IVM Institute for Environmental Studies

Coastal Protection services of coral reefs in Bonaire

Economic values and spatial maps

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Report R-12/11
10 December 2012

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This report was commissioned by: Ministry for Economic Affairs, Agriculture and Innovation
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Summary

The coastal protection value (CPV) of coral reefs is one of the ecosystem services that contribute to the economic value of coral reefs. The basic principle of coastal protection by coral reefs is the observation that reefs dissipate wave energy either by wave breaking or friction by reef structures. In this study, the coastal protection value (CPV) is estimated on 30 * 30 m grid cell level, which gives a more spatially explicit estimation of the CPV of coral reefs. The annual coastal protection values of the coral reefs of Bonaire for short-term (i.e. within 10 years) and long-term processes (i.e. beyond 10 years) are estimated at $33,000 and $70,000, respectively.

1 Introduction

The coastal protection value (CPV) of coral reefs is one of the ecosystem services that contribute to the economic value of coral reefs. The basic principle of coastal protection by coral reefs is the observation that reefs dissipate wave energy either by wave breaking or friction by reef structures (Gourlay, 1996a, 1996b; Lugo-fernandez, Roberts, & Suhayda, 1998; Massel & Gourlay, 2000; Sheppard, Dixon, Gourlay, Sheppard, & Payet, 2005).

The methodology applied in this study is based on the approach applied in the total economic valuation study of coral reefs in the United States Virgin Islands - USVI (van Beukering, Brander, van Zanten, Lems, & Verbrugge, 2011). In comparison to the USVI study, a more advanced spatial model is applied. In this study, the coastal protection value (CPV) is estimated on 30 * 30 m grid cell level, which gives a more spatially explicit estimation of the CPV of coral reefs.

This report is structured as follows. Chapter 2 provides the background of the study and presents earlier economic valuation studies that valued the coastal protection function of coral reefs. Chapter 3 elaborates on the GIS analysis, the overall methodology applied in this study, and describes the data sources used in the analysis. Chapter 4 of this report the results of the analysis are described. Conclusions and recommendations are presented in Chapter 5.

2 Background

2.1 Previous studies on the coastal protection value of coral reefs

Valuation of the coastal protection by coral reefs is rarely done. Often, CPV studies are part of a total economic valuation study (TEV), and due to time and budget constraints and methodological difficulties, estimates are often inaccurate. In the last decade, there have been some global and regional estimates on the CPV of coral reefs (Cesar *et al.*, 2003; Burke & Maidens, 2004). Cesar *et al.* (2003) estimate the CPV of coral reefs worldwide at $9 billion annually. This represents, over 50 years, a net present value (NPV) of $240 billion, taking into account a 3% discount rate.

Burke & Maidens (2004) estimated the coastal protection value of coral reefs along the Caribbean coastline at $750 million to $2.2 billion annually. The numbers for the Caribbean region are calculated using a Replacement Cost (RC) approach in combination with a classification of coastline development. Results of these studies have to be considered as rough estimates. Due to the lack of data, several simplifying assumptions were made on critical parameters.

The most extensive and arguably the most accurate studies about the CPV of coral reefs are the economic valuation of coral reefs in Tobago and St. Lucia (Burke, 2008) and the total economic valuation study of Bermuda's coral reefs by van Beukering *et al.* (2010). In the former, Burke (2008) estimates the CPV of coral reefs around the Caribbean islands Tobago and St. Lucia at a 2007 (annual) value of 18-33 million USD (Tobago), and 28-50 million USD (St. Lucia). The CPV of coral reefs around Bermuda represent a NPV of 266 million dollar per year (van Beukering, 2010). Due to high uncertainties about the frequencies of hurricanes, the CPV ranges from 134-532 million dollars per year.

In both studies the avoided Damage Cost (DC) approach is applied. The starting point in the Tobago and St. Lucia study is a spatial analysis of the physical environment, to determine the lands that are protected by coral reefs. The economic component comprises the determination of the value at risk. Burke (2008) identifies six steps in the analysis: (1) understanding the storm regime and assess the damage reported by hurricanes in the past; (2) identify "vulnerable" areas to wave-induced damage; (3) Identify coastal areas which are protected by coral reefs; (4) evaluate the stability of the shoreline and the extent of protection by coral reefs; (5) assess the property values "vulnerable" areas protected by reefs; (6) assess to what extent coral reefs prevent potential damages to property values.

The steps determined by Burke (2008) are comparable to the methodology applied in the coastal protection value chapter of the total economic valuation (TEV) report of Bermuda's coral reefs by van Beukering (2010). Van Beukering (2010) defined seven steps in the analysis. The first step, (1) determining the coastal profile, aims to assess the coastal vulnerability to floods. Key variables in this first step are land elevation, the related shore type (beach, cliffs, etc) and the coral reef cover and health. The second step is to (2) assess the local storm regime. As well as the USVI, Bermuda has a history of hurricanes and tropical storms. Key variables in this stage of the analysis are storm frequency, intensity, surge and wave heights during the storm. The third and fourth step defined are, (3) analyzing the historic information on wave-induced erosion and property damage and (4) identifying areas vulnerable to wave-induced erosion and property damage. The fifth step is (5) linking the reefs to the areas that are vulnerable to floods: identifying the shorelines protected by the reefs. The sixth step (6) is assessing the stability of the shoreline in terms of geology, geomorphology, benthic habitat, slope and exposure to storms. The final step (7) is measuring the property values in the areas protected by reefs and “vulnerable” to floods.

Although the steps defined by van Burke (2008) and van Beukering (2010) are relatively similar and both studies apply a DC approach, there are some differences. *Determining the coastal profile* is an extra step used by van Beukering (2010) in order to come up with the “vulnerable” areas. Moreover, the first step identified by Burke (2008) is split up in the Bermuda report in two different steps (2&3). Finally, in the Bermuda report there is no separate step defined to assess the avoided damage by reefs and thus the coastal protection value.

Despite the fact that in these studies a similar analytical framework is applied, the results are very different. An explanation for the differences in outcome is the analysis of the storm regime. Burke only took 25-year return time events into account, van Beukering *et al.* (2010) also estimated damages of 52-year return time events. In other words, by including severe low-probability events a more comprehensive but also a more uncertain result is generated.

2.2 Literature on energy dissipation by coral reefs

The two main reef characteristics that determine the amount of wave energy dissipation by coral reefs are reef friction and wave-breaking characteristics by coral reefs as presented in the literature (Lugo Fernandez, 1998; Thornton & Guza, 1983; Gourlay, 1996a; Gourlay 1996b; Gourlay, 1997; Sheppard, 2005).

Several coastal engineers made attempts to model the wave energy dissipation function of coral reefs. The model designed by Gourlay (1996a) is applied for designing the FEMA flood insurance rate maps (FIRMs) for the US Virgin Islands. This model is based on laboratory experiments. Wave set-up and wave generated flows are measured for horizontal reef under two different conditions: as a fringing reef and a platform reef. Wave set-up turned out to be highest during low tide and wave generated flow during high tide. Wave set-up is the increased water level on the reef as a result of wave breaking. Wave generated flow is the wave energy flow over de reef top. The model designed by Gourlay (1996a) and applied for the flood maps in the USVI is based on an idealized two dimensional reef and assumes that wave energy dissipation by coral reefs only takes place when the waves break on the reef.

An important constraint of the model by Gourlay (1996a) is that is does not take into account the dissipative function of friction by corals and sea bottom rugosity. Lugo-Fernandez (1998) examines wave transformations on Tague Reef at the US Virgin Island St. Croix. In this follow-up study by Lugo-Fernandez (1998), a model designed by Thornton & Guza (1982) is applied and tested with field data from St. Croix. The model takes into account both coral friction and wave breaking as wave energy dissipation functions. According to Thornton & Guza (1982), the relative amount of wave energy dissipation of coral reefs is currently 75%-85%. Without the dissipation function of friction thus without corals on the reef crest the wave energy dissipation function would be 57%-66%.

These results from the USVI are comparable to findings presented by Sheppard *et al.* (2005) on coral reefs in the Seychelles, where an average wave energy dissipation rate 80% was found. This study emphasizes the increase of wave energy reaching the shores caused by a trend of increasing coral mortality on the reef flat. As a result of the disintegration of dead corals, the concept of “pseudo sea level rise” was introduced. In this case, the still water sea level rises as a direct result of coral die-off and disintegration.

In our study in Bonaire, the model applied by Sheppard *et al*. (2005) is used to determine the relative wave energy dissipation for the reef types distinguished. It suits this study because the input data is available and both wave breaking and friction are included separately in the model. Furthermore it is desirable that this study and the FIRM analysis apply a similar methodology to calculate the wave set-up proposed by Gourlay (1996a, 1997). As shown in Table 2.1, Gourlay suggested that the friction factor of coral reefs varies from 0.1 (smooth, dispersed) to 0.2 (rough, dense). A sandy bottom has a friction factor of 0.08.

Table 2.1 Friction Factor and Reef Flat Zone characteristics

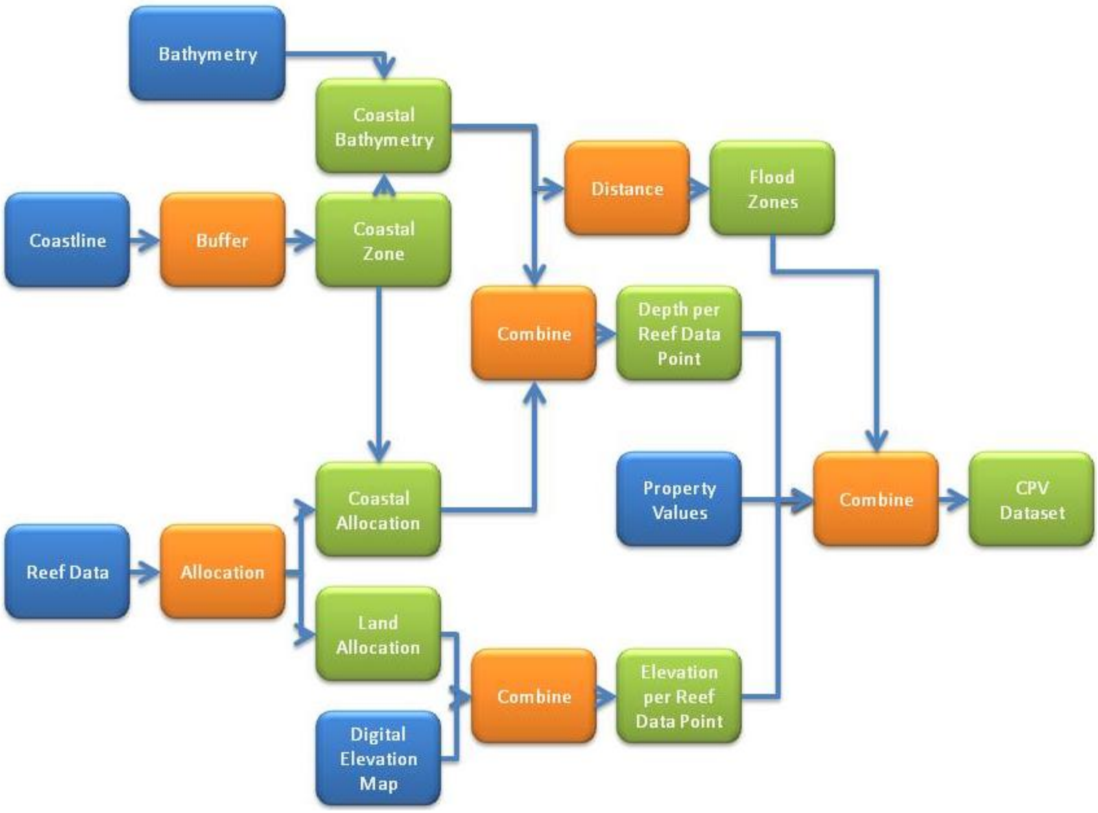
Criteria	***fw* (friction factor)**
75%-100% sand	0.08
75%-100% smooth rock or coral pavement 75%-100% sea grass or algal turf	0.10
Smooth rock or coral pavement with 50%-100% coral rubble	0.12
10%-25% live coral or dead uneroded coral or tall (>30 cm) boulders	0.14
25%-50% live coral or dead uneroded coral or tall (>30cm) boulders	0.16
50%-75% live coral or dead uneroded coral or tall (>30cm) boulders	0.18
75%-100% live coral or dead uneroded coral or tall (>30cm) boulders	0.20

Source: Sheppard, 2005

3 Methodology

3.1 Conceptual framework and GIS Analysis

Figure 3.1 provides a simplified overview of the spatial coastal protection valuation model designed for Bonaire. This simplified version is based on a more complex version represented in Annex A where the spatial model is displayed in two parts (part 1 and part 2). The blue boxes are the data sources ("Bathymetry", "Island Area", "Coral Feature Data", "Digital Elevation Model" and "Property Values" in Annex B). The yellow boxes are tools (or commands) applied in the analysis and the green boxes intermediate or result data files.



Note: Blue boxes are the data sources, yellow boxes are tools, and green boxes intermediate or result data files.

Figure 3.1 Simplified Spatial Model

A brief description is given of the steps in the spatial analyses. First, the model starts with an allocation of the "Reef Data". This means that all grid cells within the extent of the map (Bonaire and surrounding waters) are allocated to the nearest reef data point. At the same time a 200m buffer is created around the "Coastline". Within this buffer it is possible to select the "Coastal Bathymetry" and "Coastal Allocation". "Depth per Reef Data Point" is determined by combining "Coastal Bathymetry" and "Coastal Allocation".

The "Elevation per Reef Data Point" is determined by combining "Land Allocation" and "Digital Elevation Map". "Flood Zones" are a function of distance to the coast. Coastal Areas within 200m from the Coastline are assumed to be high energy zones. Areas further away from the Coastline are considered low energy zones (this determined which damage function is applied).

A combination of “Flood Zones”, “Depth per Reef Data Point”, “Property Values” and “Elevation per Reef Data Point” leads to the CPV Dataset. This dataset contains a selection of areas in Flood Zones on Bonaire that are protected by coral reefs, contain property values, and are below an elevation of 8 meters. This dataset is exported to excel.

For every protected area, the dataset provides a code of the nearest reef data point and the average depth around this data point. For every reef data point there is information on the coral cover and complexity, which can serve as input for the wave energy dissipation model.

The results of the wave model shows how much wave energy is dissipated by coral reefs in % of the total wave energy that passes the reef. It is assumed that a 5% increase in wave energy leads to an increase of 1ft flood depth in the damage curve. This allows us to calculate the Coastal Protection Value per 30 * 30 m grid cell.[1] The underlying assumptions of the wave model are depicted in Annex C.

3.2 Data sources

Table 3.1provides an overview of the data used in the coastal protection analysis. For every protected area, the dataset provides a code of the nearest reef data point and the average depth around this data point. For every reef data point there is information on the coral cover and complexity, which can serve as input for the wave energy dissipation model. The input for the model per reef data point is the friction factor and the average depth of the reef flat. Other variables in the wave model (for example 100yr return time wave characteristics) are assumed to be constant for all reef data points. The data are collected from a wide variety of sources.

- The coral data are derived from a spatial qualitative assessment by IMARES (2011). This coral dataset was as input for spatial information on coral cover and complexity. The dataset provides qualitative point information per 500 meter transect on the west coast of Bonaire.
- Bathymetry point data provided by the Netherlands Hydrological Service was interpolated and used to measure the average depth in the reef zones.
- A digital elevation model was created for the analysis, by interpolating a point elevation map, provided by IMARES.
- An AutoCAD file with spatial planning information was geo-referenced and from this dataset, the parcel layer was selected for the analysis.
- A database house prices of about 120 cases in the period 2006-2011. Local real estate agents based on Bonaire provided this dataset.

To calculate the wave energy dissipation an excel-based wave model (Sheppard *et al.*, 2005) was applied[2].

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[1] Annex B displays the relative depth-damage functions prepared by FIA, which is part of the US based Federal Emergy Management Agency (FEMA). V zones are the high-energy zones (<200m from coastline). Within these zones, the damage to the properties is relatively high, because in these areas waves lose most of the energy. A zones are low energy zones (>200 m from the coastline).

[2] Downloadable at http://www.bio.warwick.ac.uk/res /frame.asp?ID=42).

Table 3.1 Data sources applied in the analysis

Dataset	Type	Source
Spatial Coral Qual. Dataset	Point	IMARES
Bathymetry Dataset	Point	Netherlands Hydrological Service (1996, 2006)
Land Elevation	Point	IMARES
Spatial Planning Dataset	CAD	Buro Vijn (ROB data)
Real Estate Dataset	Excel	RE/Max Bonaire
Wave Model	Excel	(C. Sheppard etal, 2005)
Coastline Bonaire	Polyline	IMARES

4 Results

To determine the coastal protection value of coral reefs of Bonaire, the avoided damage costs approach is used. This implies that storm damages with coral reefs are compared with a hypothetical scenario without coral reef protection. In this study, two forms of coral reef coastal protection are recognized: (1) short term coastal protection and (2) long term coastal protection. Short-term protection only takes into account the coastal protection function of coral friction. Coastal protection by coral friction is considered short term, because coral die-off and disintegration can occur on a relatively short time scale (within 10 years).

Processes that influence the long-term coastal protection, which includes the water depth on the reef (and hence the wave breaking function), are relatively “slow” processes such as reef flat erosion, sea level rise caused by climate change and coral reef erosion caused by ocean acidification (Hoegh-Guldberg et al., 2007). This scenario assumes a degraded reef without coral structures + 1 meter erosion of the reefs. On degraded reefs, erosion of limestone reef sediments is about 1 cm per year (so 1 m erosion could take place within 100 years). Next to that: sea level rise has the same effect on wave behaviour as reef erosion (one way or another the water depth on the reef increases).

4.1 Coastal protection value

Table 4.1 shows the coastal protection value of coral reefs for a 100-year return time event categorised by short-term damages and long-term damages. Not that the total value at risk is estimated to be $108 million. The values in the first row present the damage figures as is expected over a 100-year period with current coral conditions (e.g. the baseline). This damage is simulated to be around $55 million. The second row in Table 4.1 present the simulated storm damages in a 100-year period with the degraded, but not eroded coral reefs. Without the friction function the damage will increase to almost $59 million. The third row shows the implications of heavy erosion of the coral reef structures. Without this wave-breaking function the damage will increase to $62 million in a 100-year period.

Table 4.1 Relative Protection Values Coral Reefs

Relative Protection Values Coral Reefs	Damage (in US$)	Relative Damage	Relative Protection
Damage 100yr event with current living coral reefs	$55,400,502	51.4%	0.0%
Damage 100yr event with degraded (short term) reefs	$58,743,058	54.5%	3.1%
Damage 100yr event with eroded (long term) reefs	$62,411,759	58.0%	6.5%
Total Value at Risk	$107,706,444	100.0%	9.6%

Since the estimation of the absolute Value at Risk in Bonaire is very uncertain it is important to not only consider the absolute damage estimates but also consider the relative contribution of the reef functions in avoiding damage. As shown in the last column of Table 4.1**Error! Reference source not found.** it can be concluded that compared to the baseline, living coral reefs avoid 3.1% of the damage (friction function), and the coral reef structures (wave-breaking function) avoid 6.5% of the storm damage compared to the baseline.

In summary, the avoided damage of a 100-year event attributed to coral friction (short term) is valued at $3.3 million and the avoided damage of the wave-breaking function of coral reefs of Bonaire is valued at $7 million. On annual bases, this implies a short and long term value of $33,425 and $70,113, respectively.

4.2 Value maps

Similar to most other values, the coastal protection value of the coral reefs of Bonaire is not distributed evenly. Through the creation of value maps, GIS techniques can help us visualize and better understand the spatial distribution of economic values of coral reefs. Value maps of ecosystems can be designed from the perspective of the provision of the services (i.e. the supply side) or from the perspective of the beneficiaries (i.e. the demand side). In the context of coastal protection, the location of service provision is the coral reef while the beneficiaries are the coastal properties that partially protected by the reef barriers. Both perspectives are presented in the following sections. The friction value map is based on the friction function map presented in Annex D.

4.2.1 Value maps for the “demand side”

Figure 4.1 shows the “demand side” of the coastal protection value. The map is based on the grid cells (30*30m resolution) on land representing the value at risk. Every grid cell contains minimum of 1 parcel from the spatial planning database. The map reveals the coastal protection value for coral friction of the reefs per grid cell at risk. The coastal protection function of reef structures (friction) is calculated by comparing wave energy dissipation with current reef conditions with a flat sandy bottom. Similarly, Figure 4.2 shows the “demand side” of the coastal protection value for coral reef erosion of the reefs per grid cell at risk. The coastal protection function of an eroded reef is calculated by comparing wave energy dissipation with current reef conditions with a flat sandy bottom + 1 meter erosion.

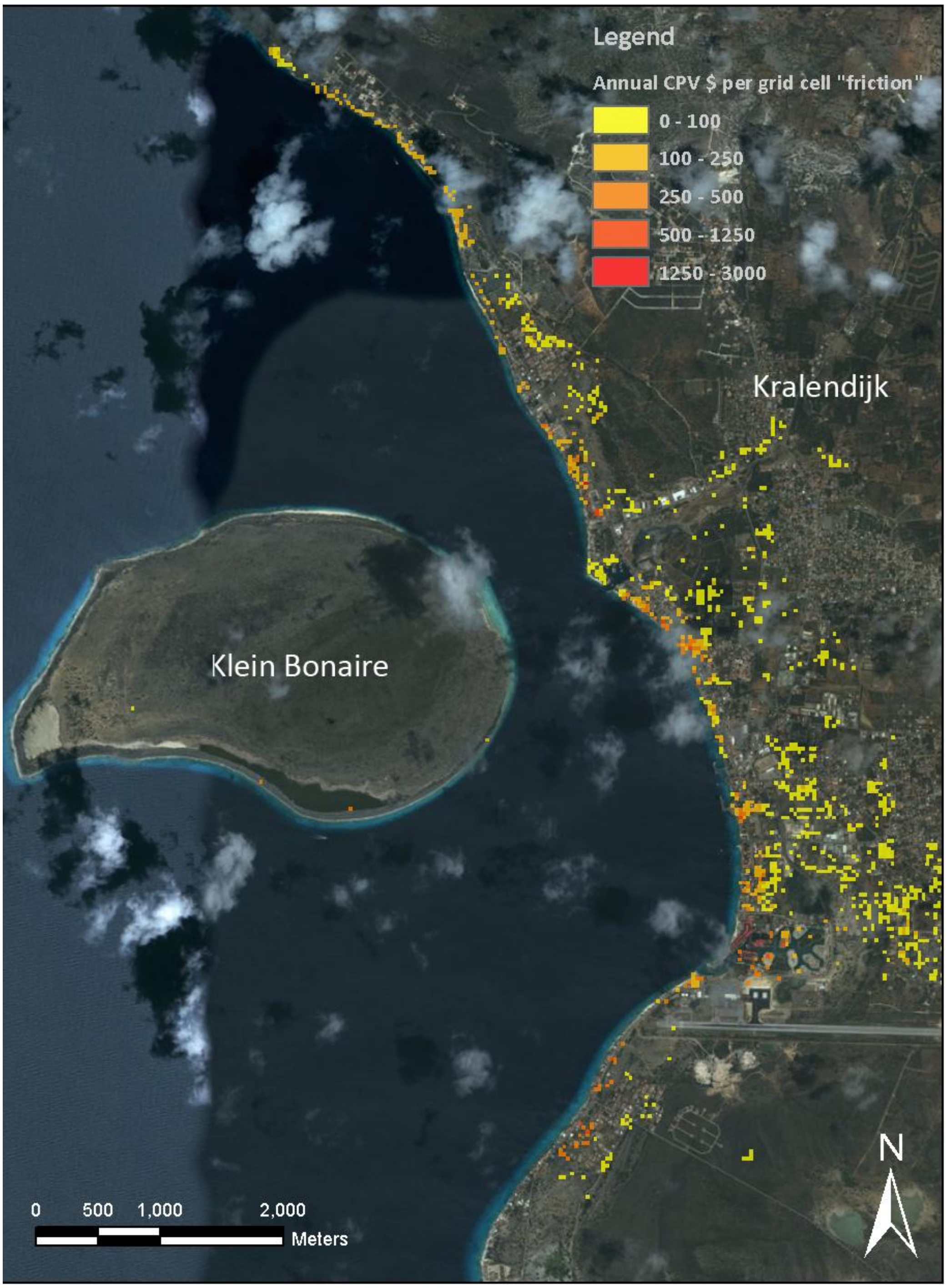

Figure 4.1 Map of "demand side" of the coastal protection value generated by the friction function

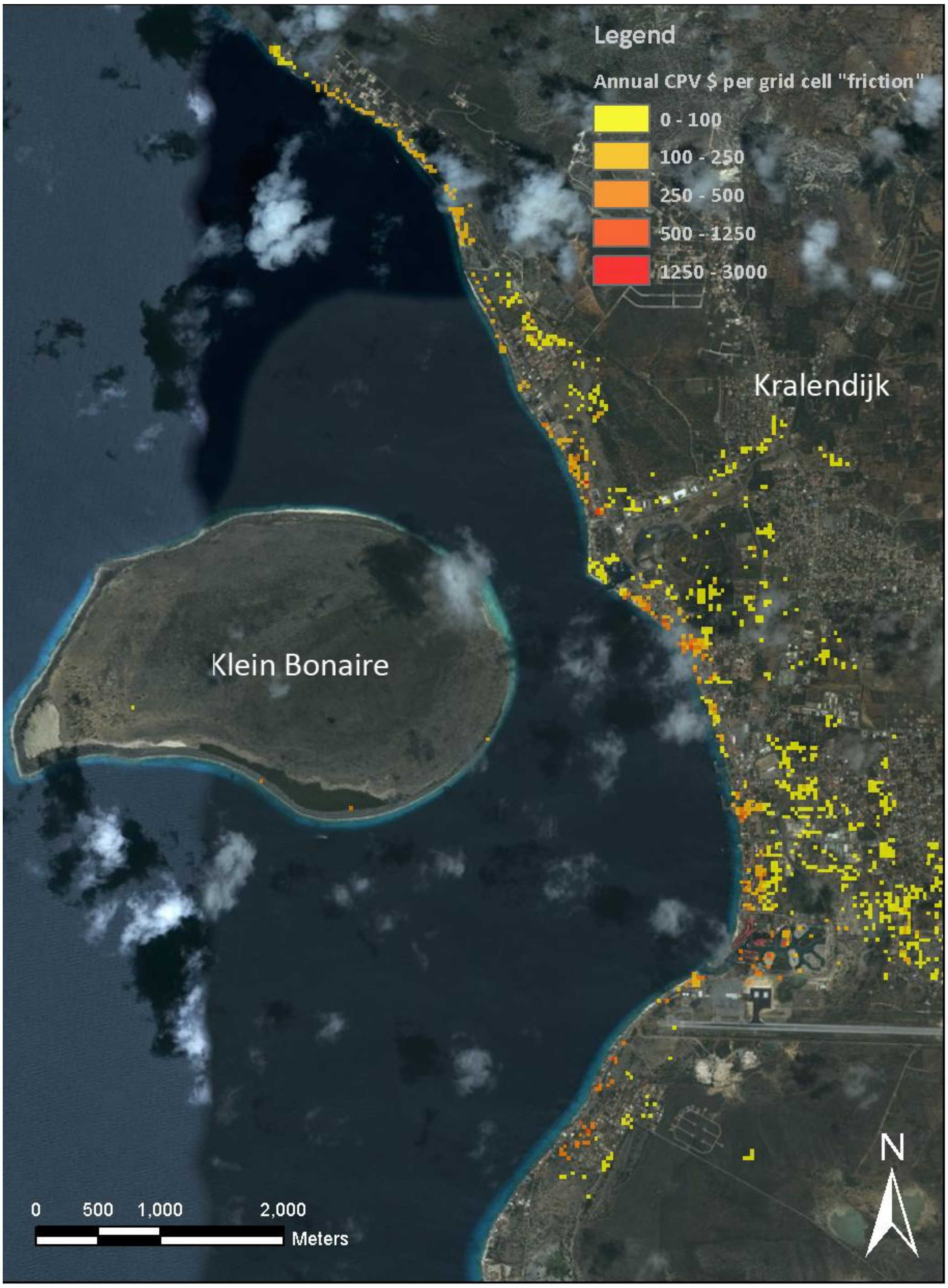

Figure 4.2 Map of "demand side" of the coastal protection value generated by the wave-breaking function

4.2.2 Value maps for the "supply side"

Figure 4.3 shows the "supply side" of the coastal protection value. The grid cells (30*30m resolution) represent the value of the reefs. This value depends on the value of the adjacent value at risk and the reef characteristics of this particular reef data point from the IMARES survey. The reef value is expressed per m2 of reef. The map reveals the coastal protection value for coral friction of the reefs per m2. The coastal protection function of reef structures (friction) is calculated by comparing wave energy dissipation with current reef conditions with a flat sandy bottom.

Figure 4.4 shows the “supply side” of the coastal protection value of the wave breaking function. The coastal protection function of an eroded reef is calculated by comparing wave energy dissipation with current reef conditions with a flat sandy bottom + 1 meter erosion.

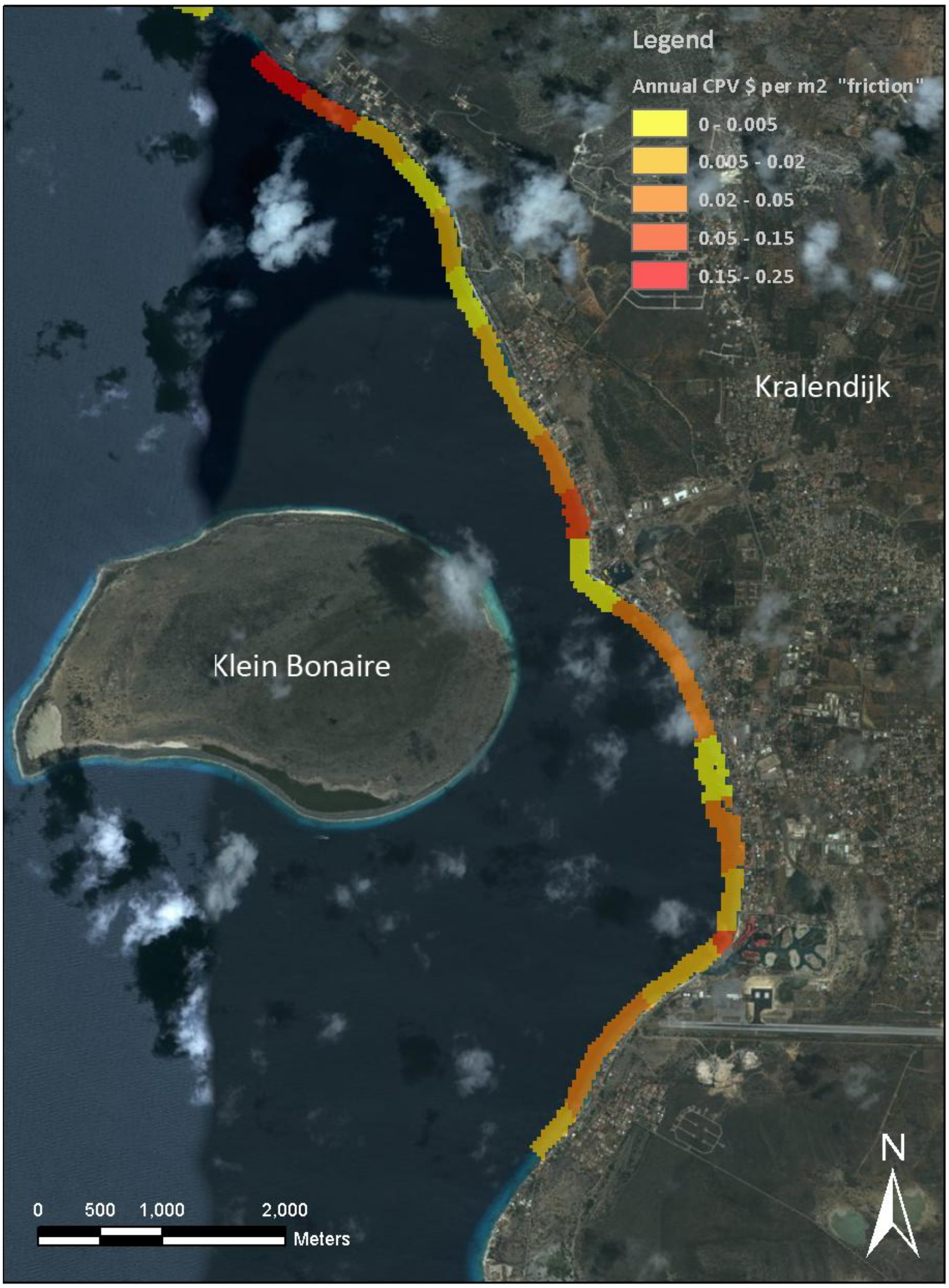

Figure 4.3 Map of “supply side” of the coastal protection value generated by the friction function

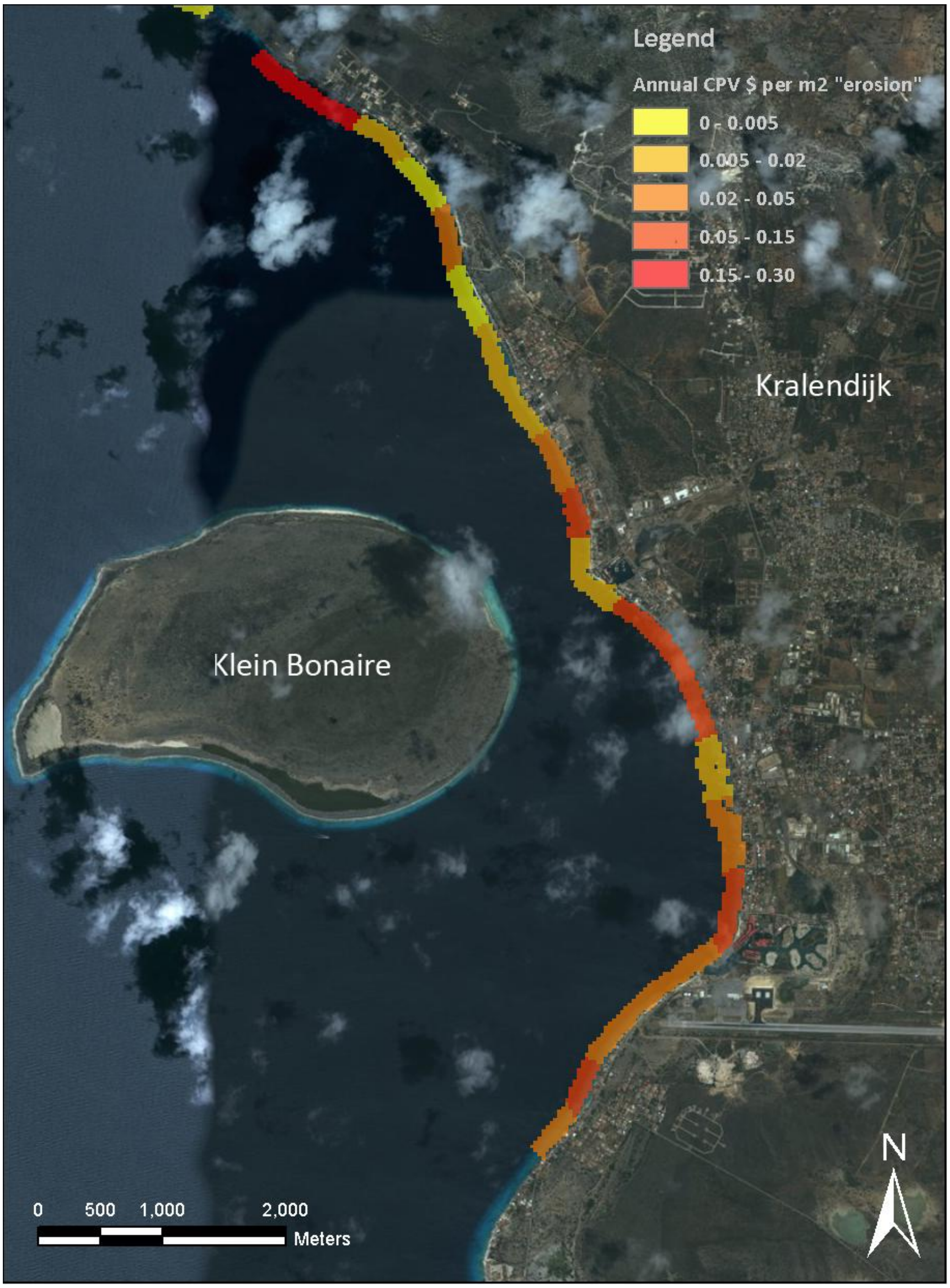

Figure 4.4 Map of "supply side" of the coastal protection value generated by the wave breaking function

5 Conclusions

The annual coastal protection values of the coral reefs of Bonaire for short-term (i.e. within 10 years) and long-term processes (i.e. beyond 10 years) are estimated at $33,000 and $70,000, respectively. With the application of the FIRMs, reef typology, the wave model designed by Sheppard (2005) and the FIA depth-damage curves, and the grid-based GIS analysis, the accuracy of the CPV modelling has undoubtedly increased. However, this approach has its limitations as well. Assumptions are made to estimate the relationship between the increase of wave energy reaching the coastline and the actual damage to properties. A sensitivity analysis on these assumptions is recommended to test the robustness of the results.

To assess the costs and benefits of coral reef conservation it is essential to gain insight in short-term and long-term processes that affect the CPV. Further research is needed to estimate whether long-term processes such as reef flat erosion and ocean acidification induced coral reef erosion are a serious threat to the Bonaire reefs. More reliable estimations and observations can be made on the disintegration time of dead corals. Therefore it is recommended that the coastal protection function of coral friction is integrated in the FIRMs provided by FEMA, in order to be able to assess the effect of coral cover decline. This change can be adopted by applying the methodology used by Gourlay (1996b) and Sheppard (2005), instead of the currently applied model by Gourlay (1996a) which assumes an idealized smooth reef without coral friction. To gather the required data on sea floor rugosity, but also in monitoring erosion on degraded reefs, better collaboration of the active research organisations is crucial. Moreover, for future research it is important to also look into events that take place more frequently (e.g. 10yr or 25yr events). Since CPV by coral reefs is non-linear the relative protection is higher under those circumstances. Furthermore, better methods should be applied to estimate the value at risk (sophisticated land use maps as is common in flood risk modelling). Finally, it is recommended to raise awareness for the coastal protection function of coral reefs in Bonaire.

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Annex A Spatial model

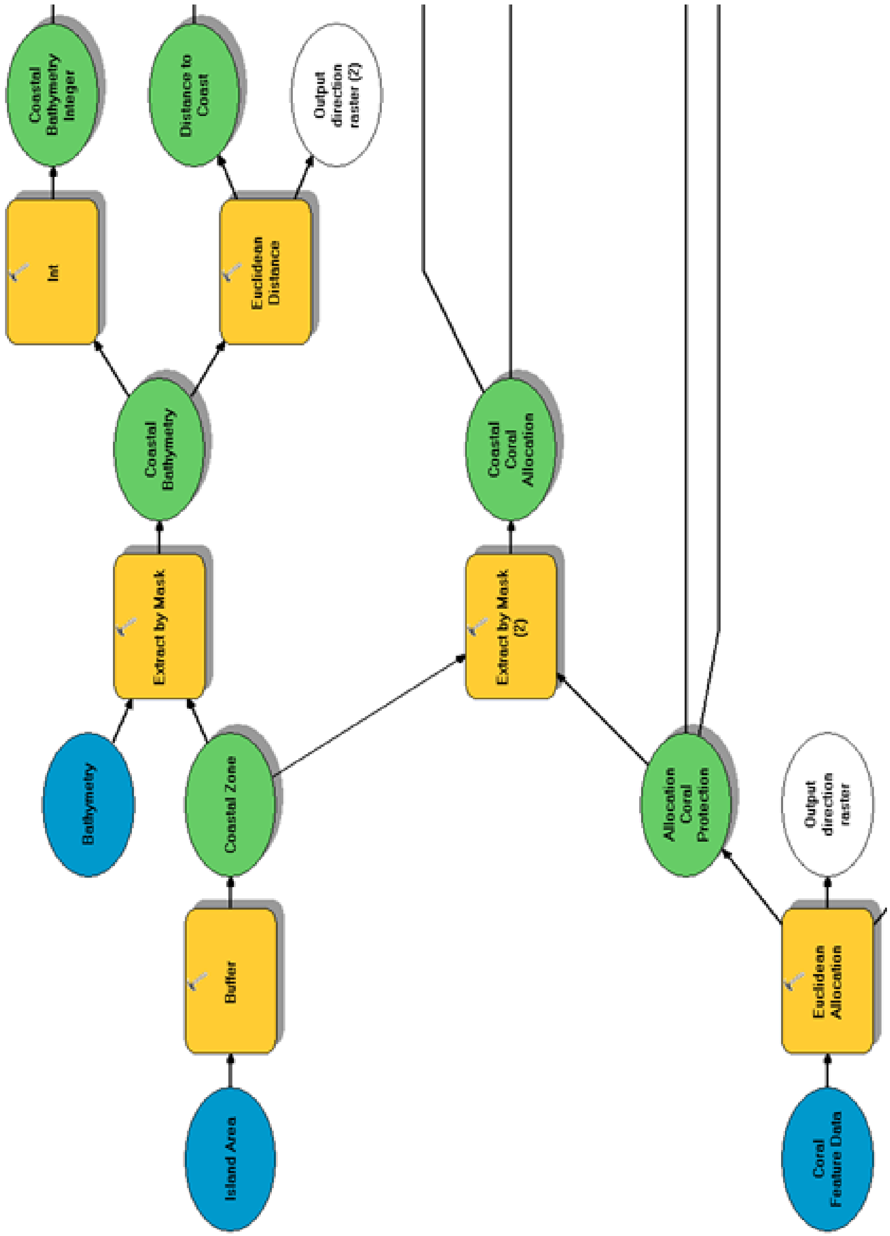

Figure A.1 Spatial Model part 1

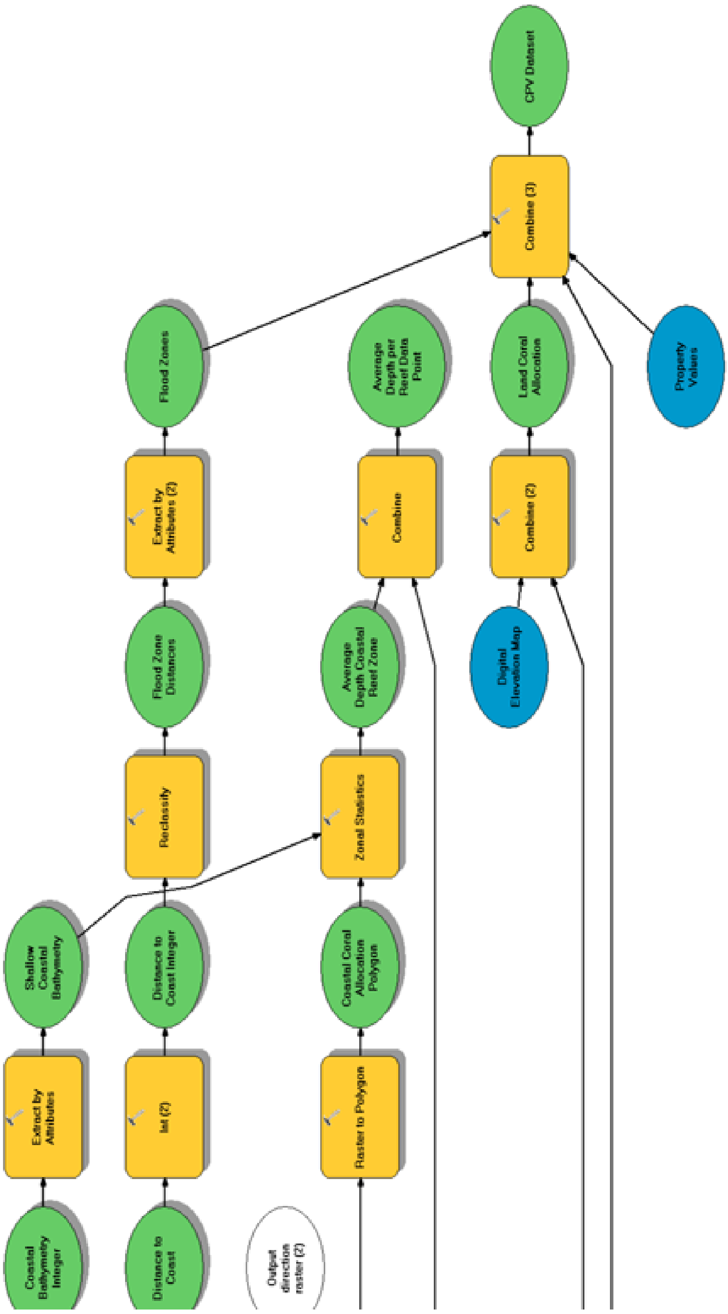

Figure A.2 Spatial Model part

Annex B FIA Damage Functions

Flood Depth (ft)	Relative Damage V Zones	Relative Damage A Zones
-2	10%	0%
-1	12%	0%
0	15%	5%
1	23%	9%
2	35%	13%
3	50%	18%
4	58%	20%
5	63%	22%
6	66.5%	24%
7	69.5%	26%
8	72%	29%
9	74%	33%
10	76%	38%
11	78%	38%
12	80%	38%
13	81.5%	38%
14	83%	38%
15	84%	38%
16	85%	38%
17	86%	38%

Annex C Assumptions underlying the wave model

Table C.1 General Assumptions Wave Model Sheppard

Model Variable	Number	unit
Friction Factor		
no reefs	0.08	
Smooth Rock or Coral Pavement (1)	0.1	
Reasonable (2)	0,14	
Much (3)	0.16	
Very much (4)	0.18	
Erosion	plus 1	m
Beach Shape		
tan alpha beach	0.04	
reef width	200	m
depth reef edge	8	m
Wave Height and Period 100yr event		
deep water wave height	8.34	m
deep water wave period	11.19	sec.

Annex D Friction Factor Map

The friction factor map represents the coastal protection function of coral reefs per reef data point. Qualitative spatial coral cover data collected by Imares was translated to a friction factor designed by (Sheppard *et al.*, 2005) that accounts for coral structures in the wave energy dissipation model.

This friction factor enables the calculation of a coastal protection value for coral friction. Note that the reefs with the highest protection functions are not necessarily the most valuable reefs in terms of coastal protection.

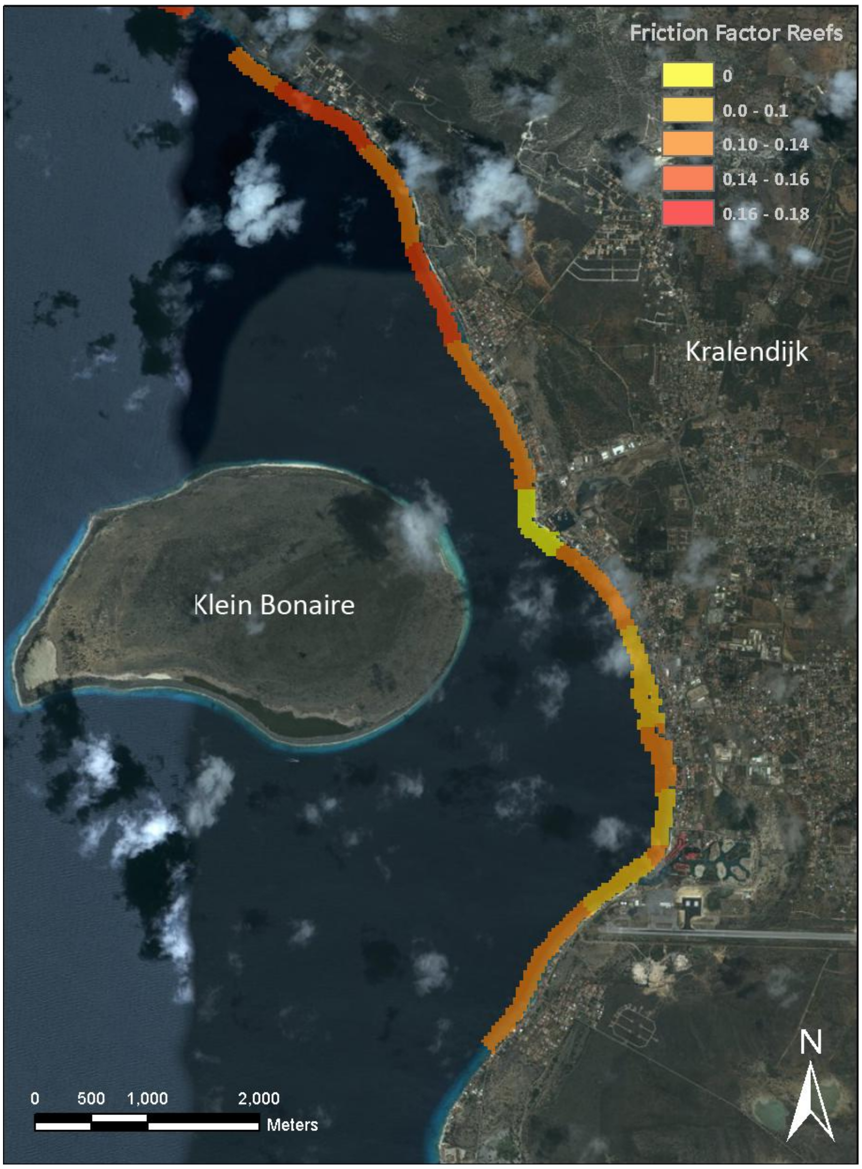

Figure D.1 The coastal protection function of coral reefs per reef data point