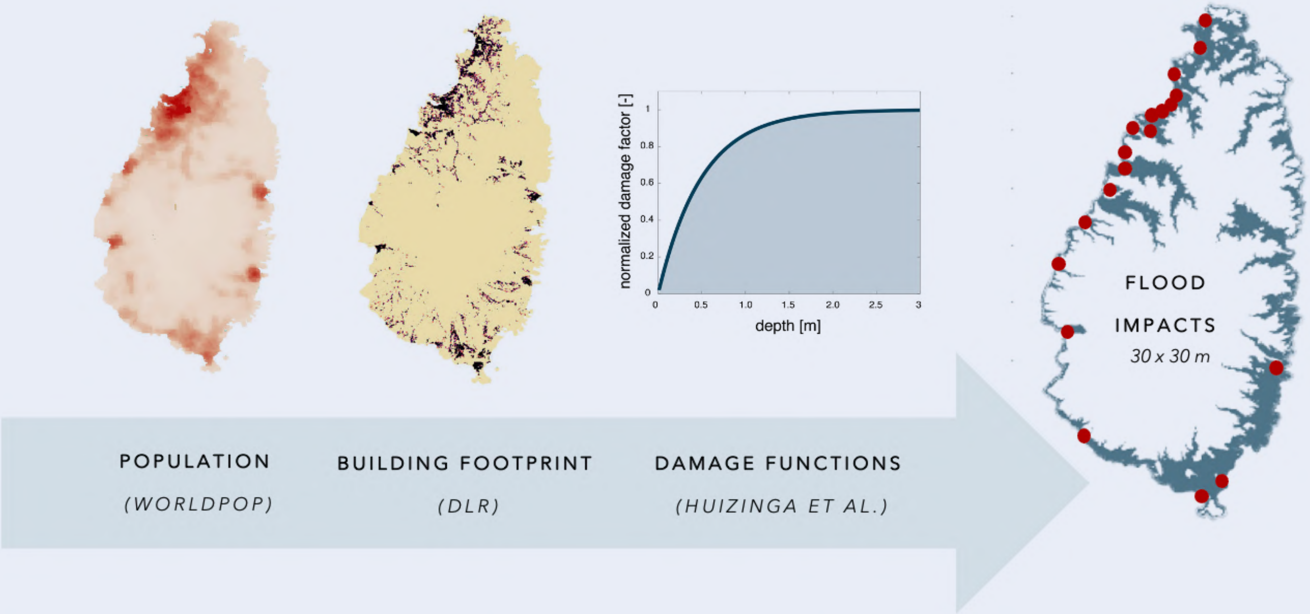
The effect of mangroves on wave run-up is disregarded because there are no comparable run-up data sets for mangroves in the literature and their effects are included in the flood model through bottom friction. In the baseline scenario, wave run-up is estimated using the ecosystem extent of 2020, water-level data from the COAST-RP data set, wave data from ERA-5, reef widths and mean water depths obtained from the Allen Coral Atlas (2022), and reef and beach characteristics (beach slope, fore reef slope) from local fieldwork studies.

B.2.3.5
ESTIMATION OF FLOOD RISK AND PRIORITY AREAS

The flood maps are combined with spatial distribution of population and buildings (map B.3). The population within flood-prone areas is obtained from High Resolution

Settlement Layer (FCL and CIESIN 2016). Exposed residential buildings are identified using the building area from the World Settlement Footprint (Marconcini et al. 2020), which provides the building coverage in a 90-meter grid. This information is combined with a vulnerability (or damage) curve that estimates the economic value. The method to assess assets at risk is explained in more detail below. The methods to identify population and buildings at risk of coastal flooding are explained below.

MAP B.3: STEPS FOR FLOOD RISK CALCULATIONS IN SAINT LUCIA



SOURCE: Original map for this publication, based on NBSOS data.
NOTE: Flood maps of SFINCS are overlaid with population data sets from High Resolution Settlement Layer and World Settlement Footprint to obtain the inundated population and residential buildings for each extreme event. The value and degree of damage of buildings is estimated using the methodology of Huizinga, De Moel, and Szewczyk 2017. Lastly, the expected annual affected population (EAAP) and expected average annual damage (EAAD) are calculated by trapezoidal integration of the different return periods for each year.

For each flood scenario, the affected population and expected damages are calculated. The expected annual affected population (EAAP) impacted by flooding is estimated by overlaying the flood maps obtained from SFINCS with population data from the High Resolution Settlement Layer (FCL and CIESIN 2016) and integrating the population (P_i) within flooded areas for different return periods (T_i, where i corresponds with return periods of 1–100 years):

$$EAAP = \frac{1}{2}\sum_{i=1}^{n}\left(\frac{1}{T_i} - \frac{1}{T_{i+1}}\right)(P_i + P_{i+1}).$$

The expected average annual damages (EAAD) due to flooding are computed in several steps:

- **Calculation of maximum damage due to flooding.** The maximum damage is calculated by multiplying the number of buildings within the flood hazard zones (from the World Settlement Footprint, Marconcini et al. 2020) by the building value of each country and by a depreciation factor of 0.6 (Huizinga, De Moel, and Szewczyk 2017). Here all buildings are considered as residential, assuming that this is the most common building use.

- **Calculation of damage using flood-damage curves.** The maximum damage values are multiplied by an average damage curve, which provides the degree of damage as a function of the local water depth. We assume a linear increase in damage from 0 to 100 percent between a water depth of 0 and 4 meters, and 100 percent damage for water depths greater than 4 meters.

- **Calculation of expected annual values of damages.** The expected average annual damages ($EAAD$) are obtained by the integration of the damage values (D_i) from different return periods (T_i, varying between 1 and 100 years), according to:

$$EAAD = \frac{1}{2}\sum_{i=1}^{n}\left(\frac{1}{T_i} - \frac{1}{T_{i+1}}\right)(D_i + D_{i+1}).$$

The process outlined above can be applied to present-day distribution of people and buildings to characterize assets currently at risk. However, coastal development in flood prone areas can be a major factor of risks, especially given the economic and demographic concentration in coastal areas, as historically demonstrated by growth patterns in coastal cities (World Bank 2022). For this reason, the coastal NBSOS also considers future changes in exposure by assuming that the locations of population and assets stay the same as in the year 2020, but the building value is adjusted at the same rate as gross domestic product (GDP) projections (Shared Socioeconomic Pathways 2, or SSP2), since GDP has been historically correlated with built-up stock values. Comparison of the expected annual affected population and expected average annual damage between 2020 and 2050 enables the identification of locations with increasing flood risk due to climate change.

B.2.4
MAPPING NBS SUITABILITY

B.2.4.1
SUITABILITY CRITERIA FOR NBS PROJECTS

For mangroves, the NBS scanning tool identifies two types of interventions: (1) conservation of mangroves by protecting areas where they exist today and remain healthy; and (2) restoration (enhancement) of mangroves at locations where they exist at present but are sparse, and also at locations where they may have been in the past but need an addition of environmental enablers to assist their restoration (sites within 100 meters of existing mangroves and at most 100 meters inland from the coastline, as a proxy for intertidal areas).

In the NBS scenarios, it is assumed that healthy mangrove areas are preserved and that potential enhancement sites are vegetated and, therefore, are able to perform as healthy mangroves. For consistency across areas, the coastal NBSOS uses the Global Mangrove Watch (Bunting et al. 2018) as the most recent mangrove distribution data to identify the present-day spatial mangrove extent (the reference year is 2020). Subsequently, historical and current characteristics of soil and land cover are used to identify healthy mangroves (that is, suitable for conservation) and less healthy mangroves that could be restored (that is, suitable for enhancement).

Categorization of mangrove regions into areas either suitable for preservation or enhancement is based on two EO indicators: (1) the bare soil frequency and (2) the productivity performance indicator. The *bare soil frequency indicator* is calculated as the number of bare soil observations from Sentinel-2 satellite data divided by the number of cloud-free Sentinel-2 observations for each pixel within the two most recent years of data (Earth Engine Data Catalog, no date-b). The productivity performance indicator aims to describe the vigor of existing

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vegetation in the city. The *performance productivity indicator* is calculated for each unique combination of landcover and soil texture within the AOI. For pixels within each unique landcover and soil texture combination, the mean Normalized Difference Vegetation Index (NDVI) is calculated for each pixel for the most recent year of Sentinel-2 observations and is divided by the 95th percentile of mean NDVI across all pixels in the landcover/soil texture class such that higher values represent greener vegetation.

For both indicators, a Jenks natural breaks clustering algorithm creates rasters categorizing pixels into integer classes (from 1 to 5), where values equal to 1 represent the most degraded land within the AOI (high bare soil frequency or low productivity performance) and values equal to 5 represent the greenest regions within the AOI (low bare soil frequency or high productivity performance). The clusters are added together to create a new raster with values ranging from 2 to 10, with lower values representing more degraded land and higher values representing existing green space to protect. The combined bare soil clusters of frequency/productivity performance are manually inspected to identify a threshold (integer value) that separates current mangrove areas suitable for protection or enhancement.

Areas outside of current mangrove extent that could be suitable for enhancement are identified by filtering out all contiguous mangrove extent areas of at least 1 hectare and creating a 100-meter-wide buffer zone around them. Within these zones, pixels with a slope under 2 degrees, lower than 10 meters above mean sea level, without obstacles (no buildings or roads), and within 100 meters of a land pixel are identified as potentially suitable locations for mangrove enhancement and restoration.

For coral reefs, potential enhancement and protection sites are identified based on the presence of coral reefs in shallow-water areas close to shore (between the shoreline and the 3-meter isobath) since these are most effective for flood reduction purposes and are locations where reef restoration, including artificial reefs, could be implemented (Reguero et al. 2018; Roelvink et al. 2021). Coral reef presence is identified using global coral reef extent data from the Allen Coral Atlas. Water depth is derived from Sentinel-2 imagery–derived bathymetry using the bathymetry based on Li et al. 2019 and Rueda et al. 2019.

For sandy beaches, the protection of existing beaches is considered, and their conservation via nourishments so that they can keep their relative height with respect to rising sea levels. The location of existing sandy beaches is obtained by manually digitizing Google Earth images from 2023.

B.2.5
MAPPING BENEFITS

B.2.5.1
FLOOD RISK REDUCTION BENEFITS

The flood risk reduction benefits and costs of coastal NBS projects identified by the suitability mapping are valued by comparing the present-day situation as a baseline scenario (with reference year 2020) with future scenarios (2050), which represent changes in the extent and condition of NBS as well as in socioeconomic exposure and in coastal hazards from climate change. The main scenarios are summarized below:

- **Baseline situation (2020).** Expected flood damages and benefits/ecosystem services in the year 2020. Friction coefficients and wave run-up are calculated using the baseline values of sections B.2.3.1 and B.2.3.2.

- **Year 2050, increased socioeconomic exposure.** Expected flood damages and ecosystem services in 2050, assuming that (1) NBS performance remains as it is at present (through conservation strategies) but that (2) socioeconomic exposure increases (in line with expected GDP growth as defined in the SSP2). This increase in socioeconomic exposure is also included in all the scenarios listed below. Friction coefficients and wave run-up are calculated using the baseline values of sections B.2.3.1 and B.2.3.2.

- **Year 2050, increased socioeconomic exposure and coastal climate change.** Expected flood damages and ecosystem services as of 2050, adding to the previous scenario climate change effects through sea-level rise and changes in storm surges, according to Coupled Model Intercomparison Project Phase 6 (CMIP6) climate projections (Muis et al. 2023).

- **Year 2050, NBS degradation.** Expected flood damages and ecosystem services in 2050 considering that coastal ecosystems will degrade. For mangroves, the degradation scenario assumes that sparse patches of mangroves disappear while dense mangrove areas become unhealthy and offer 20 percent less roughness. For corals, the scenario assumes that roughness decreases by 20 percent and that the run-up reduction by coral reef is 20 percent lower, leading to an increase in run-up. For beaches, it assumes 10 percent more run-up and an annual coastal erosion rate of 2.5 percent to assign changes in co-benefits through beach surface area.

- **Year 2050, NBS protection.** Expected flood damages and ecosystem services in 2050 considering that coastal ecosystems are protected. For mangroves and coral reefs, the protection scenario assumes that the ecosystems maintain their performance as of 2020. For beaches, it assumes they can keep up with sea-level rise, maintaining the run-up reduction of the baseline case. Therefore, sea-level rise is discarded from the total water level of coastal boundary points that are in proximity to beaches.

- **Year 2050, ecosystem enhancement.** Expected flood damages and ecosystem services in 2050, considering that NBS projects are implemented, assuming that mangroves in sparse areas, which are deemed unhealthy in 2020, are restored to become denser and healthy, offering 20 percent more roughness. Furthermore, potential new mangrove areas are created outside the current mangrove extent; and coral reef restoration can offer 20 percent more roughness and the run-up reduction by reef is 20 percent higher, leading to a reduction in run-up; beaches behave identically to the protection scenario.

To value each coastal NBS individually, the scenarios are simulated individually for each ecosystem (figure B.1). This is done for both enhancement and protection actions. In the case of enhancement, only one type of ecosystem is enhanced in each simulation while the others maintain their condition as of 2020. In the case of protection, only one type of ecosystem is maintained at its 2020 condition while the others degrade. Beaches represent an exception, as there is only a protection scenario where they keep up with sea-level rise maintaining the run-up reduction of the baseline case:

- **Mangrove enhancement only.** This assumes that only mangrove enhancement NBS are implemented, whereas corals and beaches remain in their condition as of 2020.

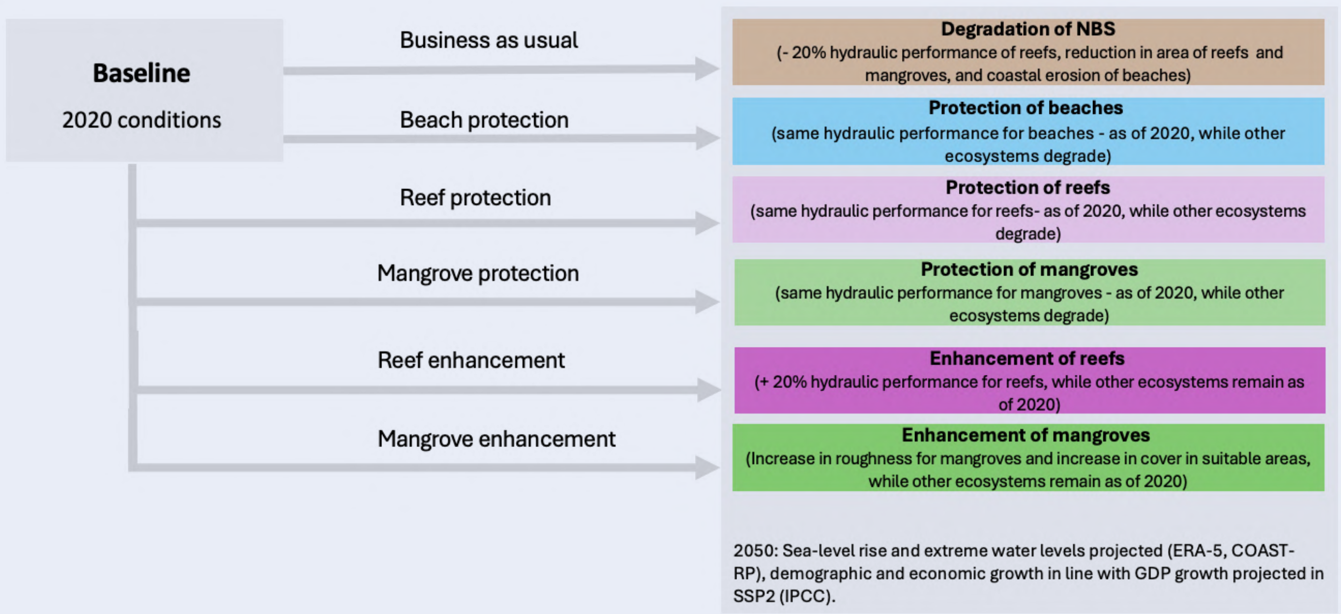
- **Coral enhancement only.** This assumes that only coral enhancement NBS are implemented, whereas mangroves and beaches remain in their condition as of 2020.

- **Mangrove protection only.** This assumes that only mangrove protection NBS are implemented, whereas corals and beaches degrade.

- **Coral protection only.** This assumes that only coral protection NBS are implemented, whereas mangroves and beaches degrade.

- **Beach protection only.** This assumes that only beach protection NBS are implemented, whereas corals and mangroves degrade.

FIGURE B.1: SCENARIOS FOR NBS, CONSISTING OF BASELINE SCENARIO IN 2020 AND FUTURE SCENARIOS IN 2050



SOURCE: Original figure for this publication.
NOTE: This is a slightly simplified version of figure 8 in the main text.

B.2.5.2
CARBON SEQUESTRATION BENEFITS

The value of additional carbon sequestration by mangroves is estimated using methods and parameters from the literature (Murray et al. 2011; Pendleton et al. 2012):

- Computation of additional carbon sequestration from NBS multiplies the cumulative additional mangrove area by a representative carbon sequestration rate per unit area: 6.3 tonnes of carbon dioxide per hectare per year (tCO_2/ha/year) (Pendleton et al. 2012).

- Carbon stored per year is valued economically using the social cost of carbon (SCC), which is the monetary value of damages caused by emitting 1 more tonne of CO_2 in a given year (Pearce 2003). The SCC, therefore, represents the value of damages avoided for a small reduction in emissions—in other words, the benefit of a reduction in atmospheric CO_2 in a given year. The SCC increases over time as a result of the increasing marginal damage caused by additional tonnes of CO_2 in the atmosphere. The NBSOS uses the US Interagency Working Group series of SCC estimates for the period 2010–2050 (Interagency Working Group 2016), which are in the range of World Bank carbon pricing scenarios consistent with a 2°C global warming scenario.

B.2.5.3
OTHER BENEFITS

The values of other ecosystem services are estimated using data from the literature and value functions. Data on corals and mangroves from the Ecosystem Services Valuation Database (ESVD) (Brander et al. 2024) are used in regression analyses to estimate functions that relate the value of coral and mangrove services to the characteristics and context of each ecosystem.[11] These regressive functions are subsequently applied to predict location-specific benefits accounting for variation in relevant explanatory factors (for example, the size of the ecosystem, population density, income of beneficiaries). An example of an estimated value function for coral ecosystem services is shown in table B.2, where the dependent variable is defined as US dollars per hectare per year and the explanatory variables include the area of the ecosystem patch in hectares and binary variables that indicate the ecosystem services, the Global Human Modification map, the Biodiversity Intactness Index of the ecosystem, the population density within a 30-kilometer radius of the ecosystem, and the GDP per capita (also for the 30-kilometer radius from the valued ecosystem). The explanatory variables have expected signs in terms of how they influence variation in ecosystem services values but they are not all statistically significant. For the example, in table B.2, the overall explanatory power (R^2) of the model is relatively low. Ecosystem service values per unit area decline slightly with the size of the ecosystem patch (that is, total values increase less than proportionately with the size of the ecosystem) and the extent of human disturbance (anthropogenic modification) but increase with biodiversity intactness. Population density and income both have positive correlations with ecosystem services values, representing demand-side factors.

11 Details about the ESVD can be found at https://www.esvd.net/.

TABLE B.2: EXAMPLE OF CORAL ECOSYSTEM SERVICE VALUE FUNCTION

EXPLANATORY VARIABLE	COEFFICIENT	P-VALUE
Constant	–1.758	0.599
Area (hectares; ln)	–0.074	0.288
Raw materials	3.579	0.219
Erosion regulation	1.928	0.149
Existence bequest	1.759	0.109
Extreme event regulation	2.457	0.066
Recreation tourism	1.500	0.154
Waste treatment	3.744	0.010
Aesthetic enjoyment	3.725	0.006
Food	1.285	0.248
Cognitive development	–2.187	0.145
Inspiration	1.067	0.714
Human Modification index	–2.890	0.010
Biodiversity Intactness Index	3.362	0.157
Population density (ln)	0.634	0.001
GDP per capita (US dollars; ln)	0.102	0.556
Adjusted R^2	0.143	
N	255	

SOURCE: Brander et al. 2024.
NOTE: The dependent variable is US dollars/hectare/year (ln). GDP = gross domestic product; ln = natural logarithm transformation; *N* = number of coral reefs.

An example of an estimated value function for mangrove provisioning services is presented in table B.3. The NBSOS tool focuses on provisioning services to address commodity consistency in the values, while regulating service values such as carbon sequestration and flood mitigation are valued separately. The dependent variable is defined as US dollars per hectare per year. The explanatory variables include the area of the ecosystem patch in hectares, the population density within a 30-kilometer radius of the ecosystem, the GDP per capita also for the 30-kilometer radius of the valued ecosystem, the human modification index of the ecosystem, and the percentage of the area within 30-kilometer radius of the ecosystem that is designated as protected area. The explanatory variables have expected signs in terms of how they influence variation in ecosystem services values and are all statistically significant. The overall explanatory power is comparable to similar analyses in the literature. Ecosystem service values per unit area decline slightly with the size of the ecosystem patch (that is, total values increase less than proportionately with the size of the ecosystem), with the extent of human disturbance (human modification), and the extent of protected area designation, which is likely to reduce direct use of provisioning services. Population density and income both have positive correlations with ecosystem service values, representing demand-side factors.

TABLE B.3: **EXAMPLE OF MANGROVE PROVISIONING SERVICE VALUE FUNCTION**

EXPLANATORY VARIABLE	COEFFICIENT	P-VALUE
Constant	−0.144	0.935
Area (hectares; ln)	−0.188	0.001
GDP per capita (US dollars; ln)	0.617	0.001
Population density (ln)	0.520	0.001
Human Modification index	−2.520	0.001
Protected area (% of area)	−0.288	0.011
Adjusted R^2	0.179	
N	371	

SOURCE: Brander et al. 2024.
NOTE: The dependent variable is US dollars/hectare/year (ln). GDP = gross domestic product; ln = natural logarithm transformation; N = number of mangrove sites.

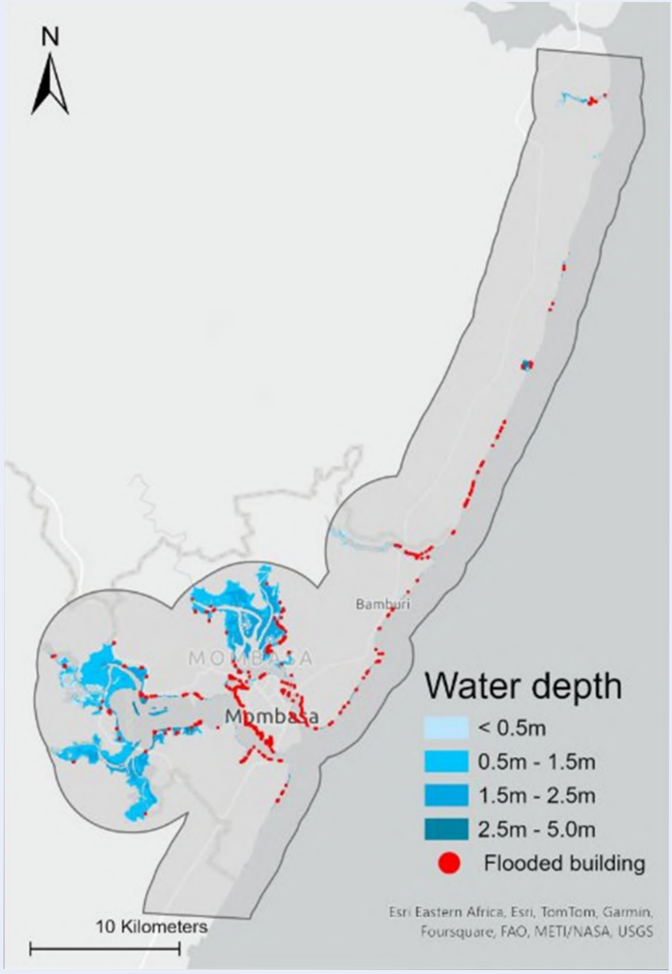
The estimation of co-benefits from beach nourishment is focused on the value of maintaining the width of beaches for tourism. Based on results of a discrete choice experiment conducted on Anguilla that estimated the willingness to pay (WTP) of international tourists to maintain beach width (Tieskens et al. 2014), beach loss is valued at $9.91 per unit meter of shoreline retreat. Annual tourist arrivals are obtained from national tourism statistics of the case study country governments and spatially distributed to beaches using information on hotel locations. Hotel locations were derived from listings on Booking.com, extracted using Python scraping. For each coastal section of 2 kilometers, a weighted sum was calculated of the number of hotels within a radius of 1, 2, and 5 kilometers with respective weights of 0.5, 0.375, and 0.125. Tourists were then allocated to each coastal section based on the relative value of this weighted sum. In addition, the added value of accommodation expenditure was estimated using estimates based on available local data on tourism arrivals and expenditures (that is, number of nights per tourist and average hotel accommodation spending). Seventy percent of added value from accommodation was estimated to be attributed to the presence of sandy beaches, in line with similar studies conducted in the Caribbean. For each beach, the tourism value of beach nourishment is computed as product of (1) the sum of the estimated WTP and added value of hotel expenditures attributed to sandy beaches, (2) the annual number of tourist visitors, and (3) the annual loss of beach width (assumed at 2.5 percent).

B.2.5.4
VISUALIZATION AND MAPPING

The outputs of the scanning tool are mapped below for an area around Mombasa, Kenya, as an example, and consist of:

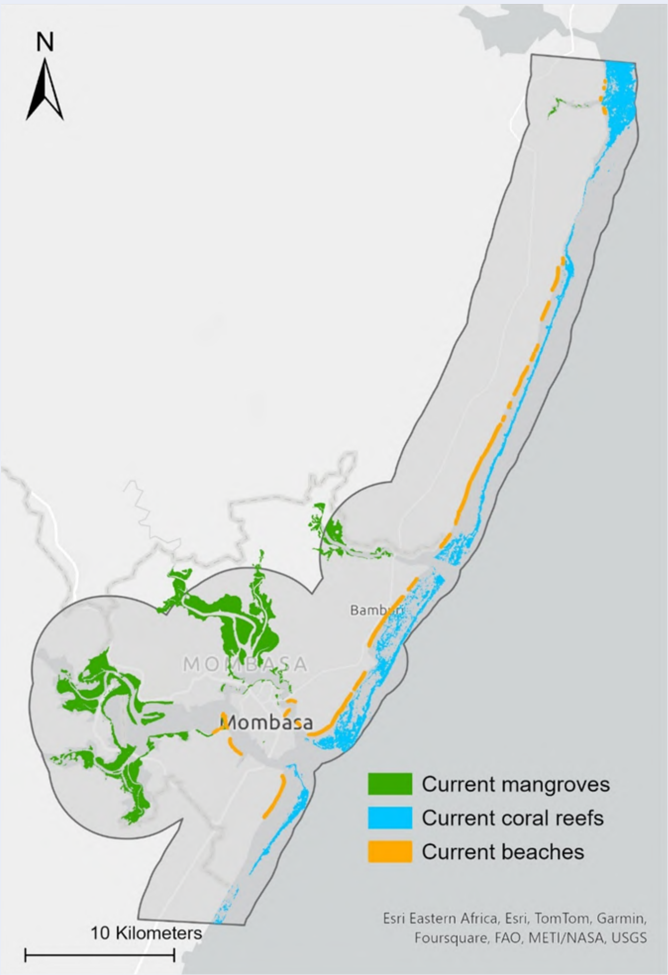
- Coastal flood hazard maps at present and by mid-century as well as built-up areas and population at risk. These maps can be generated for different return periods. Map B.4 shows an example of a storm in 2050 with a return period of 100 years.
- NBS opportunities: potential sites for nature-based adaptation using mangroves, beaches, and coral reefs (map B.5).
- Reduction of flood risks by NBS opportunities by mid-century. Results for a storm with a return period of 100 years are shown in map B.6.

MAP B.4: **FLOOD MAPS FOR A COASTAL STORM IN MOMBASA, KENYA, WITH A RETURN PERIOD OF 100 YEARS IN 2050**



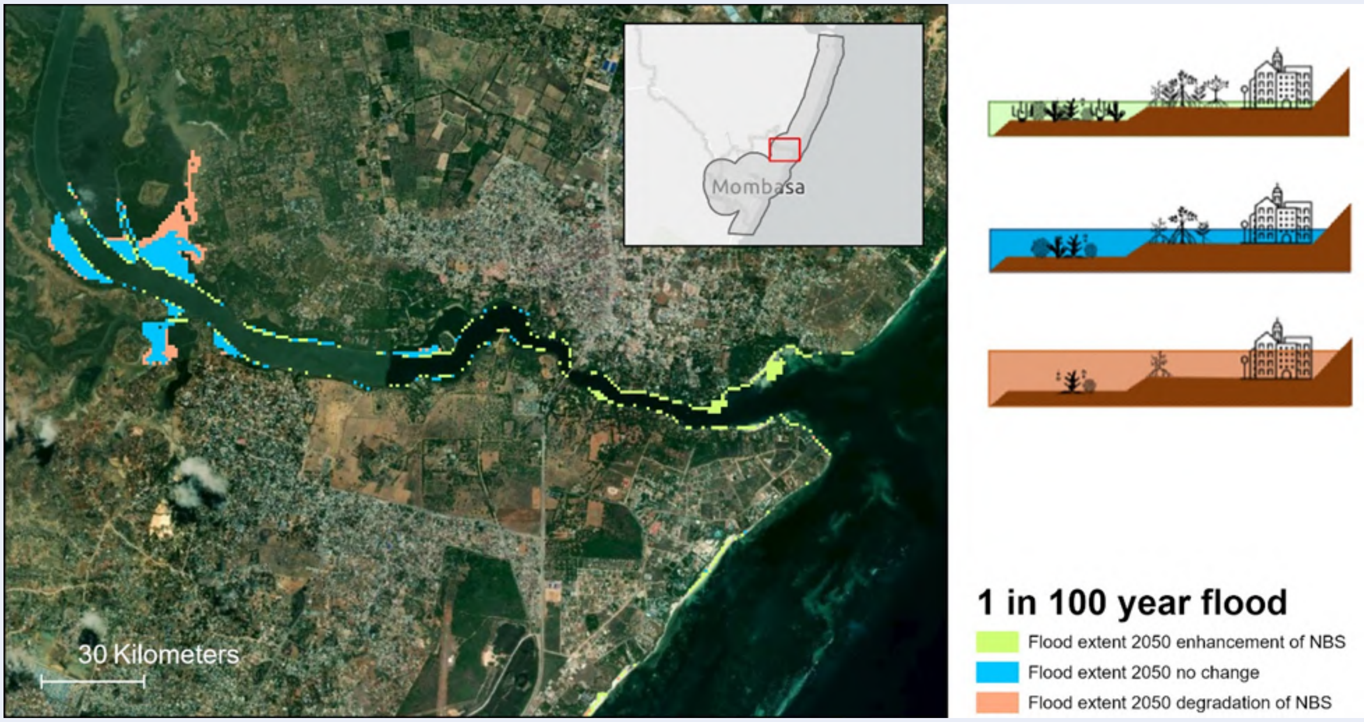
SOURCE: Original map for this publication. Basemap by Esri.
NOTE: Blue areas show flooded regions, with different shades of blue depending on the height of the water level with respect to mean sea level. Red dots show areas with buildings exposed to flooding.

MAP B.5: **NBS LOCATIONS IN MOMBASA, KENYA**



SOURCE: Original map for this publication. Basemap by Esri.
NOTE: Mangroves are shown in green, coral reefs in blue, and sandy beaches in orange.

MAP B.6: AREAS NORTH OF MOMBASA, KENYA, FLOODED BY A COASTAL STORM WITH A RETURN PERIOD OF 100 YEARS IN 2050



SOURCE: Original map for this publication. Basemap by Esri.
NOTE: Blue areas show locations where flood can be prevented by enhancement measures, and red areas show sites that would be flooded if degradation of ecosystems takes place.

B.2.6
SELECTION OF OPTIMAL SOLUTIONS

To calculate the costs and benefits for different NBS in different areas within the project AOI, NBSOS divides the total coastline into sections. All identified 10-meter pixels of mangroves, coral reefs, and beaches are then assigned to the closest 2-kilometer section to create separate patches of each NBS per coastal section. Both avoided flood damages and co-benefits, as well as protection and restoration costs, are calculated for each 2 kilometer coastal section for each NBS to provide a spatially explicit cost-benefit analysis (CBA).

B.2.6.1
COSTS OF NBS

The costs of implementing NBS using coral reefs, mangroves, and beaches are estimated using data on ecosystem restoration costs from the literature. In the case of coral reefs and mangrove enhancement, available data are used in meta-regression analyses to estimate functions that relate the costs of restoration to the characteristics and context of the restoration activity. These functions are subsequently applied to predict location-specific costs accounting for variation in relevant explanatory factors (for example, the size of the restoration site, type of intervention, purchasing power parity or PPP). In the case of beaches, unit costs of beach nourishment are obtained from the literature and adjusted at the country level to account for differences in price levels. All costs are adjusted to 2020 price levels using GDP deflator factors from the World Bank World Development Indicators.[12] To identify the cost of reef restoration, the cost per meter of constructing artificial reefs is estimated. The cost for such a hybrid solution is based on a median value identified by Ferrario et al. (2014) of $1,290 per linear meter.

Data on the costs of mangrove restoration are obtained from Bayraktarov et al. (2016) and Su, Friess, and Gasparatos (2021). Country-level information on PPP and GDP per capita are added to the data set; these are also from the World Development Indicators. An ordinary least squares regression model is estimated with the dependent variable defined as restoration cost in US dollars per hectare. The explanatory variables include the area of the restoration site in hectares, a binary variable indicating whether the intervention includes both hydrological restoration and mangrove planting, the PPP factor for the country, the GDP per capita, and the number of years over which the restoration activities are implemented. An example of estimated mangrove cost function is presented in table B.4. The explanatory variables have expected signs in terms of how they influence variation in costs and are mostly statistically significant. The overall explanatory power is relatively high. Mangrove restoration that includes both hydrological works and planting has substantially higher costs. Restoration costs also increase with higher price levels, income per capita, and the number of years over which the intervention is implemented. Costs per unit area decline slightly with the size of the restoration site—that is, total costs increase less than proportionately with the size of the restoration site.

TABLE B.4: MANGROVE RESTORATION COST FUNCTION

EXPLANATORY VARIABLE	COEFFICIENT	P-VALUE
Constant	–2.14	0.210
PPP factor	2.245	0.079
GDP per capita (ln)	0.938	0.001
Site area (hectares; ln)	–0.005	0.929
Cost years (ln)	0.748	0.003
Restoration hydrological and planting	1.274	0.002
Adjusted R^2	0.645	
N	132	

SOURCE: Su, Friess, and Gasparatos 2021.
Note: The dependent variable is US dollars/hectare (ln); PPP = purchasing power parity; ln = natural logarithm transformation; N = number of mangrove sites.

12 See the World Bank DataBank at https://databank.worldbank.org/source/world-development-indicators.

The cost of beach nourishment is obtained from Spencer, Strobl, and Campbell (2022), which reports a cost of $2,083.11/meter in 2019 prices. This unit cost is adjusted for each country using PPP factors from the World Development Indicators to reflect differences in general price levels.

Mangrove and coral reef protection costs were calculated using the establishment and maintenance cost of marine protection areas (MPA). Estimations on the per hectare cost of MPA establishment and maintenance were obtained as described by McCrea-Strub et al. (2011), using an MPA size of 2 square kilometers for coral reef protection and 50 square kilometers for mangrove protection to account for the difference in magnitude.

B.2.6.2
COST-BENEFIT ANALYSIS

CBA is an economic methodology used to compare the costs and benefits of a proposed investment over a period of time. Applications of CBA of public investments generally take a broad perspective and aim to incorporate all relevant societal (welfare economic) benefits and costs.

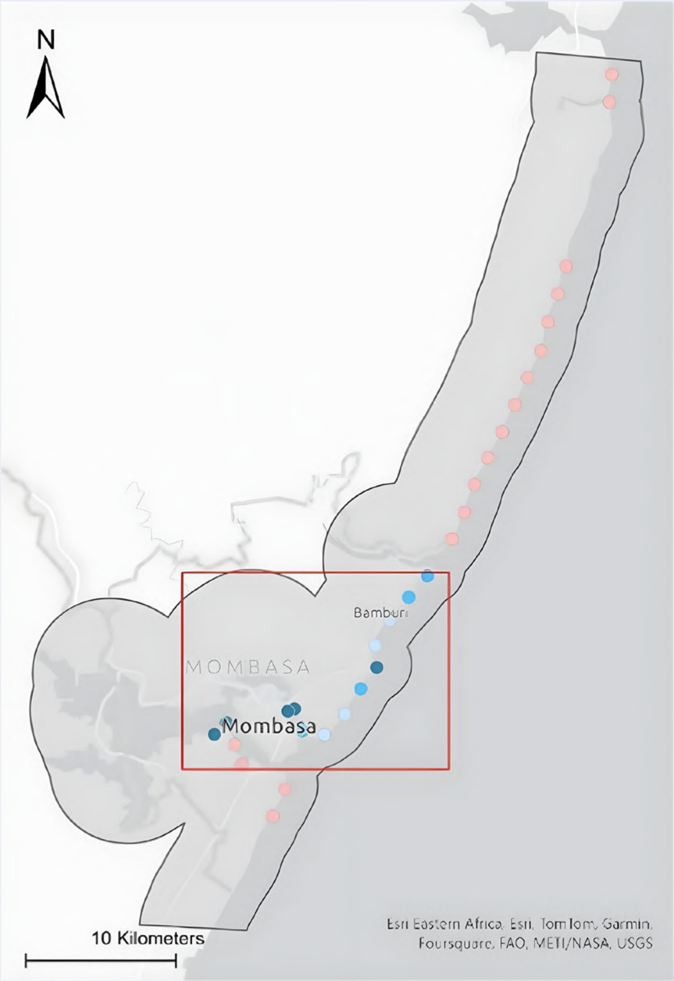
In a CBA, future costs and benefits are converted to and aggregated as "present values" using a discount rate. The discount rate represents the annual rate at which costs and benefits depreciate because people place a higher value on the present than on the future. This depreciation reflects general uncertainties about the future and the opportunity cost of investing capital in any given project when money invested elsewhere could have yielded equal or greater returns. In the present CBA, costs and benefits are estimated over a 28-year time horizon (2023–50) using a discount rate of 6 percent.

For beaches, NBSOS presents a CBA for protecting the current extent and functions of beaches, comparing the avoided flood damages and co-benefits of the 2050 degradation scenario to the 2050 beaches protection scenario. For mangroves and coral reefs, NBSOS presents a CBA for protection, comparing the 2050 degradation scenario to the 2050 mangrove/coral reef protection scenario; and a CBA for enhancement, comparing the 2050 avoided flood damages and co-benefits of the baseline scenario to the mangrove/coral reef enhancement scenario.

NBS investment options are evaluated in this report using the BCR (present value benefits minus present value costs). A BCR greater than 1 indicates a positive economic return on investment. The analysis is conducted at the level of individual patches of each ecosystem type to which restoration interventions could be applied. This enables the assessment of the relative economic viability of potential interventions across locations and the prioritization of those that yield the greatest benefits and the lowest cost.

Priority areas are identified based on their BCRs, as shown in map B.7, which highlights locations with high investment potential. By selecting areas with relatively high BCR, the NBS opportunities can be organized into investment scenarios.

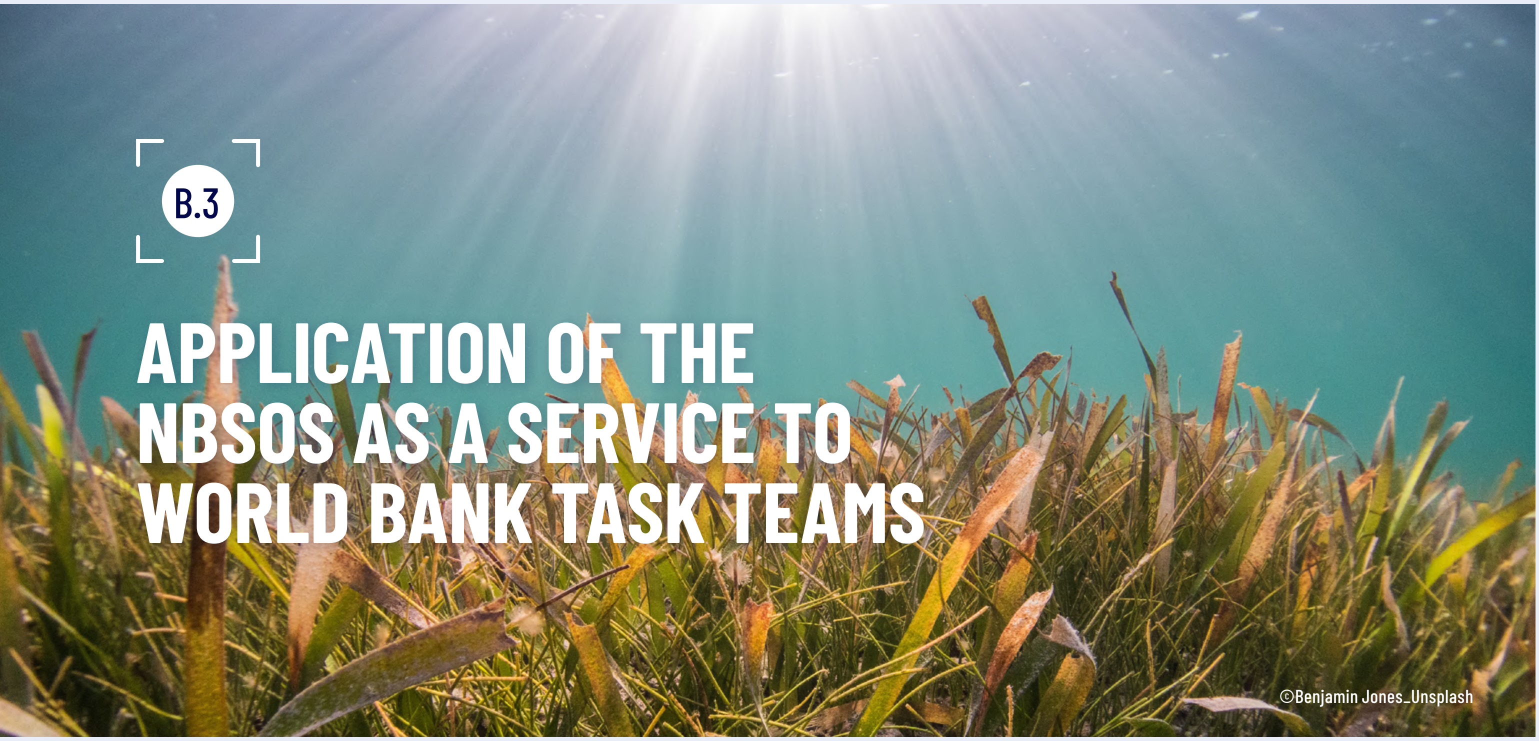
MAP B.7: BENEFIT-TO-COST RATIOS IN MOMBASA, KENYA, FOR CORAL REEF NBS PER COASTAL SECTION OF 2 KILOMETERS



BEACH PROTECTION - BCR

- < 1
- 1 - 3
- 3 - 5
- > 5

SOURCE: Original map for this publication. Basemap by Esri.
NOTE: BCR = benefit-to-cost ratio.



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B.3 APPLICATION OF THE NBSOS AS A SERVICE TO WORLD BANK TASK TEAMS

B.3.1 PROJECT TASK TEAM CONSULTATION

Consultations with local Task Teams are held at the beginning of each coastal NBSOS application. During these meetings, different types of relevant information are collected. This helps to provide a customized service that considers local characteristics, necessities, and data.

1. **Determination of the AOI.** The AOI usually covers the full coastal area of a country. Results can be provided for particular AOIs requested by local Task Teams.

2. **Identification of relevant environmental hazards and associated weights.** The main challenge of the coastal NBSOS is coastal flood risk due to coastal storms and surges.

3. **Selection of relevant NBS families.** Relevant NBS families (mangroves, corals, and/or sandy beaches) for each case are also discussed with local Task Teams.

4. **Availability of supplemental local data sets.** The availability of local data to enhance and customize the NBSOS analysis is also discussed with the local Task Team. Even though the analysis can be performed using available global data, the addition of local data can improve some results or their visualization. For instance, population vulnerability data, which usually are not available as open data, can improve coastal flood risk analyses. Administrative divisions' data can help to present results per neighborhood or district, helping to better communicate the outputs of the NBSOS.

B.3.2 INTERPRETATION, PRESENTATION, AND RECOMMENDATIONS

B.3.2.1 DELIVERABLES

The coastal NBSOS results are delivered as a slide deck that includes a summary of the methodology, contextual analysis, background (for example, local hazards), and results of the NBSOS. These outputs include the identification of priority areas from hazard-exposure analysis, NBS opportunity maps, and the CBA results. The slide deck includes an interpretation of results and recommendations from the analysis, as well as general design and implementation considerations. The outputs are also provided in a geospatial format, including raster data of the suitability of NBS families (GeoTIFF), shapefiles describing climate resilience and coastal flood challenges, and BCRs of the NBS families.

B.3.2.2 PRESENTATION TO TASK TEAMS AND CLIENTS

The slide deck is presented to the Task Team in a meeting where feedback about the preliminary results, their interpretation, and recommendations is also sought. These suggestions are integrated into a final version of the NBSOS results.

B.3.2.2 PARTICIPATORY MODELS FOR CLIENT AND STAKEHOLDER ENGAGEMENT

In some cases, further engagements with local Task Teams may be possible and may include activities to improve the use of the outputs by local stakeholders, such as presentations of results, interactive activities to facilitate discussions among local actors, and support during pre-feasibility studies.

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GLOBAL PROGRAM ON NATURE-BASED SOLUTIONS FOR CLIMATE RESILIENCE

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THE NATURE-BASED SOLUTIONS OPPORTUNITY SCAN

LEVERAGING EARTH OBSERVATION DATA TO IDENTIFY INVESTMENT OPPORTUNITIES IN NBS FOR CLIMATE RESILIENCE IN CITIES AND COASTS ACROSS THE WORLD