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Modelling Coastal Vulnerability and Adaptation to Sea Level Rise

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Abstract: Coastal regions are highly vulnerable to sea-level rise (SLR) therefore developing and implementing effective adaptation alternatives is crucial for their future development. However, there is uncertainty in the timing, duration, spatial location and extent of SLR and storms. The complexity that arises from climate, coastal systems and their interactions in space and time can easily become overwhelming for decision makers to investigate the aspects of adaptation alternatives thoroughly. Dilemmas confronting decision makers are: how to adapt and when to adapt to SLR?
Considering the complexity and dynamic nature of coastal systems interacting and changing over time, this paper introduces a new Spatial Temporal Decision (STD) framework to assess coastal vulnerability, and the adaptation alternatives to SLR. The STM is based upon a combination of: System Dynamics (SD) modelling; Geographical Information Systems (GIS) modelling; and multi-criteria analyses of stakeholders' views using the Analytical Hierarchy Process (AHP).
The results of the vulnerability assessment indicate that, at the end of a 100 year simulation period, approximately 6 % of the landscape in the study area will be gradually inundated over time, with 0.5 cm SLR per year. However, this situation dramatically changes with scenarios 2 and 3, which represent 1 cm and 1.5 cm SLR per year. Indeed, the percentage of the vulnerable area leapt to about 34 % for Scenario 2, and 56 % for Scenario 3.
Using the information obtained from vulnerability assessments, three stakeholder groups (*Politicians, Technical Experts and Residents*) were consulted to determine the goal, criteria and adaptation alternatives required for the AHP analysis. Analyses of survey data reveal that across the three stakeholder groups, *Effectiveness* and *Sustainability* are the criteria of highest priority.

***Keywords**: Decision Making; Dynamic Modelling; Sea Level Rise; Vulnerability.*

1 INTRODUCTION

There is overwhelming scientific consensus over the causes and impacts of climate change (IPCC, 2007). Sea level rise (SLR) is one of the most recognized possible impacts of changing climate. Coastal areas are economically productive and three times more densely populated than the global average (Small and Nicholls, 2003). Clearly, while communities have benefitted from the many advantage of living in these areas, inevitably they also face the threat of natural disasters and specifically from SLR via permanent inundation of low-lying regions, inland extension of episodic flooding, increased beach erosion and saline intrusion of aquifers (McLean et al., 2001). Coastal communities have been adapting to changing conditions throughout history. However, faced with increased threats due to SLR, coastal communities must act faster to develop more effective management policies. Moreover, the impacts of SLR are not expected to be spatially uniform across the world. It is therefore essential for decision makers (DM) to consider the dynamic and spatial characteristics of these changes in assessing the impacts of SLR when making decisions about the future. There is a range of analytical tools are available to improve decision makers' (DM) ability to understand and evaluate environmental management problems such as simulation models, GIS, experts systems, etc. However, although these tools provide invaluable information for decision making, each tool addresses only one aspect of a management problem. Therefore, effective decision making, in a dynamic complex environment, requires the expansion of the mental modelling boundaries and the development of additional tools to help DMs better understand how complex systems behave. Thus, DMs need to integrate each tools' analytical results into a rational choice about what to do, where to do it, and when to do it (Schmoldt, 2001). Considering the complex and dynamic nature of coastal systems interacting and changing over time, this paper introduces a Spatial Temporal Decision (STD) framework to assess coastal vulnerability, and the adaptation alternatives to SLR.

2 METHODOLOGY

1.1 Introduction

The STD approach takes into account five dimensions of the decision process in coastal dynamics (Figure 1). Space (*x,y,z*) and time (*t*) constitute the first four dimensions, and provide a common base where all natural and human processes occur. This approach is crucial in generating adequate information from which DMs can devise realistic adaptation strategies. For this reason, it is essential to incorporate the first four dimensions into the fifth dimension, the element of human decision making (*h*). Thus, developing STD is based upon a combination of: System Dynamics (SD) modelling; Geographical Information Systems (GIS) modelling; and multi-criteria analyses of stakeholders' views using the Analytical Hierarchy Process (AHP). As illustrated in Figure 1, the cyclic STD process consists of: 1) Identification of the problem; 2) Vulnerability assessment by using Dynamic Spatial Model (DSM), which combines a spatial model (GIS) and a temporal model (SD); 3) Evaluating potential adaptation strategies by using an MCDA approach, based on information obtained from the previous step.

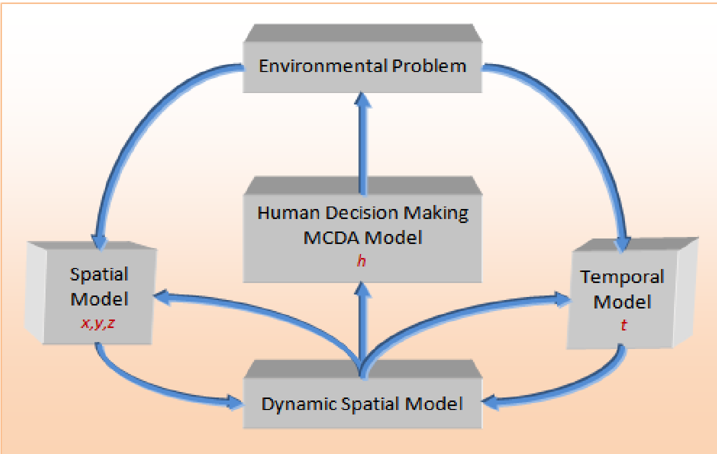

Figure 1. Five dimensional STD framework.

1.2 Model Development

To model and simulate changes in coastal zones, a number of researchers have proposed the use of a versatile approach, which considers many aspects of the problem by combining GIS with SD (Grossmann and Eberhardt, 1992, Ruth and Pieper, 1994, Ahmad and Simonovic, 2004, Gharib, 2008, Zhang, 2008). GIS and SD originated in different domains of expertise. In the proposed approach, while GIS handles spatial data, dynamic modelling processes the dynamics of the complex system, revealing its causal structure and the relations of the system components. The DSM consists of three components: SD (temporal) model, GIS (spatial) model, and the data convertor. The DSM captures the changes in time and space by obtaining and processing the temporal data from the SD and the spatial data from the GIS by exchanging data through the data convertor.

Temporal Model Component: When building the temporal model, the Vensim DSS (Decision Support System) software was chosen because of its flexibility when representing continuous or discrete time, a graphical interface, or performing causal tracing, optimization, and sensitivity analysis (Ventana Systems, 2009).

Figure 2 shows the model structure containing three state variables: *Sea Level*, *Elevation*, and *Cell Cover.* The *Sea level* is the main driver causing inundation and, therefore, puts people and properties at risk. *Elevation* defines changes in cell elevation. *Cell Cover* defines land use type which change over time.

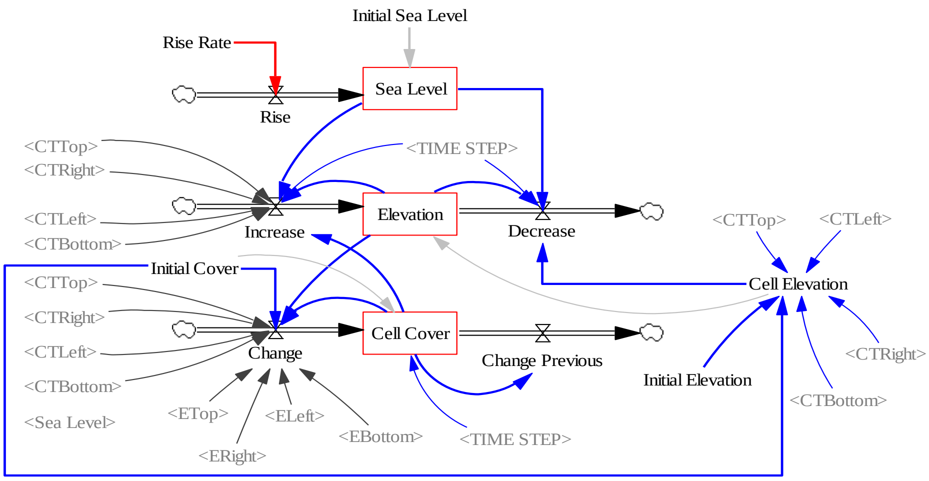

Figure 2. Inundation model based on cell elevation and cover types.

To capture the fundamental dynamic processes of inundation the area under consideration is subdivided into a cellular (*i* x *j*) grid to simulate how flood water spreads between adjacent cells. Each cell represents a specific area corresponding to one of four cover types: *Sea*, *Waterways*, *Pond*, or *Land*. Based on the following equation, the flood water diffusion from one cell to another is predicted:

$$F(X_{i,j}) = \begin{cases} 1, & CT(X_{i,j}) = L \text{ and } \exists x CT(X_{n,m}) = W, \text{and } CE(X_{i,j}) \leq \exists x CE(X_{n,m}) \\ 0, & otherwise \end{cases} \quad (1)$$

Where, *F* is, either flooded (1) or not flooded (0); *CE* is the cell elevation; *CT* ($x_{i,j}$) is the cover type, either inundated *L* or not inundated *W; CT* ($x_{n,m}$) is the adjacent cells cover types, either *L* land (or other cover types other than sea) or *W* sea (or became sea due to inundation); (*n*,*m*) refers to all adjacent cells to *i,j* (i.e.: *i,j-1, i,j+1, i+1,j and i-1,j*).

For coastal areas, along with SLR rate, *Elevation* and *Cell Cover* are the most critical factors in assessing the potential impacts. At each simulation step, as the sea level rises, the elevation of a cell is determined by its condition at the previous time step, its border conditions with its four neighbours, and the cover type of its neighbours. The elevation of a cell is determined by adjusting the elevation, at previous time steps, by the flow-in (increase) and the flow-out (decrease) of the cell, according to the properties of the adjacent cells. The *Elevation* is the integral of the net flow of *Increase* and *Decrease* calculated by the following equation:

$$E_t(x,y) = \int_0^t (I_t(x,y) - D_t(x,y)) * dt + E_0(x,y) \quad (2)$$

Where, E_t (*x,y*): Cell elevation at location (x,y) at a given time; E_0 (*x,y*): Initial cell elevation at location (x,y); I_t (*x,y*): Rate of elevation increase at location (x,y); D_t (*x,y*): Rate of elevation decrease at location (x,y).

The changes in cell elevation occur when only the *Cover Type* of a cell is *Land*, *Waterways*, or *Pond*, at time step t_n, and it is transformed into *Sea* at the next time step, t_{n+1}. Here, the cell is assumed to be inundated from the SLR and, therefore, the elevation of the cell is updated, and said to be equal to the *Sea Level* at the time period t_{n+1}. As the model runs, the state of the each cell is assessed simultaneously. This is necessary to assign only one *Cover Type* value to the cell for each time step. For example, if the *Change* alters the *Cover Type* of a cell from *Land* to *Water* at time step (t_1), then *Change Previous* discards the previous cover type value (*Land*) from the cell. The *Cell Cover* is determined based on the following equation:

$$CT_t(x,y) = \int_0^t \left(C_t(x,y) - CP_t(x,y)\right) * dt + CT_0(x,y) \tag{3}$$

Where, CT_t (*x,y*): Cell Cover type at location (x,y) at a given time; CT_0 (*x,y*): Initial Cell Cover type at location (x,y); C_t (*x,y*): Rate of cell cover type change at location (x,y); CP_t (*x,y*): Rate of previous cell cover type change at location (x,y)

Spatial Model Component: GIS, ArcInfo 9.3.1 (ESRI, 2009), is a key tool used in the spatial model construction, which is later connected to the temporal model through the data convertor. Since SD can easily use array variables for data manipulation, aggregation, and analysis, the Raster data model using a regular grid to cover the space is used. A variety of data from different sources was required as inputs to the spatial model. The spatial data on land cover, elevation, Digital Cadastral Database DCDB, study area boundaries and waterways were acquired from public sources and processed into GIS format. To obtain accurate result, high resolution elevation data (5 m DEM with 0.1 m vertical accuracy) was used. All the data layers were converted to raster format, with a resolution of 5 x 5 m cell size to match the DEM data. The attribute assignments were based on the centroid of the cell. Australian Bureau of Statistic (ABS) 2001 data on dwellings, and the Digital Cadastral Database (DCDB), represented, spatially, every parcel of land and provided land related information that was converted to a raster format.

Data Convertor: The data converter automates the format transition between the ArcGIS and SD data formats. First, it converts the ArcGIS text (ASCII) files to SD text files (.cin), then it converts the files from the SD .tab files back to the ArcGIS .txt files. All code for the data converter was written in C++ under Visual Studio 2008, using the Microsoft.NET framework version 2.0.

Decision Model: Decision making is a process of selecting from among several alternatives, based on various (usually conflicting) criteria. Information on priority alternatives is vital in aiding DMs to design more effective adaptation options and better management plans to reduce the adverse effects of SLR. The current study uses the MCDA technique because it is the most suitable approach by which to identify the priority of adaptation alternatives. Several multi-criteria decision aid techniques are suitable for comparing multiple criteria, simultaneously, and for providing a solution to a given problem. While there are no better or worse techniques, some techniques are better suited to a particular decision problem (Haralambopoulos and Polatidis, 2003). The AHP technique, despite some criticisms, has been selected for the current study because of a number of desirable attributes. The AHP is set apart from other MCDA techniques because of the unique utilisation of a hierarchy structure to represent a problem in the form of a goal, criteria and alternatives (Saaty and Kearns, 1985). This allows for breakdown of the problem into various parts for pair wise comparisons, which uses a single judgement scale. The underlying concept of the AHP technique is to convert subjective assessments of relative importance to a set of overall scores or weights (Saaty, 1980).

Stakeholder consultation is one tool among the range of participative techniques for involving stakeholders throughout evaluation process. This approach allows them to contribute to model development and ongoing improvement.Thus, the platform on which to formulate the goal, criteria and alternatives for the evaluation in the study area is derived, and based upon, the existing adaptation works by local government, an extensive literature review regarding adaptation techniques, and most importantly involving the regional stakeholders through interviews and consultations during structuring hierarchical model, and later for identifying decision criteria and alternatives. The stakeholders are classified into three groups: *Residents*, *Experts*, and *Politicians.*

The specific goal used in the AHP structure is *to reduce SLR vulnerability*. To clarify further, this goal implies the identification and evaluation of adaptation alternatives in an attempt to reduce the negative impacts from SLR. It encompasses the idea behind the entire effort to reduce the negative impacts from climate change, specifically SLR.

3 IMPLEMENTING THE APPROACH: PROOF OF CONCEPT

For testing the proposed approach, the City of the Gold Coast located in South-East Queensland, Australia has been selected. The area encompasses a diverse range of features including sandy beaches, estuaries, coastal lagoons and artificial waterways and is highly vulnerable to SLR. In this region, the maximum tidal range is 1.8m, and on average, the coast is affected by 1.5 cyclones each year (Boak et al., 2001). Many of the residential areas in the city are filled to the 1:100 year flood level (Betts, 2002).
Its purpose is to examine the timing and extent of inundation from SLR, over time. Currently, our understanding and prediction of the timing and magnitude of this process is limited, specifically due to the uncertainties in sea level rise projections. Thus, a range of SLR scenarios, ranging from 0.5 m to 1.5 m, are used to address the uncertainty issues.
A one-hundred year time horizon is considered from 2010 through to 2110, which is consistent with most SLR scenarios developed by the Intergovernmental Panel on Climate Change (IPCC, 2007).

3.1 Results

Vulnerability Assessment: To determine the effect of changes in vulnerable populations and land areas over time, the *Cover Type* and *Elevation* data were simulated under a number of SLR. The changes were captured in a SD and exported to GIS for visualisation. The inundation layer was overlayed with the 2001 ABS census data, which was aggregated by census parcel for the area. Figure 3 shows the flood maps of the areas at risk due to rising sea level, over a period of 100 years. Clearly, as inundation occurs at the water – land interface, the land area in close proximity to the sea, and around water bodies, were identified as the most vulnerable areas. The rising sea quickly penetrates inland through waterways and submerges the vulnerable areas around them, thus, putting the people currently living in those areas at risk.

Table 1. *Area at Risk* and *Population at Risk* under three SLR scenarios

	Area at Risk (%)										
Year	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110
Scn1	0	1.38	1.54	1.72	1.87	2.09	3.63	4.07	4.40	4.97	5.99
Scn2	0	1.48	1.87	3.63	4.40	5.95	9.39	13.75	19.24	26.90	33.89
Scn3	0	1.60	3.63	4.89	9.39	15.89	26.65	35.78	42.90	47.90	55.70
	Population at Risk (%)										
Year	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110
Scn1	0	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.03	0.03
Scn2	0	0.00	0.00	0.01	0.02	0.03	0.07	0.13	0.18	0.33	0.48
Scn3	0	0.00	0.01	0.03	0.07	0.15	0.33	0.54	0.92	1.48	7.06

As shown in Table 1, at the end of a 100 year simulation period, approximately 6 % of the landscape in the study area will be gradually inundated over time, with 0.5 cm

SLR per year. Importantly, a 0.5 cm SLR does not pose any significant threats to the local population. However, this situation dramatically changes with scenarios 2 and 3, which represent 1 cm and 1.5 cm SLR per year. Indeed, the percentage of the vulnerable area leapt to about 34 % for Scenario 2, and 56 % for Scenario 3. The most noticeable changes occur after the first 25 years. Further, the rate of inundation becomes much higher after the first 50 years of the simulation period for both scenario2 and scenario3.

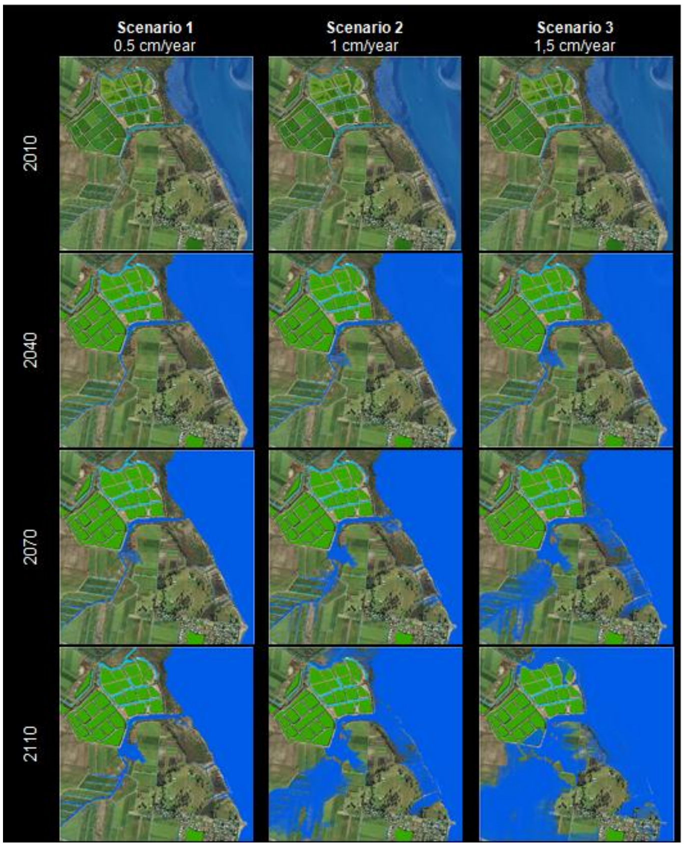

Figure 3. Flood maps generated by the model

Although a substantial fraction of the landscape is threatened by the rising SLR, the percentage of the population that can be classified as vulnerable is relatively low for Scn2 and Scn3 scenarios, only 0.5 % and 7 %, respectively. The answer lies with most of the population residing at high altitudes. Nevertheless, the population located near waterways and coastal strips was especially vulnerable. Indeed, about 6% of the study area landscape will be submerged if the sea level rises a 0.5 m by 2110 (Table 1).Hence, the area at significant risk will be increased, up to 34% and 56% with a 1 m and 1.5 m rise in sea level, respectively.

However, the inundation will, generally, be restricted to fringing shorelines and finger waterways margins (Figure 3). Additionally, although, up to 56% of the land area will be facing the risk of inundation, the impacts of the same SLR scenarios on the residential areas are much smaller.

***Multi-Criteria Decision Analysis for Adaptation options*:** The fifth component of the current framework focuses on linking vulnerability assessment with the evaluation of adaptation alternatives through the use of AHP and multi-stakeholder consultation. The implementation of the MCDM models involved: assigning weights and priorities to the criteria by stakeholders; the normalisation of the raw scores to create a common scale of measurement; and the calculation of the decision scores used to generate the final output from the models.

To achieve and facilitate a workable process to reduce the vulnerability of an area and a population to SLR, a hierarchical (AHP) structure was developed. The goal: *To Reduce Vulnerability to SLR*. The evaluation criteria were: *Applicability*, *Effectiveness*, *Sustainability*, *Flexibility,* and *Cost*. The five adaptation alternatives were: *Retreat*, *Improve Building Design*, *Improve Public Awareness*, *Build Protective Structures,* and *Take No Action*. Three key stakeholder groups were: *Expert, Residents and Politicians.* By using the questionnaire, the participants were asked to compare the relative importance of the decision alternatives pair-wise, with respect to criteria and the goal. The results were obtained through the use of

Expert Choice-11 package for computing relative weights, consistency ratio and local and global priorities (Expert Choice, 2008). Additionally, the MS Excel 2007 was also been employed for some calculations and data plotting.

The AHP allows the inconsistency of every participant's survey responses to be represented by the consistency ratio (CR). The resulting CRs are 0.02 for *Residents,* 0.02 for *Experts* and 0.06 for *Politicians* – all less than the 10% limit*.* The result indicates that stakeholder groups' judgements with respect to each criterion and with respect to the goal are expected to be highly consistent. As seen in Figure 4, regarding the *Residents*, from the five different adaptation alternatives presented in the survey questionnaire, the highest priority alternative was *Improve Building Design* (0.325 priority), closely followed by *Build Protective Structures* (0.285 priority).

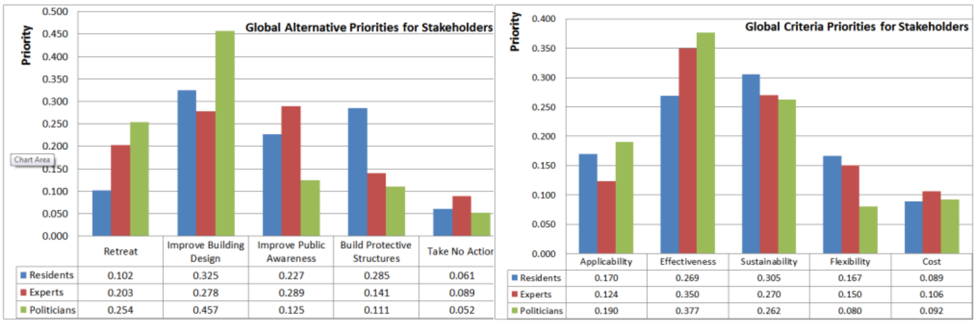

Figure 4 Global criteria and alternative priorities for stakeholders

The least preferred alternative was *Take No Action*, followed by *Retreat*, with priorities of 0.061 and 0.102 respectively. In contrast, the *Experts* gave their highest priority to *Improve Public Awareness* with priority of 0.289, while *Improve Building Design* and *Retreat* were deemed the next most important alternatives with priorities of 0.278 and 0.203, respectively. While in accord with the *Residents* judgements for their least preferred alternative (*Take No Action* had a 0.089), the experts next least preferred alternative was *Build Protective Structures* (0.141 priority).

The *Politicians* top two preferred adaptation alternatives were *Improve Building Design* with a priority of 0.457 (the *Residents* had this alternative as their top priority, while the *Experts* rated it as their second priority), and *Retreat* with a priority of 0.254, which was one of the *Residents* least preferred alternatives, but the *Experts* third top priority (Refer to the *Politicians*' row in Figure 5)*.* Once again, the least preferred option for all three groups was *Take No Action*; however, the *Politicians* rated, as second to last, the alternative to *Build Protective Structures*, which disagreed with the *Residents* judgement, but agreed with the *Experts* judgement.
The criteria priorities were obtained in the same way as the alternative priorities (Figure 4). From the combined results for each stakeholder group, the two most important criteria to consider when making a judgement to reduce the negative impacts of SLR are *Effectiveness* and *Sustainability.* It appears that the three stakeholder groups uniformly agree about the importance of the criteria. For example, *Applicability* and *Flexibility* generally rank next highest (with *Politicians the* exception), while *Cost* ranks the lowest (with *Politicians* the exception ranking *Flexibility* last).

4 CONCLUSION

The STD framework provides a critical tool for obtaining quantitative information for managing and making choices with the aim of effective decisions. This integrated approach has the capability to: (1) Generate important spatial-temporal information required by decision makers (DMs); (2) Provide new insights into complex coastal systems; (3) Address multi-criteria decision problems involving multiple stakeholders; (4) Enable DMs to examine decision alternatives through the use of the Dynamic Spatial Model; and (5) Address uncertainties and generate alternative scenarios, based on different user inputs.

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