Application of the Multiscale Coastal Risk Index-Local Scale to Kotor Bay, Montenegro

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Enhancing regional climate change adaptation in the Mediterranean Marine and Coastal Areas

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Introduction

The "Gender-sensitive Climate Risk Assessment of Kotor Bay, Montenegro" (Plan Bleu, 2022) contributed to achieving a better understanding of how to foresee and manage escalating climate risks and impacts in the Mediterranean region. Renowned for its unique ecological and cultural significance, Kotor Bay, Montenegro has increasingly been subjected to the multifaceted impacts of climate change. Our analysis revealed a broad spectrum of vulnerabilities, predominantly stemming from rising sea levels, intensifying storm events, and significant socio-economic challenges, which were also analysed using a gender perspective.

These findings underscored the urgency for enhanced and targeted risk management strategies, capable of addressing the specificities of Kotor Bay's coastal environment. In this regard, the application of the Multi-scale Coastal Risk Index (MS-CRI) and its Coastal Risk Index-Local Scale (CRI-LS) (Satta, 2014) represented a significant stride towards a more nuanced and effective approach to coastal risk assessment and management.

The CRI-LS, with its multi-dimensional analysis framework, enables a more granular understanding of coastal risks. This methodology not only quantifies physical vulnerabilities, but also intertwines them with the socio-economic fabric of the area of study, thus offering a holistic view of the potential impacts of coastal risks.

In the following subsections, we apply the CRI-LS to Kotor Bay. Drawing from the national scale analysis presented in the "Gender-sensitive Climate Risk Assessment of Kotor Bay, Montenegro", this area has been identified a climate hotspot notably due to its expos including storms (heavy precipitation, wind gusts), sea level rise, surges, and floods from torrential waters caused for instance by the Sutorina river and the Opačica river in Herceg Novi municipality.

The CRI-LS encompasses the following four phases:

1. Definition of the coastal unit for local analysis;
2. Identification and scoring of variables related to each factor (sub-index);
3. Aggregation of variables, calculation of the three sub-indices and the final index;
4. Development of risk maps.

This robust approach, underlined by other findings from the GEF MedProgramme and its SCCF Project as well as the overall climate risk assessment of Kotor Bay, emphasises the urgency and importance of implementing climate change adaptation measures in this Mediterranean climate hotspot.

I. Background and Context

The Mediterranean region, grappling with the adverse consequences of climate variability and change, faces growing bio-geographical vulnerability and exposure in its coastal areas. This situation has increasingly put coastal communities, ecosystems, and assets at risk. In response, the Global Environment Facility's "Mediterranean Sea Programme (MedProgramme): Enhancing Environmental Security" was launched, as the first programmatic multi-focal area initiative of its kind in the Mediterranean region. It is strategically designed to operationalise priority actions to mitigate major transboundary environmental stresses in the Mediterranean's coastal areas, while simultaneously strengthening climate resilience and water security, and improving the health and livelihoods of coastal populations.

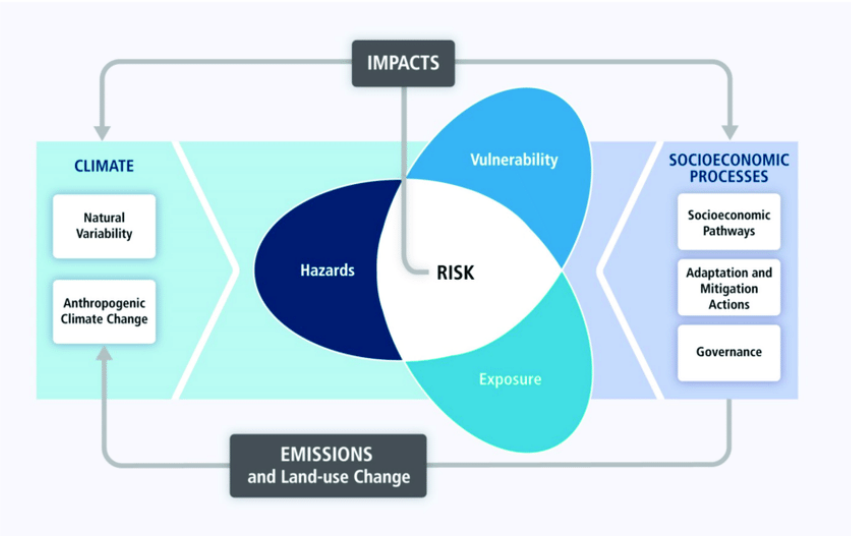
Implemented across ten beneficiary countries including Montenegro, the MedProgramme integrates efforts across various GEF Focal Areas (International Waters, Biodiversity, Chemicals and Waste and Climate Change). Its Special Climate Change Fund (SCCF) Project: "Enhancing Regional Climate Change Adaptation in the Mediterranean Marine and Coastal Areas", is of particular relevance to Kotor Bay. Devoted to climate change adaptation, it aims to build the capacity of individuals, companies and institutions to adapt to the impacts of climate change in vulnerable Mediterranean coastal areas.

In this context, the application of the CRI-L) provides a nuanced understanding of coastal risks and can inform the subsequent development of effective climate adaptation strategies. This integration is particularly significant to inform the MedProgramme's Child Project 2.1 "Mediterranean Coastal Zones Climate Resilience Water Security and Habitat Protection", which aims to support the implementation of the Barcelona Convention's Protocol on Integrated Coastal Zone Management (ICZM Protocol), thereby reducing environmental stresses and building climate resilience. The CRI-LS complements these broader efforts by offering a targeted tool for risk assessment, bridging the gap between wide-ranging regional strategies and localised action plans.

II. The Coastal Risk Index: Local Scale - Concepts and Application

The Coastal Risk Index-Local Scale is an index-based approach that integrates qualitative and quantitative spatial attributes to assess risks in coastal zones. This methodology, derived from the broader framework of the Multi-Scale Coastal Risk Index (MS-CRI) and informed by the latest Intergovernmental Panel on Climate Change (IPCC) reports, is designed to evaluate the physical, environmental, and socio-economic variables of coastal systems. The CRI-LS aligns with the concept of risk as defined in the IPCC's Sixth Assessment Report (AR6), emphasising the interaction between climate-related hazards, exposure, and vulnerability of affected human or ecological systems[1].

Figure 1. The interplay of Climate Hazards, Exposure, and Vulnerability in Risk Generation in the IPCC AR6 Conceptual Framework of Risk



Source: IPCC, 2014

In alignment with Figure 1, it is understood that vulnerability and exposure in coastal zones are significantly shaped by developmental factors, including socio-economic pathways, adaptation and mitigation actions, and governance structures. These elements, along with climate change, are the main drivers affecting the core components of risk: vulnerability, exposure, and hazards. Consequently, risk in coastal areas can be conceptualised as a function of these three key factors: hazards, vulnerability, and exposure. This aligns with the established scientific perspective, as noted by Davidson and Lambert (2001) and Peduzzi et al. (2009), where risk (R) is formulated as the product of hazards (H), vulnerability (V), and exposure (E), encapsulating this relationship in the equation **R = H * V * E**.

The MS-CRI, as developed by Satta et al. (2015) and applied within the ClimVar Project, adopts this approach. It is an index-based methodology that assesses coastal risks by considering both qualitative and quantitative attributes, encompassing the physical, environmental, and socio-economic variables of coastal systems. This index offers a straightforward numerical basis for categorising different sections of the coastline according to their potential for change. This categorisation is useful for coastal managers to identify areas where risks might be higher, notably by visualising them with maps.

Key features of the MS-CRI include:

- A multi-scale risk assessment approach;
- Incorporation of the theoretical framework from AR5 (IPCC, 2014);

[1] Application of a Multi–Scale Coastal Risk Index at Regional and Local Scale in the Mediterranean, Plan Bleu, 2015).

- Integration of a comprehensive set of socio-economic variables;
- Division of risk assessment targets into three sub-indices;
- Inclusion of interactions among different subsystems in the analysis;
- Generation of vulnerability and risk maps as outcomes.

Expressed as **MS-CRI = CH * CV * CE**, the index represents a product of Coastal Hazards (CH), Coastal Vulnerability (CV), and Coastal Exposure (CE). This combination of multiple variable layers results in sub-indexes for hazards, vulnerability, and exposure, thereby highlighting both risk 'hotspots' and areas of lower risk through its integrated layers.

When applied at the local scale (CRI-LS), this methodology can support policymakers and coastal managers in evaluating how climate and non-climate factors interact with existing hazards to affect coastal zones. The CRI-LS methodology, consistent with Article 8 of the Barcelona Convention’s ICZM Protocol, thus aids in defining coastal hazard zones and generating risk maps. These tools are instrumental for policymakers in prioritising coastal management efforts, notably in order to minimise or mitigate risks related to climate and non-climate hazards.

Furthermore, the adaptability of the CRI-LS makes it an ideal fit for integration into comprehensive coastal management and adaptation strategies in diverse settings, including Kotor Bay. This adaptability is crucial for supporting the implementation of the ICZM Protocol.

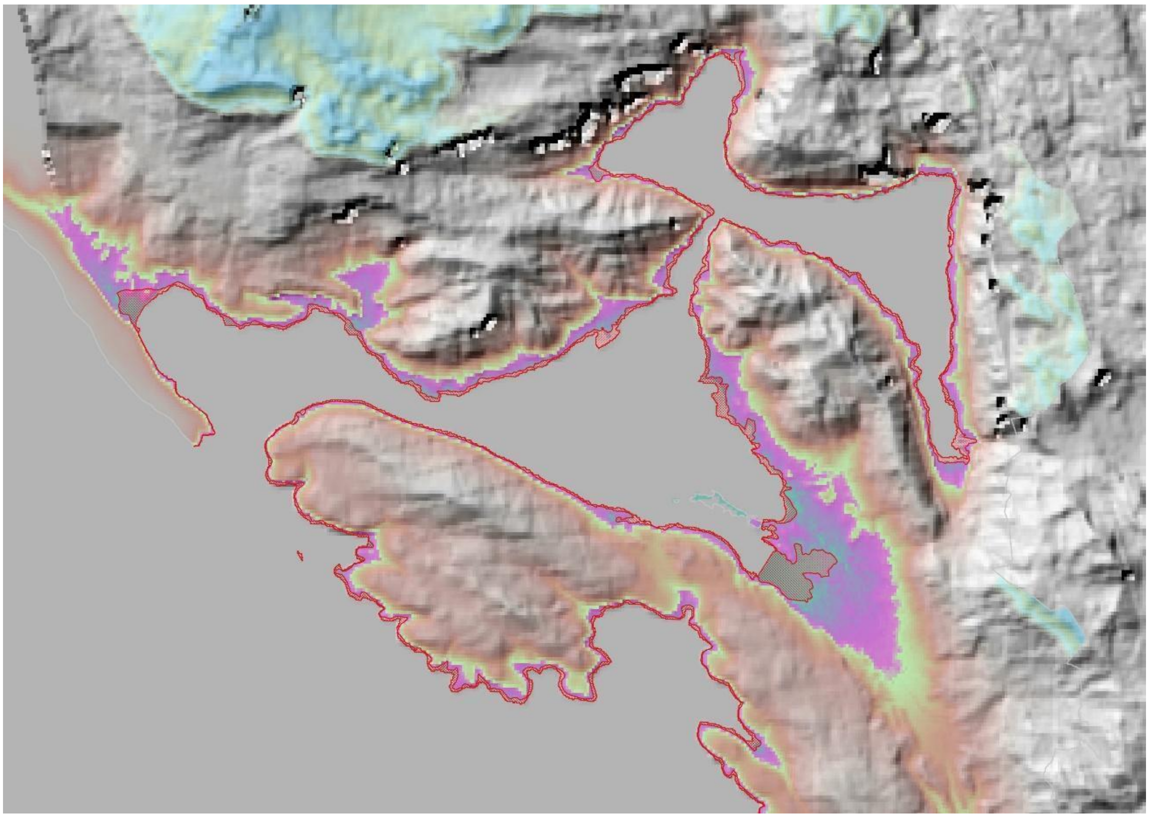
The CRI-LS methodology encompasses five main steps:

1. **Definition of the coastal hazard zone** - This involves determining the area’s most susceptible to climate-induced hazards like erosion, flooding, and sea level rise.
2. **Selection and ranking of variables** - Variables are selected and ranked based on their relevance to the local climate, geography, socio-economic conditions, and environmental aspects.
3. **Assignment of weights to risk variables** - Weights are assigned to these variables through a process involving local experts, ensuring that the risk assessment reflects the unique characteristics of Kotor Bay.
4. **Aggregation of variables, sub-indices, and final index calculation** – The variables are aggregated into sub-indices and a final index. This data will be used to create risk maps using GIS, highlighting risk 'hotspots' as well as areas of lower risk in Kotor Bay.
5. **Development of risk maps.**

III. Definition of the spatial scale and study area

The coastal region of Kotor Bay is an area of substantial interest for the CRI-LS due to its unique geographic and hydrological features. Ensconced within the rugged terrain of the Dinaric Alps in Montenegro, it features a dramatic coastline that wraps around the municipalities of Kotor, Tivat, and Herceg Novi. This region, characterised by its steep limestone cliffs and the deep incursion of the sea, creates a diverse set of micro-environments along the coast.

Figure 2. Hillshade map of Kotor Bay



Source: own production

Kotor Bay, known for its distinct geomorphology, is carved into the southeastern part of the Dinaric Alps' coastline. Its geographical position is defined by extreme coordinates: to the north at 42°31'00", to the south at 42°23'32", to the east at 18°46'32", and to the west at 18°30'29". It comprises four interconnected bays—Herceg Novi, Tivat, Risan, and Kotor—interlinked by two channels. The first channel connects the open sea with Herceg Novi Bay, while the second, known as Verige, links Tivat Bay with Kotor and Risan Bays. The external part of the Bay extends northwest into the Sutorina valley and southeast into the Grbalj valley, while the internal part continues west into the Morinj valley and south into Kotor valley. Its direction aligns with the typical Dinaric orientation.

The imposing slopes of Orjen and Lovćen mountains frame the Bay. The area stretching from Morinj to Kotor is a stark karst region with sheer cliffs. In contrast, the terrain softens around Igalo to Savina and near Zelenika. The Devesilj Hill features steep western slopes descending towards Zelenika, with more gentle slopes leading to Đenovići, Baošići, Bijela, and Morinj. The flysch terrain of Vrmac, marked by numerous parallel gullies, continues this trend. Transitioning from Tivat Bay and Tivatsko Field, the Luštica Peninsula emerges as a plateau with notable karst features such as sinkholes and ridges. The coast along Luštica towards the Bay's inner parts becomes steeper, in contrast to the more indented coastline facing the open sea.

The entire Kotor Bay area falls within the Adriatic Sea Basin and exhibits a sparse network of surface watercourses, mainly due to the carbonate rock-dominated geological structure, which facilitates deep water infiltration. Surface water features include a network of ephemeral streams and brooks, with the Sutorina river near Herceg Novi being the most significant. Karst groundwater systems are particularly complex, with several identified movement directions, including a hydrological connection between the Grahovska river and the Spila well in Risan, and underground drainage from the Trešnjevo karst valley to the Ljuta well near Orahovac.

The Bay features several karst wells and springs, including the Morinjska wells, Sopot and Spila near Risan, and the Škurda and Gurdić wells in Kotor, which collectively contribute an average water flow of 230 m^3/s during the winter. The narrow coastal strip between Kotor and Morinj is home to numerous smaller brackish wells, adding to the area's hydrological diversity.

In terms of seabed topography, Kotor Bay can be differentiated according to two main features: the shallows and the continental shelf. The steep, rocky slopes descend directly from the sea surface down to the Bay's bottom, forming a continuous continental surface without distinct terraces due to the limited space and depth.

The Bay's aquatory covers an area of 87.334 km^2, constituting 0.06% of the Adriatic Sea. It has a maximum depth of 61 metres, with an average depth of 27.6 m. Its intricacy is reflected by the extensive length of the coastline, which measures 105.7 km. According to Richthofen's classification, two types of coasts are distinguished: longitudinal (developed in the bays) and transverse (in the channels).

The Bay also encompasses nine islands, with notable ones including Prevlaka, Mamula, and Ostrvo Vavedenje at its entrance, Gospa od Milosti, Sveti Marko, and Ostrvo Cvijeća in Tivat Bay, and the islands within Krtoljska Bay and Risan Bay.

The study area definition for the CRI-LS includes the following area, which falls within the three following municipalities:

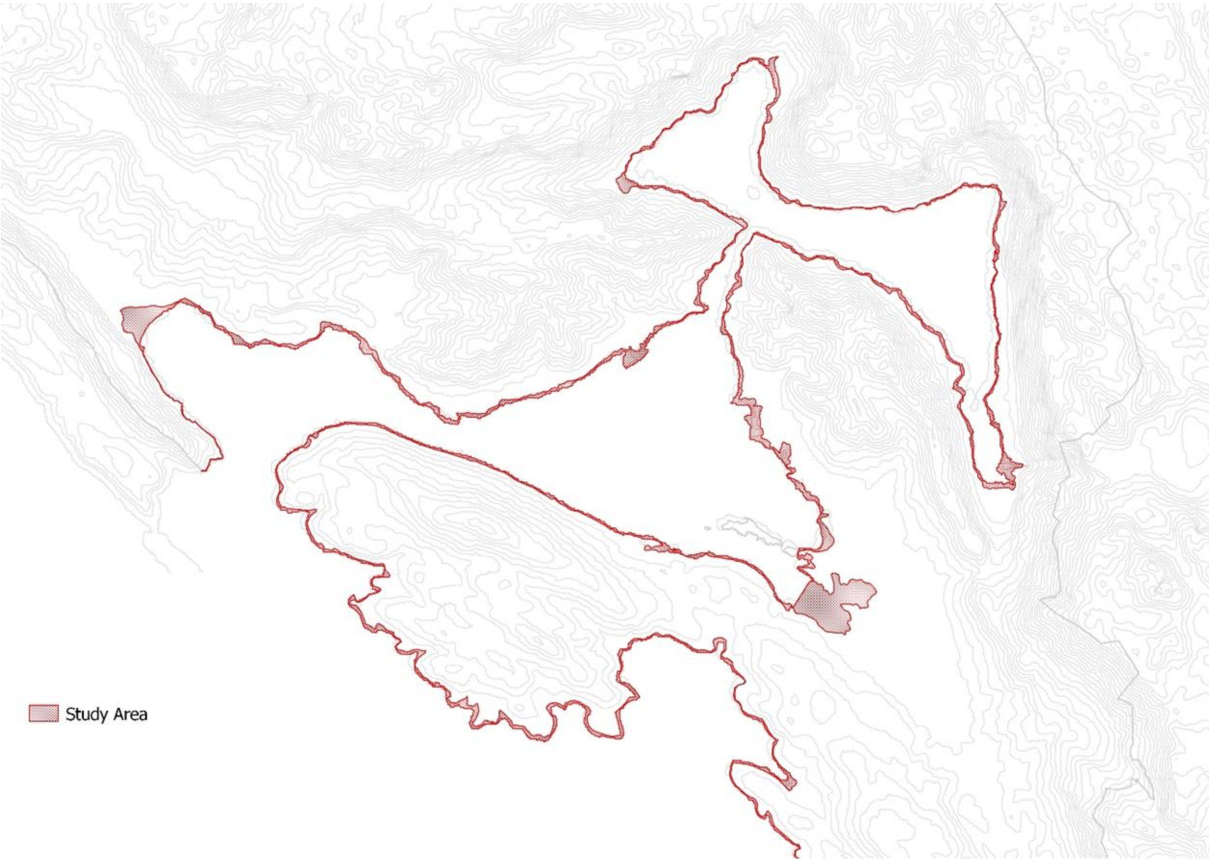
- Kotor: The coastal strip here is bordered by precipitous mountain slopes, with historical settlements nestled along the shoreline. The area's natural topography and urban development patterns are significant factors in assessing the risk of flooding and sea-level rise.
- Tivat: Featuring a mix of developed waterfronts and natural areas, Tivat's coast serves as a transitional zone with varying topography. It's a crucial area for evaluating human-environment interactions and the risks associated with coastal development.
- Herceg Novi: With a coastline that extends from the gentler slopes of Igalo to the more abrupt terrains of Orjen mountain, Herceg Novi's coastal region is key for studying sediment dynamics and the impacts of hydrological changes.

As described in the “Gender-sensitive climate risk assessment of Boka Kotorska Bay”, six bays are recognized as vulnerable to sea level rise due to climate change.

- Igalo (including Sutorina estuary), Morinj, Tivat, Kotor, Krtole and Bigova.

During storm episodes (heavy rainfall and strong winds), these areas are also flooded by torrential rivers and by the sea, which are not able to receive such a quantity of water.

Figure 3. Topographic map of Kotor Bay with the defined Study Area



Source: own production

IV. Definition of the variables associated to each factor (sub-index) and the scores of the variable's classes

Table 1. Variables and sources for the applications of the CRI-LS method

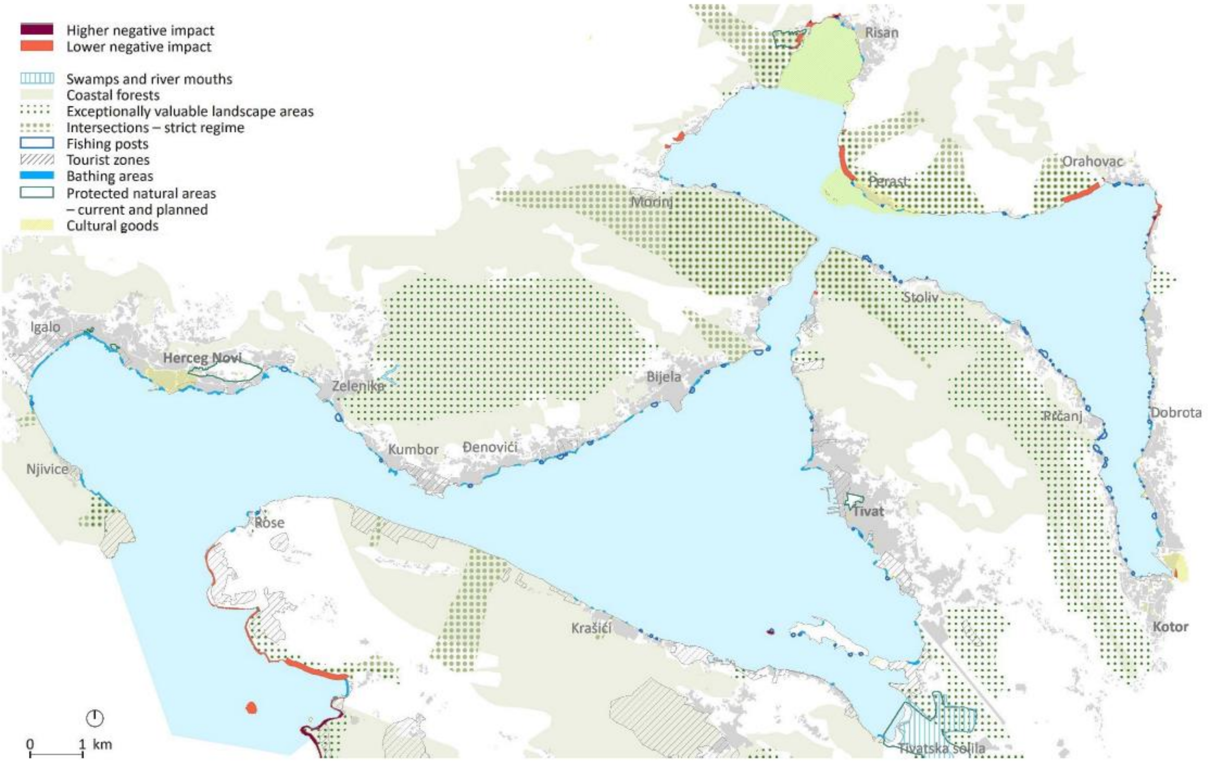
COASTAL HAZARDS/ FORCING	SOURCE									
Variable	**DESCRIPTION**	**FORMAT**	Source at regional/MEDSEA Mediterranean scale (data already collected for the regional analysis)	**Weight**	**Unit**	**1**	**2**	**3**	**4**	**5**
Sea Level Rise (SLR)	Sea level increase increased in one year. Satellite altimetry data provides accurate measures for a limited time range.	Raster	https://www.aviso.altimetry.fr/?id=1599	30	mm/y	<1	1-1,6	1,7-2,4	2,5-3,2	N>3,2
Significant Waves (SWH)	Average number of SWH with a return period Tr =100 yrs.	Shapefile or raster	Copernicus Climate Change Service Dataset title: Ocean surface wave indicators for the European coast from 1977 to 2100 derived from climate projection. Periods: 2041-2070, 2071-2100 https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-ocean-wave-indicators?tab=overview	5	cm	< 50	50 – 150	151–250	251–350	> 350
Very Heavy Precipitation days or Annual Max Daily Precipitation (MDP)	Equal to the highest amount of precipitation received during the year, averaged over 30 years. Daily rainfall categories adapted from Satta et al. (2022).	Shapefile or raster	Own analysis based on available data of the Institute of Hydrometeorology and Seismology, Montenegro: www.meteo.co.me	25	mm/d	< 16	16 – 32	33 – 64	65 – 128	> 128
Droughts (DRO)	A period with an abnormal precipitation deficit, in relation to the long-term average conditions for a region. Low values indicate a scarce sediment supply to	Shapefile or raster	https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1111 Own analysis	10	mm/d	<16	16-32	33-64	65-128	>128

	beaches contributing to erosion									
Storm Surges	Storm surge level, defined as the difference between the pure tide and the total water level simulations, for the return period of 100 years. The return period is a standard way of describing the likelihood and severity of an event. It describes the estimated time interval between events of a similar size or intensity.	Shapefile or raster	https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-water-level-change-indicators?tab=overview	5	mm	>36	36-12	11 -'-12	-13 '-36	<-36
Population growth (PGR)	Population growth (annual %) is the exponential rate of growth of midyear population from year t-1 to t.	Shapefile or table	Monstat table & own analysis https://monstat.org/eng/page.php?id=48&pageid=48	20	%	< 0.1%	0.1%–0.5%	0.51%–1%	1.01%–2%	> 2%
Land use change	The CORINE Land Cover (CLC) updates have been produced in 2000, 2006, 2012, and 2018. The inventory contains 44 land cover classes. it has a Minimum Mapping Unit (MMU) of 25 hectares (ha) for areal phenomena and a minimum width of 100 m for linear phenomena. The time series are complemented by change layers, which highlight changes in land cover with a MMU of 5 ha.	Shapefile	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018	10	%	> 0%	0% – 1%	1,01% – 5%	5,01% – 10%	> 10%
COASTAL VULNERABILITY			**SOURCE**							
VARIABLE	**DESCRIPTION**	**FORMAT**	Source at regional/ Mediterranean scale (data already collected for the regional analysis)	**Weight**	**Unit**	**1**	**2**	**3**	**4**	**5**
Landform (LF)	Expresses the erodibility of the coastal zone. Scores are ranked according to the	Shapefile	Own analysis based on reports about erosion within CAMP project and GEF Adriatic: Land- Sea Interaction Analysis for Montenegro	5	Qualitati-ve	Hard Rock shores	Soft Rock shores	River deltas, estuaries and	Sandy shores backed by	Sandy shores and

	relative resistance of a given landform to erosion.							cobble beaches	bedrock or artificial frontage	water plains
Elevation (ELE)	Represents the surface of selected coastal unit (pixel) within a specific class of elevation Xi (e.g. 0.15m_Xi _ 0.3 m).	Raster pixel resolution 100m	https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1 GIS DEM Montenegro	30	m	8-5.26	5.25-3.6	3.59-2.76	2.75-1	<1
Coastal Slope	The slope of the coastal region landward and seaward (Oziurt, 2007). It is used to determine the relative risk of the shoreline retreat. Low sloping coastal regions should retreat faster.	Raster pixel resolution 100m	Own analysis based on the Elevation map (DEM)	25	%	>0.1	0.1-0.05	0.049-0.034	0.033-0.02	<0.02
Distance from the shoreline	Susceptibility decreases as the distance from the shoreline increases. Scores are based on real progression of the risk according to the inland penetration of the flooding.	Shapefile	Own elaboration based on the coastline shapefile within the Kotor Bay CAMP Project. GIS	10	m	>4 500	4 500-2 100	2 099-900	899-300	<300
River flow regulation	Represents the impact of any dam infrastructure on rivers in term of flow regulation that is negative in terms of new sediment contribution (Oziurt, 2007).	Shapefile	Own elaboration based on Google Earth analysis and the Kotor Bay CAMP Project.	5	No. of dams	No dams	/	Dams only in the minor tributaries	/	Dams in the largest tributary
Roughness	Roughness represents the resistance to surface flow exerted by the land surface and is measured with the so-called Manning's coefficient.	Shapefile	Own elaboration based on the Corine Land Cover map	9	Manning's coefficient	Urban areas	Forest and water bodies	Shrubland, grasslands, sparse vegetation	Agriculture	Bare areas
Ecosystems health (EH)	Expresses the contribution of the ecosystem as a protection against storm surges, flooding and other coastal hazards. Ecosystems include coral reefs, sea grass beds, sand	Shapefile	ICZM in Kotor Bay, Jelena Knezevic and Slavica Kascelan, 2016	5	Qualitative	No detectable change	Slight signs of disturbance	Moderate distortions with loss of 50% of species	Major distortions	Severe distortions with loss of all species

	dunes, coastal wetlands and coastal forests.									
Education level (EDU)	Percentage of population whose level is equal at least to the level 3 of the international standard classification of education (ISCED).	Shapefile or table	Monstat census data table https://monstat.org/eng/page.php?id=57&pageid=57	5	%	> 60	60 – 44	43 – 28	27 – 10	< 10
Age of population (P65)	Percentage of population that is aged 65 years or older.	Shapefile or table	Monstat census data, own analysis https://monstat.org/eng/page.php?id=57&pageid=57	5	%	< 3	3 – 8,5	8,6 – 15	16 – 20	> 20
Coastal protection structures	Artificial protection to erosion.	Shapefile	Own elaboration based on Google Earth analysis. https://www.adriatic.eco/wp-content/uploads/2021/07/The-State-and-Pressures-of-the-Marine-Environment-in-Montenegro.pdf (page 111)	5	%	>50	50-31	30-21	20-'5	<5
COASTAL EXPOSURE			**SOURCE**							
VARIABLE	**DESCRIPTION**	**FORMAT**		**Weight**	**Unit**	**1**	**2**	**3**	**4**	**5**
Land Cover (LC)	The LC map from 2010 is a global land cover map at 300m spatial resolution.	Shapefile	https://land.copernicus.eu/pan-european/corine-land-cover/clc2018	62	Qualitative	Bare areas	Shrub land, grasslands, Sparse vegetation	Forest and water bodies	Agriculture	Urban areas
Population density (PDE)	The population density is derived by dividing the population count by the land area. It represents population per km^2.	Raster	Own elaboration based on Monstat census data table https://monstat.org/eng/page.php?id=57&pageid=57	38	Pop/km^2	< 25	26 – 50	51 – 100	101 – 250	> 250

Figure 4. Impact of coastal erosion on land: Kotor Bay, GEF Adriatic: Land- Sea Interaction Analysis for Montenegro)



Source: UNEP/MAP-PAP/RAC and MESPU, 2021

V. Aggregation of variables and calculation of the three sub-indices and of the final index

The Coastal Forcing (CF) sub-index is calculated using a formula that integrates various climate-related factors. This sub-index reflects the direct impact of climatic forces on the coastal area. Each component, including sea level rise (SLR), significant wave height (SWH), and mean annual maximum daily precipitation (MDP), among others, is weighted and scored based on its relevance and impact.

Coastal Forcing CFsub-index= {[(WSLR * SSLR + WSLR * $_{SSWH}$ +WMDP*SMDP +WDRO *SDRO +WPGR *SPGR+ WTOUR * STOUR) – 1] / 4}

Where each variable (**S_{LR}, S_{WH}, M_{DP}, W_{DRO}, P_{GR}, T_{OUR}**) is scored and weighted to reflect its impact on coastal forcing. This calculation provides a nuanced understanding of how different climatic factors cumulatively affect the coastal region.

Where:

SSLR = score of SLR variable; SSWH = score of SWH variable;

SMDP = score of Mean Annual Maximum Daily Precipitation; SDRO = Score of DRO variable;

SPOP = score of POP variable; STOUR = score of TOUR variable;

WSLR = weight of SLR variable; WSWH = weight of SWH variable;

WMDP = weight of Mean Annual Maximum Daily Precipitation; WDRO = weight of DRO variable; WPGR = weight of PGR variable; WTOUR = weight of TOUR variable.

Coastal Vulnerability (CV) sub-index={[(WLF *SLF +WSLO * SSLO + WLR*SLR+WELE * SELE +WD * SD + WRFR *SRFR+ WEH * SEH + WEDU * SEDU + WP65 * SP65 + WCPS * SCPS) – 1] / 4}

Where:

SLF = score of Landform variable; SSLO = Score of Slope variable;

SELE = score of Elevation variable;

SD = Score of Distance from the shoreline; SRFR = Score of River Flow Regulation;

SEH = Ecosystem Health; SP65 = score of P65 variable; SEDU =score of EDU variable;

SCPS = Score of Coastal Protection Structures;

WLF =weight of Landform variable; WSLO = Weight of Slope variable.

The Coastal Vulnerability (CV) sub-index assesses the inherent susceptibility of the coastal region to the identified hazards. This sub-index includes variables such as landform, coastal slope, land roughness, and elevation, each contributing to the overall vulnerability of the area.

Finally, the Coastal Exposure (CE) sub-index quantifies the extent of exposure of human and ecological systems to coastal hazards. This includes evaluating land cover and population density, which are critical in understanding how exposed the population and infrastructure are to coastal risks.

Coastal Exposure (CE) sub-index={(WLC * SLC + WPDE*SPDE) / 5}

Where:

S_{LC} = score of LC variable; **S_{PDE}** = score of PDE variable;

W_{LC}= weight of LC variable; **W_{PDE}** = weight of PDE variable.

A. THE COASTAL FORCING SUB-INDEX/HAZARD

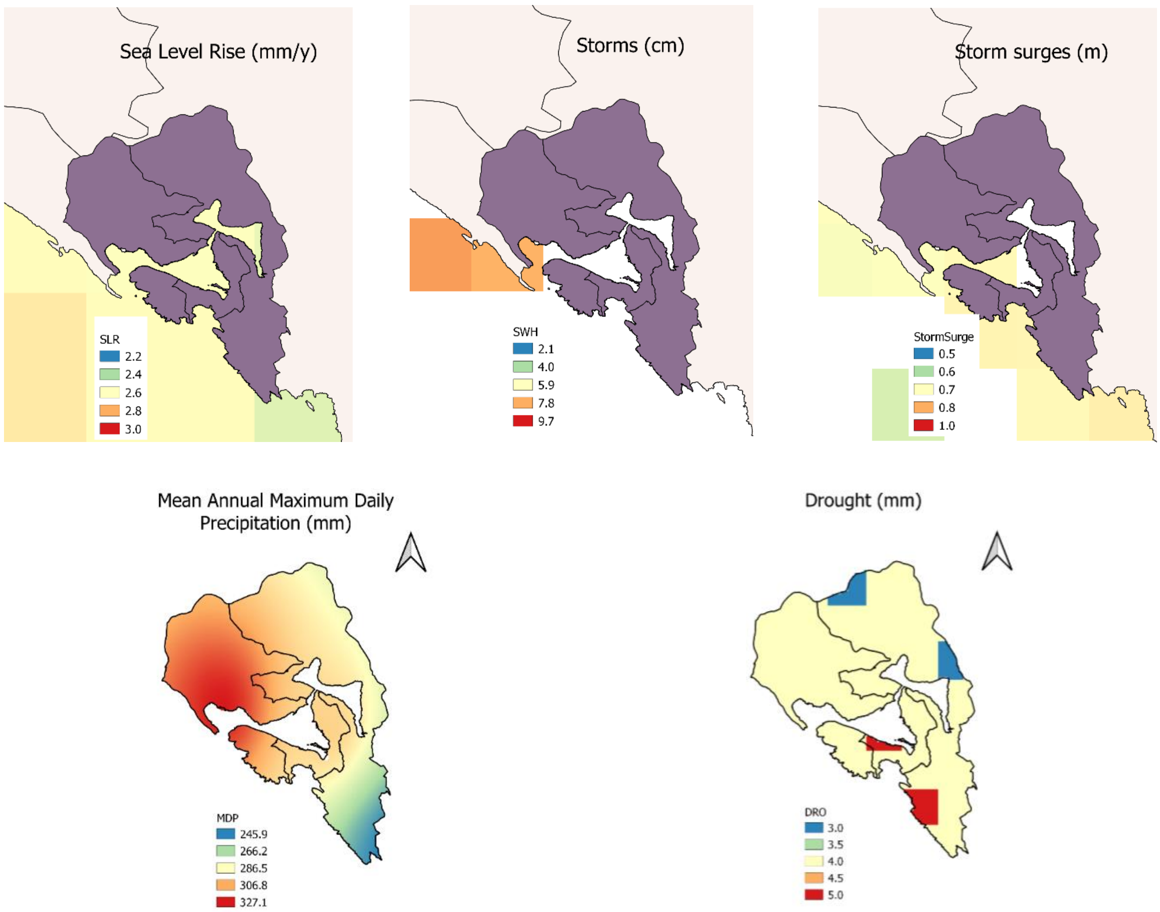
The Coastal Forcing Index is a critical component of the CRI-LS, designed to encapsulate the multidimensional aspects of climatic and socio-economic forces acting upon the coastal zones of Kotor Bay. This index evaluates the combined effects of several key variables to assess the level of hazard posed to the coastal area.

The map of Sea Level Rise (SLR) variable shown in Figure 4, indicates an increasing trend in SLR, with rates varying from 2.2 to 3.0 mm/year across different segments of the Bay. The highest scores of 3 and 4 are attributed to regions that experience the greater rates, highlighting areas where proactive measures against potential flooding and land loss are essential. However, due to the limitations of the data used for the Kotor Bay scale, sea level rise and areas prone to flooding are studied in Section 6: Site-Specific Coastal Risk Assessments.

An analysis of storm patterns reveals a variation in significant wave heights ranging from 2.1 to 9.7 cm on the open part of Kotor Bay. A score of 1 is given to this variable, as it poses a comparatively lower risk in the context of the Bay's sheltered nature. However, its impact in conjunction with other variables such as storm surges could be significant and thus warrants continuous monitoring.

The spatial distribution of Mean Annual Maximum Daily Precipitation (MDP) ranges from 245.9 to 327.1 mm, with the highest concentrations indicated towards the northern sections of the Bay in its hinterlands, towards the Crkvice region). This variable receives a score of 5, acknowledging the significant risk of heavy precipitation events that can lead to flash floods and exacerbate land erosion processes. The occurrence of drought, indicated by the map, presents variable conditions across the bay with measurements spanning from 3.0 to 5.0 mm. Drought receives a score of 3, reflecting the moderate yet tangible risk it poses to water supply, agriculture, and ecological balances within the region.

Figure 5. Variables of the Coastal Forcing Sub-Index



Source: own production

In Kotor Bay, the population trends observed in the municipalities of Herceg Novi, Kotor, and Tivat between 2018 and 2022 do not follow the conventional narrative of unrestrained growth. Instead, we see a stabilising, if not decreasing, pattern in resident numbers. Herceg Novi's population slightly decreased from 30,647 to 30,150, Kotor's from 22,683 to 22,540, and Tivat showed a slight increase from 14,923 to 15,377, hence this variable receives the score 3. These figures suggest that contrary to many coastal regions were increasing permanent populations strain resources, Kotor Bay's risk due to population growth is not as acute. However, a declining or stagnant population does not necessarily imply a lower risk profile.

Table 2. Population estimates for 3 municipalities in Kotor Bay

Population estimates	2018	2019	2020	2021	2022
HERCEG NOVI	30,647	30,597	30,480	30,356	30,150
KOTOR	22,683	22,753	22,793	22,713	22,540
TIVAT	14,923	15,069	15,205	15,248	15,377

Source: Monstat, Population estimates, available online at: https://www.monstat.org/cg/page.php?id=48&pageid=48)

In stark contrast to the moderate shifts in resident populations, tourist arrivals tell a different story. The number of tourists visiting these municipalities vastly exceed the local population, with 2022 figures indicating 350,847 tourists in Herceg Novi, 196,953 in Kotor, and 139,048 in Tivat. A dramatic drop notably occurred in 2020 due to travel restrictions imposed by the COVID-19 pandemic, but a significant rebound was observed in subsequent years.

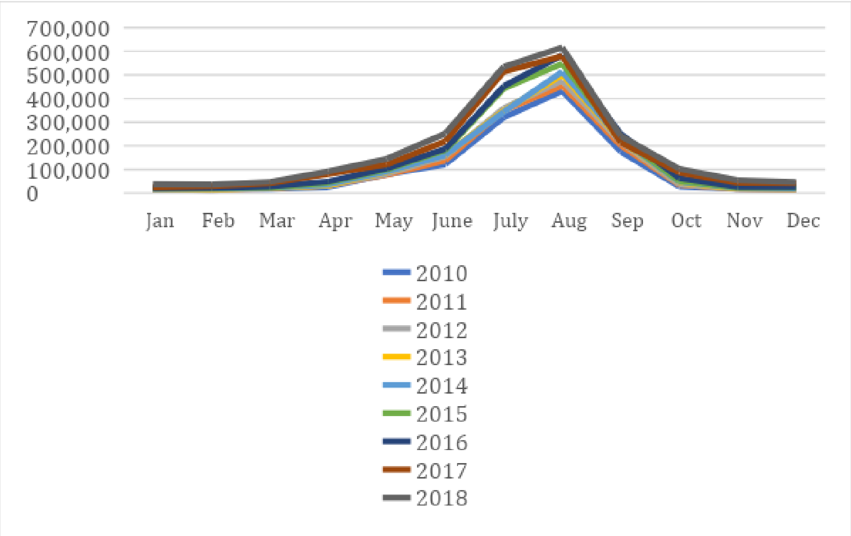
Table 3. Tourist arrivals for 3 municipalities in Kotor Bay

Tourist arrivals	2018	2019	2020	2021	2022
HERCEG NOVI	313,985	383,048	59,089	253,674	350,847
KOTOR	139,573	170,852	26,962	133,042	196,953
TIVAT	123,289	161,153	37,724	108,981	139,048

Source: Monstat, arrivals and overnight stays, available online at: *https://www.monstat.org/cg/page.php?id=44&pageid=44)*

The seasonal surge of tourists, especially during peak seasons, places acute demand on local infrastructure, stretching resources such as water supply, waste management, and transportation systems.

Figure 6. Tourist arrivals by year in Montenegro



Source: Monstat, Arrivals and overnight stays, available online at: https://www.monstat.org/cg/page.php?id=44&pageid=44)

This temporary yet intense increase in population can lead to significant environmental stress, exacerbating coastal erosion, pollution, and habitat disruption. Moreover, the seasonal nature of tourism means that adaptation and mitigation strategies must be flexible and robust enough to cope with these fluctuations. Thus, tourist arrivals as a variable are assigned the highest score of 5, reflecting the critical need for adaptive risk management strategies capable of addressing such seasonal volatility.

The following table encapsulates the assigned scores for each variable, reflecting their respective impact within the Coastal Forcing Index:

Table 4. Assigned scores within the Coastal Forcing Sub-Index

Variable	Score	Variable	Score
SLR	3 and 4	DRO	3
SWH	1	Population Growth	3
Storm Surge	Not available	Touristic Arrivals	5
MDP	5		

Source: own production

This assessment encountered several limitations that are critical to acknowledge for an accurate interpretation of the findings and to guide future research.

- The sea level and storm surge data utilized in this study present significant challenges due to the scale of available data, which is not finely resolved enough for the unique geographical nuances of Kotor Bay. These broad-scale datasets, while valuable, fail to capture the localised phenomena that are essential for precise risk calculation. Consequently, the methodology recommended by Satta et al. (2014) had to be adapted to accommodate alternative datasets that provided a more detailed view of the Bay's topography and hydrodynamics.
- The drought assessment, initially based on direct measurements, would benefit from the integration of the Standardized Precipitation Index (SPI) as provided by the Institute of Hydrometeorology and Seismology of Montenegro. The SPI offers a more comprehensive understanding of drought conditions over time. However, incorporating this index requires methodological adjustments to align with the CRI-LS framework, presenting a methodological challenge that was addressed during the study.

In light of these limitations, this study has necessitated the adaptation of the CRI-LS methodology. While such changes allowed for a more tailored risk assessment of Kotor Bay, they represent a departure from the established method, which may affect comparability with other studies. It is imperative that future research continues to refine these adaptations, ensuring that the methodology remains robust, consistent, and reflective of the actual conditions in coastal zones similar to Kotor Bay.

B. THE COASTAL EXPOSURE SUB-INDEX MAP

The Coastal Exposure Index (CE) map integrates critical environmental and socio-economic factors to provide a spatial representation of the vulnerability of coastal zones in Kotor Bay. This mapping is essential for identifying areas at risk and developing targeted climate adaptation strategies.

Land Cover Analysis:

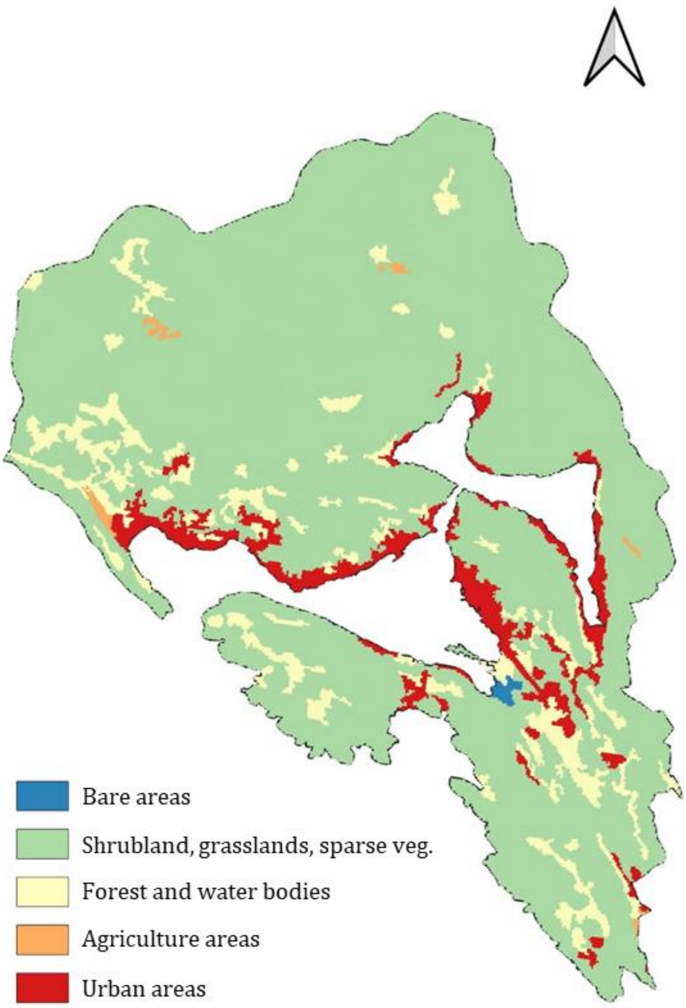
The land cover map, a key component of the Coastal Exposure sub-index, categorises the physical cover of the earth's surface within the Bay. It discerns various types of coverage such as urban areas, vegetation, and bare surfaces, which are instrumental in understanding the potential impacts of climate hazards on different coastal assets.

This map has classified the Bay's land into five primary categories, each representing distinct types of earth coverage with varying degrees of vulnerability to climate hazards:

- **Bare areas** are typically the least vegetated areas, which are potentially more susceptible to erosion and have minimal buffer against storm surges. For instance, the Tivat Salines, a protected natural area, figure prominently in this category. Its representation on the map underscores the need for conservation efforts to maintain its ecological integrity and enhance its resilience to coastal hazards.
- **Shrubland, grasslands, and sparse vegetation** cover areas that offer some protection against climate hazards but are often susceptible to changes in the local microclimate.
- **Forest and water bodies** are crucial for biodiversity and can act as natural barriers against coastal hazards, absorbing excess water during floods and providing windbreaks during storms.
- **Agriculture areas** represent managed ecosystems that are vital for local livelihoods but can be sensitive to salinity changes and flooding.

- **Urban areas** are the most impacted by coastal hazards, where infrastructure and high population densities lead to significant potential impacts from climate-related events.

Figure 7. Land Cover Map of Kotor Bay



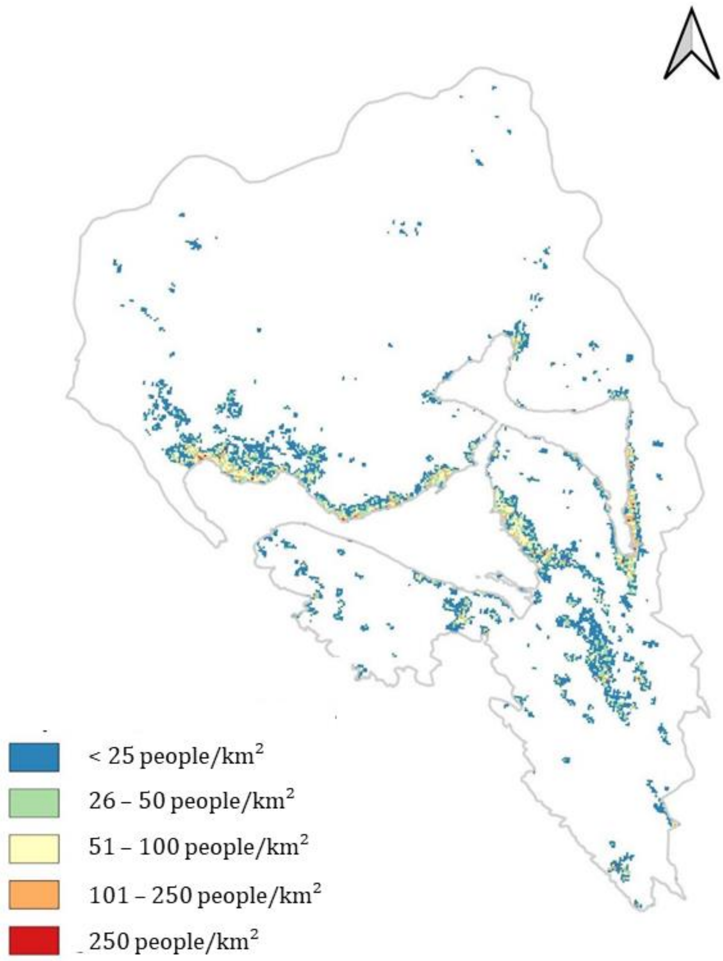
Source: own production

1. Population Density Assessment

The population density map complements the land cover analysis by highlighting areas where human assets are concentrated. High-density areas often correlate with urban centres that are more susceptible to the impacts of sea-level rise and coastal storms. These regions are prioritised within the Coastal Exposure sub-index due to the higher potential for economic loss and social disruption. These areas, particularly along the coasts near Kotor, Tivat, and Herceg Novi, face increased risks due to their proximity to the sea.

From Figure 8, it is evident that a significant portion of the population resides in the coastal belt. The clustering of populations in these regions underscores the need for robust coastal defence mechanisms and sustainable planning to mitigate the risks associated with high population density. The map's depiction of population distribution guides the prioritization of protective measures in these densely populated areas, which are also zones of heightened economic activity and thus more vulnerable to potential disruptions.

Figure 8. Population density map of Kotor Bay



Source: own production

The map quantifies population density in terms of inhabitants per square kilometre, with the following classifications:

- **< 25 people/km²:** These sparsely populated areas, often rural or natural landscapes, are less likely to experience significant social disruption from coastal hazards.
- **26–50 people/km²:** Regions with low population density, which may include smaller communities or suburban areas that interface with urban zones.
- **51–100 people/km²:** Moderately populated areas where the risk begins to increase, often representing the outskirts of larger towns or peri-urban areas.
- **101–250 people/km²:** These are densely populated areas that likely include urban suburbs and towns where the population begins to cluster significantly.
- **250 people/km²:** The most densely populated regions, corresponding to major urban centres, are at the highest risk of economic loss and social disruption from coastal hazards.

It is important to acknowledge the constraints encountered during the population density assessment. The study primarily relied on population growth and tourism data available prior to the most recent 2023 national census. Although newer data has been released, it lacks the detailed municipal breakdown necessary for granular analysis, which is anticipated to be made public in June 2024. This absence of locality-specific data significantly hinders our capacity to accurately assess demographic shifts and their implications for coastal risk at the municipal level. While provisional estimates were employed to approximate these impacts, it is crucial to recognize that access to more detailed data could substantially refine and potentially alter the risk profiles presented in this study.

2. Coastal Exposure Index Development

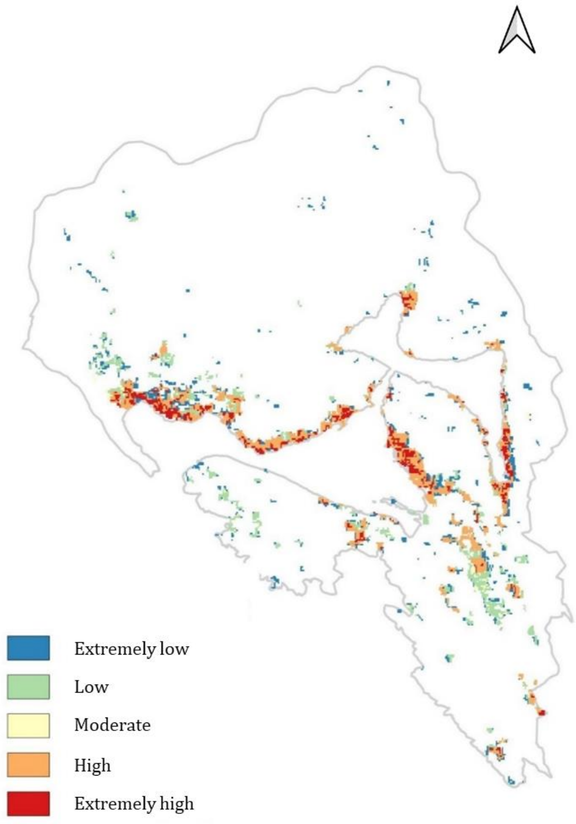
This section introduces the Exposure Index for Kotor Bay, developed to provide insights into the spatial distribution of risk across the region. The Exposure Index serves as a foundational component for calculating the Coastal Exposure Index. It is derived from an integrated analysis of land cover and population density data, synthesized to depict the relative exposure of different areas to coastal hazards.

The methodology involves overlaying land cover maps with population density data. Each element is weighted according to its relevance to exposure risk. For example, areas with dense human settlements or critical natural habitats are assigned higher weights, reflecting their potential vulnerability to climate impacts such as flooding or erosion. The composite map produced from this synthesis assigns exposure levels ranging from 'Extremely low' to 'Extremely high'.

Figure 9. visually represents the distribution of exposure levels throughout Kotor Bay. Areas marked with 'Extremely high' exposure are typically characterised by dense population clusters. These areas are particularly vulnerable to coastal hazards, necessitating targeted intervention and robust planning to mitigate potential impacts. Conversely, regions labelled as 'Extremely low' tend to have sparse populations and less vulnerable land cover, implying a lower immediate risk from coastal phenomena.

A clear correlation exists between high population density and increased exposure levels. This pattern underscores the need for enhanced infrastructural resilience in densely populated coastal segments.

Figure 9. Coastal Exposure Index Map for Kotor Bay



Source: own production

Continued refinement of the Exposure Index is essential as new data becomes available. Enhancements may include integrating updated demographic information following the 2024 national census, incorporating more detailed climatic data, and considering the impacts of economic development on land use patterns. By continually updating the index, the region can better anticipate and adapt to the evolving landscape of coastal risk.

VI. Site-Specific Coastal Risk Assessments

These site-specific coastal risk assessments focus on three critical areas of Kotor Bay: the Sutorina' river's valley and Igalo in Herceg Novi Municipality, Kotor, and Tivat Bay. These sites were selected due to their unique geographical features, ecological sensitivity, and the elevated risk that they pose to human settlements and critical infrastructure. Each site presents distinct challenges that necessitate a detailed and tailored approach to effectively manage and mitigate coastal risks.

The assessments are designed to quantify the risk levels using specific indices—Coastal Forcing (CF), Coastal Vulnerability (CV), and Coastal Exposure (CE)—calculated based on various contributing factors and tailored to the unique characteristics of each location.

A. HERCEG NOVI BAY

The Sutorina river's valley and Igalo

Sutorina, a river known for its propensity to overflow during heavy rainfall, poses a significant flood risk, especially to the adjacent plains of Igalo. This area's topography exacerbates the impact of floods, leading to more widespread water dispersion and prolonged water retention, which can severely disrupt normal life and damage property.

Igalo is densely populated and hosts critical infrastructure. The combination of high population density and vital infrastructure within a flood-prone plain makes it imperative to prioritize this area for detailed risk assessment and robust flood management strategies.

Risk Calculation Overview:

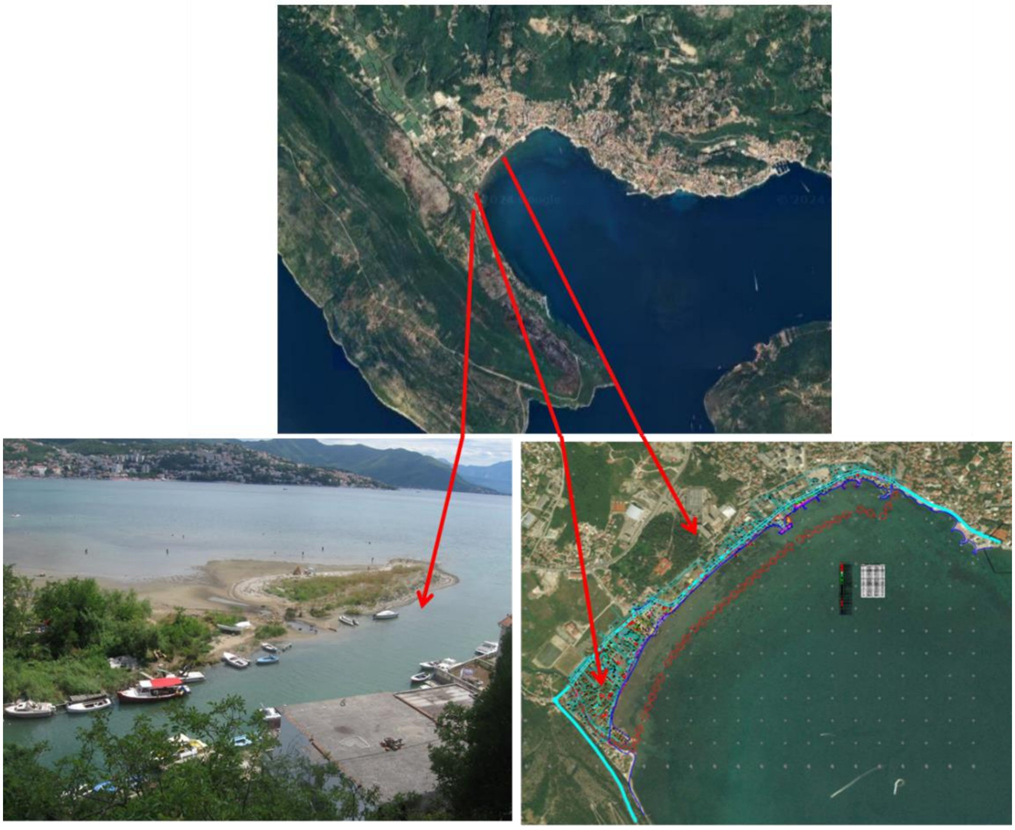
$$CF=\{[(30\%*4+25\%*2+10\%*5+5\%*5+20\%*3+10\%*5)-1]/4\} = 0.6375 = 0.64$$

$$CV=\{[(5\%*3+25\%*4+30\%*5+10\%*3+5\%*1+10\%*5+5\%*2+5\%*1+5\%*3+5\%*2)-1]/4\}=0.72$$

$$CE=\{(70\%*5+30\%*4)\ /\ 5\}=0.94$$

- **Coastal Forcing Index (CF)** calculates at **0.64**, derived from the aggregation of various factors such as flood frequency, wave action, and land cover. This indicates a significant forcing of natural elements that can amplify the risk of coastal hazards.
- **Coastal Vulnerability Index (CV)** is slightly higher at **0.72**, reflecting the region's susceptibility due to human settlements, infrastructural density, and ecological sensitivity.
- **Coastal Exposure Index (CE)** peaks at **0.94,** emphasizing the high exposure of Igalo's population and critical infrastructure to coastal threats, compounded by the river's tendency to overflow during heavy rainfall, making this area particularly crucial for targeted risk mitigation strategies.

Figure 10. Assessment of the river Sutorina's valley and Igalo specific locations



The river Sutorina's mouth

The river Sutorina's valley, Igalo

Source: own production

B. KOTOR BAY

Kotor Bay is heavily built-up, and urban development often extends very close to the shoreline. This overdevelopment increases the vulnerability of the area to flooding, particularly during storm surges when water can inundate streets and the old town of Kotor.

The presence of the river Skudra, a crucial local water source, adds another layer of complexity. During storm surges and droughts during summer months, the intrusion of saltwater into freshwater resources threatens water quality, affecting both human consumption and ecological balance.

Calculations for Kotor Bay:

*CF= { [(30%*4+25%*2+10%*5+5%*5+20%*3+10%*5)-1]/4} = 0.6375 = 0.64*

*CV= {[(5%*4+25%*4+10%*1+30%*5+10%*5+5%*1+5%*2+5%*1+5%*3+5%*1)-1]/4}=0.68*

*CE= {(70%*5+30%*4) / 5}=0.94*

- **Coastal Forcing Index (CF)** remains consistent at **0.64**, indicating a substantial natural impact from sea-level rise and storm surges, especially given the low elevation of the urban coastline.
- **Coastal Vulnerability Index (CV)**, scored at **0.68**, highlights the area's vulnerabilities stemming from overdevelopment and its effect on drainage and flood management systems.
- **Coastal Exposure Index (CE)** is computed at **0.94**, reflecting the intense exposure to coastal hazards, exacerbated by the historic and densely populated nature of Kotor, alongside environmental concerns related to the salinization of the Skudra river during surge events.

C. TIVAT BAY

Within Tivat Municipality lies the Salinas, a recognized nature park and an ecological hotspot that supports a diverse array of bird species. This area is particularly vulnerable to changes in sea level and storm activity, which can alter its salinity and overall ecosystem health.

Similarly to Kotor, Tivat is also extensively developed. This development, especially in low-lying areas, heightens the risk of flooding and ecological degradation, posing long-term challenges to both human and wildlife populations.

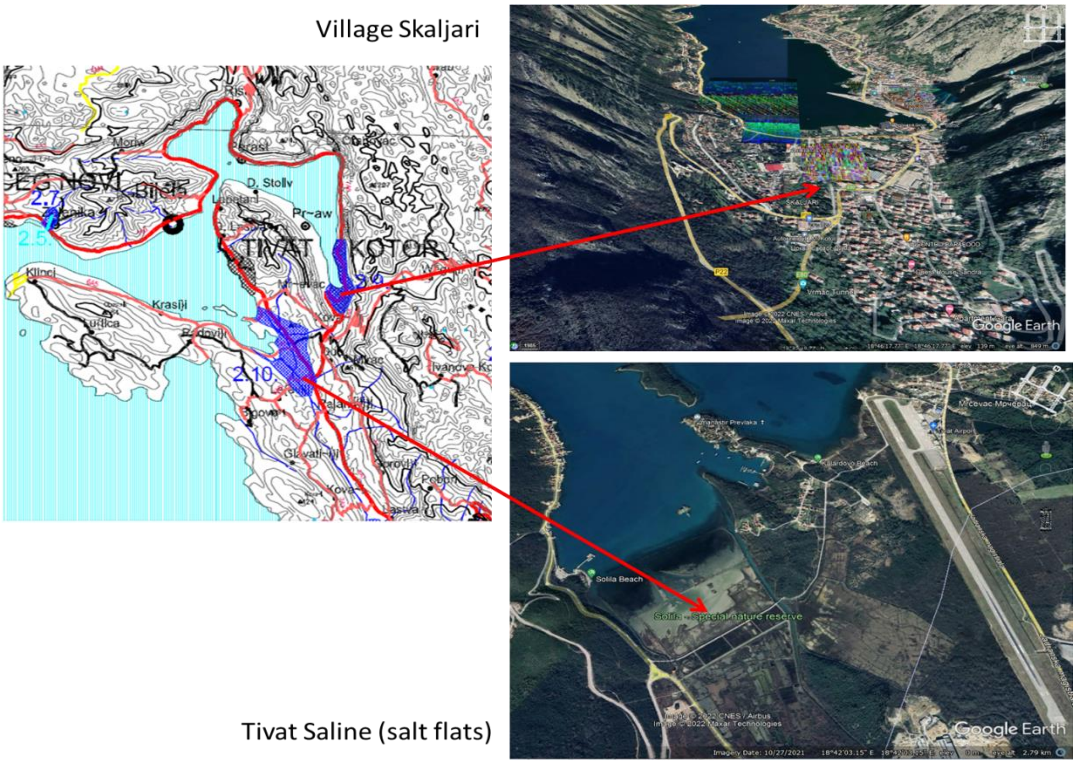
Calculations for Tivat Bay:

*CF= { [(30%*4+25%*2+10%*5+5%*5+20%*3+10%*5)-1]/4} = 0.6375 = 0.64*

*CV= {[(5%*4+25%*4+10%*1+30%*5+10%*5+5%*1+5%*2+5%*1+5%*3+5%*1)-1]/4}=0.68*

*CE= {(70%*5+30%*5) / 5}=1*

Figure 11. Assessment of the Kotor and Tivat locations



Source: own production

- **Coastal Forcing Index (CF)** matches the other areas at **0.64**, driven by similar factors of sea-level rise and hydrodynamic changes.
- **Coastal Vulnerability Index (CV)** also indicates a score of **0.68**, considering the built environment's density and ecological pressures on Salinas, a natural lowland and a critical ecological site.
- **Coastal Exposure Index (CE)** reaches **1.0**, the highest among the studied areas, pointing to extreme exposure due to both the concentration of development and the ecological significance of the Salinas nature park, particularly vulnerable to climate-induced changes.

For all three sites, our assessments aimed to overcome the mentioned limitations posed by the broader scale analyses employed in this coastal risk evaluation. These site-specific assessments enable a nuanced understanding of risk across different coastal segments, highlighting the need for differentiated management strategies that account for the varied dynamics of each area. For instance, the high Coastal Exposure scores suggest that proactive measures are urgently needed to reduce exposure and enhance resilience, particularly in areas with significant ecological and socioeconomic stakes.

Conclusion

Our application of the CRI-LS in Kotor Bay, Montenegro, has shed light on the complex dynamics of climate risks affecting this region, renowned for its unique ecological and cultural heritage. By leveraging the CRI-LS methodology, we have made substantial progress in understanding, predicting, and managing the escalating climate challenges along the Mediterranean coast in this coastal hotspot.

In preparing this assessment, we conducted a comprehensive review of existing methodologies and tools, and, inspired by research such as Satta et al. (2015), we selected the Multi-scale Coastal Vulnerability Index (McLaughlin and Cooper, 2010) as our foundational methodology. This decision was driven by the method's ability to thoroughly integrate both physical and socio-economic factors, providing a robust framework for regional and local risk assessments.

Throughout the study, we identified a spectrum of vulnerabilities primarily associated with rising sea levels, increasing storm frequency and intensity, and their subsequent socio-economic impacts.

However, the study encountered significant challenges, particularly in data management. The integration of diverse data types—from numerical data and vector graphics to georeferenced rasters of varying resolutions—required substantial efforts to standardize this information into homogeneous formats suitable for GIS processing. This process often obscured localized phenomena that are critical to generate precise risk calculations, prompting us to adapt our methodologies and integrate alternative data sets for enhanced local analysis.

A pivotal finding of our assessment, echoing the conclusions of Satta et al. (2017), is the direct correlation between regions designated as high risk and their inherent high vulnerability. This pattern is consistent with observations across other Mediterranean areas, underscoring the urgent need for integrated risk management strategies that effectively address both physical threats and socio-economic vulnerabilities.

Looking ahead, the path forward will focus on deepening community engagement and strengthening capacity-building efforts to ensure that local populations are not merely informed about risks, but are actively participating in adaptation strategies to address the alter. Furthermore, by expanding collaboration with regional and international bodies, Montenegro can increase its resource base and integrate external expertise, which is vital for implementing comprehensive coastal management practices.

The insights from this report contribute to a dynamic, ongoing discussion with Mediterranean stakeholders and experts about optimizing decision-support tools to evaluate and address climate-related risks. In doing so, this study can inform institutional processes under UNEP/MAP, supporting the development of the Regional Climate Change Adaptation Framework and the revision of the Mediterranean Strategy on Sustainable Development. Our collective efforts are aimed at enhancing regional strategies and policies to protect coastal communities and ecosystems from the increasing impacts of climate change, ensuring a resilient future for Kotor Bay and beyond.

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