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Sea-Level Rise and Adaptation Responses for Coastal Construction: A Spatial-Temporal Decision Making Tool

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Abstract

Most infrastructure, settlements and facilities are located near the coast and are highly vulnerable to sea-level rise (SLR), coastal erosion and storms. Continued population growth in low-lying coastal areas will increase vulnerability to these hazards. The impacts of SLR are highly variable across regions and difficult to predict over time and space. Principally, due to constraints on the adaptive capacities of coastal areas, SLR increases the challenge of achieving sustainable development in these areas in developing countries, and they are likely to be hit hardest. Generally speaking, vulnerability and adaptation to climate change are urgent issues, especially among developing countries.

The dilemmas confronting decision makers are: how and when to adapt to SLR. The complexity can easily overwhelm the ability of decision makers to thoroughly investigate the outcomes of adaptation alternatives. Therefore developing and implementing effective adaptation options is crucial for future coastal development. However, in many cases, it is difficult to determine whether taking a specific action to prepare for SLR is justified, due to uncertainty in the timing and magnitude of impacts. By considering the uncertain nature of projected changes in climate and addressing these dilemmas, this paper intends to provide a dynamic model for a comprehensive vulnerability assessment of coastal areas to assist decision makers to identify and evaluate effective adaptation alternatives for reducing climate change impacts.

To achieve this outcome, two modeling techniques are combined: (1) System Dynamics, and (2) Geographical Information Systems. A combination of these approaches would provide the potential to address temporal and spatial problems concurrently.

Keywords

Vulnerability assessment, coastal flooding, sea level rise, dynamic modeling, decision making.

1. Introduction

There is general consensus among scientists that the climate is significantly and inevitably changing. Warming of the climate system is now unequivocal, based on observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising sea level (Solomon et al., 2007).

SLR is one of the most recognized possible impacts of changing climate in the literature. It is estimated that the global-mean sea level may rise between 0.18 and 0.59 m by 2100, (Meehl et al., 2007). If the contribution from the Greenland and Antarctica Ice Sheets is taken into account, the upper ranges of sea level rise will increase by 10 to 20 cm. However, another study published after the

IPCC Fourth Assessment Report (4AR) suggests an even higher range of 0.5 to 1.4 m by 2100 (Rahmstorf, 2007).

SLR, at the estimated rate, will not pose an immediate threat to coastal areas; however a higher sea level will provide a higher base for storm surges to build upon. Thus, storm surges occurring in conditions of higher mean sea levels will enable inundation and damaging waves to penetrate further inland, increasing flooding, erosion and the subsequent impacts on built infrastructure and natural ecosystems (Pearce et al., 2007). Moreover, SLR is expected to continue for many centuries, even if Greenhouse Gas (GHG) concentrations are stabilized at relatively low levels (Nicholls and Lowe, 2004, Church et al., 2001). As a result, SLR will exacerbate the vulnerability of coastal populations and ecosystems via permanent inundation of low-lying regions, inland extension of episodic flooding, increased beach erosion and saline intrusion of aquifers (McLean et al., 2001). These physical impacts may result in socioeconomic impacts on the coastal zone such as loss of properties and coastal habitats, and loss of tourism, recreation and transportation functions. Thus, SLR will intensify the stress on coastal zones where adaptive capacities of natural and social systems have been weakened. Considerable human activity and population growth takes place in coastal areas. It is well known that SLR will have profound implications for many coastal populations and the systems on which they depend (Brooks et al., 2006). The near-coastal population within 100 km of a shoreline and 100 m of sea level is estimated as 1.2 billion people, with average densities nearly three times higher than the global average density (Small and Nicholls, 2003).

With concern for the consequences of SLR, development and implementation of methodologies to assess the vulnerability of coastal systems to climate change is fundamental in supporting effective policy responses to reduce climate-change-related risks (McFadden et al., 2006). There are numerous studies which focus on assessing coastal vulnerability on national and global scales. However availability of regional scale comprehensive vulnerability assessments studies, which are required by local stakeholders to design adaptation strategies at local level, are limited (Torresan et al., 2008, Cooper et al., 2008).

2. Problem Definition

Traditionally, due to uncertainty in climate change predictions, coastal vulnerability assessments and most town planning activities are based on an assumption that sea level will remain constant in the future. However, climate change is undeniable and the resulting rise in sea level is a reality that coastal communities will face in the coming decades. A changing sea level means that the baseline upon which current vulnerability is being assessed is also changing. As a result, planning our cities under the conditions of rising sea level becomes more difficult when considering longer planning horizons. It is essential to consider coastal dynamics under various scenarios to deal with the uncertainties when preparing our cities for the future. We, therefore, need to understand the impacts of SLR, how to manage a response system and how to plan our cities (Sahin and Mohamed, 2009).

Societies need to respond to SLR in order to reduce adverse impacts and improve adaptive capacity. However, designing and applying a robust and flexible method to assess present and future vulnerabilities to SLR, and the need to identify and analyse adaptation options for reducing vulnerabilities, are challenging issues in vulnerability and adaptation research. Identifying and implementing suitable adaptation options is a difficult process due to uncertainties in future climate change projections. Therefore, developing an adequately flexible and well structured method is essential so as to provide the vulnerability information required for designing more effective adaptation strategies, as well as better management plans for reducing the adverse effects of SLR.

In light of the above observations and studies, this research focuses on assessing present and future vulnerability of waterfront properties and populations in coastal areas to SLR and storm surge events. It subsequently examines and evaluates alternative adaptation options for reducing the adverse effects of SLR in the selected study area.

3. Approach

3.1. Vulnerability Assessment (VA)

The IPCC defines vulnerability as: “the degree to which a system is susceptible to, and unable to cope with, adverse effects of *climate change*, including *climate variability* and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its *sensitivity*, and its adaptive capacity” (Parry et al., 2007).

According to this, vulnerabilities are determined by three main variables; (1) exposure to climatic variations, (2) sensitivity and (3) adaptive capacity of a system to various stressors. The concepts of adaptation, adaptive capacity, vulnerability, resilience, exposure and sensitivity are interrelated and have wide applications for global change science (Smit and Wandel, 2006). Differences in exposure to the various direct effects of climate change and different sensitivities to these direct effects lead to different potential impacts on the system of interest. The system’s adaptive capacity then determines its vulnerability to these potential impacts. These causal relationships are illustrated by the causal loop diagram (CLD) in Figure 1.

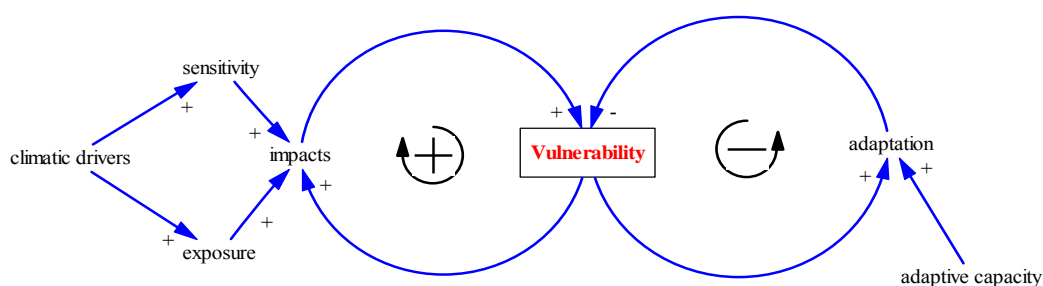


Figure 1 : Causal Loop Diagram for Vulnerability

The CLD above can be interpreted as follows: The climatic drivers trigger sensitivity and exposure, which cause increase in impacts, and increased impacts cause higher vulnerability. This part of the loop is called positive feedback. The adaptation is a function of the adaptive capacity and the vulnerability. The higher the adaptation, the less the vulnerability. However, higher vulnerability will increase the need for adaptation. This part of the loop is called the negative feedback loop.

The ultimate goal of VA is to produce recommendations on actions to reduce vulnerability. It includes both the present and future vulnerability assessments and available adaptation options. There are two general types of assessment approaches described in the literature; impact led and vulnerability led approaches (Adger et al., 2004, Dessai and Hulme, 2004, Carter et al., 2007, Richards and Nicholls, 2005). The impact approaches begin with the climate system scenarios and move through biophysical impacts towards socio-economic assessment and mainly focus on potential long-term impacts of climate change (Dessai and Hulme, 2004), whereas the vulnerability led approaches commence with local scale by addressing socio-economic responses to climate and focus on adaptation with stakeholders’ involvement (Carter et al., 2007).

What is desirable, however, is if these approaches were to be merged in a manner that could begin with present vulnerabilities but could integrate long-term risks posed by climate change. Mindful of this, the research attempts to merge both approaches in order to provide a flexible model addressing both short and long term VA issues.

Increased flood risk associated with storm surges is one of the primary impacts of SLR on low-lying coastal areas. These areas, depending on the rate of sea level rise which will provide an elevated base for a storm surge, most likely will face increased flooding before being permanently inundated due to increased flood levels. Therefore, for the future VA, the research will consider only coastal flooding resulting from sea level rise and storm surge. The degree to which coastal land is at risk of flooding

from storm surges is determined by a number of morphological and meteorological factors, including: coastal slope and wind and wave characteristics (Klein and Nicholls, 1998). Additionally, spatial dependency is a key concept for understanding and analysing spatial events. According to Waldo Tobler, the first law of geography is that everything is related to everything else, but near things are more related than distant things (Tobler, 1970). Generalizing, we can state that most of the occurrences, natural or social, present among themselves a relationship that depends on distance. What does this principle imply? If proximity of a property to the coast would increase or decrease, so would the risk it is exposed to due to SLR.

Vulnerability in this study is considered as people-at-risk and loss of residential property due to exposure to SLR and related storm surge. Therefore, the research focuses on natural and socio-economic systems that are already vulnerable to climate variability by analysing their current conditions to provide a reference map to compare future conditions. It then analyses the systems under various scenarios to identify how climate variability will affect the already troubled systems over time.

The critical vulnerability of coastal areas to coastal storms (in the short term) and SLR (in the long term) works through flooding. The extent and timing of coastal flooding and its impacts under various scenarios will be assessed in terms of two indicators: (1) Population within the 1/100 year flood level and, (2) Number of residential properties within the 1/100 year flood level.

Three SLR scenarios are considered in this research: the IPCC lower and upper range projections (including 10-20 cm ice sheet contribution) and Rahmstorf's (2007) estimation together with additional local adjustment. Thus, while the lower (0.5 m) and mid range (1.0 m) scenarios match approximately to relative SLR projections of the IPCC including local subsidence, the higher range (1.5 m) scenario combines the local subsidence with the global SLR projection proposed by Rahmsorf (2007).

Key data sets used in this research are; 5 m digital elevation model (DEM) with 10 cm vertical accuracy, mean and high water level data, land use data, surface flood level data and population data.

For case study analyses, the Gold Coast, a low coastal city, has been selected. The city is located in south-east Queensland, Australia and spans across 1402 km², featuring more than 270 km of navigable waterways and 70 km of coastline (GCCC, 2008). The area encompasses a diverse range of features including sandy beaches, estuaries, coastal lagoons and artificial waterways and is highly vulnerable to sea level rise. 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). The population of the Gold Coast increased from 214,949 in 1986 to 524,667 persons in 2007 and is expected to increase to 886,700 residents in the year 2031 (Queensland Government, 2008 , ABS, 2008).

3.2. Assessment Tools

Traditional modelling approaches focus on either temporal or spatial variation, but not both. However, it is the space-time integration that provides the explanatory power to understand and predict reality. Additionally, there is important feedback between time and space therefore they have to be examined together (Ahmad and Simonovic, 2004).

Considering the complexity and dynamic nature of coastal systems with many feedbacks and dependencies changing over time, this research focuses on modelling temporal and spatial variations of coastal processes in assessing vulnerability of the systems to SLR and storm surges. In order to achieve this, the following two methods are combined:

- System Dynamics (SD) modelling, and
- Geographical Information Systems (GIS) modelling

By combining SD and GIS approaches and linking them through a dynamic data exchange between SD and GIS, the proposed model will provide feedback in time and space. While GIS provides spatial information to the SD, the SD model will capture changes in spatial features over time and feed them back to GIS. As a result, the dynamic nature of coastal processes and their interactions can be captured in time and space.

3.2.1. System Dynamics Approach

System Dynamics (SD) is a powerful methodology and computer simulation modelling technique for understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system.

SD modelling is becoming increasingly popular in addressing complex natural processes. SD is used for; modelling sea-level rise in a coastal area (Ruth and Pieper, 1994); modelling environmental issues (Ford, 1999); simulating flooding in the Red River basin Canada (Ahmad and Simonovic, 2004); US flood policy analyses (Deegan, 2006) and evaluating adaptation options for responding to coastal flooding in Metro Boston USA (Kirshen et al., 2008). Temporal process is adequately represented in SD models; however, spatial dimensions are not explicitly dealt with.

3.2.2. Geographical Information Systems - GIS

Geographic Information System (GIS) is used for geospatial data management and analysis, image processing, graphics/maps production, spatial modelling, and visualization. Owing to its capability of analysing spatial data, the GIS approach has been widely used in vulnerability and impact analyses. Many researchers used GIS in coastal vulnerability assessments (Al-Jeneid et al., 2008, Gravelle and Mimura, 2008, Lathrop and Love, 2007, Szlafsztein and Sterr, 2007, Hennecke and Cowell, 2000, Poulter and Halpin, 2008).

However, GIS, like System Dynamics, has its own strengths and weakness. While having strong capabilities of modelling the spatial dimensions of the real world, GIS has difficulties in handling temporal dimensions.

3.2.3. Combining System Dynamics (SD) and Geographical Information Systems (GIS)

By considering weaknesses and strengths of both, SD and GIS, a combination of these two approaches would provide the potential to simultaneously address temporal and spatial problems. Some researchers have combined SD and GIS to enhance the temporal and spatial aspects of these two approaches. For example; a model was developed for a coastal process (Ruth and Pieper, 1994), SD and GIS were combined to capture space-time interaction in overland flood modelling (Ahmad and Simonovic, 2004) and a model in which nitrogen flows are simulated for 16 cells within a catchment (Ford, 1999).

Advantages of both approaches will be combined in the dynamic model while eliminating their shortcomings. As a result, the model dynamically captures the changes in time and space by obtaining and processing temporal data from SD and spatial data from GIS through dynamic data exchange. Microsoft Excel will be employed for exchanging data between the two models due to ease of use. Data can be automatically transferred between an Excel spreadsheet and models by creating import/export links.

3.3. Inundation Modeling

Inundation risk is best expressed as the likelihood of exceeding a given level of tide, surge and flood height over a particular time horizon. Inundation events vary in frequency and magnitude. Frequency is measured as average recurrence intervals of events. For example, a 1-in-100 year flood is the flood height that is expected to be exceeded on average once every 100 years. Magnitude refers to a given level of flood height. The less frequent the event generally the larger in size it is.

Coastal risks have traditionally been assessed with an assumption that the mean sea level will remain constant. However, sea level is changing. Consequently the baseline upon which current inundation

risk is being calculated is also changing as seen in Figure 2. Depending on the rate of SLR, an area that is now subject to a 1 in 100 year flood risk may in time face more frequent flood events, for instance; an event that currently happens every 100 years would happen annually in 2100. As a result, the problem of planning for longer horizons becomes more difficult due to the changing baseline.

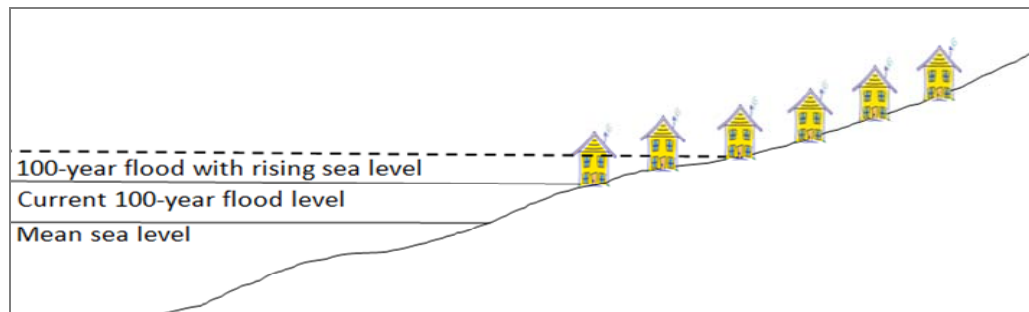


Figure 2 : Relationship between SLR and a 100 Year Flood Level

The research models the coastal inundation to analyse this dynamic and complex real-world problem in order to make predictions about what might happen with different actions under various scenarios. In doing so, some degree of simplification has to be made for reducing the reality to manageable proportions, since the real world is too rich for all components and relationships to be considered. The stock (level) and flow (rate) diagram expresses ideas about variables assumed to be important in a coastal system and their interactions (Figure 3). The diagram provides an abstraction of a pure picture of a system. The condition of the system is described by state variables that are measures of system components whose values vary with time. In the model below, the system comprises three state variables; Cover, Elevation and Sea Level. The Sea Level is an exogenous or driving variable causing changes in both Elevation and Cover variables over time. Besides, a change in one state variable effects a change in the others if they are connected. Thus, the modelled system acts as a single unit through the interrelations among its components.

However, in environmental systems, modelling the behaviour of process in space is just as important as modelling time. The model shown in Figure 3 is a non-spatial model required to be converted to a spatial model. The modification has been done by linking GIS to the SD model through a dynamic data exchange (Figure 4). As a result, temporal and spatial changes in the system are dynamically captured.

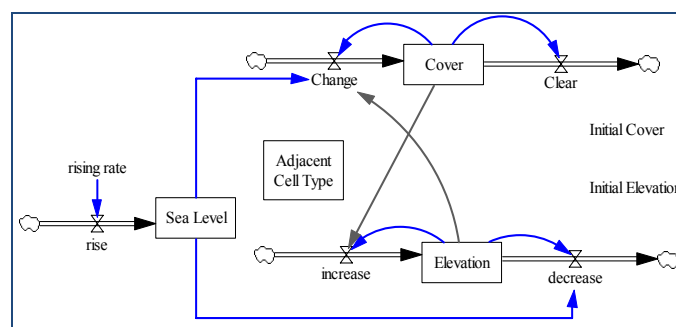


Figure 3: Conceptual Model – Modelling Inundation with SD

The spatial and temporal data are processed and exchanged between GIS and SD through dynamic data exchange. The model calculates potentially inundated areas, based on elevation, states of adjacent cells states (*Water* or *Land*) and their proximity to *Water* cells. For this, initial elevation value and cover type of each cell are determined in GIS and get transferred to the SD model. Then, in SD, elevation and cover type value of each cell is recalculated depending on the sea level at the next time step. Figure 5 shows three different stages of an area shown as 20x20 grid cells that are inundated over time under three different sea level rise scenarios.

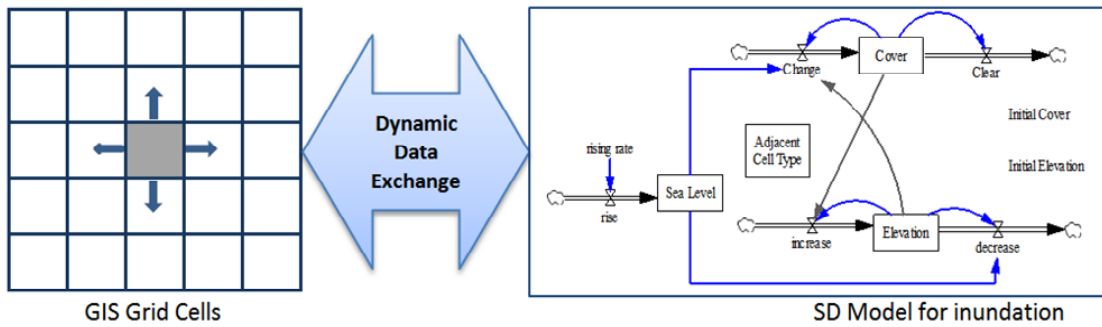


Figure 4: Coupling SD-GIS for Modelling Coastal Inundation

The dark coloured cells represent *Water (W)* or inundated cells, while the light coloured cells show *Land (L)* cells. As sea level rise is simulated, the flood water spreads from one cell to another and the total number of inundated cells increases accordingly. Subsequently, for each incremental sea level rise, total inundated surface area is computed by summing the number of inundated cells for a 1 m SLR (Figure 5). For example; a cell at a location x_i, y_j will be flooded if two conditions are satisfied:

- (1) Elevation of the cell \leq adjacent cells and
- (2) The cell cover type is L and at least the cover type of one adjacent cell is W.

The following equation describes how the model predicts flood water diffusion from one cell to another:

$$F(x_i, y_j) = \begin{cases} 1, & CT(x_i, y_j) = L \text{ and at least one } CT(x_n, y_m) = W \text{ and } CE(x_i, y_j) \leq CE(x_n, y_m) @ 0, \\ 0, & \text{otherwise} \end{cases}$$

where:

- F is, either flooded (1) or not flooded (0),
- CE is cell elevation,
- $CT(x_i, y_j)$: cover type, either land L or water W
- $CT(x_n, y_m)$: adjacent cells cover types, either land L or water W
- (n, m) refers to all adjacent cells to i, j (i.e.: $i, j-1, i, j+1, i+1, j$ and $i-1, j$)
- WL is water level.

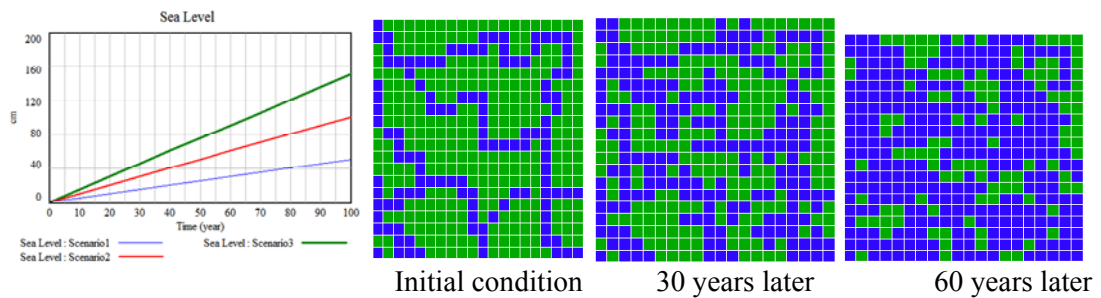


Figure 5: Inundation Model for Vulnerability Assessment - 1m SLR Scenario

4. Discussion

Coastal regions are highly vulnerable to climate change. Therefore developing and implementing effective adaptation options are crucial for their future development. However, there is uncertainty in the timing, duration, spatial location and extent of SLR and storms. So, while the probability and magnitude of a particular flood event that may occur within the next 100 years can be estimated, it is not possible to say when exactly this will happen.

The complexity that arises from climate, coastal systems and their interactions in space and time can easily overwhelm the ability of decision makers to thoroughly investigate the outcomes of adaptation alternatives. Dilemmas confronting decision makers are: how to adapt and when to adapt to SLR. Determining how and when specific actions should be taken is not simple, due to uncertainty in the timing and magnitude of SLR impacts (Sahin and Mohamed, 2009). To facilitate these decisions, policy makers require credible scientific data and information.

By considering the uncertain nature of projected changes in climate and addressing these dilemmas, this research provides a dynamic model for a comprehensive current and future vulnerability assessment of coastal areas focusing on changes in sea level, therefore assisting decision makers in identifying and evaluating effective adaptation alternatives for reducing climate change impacts. The model also provides a number of spatial maps of inundation at regional scale which show areas and population at risk on various time scales. These maps can be very useful for increasing public awareness as well as planning purposes. Significant characteristics of the model are that:

- It is flexible and modular therefore other elements affecting coastal systems can be integrated as needed.
- It is dynamic in terms of capturing feedbacks and dependencies changing over time.
- It takes into account spatial characteristics of the study area.

Finally, all research has limitations and this one is no exception. This research considers only impacts from inundation and coastal flooding due to storm surge and SLR. All other impacts, such as flooding due to heavy precipitation, are disregarded. Additionally, determining an inundation area with less than 10 cm elevation is not possible since vertical resolution of DEM data sets is 10 cm.

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