DOI: https://doi.org/10.53256/COSE_240202

Bottom-Up Approach for Flood Risk Assessment in Coastal Areas

E. Leone[a,*], A. Francone[b], A. Paglialunga[a], A. Lauria[b], S. De Bartolo[b], W. Hamza[c], G.R. Tomasicchio[b]
[a]*eCampus University, Novedrate, Como, Italy*
[b]*Department of Engineering for Innovation, University of Salento, Lecce, Italy*
[c]*Biology Department, Faculty of Sciences, United Arab Emirates University, Al-Ain, UAE*

[*]*Corresponding author: elisa.leone@uniecampus.it*

ABSTRACT: Coastal flood risk assessment under climate change increasingly requires the integration of multiple methodological approaches to address both global uncertainty and local specificity. This paper compares two complementary frameworks: a traditional top-down, scenario-driven approach based on downscaled climate projections, and a bottom-up, vulnerability-focused approach grounded in local knowledge and participatory engagement. Particular emphasis is placed on the bottom-up methodology, highlighting its ability to identify site-specific thresholds, capture socio-environmental dynamics, and assess adaptive capacity through stakeholder involvement and climate stress-testing. By analysing the respective strengths and limitations of each framework, the study demonstrates the added value of an integrated assessment strategy that improves the robustness, flexibility, and responsiveness of coastal adaptation planning. Finally, the paper highlights the role of iterative and flexible decision-support tools—such as adaptation pathways—in bridging long-term climate projections with actionable, locally tailored risk reduction and adaptation measures.

KEYWORDS: Risk assessment; coastal engineering; bottom-up approach

1 INTRODUCTION

Coastal regions worldwide are experiencing increasing pressure as a result of the rapid and accelerating rise in mean global sea level. Since the early twentieth century, global mean sea level has risen by approximately 0.2 m, with the rate of increase accelerating from about 1.3 mm yr^{-1} during the twentieth century to more than 3.7 mm yr^{-1} in recent decades. Satellite altimetry observations since 1993 confirm a clear acceleration in the twenty-first century, with rates exceeding 4.5 mm yr^{-1} over the last decade (IPCC, 2021). This ongoing sea-level rise (SLR), primarily driven by ocean thermal expansion and land-ice melt associated with global warming, is unprecedented over at least the past three millennia.

The implications for low-lying coastal areas are profound and include more frequent and severe coastal flooding, accelerated shoreline erosion, saltwater intrusion into freshwater systems, and the compounding of multiple coastal hazards that threaten both ecosystems and human settlements (Griggs and Reguero, 2021). Densely populated river deltas, small island developing states, and gently sloping low-elevation coastlines are among the most vulnerable regions. Many of these areas are characterized by extensive development located only a few metres above present mean sea level and often lack natural protective features, making even relatively modest SLR particularly hazardous.

This context underscores the urgent need for integrated and robust approaches to assess and reduce coastal vulnerability in a warming climate. Risk assessment constitutes a fundamental component of effective coastal adaptation planning. Broadly, two methodological paradigms have emerged for the assessment of climate-related coastal hazards: top-down (scenario-driven) and bottom-up (vulnerability-driven) frameworks (Hinkel et al., 2018). The top-down approach typically begins with global or regional climate scenarios and numerical models to project future hazards (Di Risio et al., 2017; Skinner, 2024). In contrast, the bottom-up approach focuses on local conditions, examining site-specific vulnerabilities, exposure, and adaptive capacity within coastal systems (Padulano et al., 2021; Guan et al., 2023).

Each approach provides valuable yet distinct insights; when applied in combination, they can yield a more comprehensive and robust characterization of coastal risk. The present paper examines and compares these two methodologies, with particular emphasis on their applicability to low-lying coastal areas under climate change. First, recent trends and future projections of sea-level rise—recognized as a key driver of intensifying coastal hazards—are reviewed. The analysis then explores the structure, strengths, and limitations of both top-down and bottom-up risk assessment frameworks. Finally, attention is given to integrated strategies, such as adaptive pathway planning, which are especially well suited to managing long-term uncertainty. The discussion is framed within the broader context of coastal engineering and environmental science, with the objective of supporting more resilient infrastructure design and evidence-based policy-making in climate-exposed coastal zones.

2 SEA-LEVEL RISE TRENDS

2.1 Observed Trends

Long-term records derived from tide gauges and satellite altimetry reveal a clear acceleration in sea-level rise (SLR). During the twentieth century, global mean sea level increased at an average rate of approximately 1–2 mm yr^{-1}, corresponding to a total rise of about 15–25 cm between 1900 and 2018. This long-term increase has not been linear; rather, the rate of rise has intensified markedly in recent decades.

Satellite observations, available since 1993, indicate a mean global sea-level rise of approximately 3.3 mm yr^{-1} over the past 30 years—nearly three times the rate observed in the early twentieth century. Moreover, the rate of rise continues to accelerate. During the most recent decade (2013–2023), the observed rate exceeded 4.5 mm yr^{-1} (IPCC, 2021). Consistently, the World Meteorological Organization reported an average rise of about 4.8 mm yr^{-1} over the period 2014–2023, compared with approximately 2.1 mm yr^{-1} in the early 1990s. As a result, by 2023, global mean sea level reached its highest value in the modern satellite record, standing roughly 9–10 cm above the 1993 baseline.

Anthropogenic warming has been identified as the dominant driver of accelerated SLR since at least the 1970s, primarily through the combined effects of land-ice melt and ocean thermal expansion. The current rate of sea-level rise exceeds any observed during the past 3,000 years, underscoring the unprecedented nature of contemporary changes.

Although regional and local sea-level trends may deviate from the global mean due to processes such as land subsidence or uplift, tectonic activity, ocean circulation variability, and gravitational redistribution of water mass, the vast majority of coastal regions are experiencing rising sea levels to varying degrees. This widespread increase significantly amplifies the exposure of vulnerable coastlines to high tides, storm surges, and associated coastal hazards worldwide.

2.2 Future Projections

Projections of global mean sea-level rise (SLR) depend primarily on future greenhouse gas emission pathways and the response of polar ice sheets. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) provides scenario-based projections of global mean SLR through 2100 and beyond. Figure 1 (from AR6) illustrates the median projected SLR under several Shared Socioeconomic Pathway (SSP) scenarios, together with likely uncertainty ranges (17th–83rd percentiles) and broader possible bounds. It is important to note that the IPCC is not a research institution; rather, it synthesizes and assesses findings from peer-reviewed scientific literature and technical reports produced by climate change experts worldwide. Consequently, the SLR projections presented in AR6 reflect the current scientific consensus as well as the associated uncertainties identified across the broader research community .

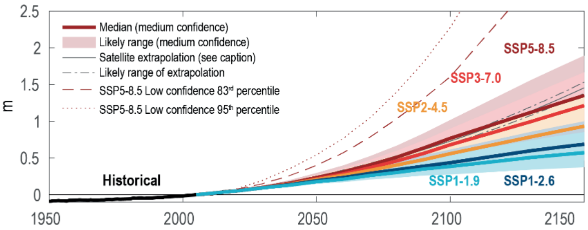

Figure 1. Global mean SLR projections under different emissions scenarios (SSPs), incorporating historical observations and future estimates with associated uncertainty ranges. Source: IPCC (2021), AR6, Chapter 9, Figure 9.27).

Under a low-emissions, high-mitigation scenario consistent with the Paris Agreement (SSP1-1.9, corresponding to approximately +1.5 °C of global warming), the IPCC projects a likely global mean SLR of about 0.28–0.55 m by 2100 relative to 1995–2014 levels. For an intermediate emissions scenario (SSP2-4.5), global mean sea level is projected to rise by approximately 0.5 m by 2100. In a high-emissions scenario with limited climate policy (SSP5-8.5), global mean sea level is projected to increase by 0.63–1.01 m by 2100, with a median estimate close to 0.77 m.

Beyond 2100, the divergence between scenarios becomes increasingly pronounced. By 2150, median SLR under the high-emissions scenario approaches 1.5 m, while the upper end of the very likely range may approach 2 m if certain ice-sheet instabilities are triggered. Uncertainty in ice-sheet response dominates high-end SLR projections for the late twenty-first century and beyond (Bamber et al., 2019). In particular, the dynamics of the Greenland and West Antarctic ice sheets remain poorly constrained. Processes such as marine ice-sheet instability and marine ice-cliff instability could lead to substantially greater sea-level contributions if critical temperature thresholds are exceeded.

Although the IPCC's likely range under SSP5-8.5 by 2100 extends to approximately 1 m, several studies indicate that SLR on the order of 1.5–2.0 m by 2100 cannot be ruled out if ice-sheet collapse processes accelerate. These outcomes are considered low-probability but high-impact scenarios (Bamber et al., 2019; DeConto et al., 2021). From a coastal risk management perspective, such tail-risk scenarios warrant careful consideration due to their potentially catastrophic implications for low-lying coastal regions and island nations.

Future SLR projections are characterized by deep uncertainty, particularly with respect to the timing and magnitude of ice-sheet mass loss, for which expert consensus remains limited. This uncertainty affects confidence in long-term projections and underscores the importance of considering a wide range of plausible futures. Projected outcomes vary substantially depending on emissions pathways and the sensitivity of polar ice masses to warming.

Moreover, translating global mean SLR projections to regional and local scales requires accounting for multiple modifying factors, including vertical land motion (e.g., subsidence or uplift), regional oceanographic conditions (e.g., circulation patterns and wind forcing), and gravitational and rotational effects. Ongoing research is progressively improving the accuracy of regional and local SLR estimates, which is essential for impact assessment and adaptation planning.

Recent methodological advances aim to strengthen the linkage between large-scale climate projections and site-specific sea-level responses. For example, Tomasicchio et al. (2018) proposed a direct scaling approach that relates projected global mean SLR to observed trends at individual tide-gauge stations. Using long-term observational records, they demonstrated consistent acceleration in local SLR and derived site-specific projections aligned with global estimates. Similarly, Kopp et al. (2023) introduced the FACTS (Framework for Assessing Changes to Sea Level) platform, a flexible and modular system for probabilistic SLR assessment. This framework explicitly accounts for both statistical and structural uncertainties, with particular emphasis on the role of Antarctic and Greenland ice-sheet dynamics in shaping the range of future outcomes.

Overall, the scientific evidence points unequivocally toward rising sea levels with potentially severe impacts, while also highlighting a broad envelope of plausible future trajectories. Coastal engineers and planners must therefore prepare for a range of scenarios. Robust analytical approaches, transparent treatment of uncertainties, and careful interpretation of projection data are essential when assessing SLR impacts at regional and local scales.

3 COASTAL RISK ASSESSMENT APPROACHES

Assessing the impacts of climate change on coastal zones typically involves top-down approaches, bottom-up strategies, or an integration of both. Contemporary methodologies increasingly seek to combine large-scale, scenario-based modelling with localized assessments of vulnerability in order to better inform adaptive planning. This section provides a comparative overview of these approaches, examining their respective workflows, strengths, and limitations. Particular emphasis is placed on the critical role of stakeholder engagement and cross-disciplinary collaboration in developing comprehensive and context-sensitive coastal risk assessments.

3.1 Top-Down Scenario-Driven Assessment

Top-down methods, often referred to as impact-driven or prediction-led approaches, begin with broad climate scenarios and progressively translate these projections down to the coastal scale. They typically rely on future greenhouse gas emission scenarios to drive Global Climate Models (GCMs). The outputs of these models (e.g. temperature change, sea-level rise, and variations in storm frequency and intensity) are subsequently downscaled to regional and local scales using regional climate models or statistical techniques. These downscaled climate variables are then applied to local coastal impact models.

Through this modelling chain, global climate change signals are translated into site-specific hazard scenarios, such as coastal inundation extents, flood frequencies, or shoreline change projections. A key strength of the top-down framework is its capacity to explore multiple plausible futures by evaluating discrete emission pathways (e.g. low, intermediate, and high emissions scenarios). Moreover, this approach ensures consistency with established climate science, as local hazard assessments are directly linked to the best available global climate projections. As a result, top-down assessments have become the dominant approach for long-term coastal hazard analysis and are widely used in planning studies and climate impact assessments spanning several decades to a century.

Despite these advantages, top-down approaches are subject to a cascade of uncertainties at each stage of the modelling process. Uncertainty arises from assumptions about future socio-economic development and emissions trajectories, differences among GCM outputs, variability in sea-level rise projections, the choice of downscaling techniques, and the parameterization of local impact models. These uncertainties tend to accumulate as analyses progress from global to regional and ultimately to local scales, often leading to a wide spread of projected outcomes.

For example, Toimil et al. (2020) demonstrated that projections of beach erosion by 2100 at a given site can differ substantially depending on the selected climate model ensemble or sea-level rise scenario. Figure 2 provides a schematic overview of the top-down modelling sequence, illustrating how global climate projections are successively downscaled through regional models to inform localized impact assessments. At each stage, uncertainties propagate and compound, reflecting the progressive transfer of imprecision from emission scenarios to site-specific risk evaluations.

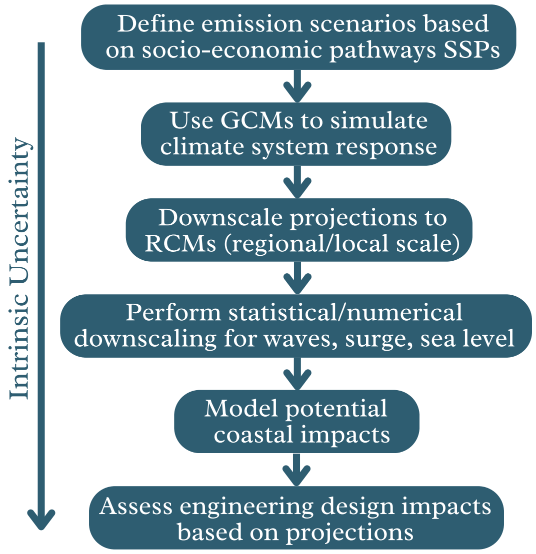

Figure 2. Schematic representation of a top-down coastal risk assessment framework.

Major contributors to this uncertainty include the selected emissions scenario, inter-model variability among global climate models, alternative sea-level rise estimates (e.g. median versus upper-bound projections), downscaling methodologies, and assumptions embedded within coastal impact models, such as erosion formulations and flood threshold definitions. In practical terms, this means that while top-down assessments provide a valuable broad-scale perspective, they may overlook fine-scale features that are critical for local risk management.

In response, researchers have sought to enhance the robustness of top-down coastal risk assessments through improved data sources and modelling techniques. Appelquist (2013), for instance, developed a globally applicable framework for coastal classification and meso-scale hazard assessment to support climate adaptation planning. Lin et al. (2020) combined remote sensing (including UAV surveys), geographic information systems (GIS), and statistical modelling to quantify vulnerability and resilience in coastal communities, demonstrating the added value of high-resolution datasets in top-down analyses. Igigabel et al. (2023) proposed a systemic approach linking sea-level rise projections with meteorological-oceanographic forcing and coastal geomorphology to assess the temporal evolution of hazard profiles. Similarly, Skinner (2024) introduced a framework that integrates multi-decadal shoreline response models with climate variability and sea-level trends to support strategic coastal infrastructure planning.

While these advances substantially improve top-down methodologies, even the most sophisticated models remain limited in their ability to represent local complexities. Generalized scenarios, even after downscaling, may fail to capture fine-scale variations in topography, land use, exposure, and adaptive capacity that strongly influence real-world risk. For example, coarse models may overlook localized low-lying sections of coastal defenses or densely populated informal settlements—factors that can critically alter flood outcomes. As noted by Di Risio et al. (2017), national-scale vulnerability assessments may mask local hotspots of risk that only detailed, site-specific investigations can reveal.

In summary, top-down approaches provide an essential "big-picture" perspective and ensure scientific coherence across scales. However, to effectively support coastal risk management and adaptation planning, they should be complemented by locally grounded data, knowledge, and participatory processes.

3.2 Bottom-Up Vulnerability Assessment and Climate Stress-Testing

Bottom-up approaches, in contrast to the climate-led nature of top-down methods, take the local system as their starting point, assessing vulnerabilities, stressors, and capacity limits by building the analysis from the coast upward. A bottom-up assessment begins by focusing on current conditions and the specific challenges faced by a given coastal area or community. It involves active engagement with local stakeholders—such as residents, community leaders, engineers, planners, and ecologists—to collect detailed, site-specific information and to understand local concerns, priorities, and values.

This process often includes participatory mapping of low-lying neighbourhoods, critical infrastructure, and sensitive ecosystems to identify assets at risk. Data on local topography and bathymetry are collected, together with historical records of flooding and erosion, as well as indicators of social vulnerability (e.g. population characteristics, mobility constraints, and evacuation capacity). By grounding the assessment in local knowledge and empirical data, bottom-up approaches capture factors that may be overlooked in purely top-down analyses, such as the deteriorating condition of a specific seawall or a community's limited access to evacuation resources. As a result, the outcomes of bottom-up assessments are often more directly relevant and credible to those responsible for implementing adaptation measures, as they reflect lived experience and local realities.

A key analytical tool within bottom-up risk assessment is climate stress testing. This technique evaluates how a coastal system—whether a settlement, infrastructure network, or ecosystem—performs under a wide range of hypothetical stress conditions rather than a limited set of predefined climate projections. Climate stress testing can be understood as a structured sensitivity analysis in which the system is subjected to progressively more severe conditions, such as incrementally higher water levels, stronger storms, or increased rainfall intensity, in order to identify thresholds beyond which system performance becomes unacceptable.

For example, engineers may simulate gradually rising floodwater levels to determine the point at which a town's levee is overtopped, resulting in widespread inundation. Similarly, increasing wave heights may be tested to identify failure thresholds for breakwaters or coastal defenses. By exploring a continuum of possible futures—rather than a small number of discrete scenarios—this approach identifies tipping points and failure conditions that the system cannot tolerate.

Figure 3 outlines the logic of a bottom-up climate stress-testing framework applied to a coastal city. The process begins with defining the local system of concern, including its geographic extent, assets, and stakeholders, followed by the collection of baseline data on coastal flooding, infrastructure, population distribution, and ecosystems.

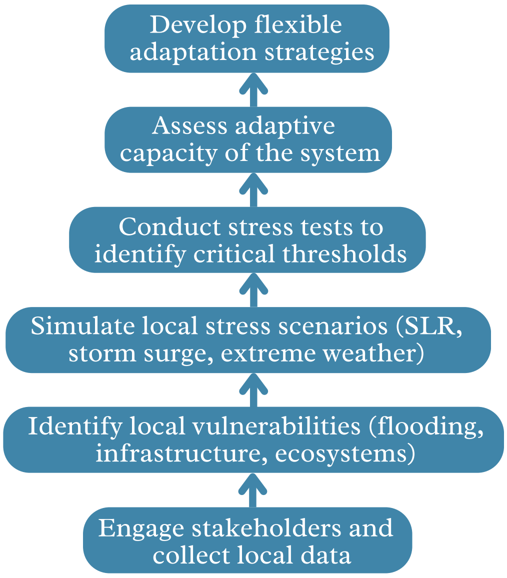

Figure 3. Bottom-up climate stress-testing framework applied to a coastal city.

Stakeholders are engaged early in the process to incorporate local observations of change and community concerns. Subsequently, local hazard models (e.g. flood inundation or shoreline change models) are run under a wide range of conditions combining sea-level rise, storm surge, extreme rainfall, wave action, and other relevant drivers. These conditions are not tied to a single emissions pathway or time horizon but instead span a spectrum of plausible extremes, including compound worst-case combinations (e.g. 0.5 m of sea-level rise combined with a 100-year storm and peak astronomical tide). Through iterative simulations, analysts identify threshold conditions beyond which the system fails or experiences unacceptable impacts.

Threshold metrics may include flood depths at which critical roads become impassable, surge heights that cause coastal defenses to be overtopped or breached, or erosion rates that undermine buildings or infrastructure. Once vulnerability thresholds are identified, the results are used to inform targeted adaptation strategies. In essence, climate stress testing reveals how much change a coastal system can accommodate before existing defenses, practices, or governance arrangements are overwhelmed.

An additional strength of bottom-up approaches is their explicit consideration of non-climatic stressors alongside climate-related drivers. Real-world vulnerability is often exacerbated by factors such as land subsidence, sediment starvation due to river regulation, coastal development that removes natural buffers, or institutional and socioeconomic constraints, including limited emergency response capacity. Bottom-up assessments can integrate these factors directly into stress-testing exercises to reflect the full complexity of local risk.

For example, a coastal city built on reclaimed or former marshland may be subsiding several millimetres per year due to groundwater extraction; a bottom-up analysis would explicitly incorporate this subsidence into future flood scenarios. Similarly, the loss of mangroves or dunes can be accounted for by adjusting wave attenuation or surge exposure in vulnerability assessment.

Bottom-up approaches are inherently interdisciplinary and participatory. By involving local actors throughout the assessment process, they help ensure that adaptation strategies are feasible, socially acceptable, and aligned with community priorities. A particular strength of this approach lies in its capacity to identify practical, context-specific adaptation options. Following stress testing, the analysis often progresses to the evaluation of measures aimed at increasing system resilience by raising identified failure thresholds.

This may involve iterative testing of proposed adaptations. For instance, analysts may examine whether raising a seawall by 0.5 m sufficiently delays overtopping under extreme scenarios, or whether wetland restoration seaward of a dike effectively reduces wave energy during major storms. Through this iterative exploration, bottom-up assessments not only diagnose vulnerabilities but also directly inform the design and prioritization of adaptation measures.

Recent studies illustrate the growing refinement and applicability of bottom-up frameworks. Knighton et al. (2017) developed a vulnerability-based flood risk assessment that integrates physical hydrologic modelling with a peaks-over-threshold statistical approach to account for non-stationarity in extreme events. Padulano et al. (2021) proposed a simplified yet robust method for assessing climate change impacts on urban flooding that avoids reliance on uncertain future rainfall projections by focusing on critical process thresholds. Guan et al. (2023) introduced a multi-level flood hazard mapping approach for data-scarce cities, demonstrating how bottom-up methods can improve risk estimation even where high-resolution inputs are unavailable. Collectively, these examples show that bottom-up approaches are becoming increasingly accessible and transferable, including in regions with limited data availability.

4 ADAPTATION PLANNING AND STRATEGIES UNDER UNCERTAINTY

Given the complementary strengths of top-down and bottom-up approaches, current best practice increasingly supports their integration within a single, flexible planning framework (Lawrence et al., 2019). In practice, this often takes the form of dynamic adaptive planning, whereby large-scale climate scenarios inform long-term strategic objectives, while local vulnerability assessments guide near-term actions and define trigger points for future adjustments.

One widely adopted method within this paradigm is the adaptation pathways approach, which develops an adaptive roadmap of decisions over time based on how future conditions actually unfold. Rather than committing to a single, fixed solution over a century-long horizon, an adaptation pathways plan outlines a sequence of potential measures and specifies the conditions under which a transition from one measure to the next should occur. For example, a low-lying coastal city may initially enhance drainage systems and construct modest floodwalls. The plan would then define thresholds—such as a mean sea-level rise of X cm or flood events exceeding Y occurrences per year—at which additional interventions, such as higher dikes or storm surge barriers, would be implemented. This approach preserves flexibility and helps avoid both premature overinvestment and delayed action that could lead to unacceptable risk.

The development of adaptation pathways is typically participatory, involving stakeholders in the selection of preferred strategies and acceptable trade-offs.

Communities may prioritise “soft” measures—such as beach nourishment or wetland restoration—in the early stages, postponing more capital-intensive engineering solutions unless they become strictly necessary. By incorporating local values, risk tolerance, and development objectives, pathways can be designed to be both robust and context-sensitive. Interdisciplinary collaboration is essential in this process. Each potential action along a pathway must be evaluated in terms of technical feasibility, economic cost, ecological impact, and social acceptability. Haasnoot et al. (2019) applied this approach across a range of coastal archetypes, illustrating “generic adaptation pathways” for deltas, estuaries, and atoll islands under uncertain sea-level rise conditions. Their results emphasised the need for context-specific strategies, as the effectiveness and timing of adaptation measures are closely linked to local environmental and socioeconomic characteristics. Nevertheless, the pathways framework provides a coherent structure for comparing and coordinating adaptation efforts across diverse settings.

A recent example of integrated planning is the European CoCliCo project (Coastal Climate Core Service), which combines top-down and bottom-up elements to deliver high-resolution coastal risk assessments. CoCliCo develops dynamic coastal flood hazard simulations across Europe under multiple climate scenarios, while integrating detailed exposure data (e.g. population and assets) and downscaled socioeconomic projections. By linking long-term climate projections with local-scale impact models and fostering iterative learning with stakeholders, such hybrid approaches aim to enhance resilience while reducing the risk of maladaptation.

A comprehensive study by Magnan et al. (2023) examined coastal adaptation efforts across 61 case studies worldwide, assessing their level of advancement. Figure 4 presents the resulting global coastal adaptation imprint, evaluated across six key dimensions: risk knowledge, planning, action, capacities, evidence of risk reduction, and long-term strategies. Each dimension is scored on a 0–4 scale, reflecting its contribution to effective local adaptation. Scores are grouped into qualitative categories—No-to-Very Low (0–1), Low-to-Moderate (1–2), Moderate-to-High (2–3), and High-to-Very High (3–4)—providing a clear overview of where adaptation progress is strongest (notably in risk knowledge) and where it remains limited, particularly in long-term strategic planning and the avoidance of maladaptation.

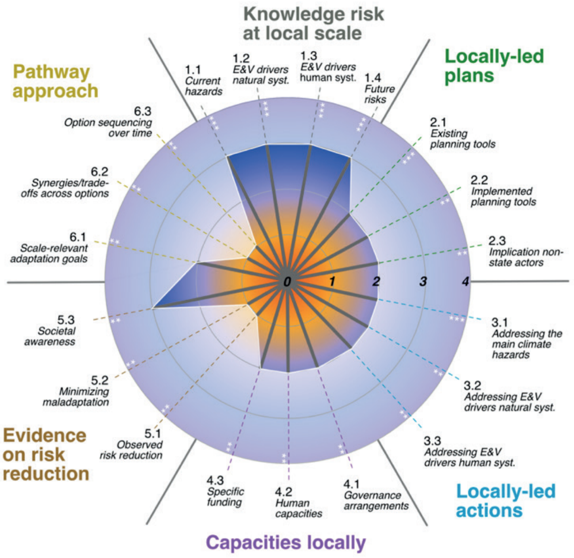

Figure 4. *Global coastal adaptation imprint based on six key dimensions, scored from No-to-Very Low to Very High (source: Magnan et al., 2023).*

In summary, global adaptation responses to coastal climate risks remain modest relative to the scale and pace of projected impacts. Most actions to date have been incremental rather than transformational, despite the likelihood that more profound changes will be required under continued sea-level rise and intensifying climate extremes. Short planning horizons, reactive (rather than anticipatory) decision-making, and sector-based governance structures have constrained the effectiveness of adaptation efforts.

Nevertheless, there remains a critical window of opportunity. By rapidly scaling up investment in coastal resilience, improving coordination between national policy frameworks and local implementation, and embracing innovative solutions—both engineered and nature-based—that extend beyond moderate climate scenarios, coastal societies can shift from ad hoc responses to strategic, long-term adaptation. Ultimately, only proactive and comprehensive planning can enable the most vulnerable coastal regions to avert the most severe consequences of climate change along the world's shores.

CONCLUSIONS

Effective coastal risk management in low-lying areas under climate change requires the integration of both top-down and bottom-up approaches, leveraging their complementary strengths. Top-down methods, grounded in large-scale models and future climate scenarios, provide estimates of the range of potential hazards and support strategic long-term planning. Bottom-up methods, which actively engage local stakeholders, reveal on-the-ground vulnerabilities, site-specific failure thresholds, and community priorities that may be overlooked by purely scenario-driven analyses. This study demonstrates that a blended approach—combining global projections with detailed local assessments—yields a more robust and actionable understanding of coastal risk.

Such integration enables the development of dynamic adaptation pathways that can be phased over time and adjusted as new information becomes available. Rather than relying on one-off interventions, coastal adaptation should be framed as a continuous, iterative process of learning, monitoring, and adjustment.

Although significant uncertainties persist—particularly regarding the magnitude and timing of future sea-level rise—adopting robust and flexible strategies can enhance preparedness across a wide range of plausible futures. These strategies typically involve a diversified portfolio of measures, including engineered defenses (e.g. surge barriers and levees designed with safety margins or upgrade options), nature-based solutions (e.g. mangroves, reefs, and marshes that evolve over time), forward-looking land-use planning to limit development in high-exposure areas, and adaptive policy instruments (such as rolling easements or insurance schemes) that facilitate adjustment as conditions change. No single solution is sufficient; instead, a context-specific combination of measures is required.

In conclusion, the integration of bottom-up and top-down perspectives—supported by iterative, inclusive planning processes—is essential for managing the escalating risks associated with sea-level rise in low-lying coastal regions. Continued refinement and implementation of integrated risk assessment and adaptation strategies will be critical to safeguarding both communities and ecosystems in the face of uncertain, but unequivocally rising, seas.

REFERENCES

Appelquist, L.R. (2013). Generic framework for meso-scale assessment of climate change hazards in coastal environments. Journal of Coastal Conservation, pp.59-74.

Bamber, J.L., Oppenheimer, M., Kopp, R.E., Aspinall, W.P. and Cooke, R.M. (2019). Ice sheet contributions to future sea-level rise from structured expert judgment. Proceedings of the National Academy of Sciences, 116(23), pp.11195-11200.

DeConto, R.M., Pollard, D., Alley, R.B., Velicogna, I., Gasson, E., Gomez, N., Sadai, S., Condron, A., Gilford, D.M., Ashe, E.L. and Kopp, R.E. (2021). The Paris Climate Agreement and future sea-level rise from Antarctica. Nature, 593(7857), pp.83-89.

Di Risio, M., Bruschi, A., Lisi, I., Pesarino, V. and Pasquali, D. (2017). Comparative analysis of coastal flooding vulnerability and hazard assessment at national scale. Journal of Marine Science and Engineering, 5(4), p.51.

Griggs, G., & Reguero, B. G. (2021). Coastal adaptation to climate change and sea-level rise. Water, 13(16), 2151.

Guan, M., Guo, K., Yan, H. and Wright, N. (2023). Bottom-up multilevel flood hazard mapping by integrated inundation modelling in data scarce cities. Journal of Hydrology, 617, p.129114.

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change, 23(2), 485–498.

Hinkel, J., Aerts, J.C., Brown, S., Jiménez, J.A., Lincke, D., Nicholls, R.J., Scussolini, P., Sanchez-Arcilla, A., Vafeidis, A. and Addo, K.A. (2018). The ability of societies to adapt to twenty-first-century sea-level rise. Nature Climate Change, 8(7), 570-578.

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Igigabel, M., Yates, M., Vousdoukas, M. and Diab, Y. (2023). A systemic and comprehensive assessment of coastal hazard changes: method and application to France and its overseas territories. Natural Hazards and Earth System Sciences Discussions, 2023, 1-35.

Knighton, J., Steinschneider, S., & Walter, M. T. (2017). A vulnerability-based, bottom-up assessment of future riverine flood risk using a modified peaks-over-threshold approach and a physically based hydrologic model. Water Resources Research, 53(12), 10043–10064.

Kopp, R.E., Garner, G.G., Hermans, T.H., Jha, S., Kumar, P., Reedy, A., Slangen, A.B., Turilli, M., Edwards, T.L., Gregory, J.M. and Koubbe, G. (2023). The Framework for Assessing Changes to Sea-level (FACTS) v1.0: a platform for characterizing parametric and structural uncertainty in future global, relative, and extreme sea-level change. Geoscientific Model Development, 16(24), 7461-7489.

Lawrence, J., Bell, R., & Stroombergen, A. (2019). A hybrid process to address uncertainty and changing climate risk in coastal areas using dynamic adaptive pathways planning, multi-criteria decision analysis & real options analysis: a New Zealand application. Sustainability, 11(2), 406.

Lin, S.W., Yen, C.F., Chang, C.H., Wang, L.J. and Shih, H.J. (2020). Comprehensive natural environment and landscape signs in coastal settlement hazard assessment: case of east Taiwan between the coastal mountain and the Pacific Ocean. Journal of Marine Science and Engineering, 8(7), 478.

Magnan, A.K., Bell, R., Duvat, V.K., Ford, J.D., Garschagen, M., Haasnoot, M., Lacambra, C., Losada, I.J., Mach, K.J., Noblet, M. and Parthasaranthy, D. (2023). Status of global coastal adaptation. Nature Climate Change, 13(11), 1213-1221.

Padulano, R., Costabile, P., Costanzo, C., Rianna, G., Del Giudice, G. and Mercogliano, P. (2021). Using the present to estimate the future: A simplified approach for the quantification of climate change effects on urban flooding by scenario analysis. Hydrological Processes, 35(12), e14436.

Skinner, W.K. (2024). Coastal Hazard Assessment from Multidecadal Profile Response Incorporating Climate Patterns and Sea-Level Rise. Journal of Coastal Research, 40(3), 511-526.

Toimil, A., Camus, P., Losada, I.J., Le Cozannet, G., Nicholls, R.J., Idier, D. and Maspataud, A. (2020). Climate change-driven coastal erosion modelling in temperate sandy beaches: Methods and uncertainty treatment. Earth-Science Reviews, 202, 103110.

Tomasicchio, G.R., Lusito, L., D'Alessandro, F., Frega, F., Francone, A. and De Bartolo, S. (2018). A direct scaling analysis for the sea level rise. Stochastic Environmental Research and Risk Assessment, 32, 3397-3408.