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Mangrove Ecological Land Suitability. A Tool for Integrating Mangroves Conservation in Urban Green Infrastructure in Sub-Saharan African Coastal Cities—A Case Study of Maputo, Mozambique †

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Abstract: The mangroves along the Mozambique coastline represent 2.3% of the world's total mangrove area. Theyare fundamental ecosystem services providers, namely as soft infrastructures for mitigation and adaptation to extreme weather events and urban floods. In the context of Maputo, these ecosystems are currently under threat, through ongoing land-use changes (short-term) and sea-level rise (SLR) (mid-term) events. The study presents a methodology to map mangrove potential areas according to their ecological land suitability (MELS) in Maputo by applying a GIS-based integrated model that uses a set of bio-physical criteria. Mapping the existent and potential MELS areas, currently and facing a SLR scenario shows possibilities for integrating mangroves within an urban green infrastructure whilst contributing to mangrove conservation, using MELS as an assessment tool within the scope of coastal climate change adaptation.

Keywords: mangrove wetlands; GIS spatial analysis; urban green infrastructure; Maputo; sea level rise scenario

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1. Introduction

In tropical coastal areas, mangroves are one of the most productive wetland ecosystems, playing a role in coastal protection from erosion, storms, high tides [1,2] and flood events [3]. They are part of carbon-cycle mechanisms [4,5], working as efficient carbon storage habitats [6]. These ecosystems are also valued for providing habitats that support biodiversity and nutrient cycling, food and job security, provision of renewable products, and a range of cultural benefits [7–9]. Despite the importance, variety, and quantity of ecosystems services, mangroves are being degraded or lost at an alarming rate [10,11]. Mangroves, as other wetland areas worldwide, are changing to other land uses or to degraded conditions [4,12] due to the overexploitation of natural resources, land fragmentation, urban expansion, water and soil pollution, and changes in water dynamics induced by climate change [10,13,14].

Present in considerable extent along the coastline of Mozambique, these ecosystems are currently under threat. As in other Sub-Sahara African (SSA) coastal cities, mangroves in Mozambique's major cities still maintain valuable remnants of native ecosystems [15]. However, in Maputo, the capital of Mozambique, the urban sprawl associated to recent road infrastructure construction and real estate pressure are degrading and consuming mangroves and saltmarshes at its coastline. This is placing human livelihoods at risk in progressively encroached areas [16], as they became more vulnerable to extreme climate events and to the increased risk of sea level rise (SLR). Examples of such events occurred in March and April 2019, when two category 4 cyclones have seriously affected the north-eastern coast of Mozambique in a very short timeframe, damaging the urban areas of Beira and Pemba, as well as their adjacent regions at an unprecedented scale.

Given the problems, there is an urgent need to find practical tools that can support the identification and protection of mangroves for their inclusion in urban strategies. The hypothesis that mangroves can integrate urban green infrastructures (GI) [17] is of extreme relevance, as these play a relevant role in the urban context, having a confirmed positive impact on improving cities resilience, through the creation of socio-ecological networks [18,19] and as ecosystem services providers [20].

The study area comprises part of the Maputo municipality, with a population of 1.101.170 people in 2017 [21], within the Maputo Bay, in the south-eastern coast of Mozambique. Its coastline is influenced by the confluence of five rivers, that together form a large body of water of 1280 km2 and an average depth of 10m [22]. This bay is strongly influenced by the tide [23] and by its sub-tropical climate, with 800 mm annual rainfall and an average temperature of 25ºC [24,25]. Within the past 50 years period (1967–2017) mangrove ecosystems show an area loss of 1.3% of the total area of the municipality [26], which corresponds to an overall mangrove area loss of 24.3 % of its original area. Adding to this, climate change and consequent SLR projections imply that there will be a shift in coastal areas hydrological dynamics, which will directly affect mangrove ecosystems.

The main goal of this study is to define a method to map the Mangrove Ecological Land Suitability (MELS) for the Municipality of Maputo, through a GIS-based model that combines multi-criteria information, focusing on its biophysical systems (MELS1). In addition, this method is applied to map the potential Mangrove Ecological Land Suitability in a SLR scenario (MELS2), by adjusting criteria combinations considering SLR induced landscape changes, to foresee possibilities for urban development to accommodate such an event. Mangrove conservation and management in urban areas [27–29] and its ecological potential or land suitability [30] are to be related in a propositive perspective, to include existing mangroves conservation and potential new mangrove areas and their ecosystem's related functions, into urban GI, to fundamentally provide a safer and healthier environment.

2. Mangrove Ecological Land Suitability Mapping Method

The method consists of a sequence of analysis supported by a GIS assessment of the weight of each spatial component in the modelling of the mangrove suitability areas. A GIS model is used to map mangrove ecological land suitability (MELS) in Maputo's Municipality area, making use of ArcGIS 10.4 Esri© software. The model was developed by following the steps (Figure 1):

a. compilation of existing data.

b. map layer creation via data acquisition and production of georeferenced cartography for the several landscape components based on the ideal conditions for mangrove development.

c. analysing spatial data through spatial modelling and overlaying data into two scenarios, MELS1 and MELS2.

d. comparing the two scenarios with the land use, as in 2017.

The physical system is composed by the following sub-systems: geology, land morphology, soils, hydrology, and climate components, whereas the biological system considers original mangrove vegetation areas. Land use in 2017 is also integrated for comparison purposes. Based on the GIS model from [31] where each component had a GIS code assigned, the abovementioned ecological components relevant for mangrove suitability were included in a sequence of analysis and evaluations. The landscape systems, components description and data sources are summarized in Table A1.

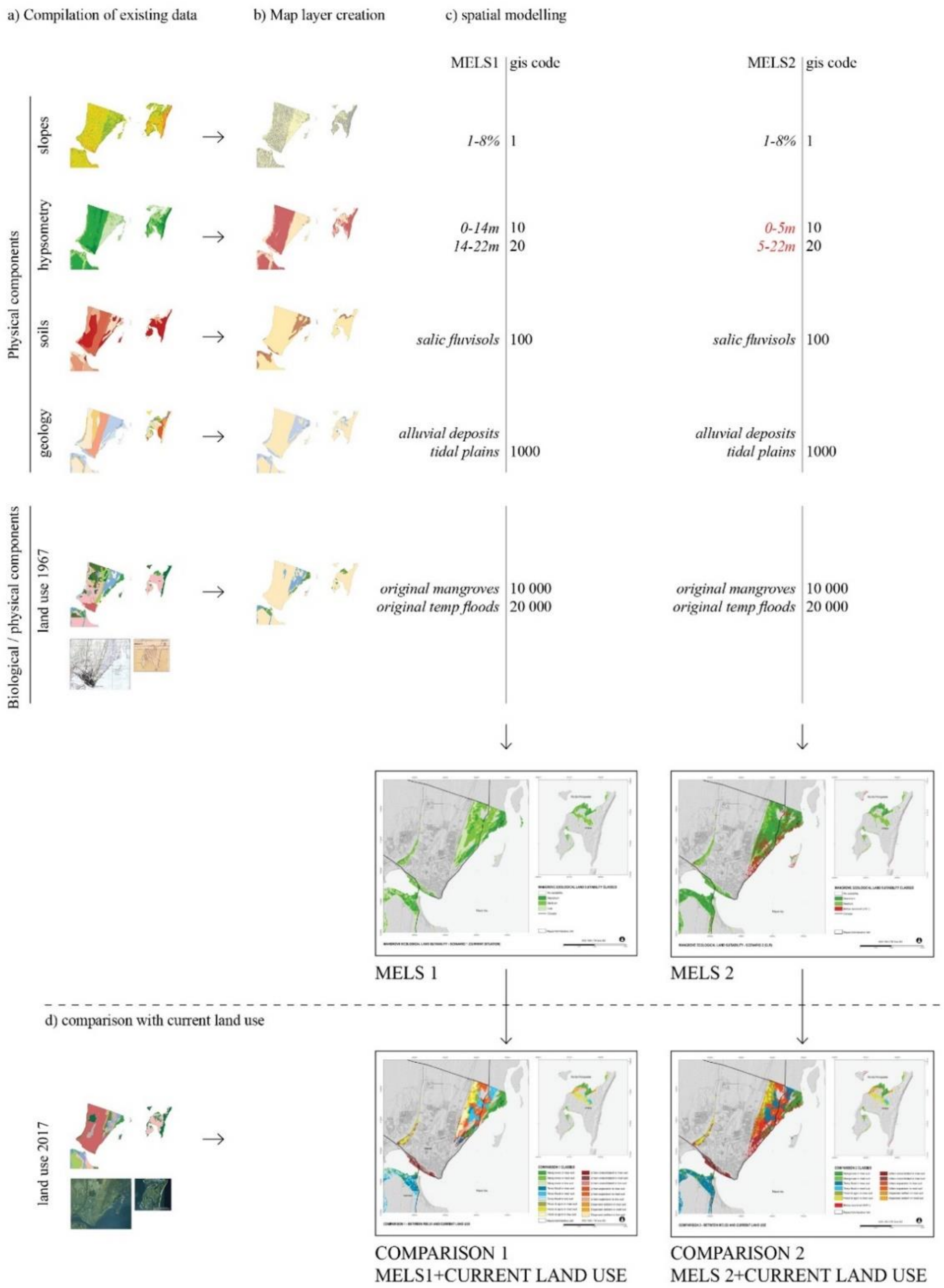

Figure 1. MELS mapping method diagram.

Mangrove ecological land suitability is hierarchized according to the ecological value of the possible criteria combinations in two scenarios. The first scenario is MELS1, developed for mapping several classes of mangrove suitability areas, from high to low suitability, in current landscape, climate, and sea level conditions. The second scenario is MELS2 that considers a 5m sea level rise (SLR) projection for 2100. MELS2 takes MELS1 as a starting point and maps mangrove suitability classes from high to medium suitability, in adaptation to SLR in a near future. Both scenarios are compared with the 2017 land use map, to quantify and evaluate urban development trends in MELS areas.

MELS1 criteria (Figure 2a) are based on the physical thresholds on which potential mangroves currently develop: slopes between 0-8%; hypsometry below 22m, salic fluvisols and tidal plains and alluvial deposits geology. Criteria combinations for MELS2 takes the INGC's High SLR (Table A1) scenario as the 5m SLR scenario for 2100 (Figure 2b). It becomes an incremental projection of MELS1, where new areas are added to the ones of high suitability class, considering that temporary flood zones with favourable physical features increase their suitability due to SLR effects, mainly by tidal inundation influence [32]. The relevant hypsometry component becomes the 5 to 22m altitude, as frequent tidal flooding will happen at higher grounds. The altitude from 0 to 5m is considered to become submerged due to SLR.

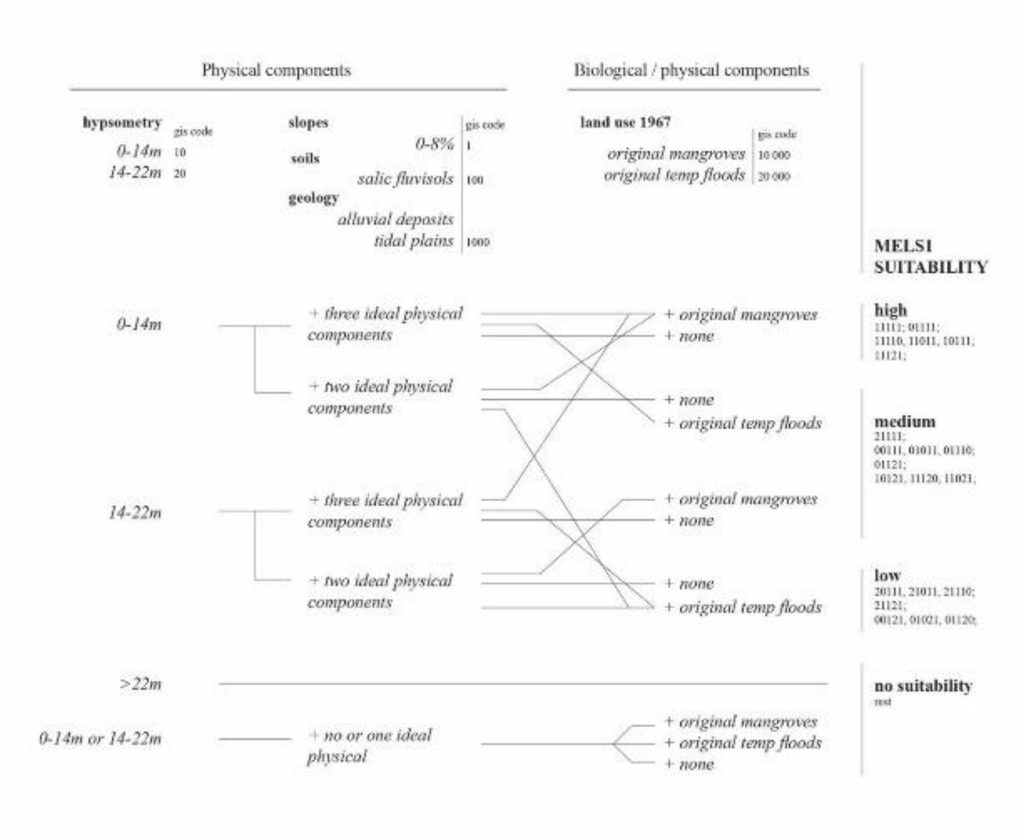

Figure 2. MELS1 criteria combination.

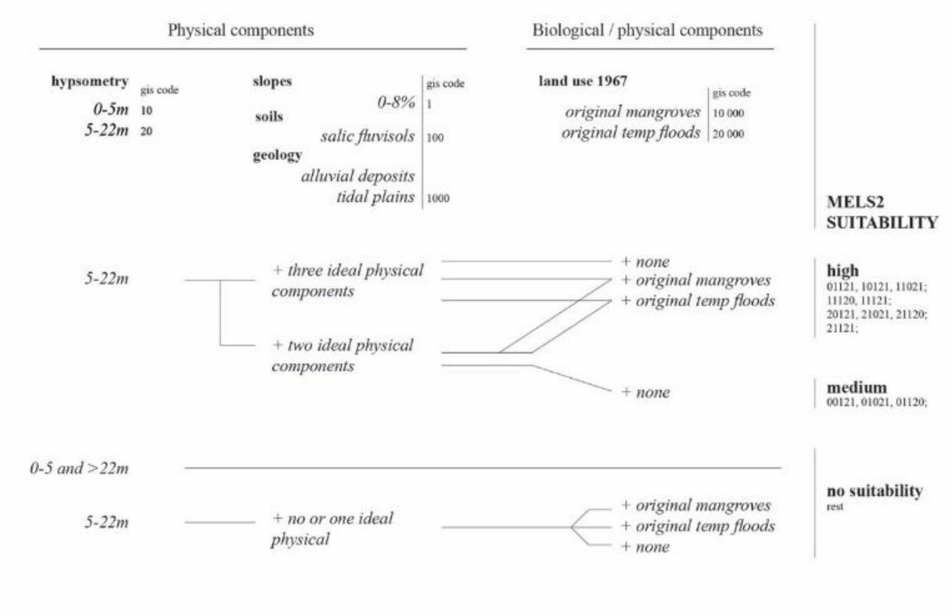

Figure 3. MELS2 criteria combination.

3. Results and Discussion

3.1. Mangrove Ecological Land Suitability in Present Days (MELS1)

The results focus only on MELS1 areas, that correspond to 19,9% of the total area of the Municipality, equivalent to an area of 5698.2 ha, which are mainly areas below 22m height (see MELS criteria in Figure 2).

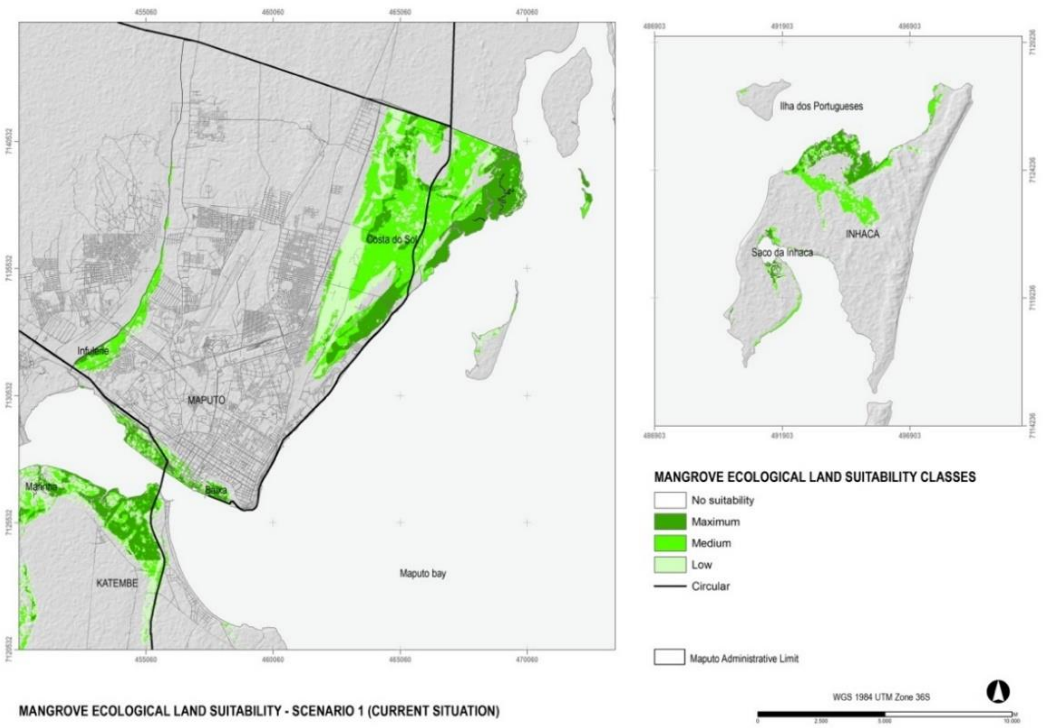

Figure 4. MELS1: Mangrove ecological land suitability for Maputo in 2017.

In the MELS1 scenario (Figure 4) for the whole Municipality, only 5.4% of the area coincides with the 'maximum suitability' class. These are into great extent coincident with temporary flood zones [26], showing that the mangrove extension is far from achieving its maximum potential.

The results of the quantification of MELS1 comparison to the different land uses are resumed in Figure 5.

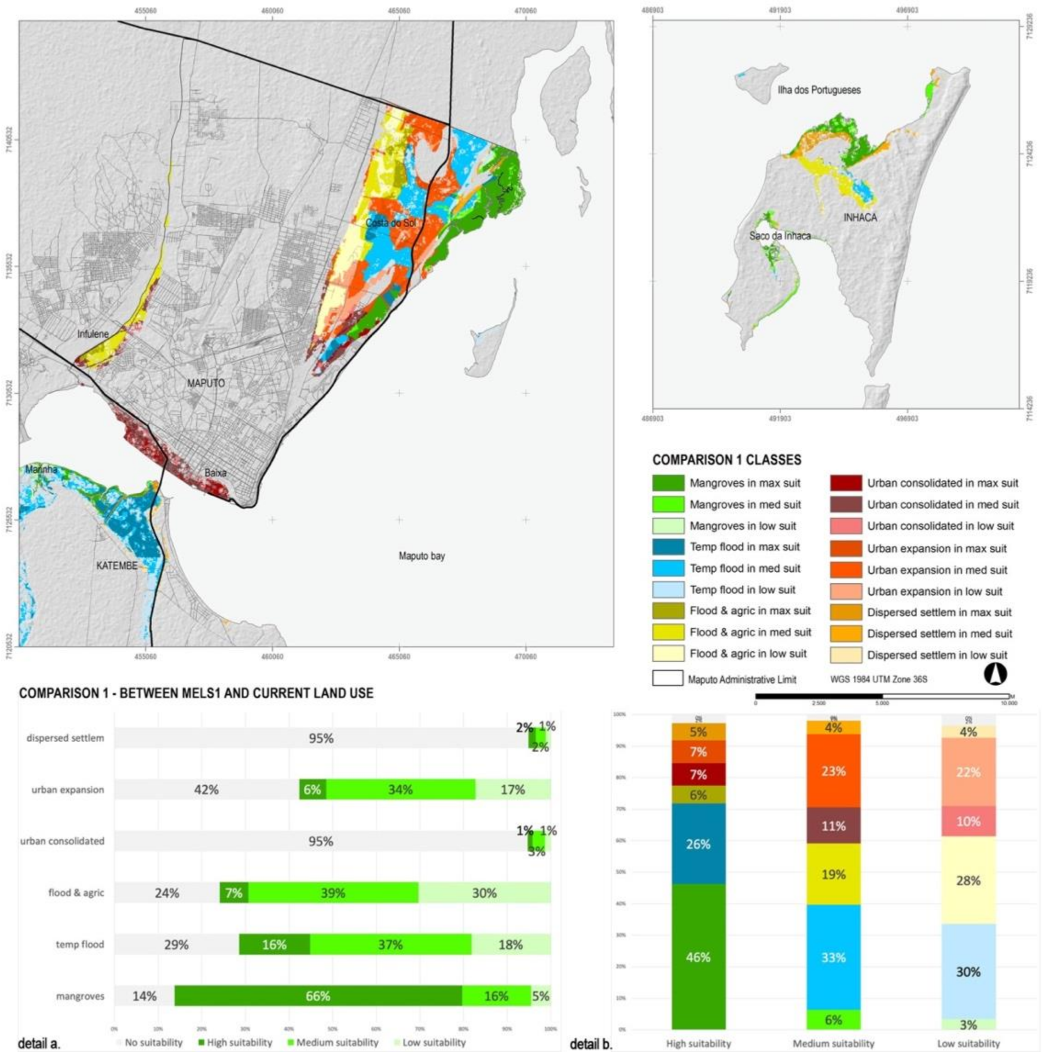

Figure 5. Comparison between MELS1 and current land use (in 2017).

The MELS1comparison with the current land use (Figure 5 detail b), allows to evaluate the current mangroves and temporary flood plains, and the impact of urbanization on mangrove suitability areas.

It is positive to see that 46% of high suitability still maintains mangrove vegetation. About one third of mangrove suitability areas (26% high, 33% medium and 30% low) are temporary flood zones. Considering that they face increased risk in the case of flood events, which are expected to become more frequent in climate change scenarios [33], and considering the beneficial role of mangrove to mitigate flood events, mangrove establishment on these areas could be beneficial both in terms of the suitability to grow mangrove, as in terms of its GI function in those areas.

About 7% of high suitability areas are lost to consolidated urban areas with similar rates for medium (11%) and low suitability (10%). More than half of urban expansion land-use of the municipality of Maputo (57%) is in areas with mangrove suitability. It becomes clear that the city's expansion is pushing towards temporary flood and the mangrove areas, as 19% of any suitability is threatened by urban expansion compromising the ecosystem's viability.

3.2. Mangrove Ecological Land Suitability in A Sea Level Rise Scenario for 2100 (MELS2)

In turn, the MELS2 scenario shows that areas that have suitability represent 18.1% of the total area of Maputo's Municipality (Figure 6). The decrease in the overall percentage of areas with suitability derives from the fact that in a projected 5m SLR scenario, 3.1% of dispersed areas along the coast will become permanently submerged. MELS2 also shows a positive evolution of high suitability areas rising from 5.4% (in MELS1) to 13.0% of the Municipality's total area, when assuming SLR and increased tidal influence in the temporary flood areas.

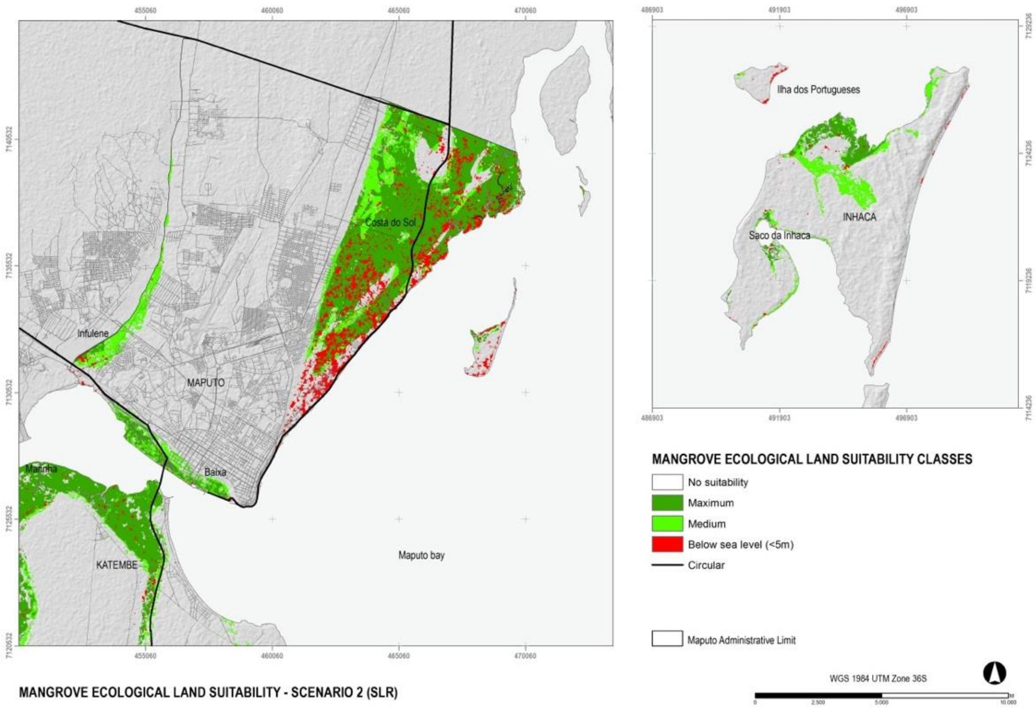

Figure 6. MELS2: Mangrove ecological land suitability scenario for Maputo in 2100.

In the MELS2 scenario, the total of potentially suitable areas for mangrove establishment decreases to 18,1% due to SLR areas submersion. On the other hand, high suitability for mangrove increases from 5.4% (in MELS1) to 13%, also with more expression in temporary flood areas. This indicates that the SLR induced increasing tidal influence, in areas that are now (MELS1) dominated by freshwater run-off and accumulation, will benefit mangrove high suitability areas increase.

The results of MELS2 comparison in relation to the different land uses are represented in Figure 7.

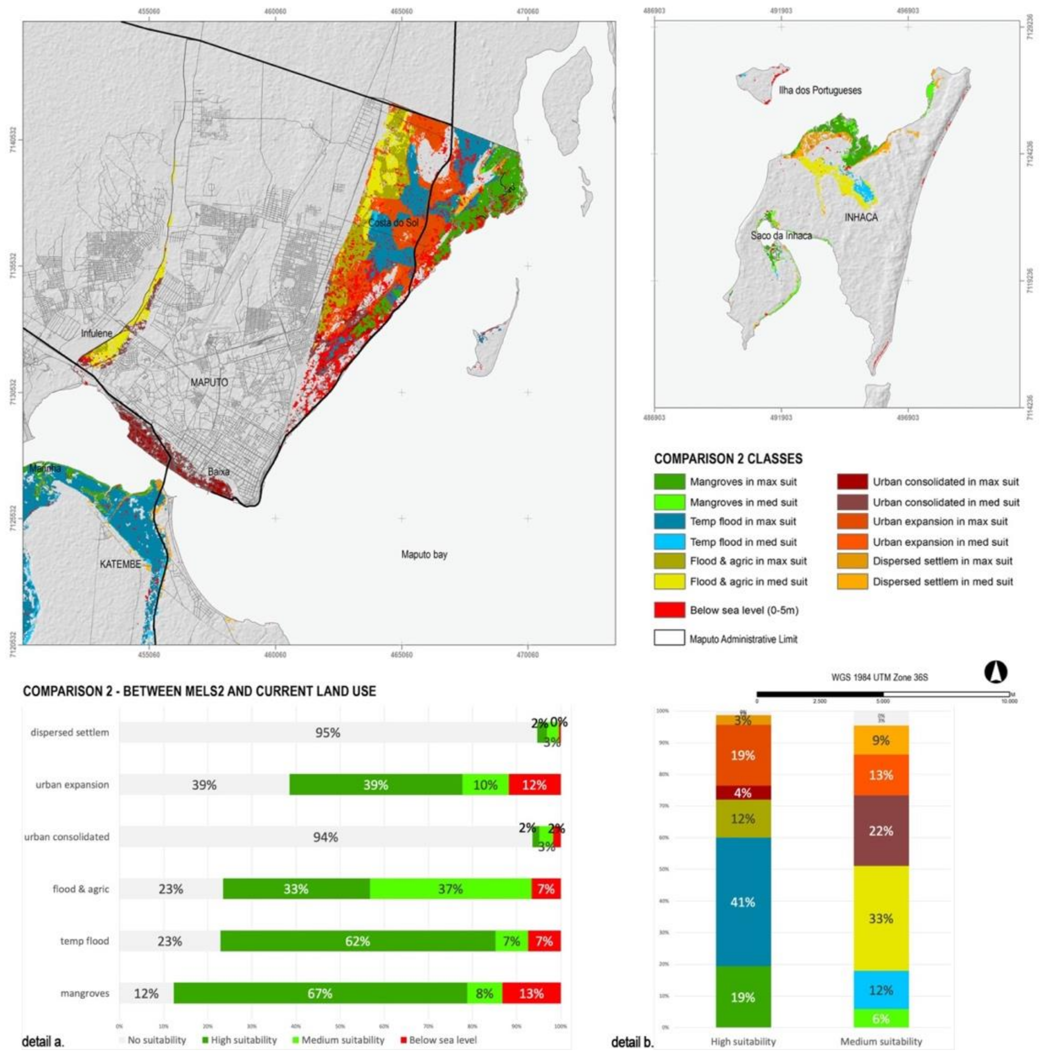

Figure 7. Comparison between MELS2 and Current Land Use (in 2017).

Results concerning MELS2 in comparison to current land use (Figure 7 detail b) show that 19% of high suitability is in mangrove areas and 41% of high suitability in temporary flood areas, indicating the shift in mangrove suitability towards temporary flood plains. In the MELS2 scenario, 10% of any suitability (4% high and 22% medium) is in urban consolidated area, also meaning an increase in relation to MELS1. 61% of Maputo's urban expansion area is either submerged (12%) or in high (39%) or low (10%) suitability showing that location of urban expansion areas are to become more problematic than in MELS1.

In both MELS scenarios when compared with current land use, mangrove suitability areas are considerably occupied by urban expansion (Figs. 5 and 7). Referring to the results for MELS2, a 5m SLR will imply that some areas will be permanently flooded. The remaining coastal plains will increase mangrove suitability, due to tidal influence in areas with ideal conditions for mangrove development. Still, it is relevant to stress that urban expansion areas (that are expected to become consolidated urban areas in a near future) remain the main threat against existing mangrove conservation and further development on suitable areas, in both scenarios. Hence, these stand out as priority working areas to act against mangrove encroachment, and to promote community-based mangrove management.

The MELS method locates and quantifies mangroves that are still present in Maputo, as well as mangroves suitability areas as a step into an urban Green Infrastruture (GI) implementation, to be considered in future plans [27]. It also provides the opportunity to incorporate original temporary flood areas into the same GI, acting as mitigation for floods, extreme storm events and SLR [34], as well as for future mangrove establishment due to landward tidal influence [34,35] in MELS2 scenario.

The MELS method shows that once defined the thresholds of mangrove suitability for each scenario, the amount of information that can be accurately extrapolated is very rich. The maps visualisation, of areas with mangrove suitability and of the coincident land use are a powerful communication tool, showing a comprehensive overview of Maputo's biophysical suitability nowadays (MELS1), as well as with the construction of scenarios for flood. This will enable management actors, stakeholders and hopefully, communities to establish the control measures [36] that are needed now, and certainly in a near future climate change induced SLR scenario (MELS2) [37].

4. Conclusions

The MELS method brings precise insights in what concerns the location and quantification of areas with potential mangrove land, allowing to read the landscape beyond the current situation, and to construct a set of scenarios for mangroves in close relation with urban development trends. The results show that MELS is a relevant method as it can combine, in a single spatial framework both physical and biological components, allowing for the integration of mangrove wetlands as a relevant soft infrastructure in a broader urban GI at city and regional scales.

It has the advantage of being flexible, allowing for site specific criteria threshold adjustments to be applied in other urban contexts. This is particularly useful in SSA coastal cities, as a spatial tool that bridges the gap between urban development strategies and mangrove conservation strategies. In practical terms, MELS delivers a spatially well-defined set of land use scenarios that can inform planners, stakeholders, and public authorities of Maputo's territorial vocations and that can lead to the implementation of an urban GI that include mangroves and temporary flood areas at its core in coastal plains. It presents results that are possible to be included in the currently applied planning tools, as the Urbanization Partial Plans (PPU), which can undoubtedly improve the city's resilience to flood events and climate change with lower implementation costs, while safeguarding urban population from risk factors and improving standard of living.

Also, since the management of mangrove wetlands and GI implementation is meaningful if realized with a long-term, integrative vision, MELS can be a base for analysis and evaluation by superposition for other inputs, both in type (e.g., infrastructure projects or wastewater management plans) as in time (e.g., future land-use changes).

The MELS mapping method can serve as an integrative instrument to articulate legal and operative frameworks for mangrove conservation areas along with other uses, such as in urban parks, urban agriculture in temporary flood areas and urban forestry areas. Working across scales, from neighbourhoods to municipal and metropolitan scales, MELS can act as a building block for the management of risk prone, and ecosystem conservation areas within the scope of climate change mitigation and adaption strategies. A sustainable urban expansion along the coastal plains of Maputo can only be achieved through a "let-the-water-in" concept, with soft engineering solutions that include mangroves and people as part of an urban GI.

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Appendix A1: MELS summary of landscape systems, sub-systems, components definition and data sources.

System	Subsystem	GIS code	Original Legend	Definition	Data Source
Physical	**Slopes**	**1**	0-8%	Coastal plains; Very gentle slopes;	
	Hypsometry	**10**	**0-14m** (in MELS1) **0-5m** (in MELS2)	Recent alluvial deposits and areas where there are mangrove patches;	Aster Global Data Elevation Model ©METI and NASA doi:10.5067/AS-TER/ASTGTM.002
		20	**14-22m** (inMELS1) **5-22m** (in MELS2)	Older alluvial terraces and where there were mangrove patches in the 1967 land use;	
	Soils (FAO)	**100**	Fe	Salic fluvisols: Alluvial deposits subject to flooding;	INIA, 1990, 1991
Physical	**Soils**		Fem	Salic fluvisols with mangroves: consist in a shallow coverage of fine sediments with vegetation cover;	scale 1:250 000
	Geology	**1000**	Qa	Alluvial deposits;	Momade et al., 1995; Saranga et al., 2008; Sénvano et al. 1999
			Qpm	Tidal plains with mangroves;	
			Qpt	Paleo-tidal plains;	scale 1:50 000
	Hydrology		Water lines	Rivers and hydrographical basins	Cenacarta, 2014
		20000	Temporary flood areas	Traced from 1958 - 1967 temporary flood areas, before occupation of peri-urban areas; Original flooding areas are considered a priority criteria for mangrove suitability in MELS2;	(DPSGC, 1958a, 1958b, 1965, 1967) scale 1:50 000
		10	Tidal influence (included in the Hypsometry levels)	Maputo tide gauge geographical location: Lat S 25º58′ Long 35º34′ High Tide max: + 3,81m (astronomic high tide 11/09/2018 17h51′); High Tide st: + 3,56m (Spring Tide - every 15 days); Mean sea level (MSL) in relation to the hidrographical zero (HZ): + 2m; Min Low Tide = +0.20m; Tidal amplitude: +2,36m (13/04/18);	
			Saline intrusion	Ocean tides are the largest natural forcing affecting sea water intrusion into river systems. It is occurring now, in a higher rate than sea level rise and storm surge, at least until 2030. Saltwater intrusion in the Incomati river is predicted to cause impacts up to 28 km upstream by 2030, in an area of 9 km2, whereas in the Maputo River it is predicted to affect 11 km upstream affecting an area of 5 km2. The exploitation of ground water table aquifers in coastal areas, especially in urban areas, will also contribute to this problem;	INGC, 2009; Juízo, D., 2014
Physical	**Hydrology**	**10**	Sea level rise (included in the Hypsometry levels for MELS2)	The INGC High SLR scenario foresees a 5m SLR for the year 2100. There will be permanent flooding of the coast and low-lying areas, namely in large estuaries and subsiding deltas as is the case of Maputo Bay.	IPCC, 2013; INGC, 2009
		20	Flood levels in extreme events (included in the Hypsometry levels for MELS1)	Reference to 2013 flood levels inland, considering 14m to 20m heights as flooding areas and 22m height as maximum height prone to flooding.	DRPUA, 2013

System	Subsystem	GIS code	Original Legend	Definition	Data Source
	Climate		Sub-tropical Climate	800mm Annual Rainfall; 25ºC Average temperature; Max temperature and max precipitation from Jan-Mar; Dry season June-Aug, min temperature 18ºC and precipitation of less than 20mm; Annual relative humidity 76%; Wind speed from 10-30 KM/h, from North in rainy season; Wind speed up to 50km/h from SW in dry season;	MER, 2015; Silva & Rafael, 2014
Biological	**Vegetation (1967)**	**10000**	Mangroves	Traced from 1958 - 1967 Original mangrove vegetation patches, before occupation of peri-urban areas;	DPSGC, 1958a, 1958b, 1965, 1967 scale 1:50 000
	Land Use (2017)		Current land uses	Traced from 2017 ESRI Satellite Imagery;	ESRI, 2017

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