ICCE 2018

36TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING 2018

Baltimore, Maryland | July 30 – August 3, 2018

The State of the Art and Science of Coastal Engineering

CLIMATE CHANGE KEY CHALLENGES IN COASTAL ENGINEERING

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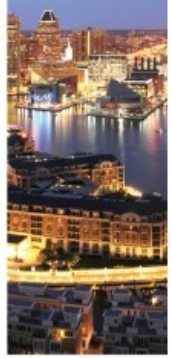
1. Risk framework and uncertainties
2. Climate drivers/hazards: projections and downscaling
3. Impact models
4. Adaptation: options/strategy
5. Conclusions



Risk framework

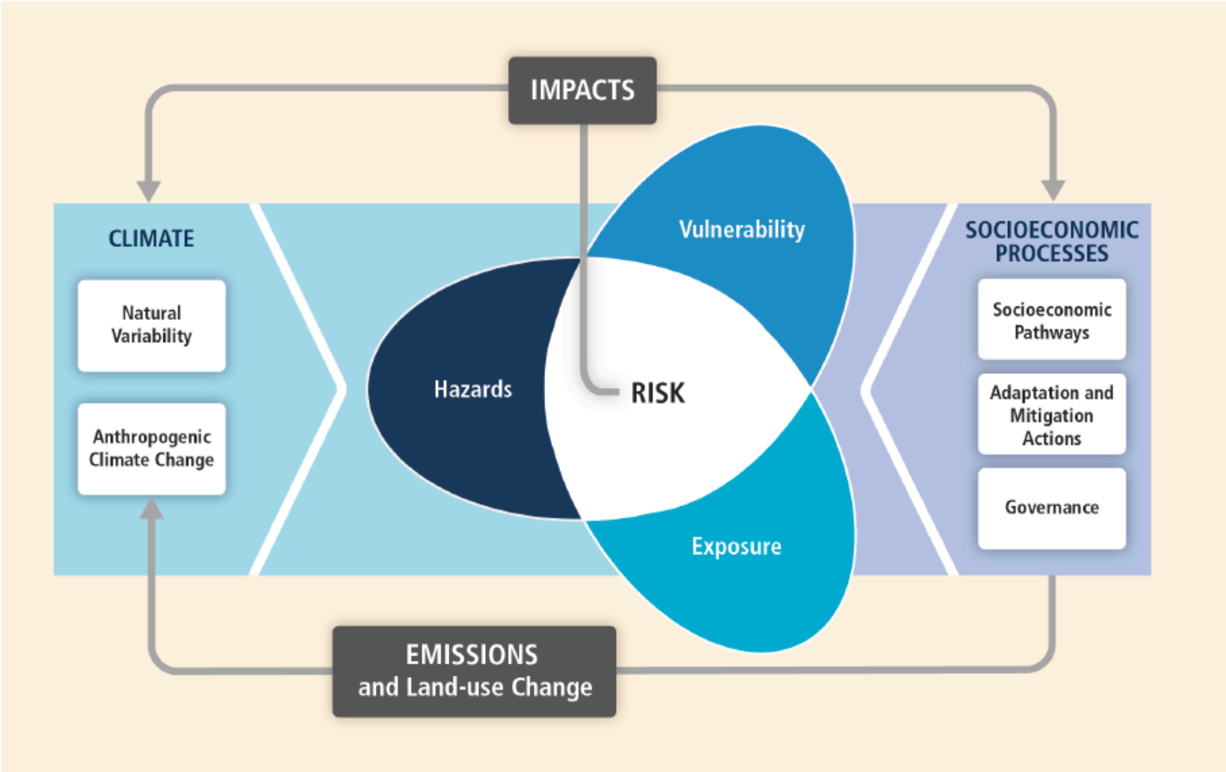


Figure SPM.1.

HOW CAN WE TRANSLATE THE REFERENCE FRAMEWORK INTO PRACTICE?

Risk framework: multiple impacts

Risk framework: multiple impacts

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Risk framework: hazard multiple components

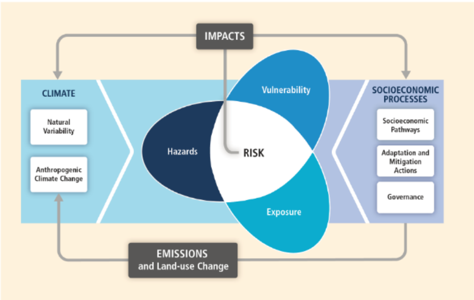
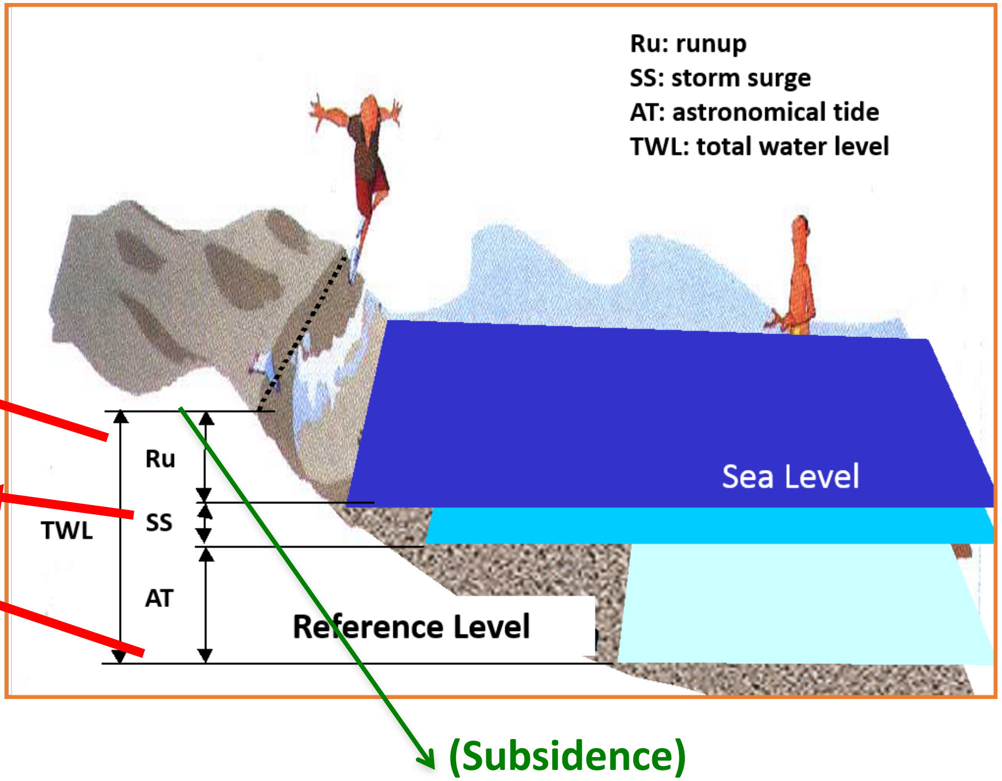


Figure SPM.1.

Flooding:

Combined effects!!!

- Waves
- Wind
- Atmospheric Pressure
- Mean Sea Level



Risk framework: over multiple sectors

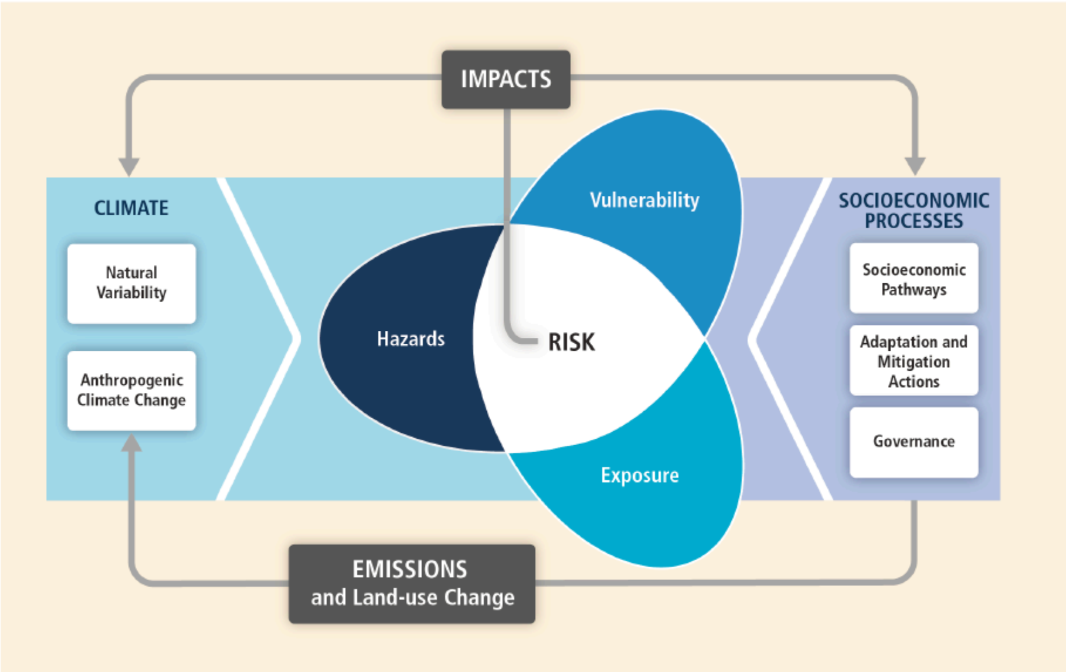
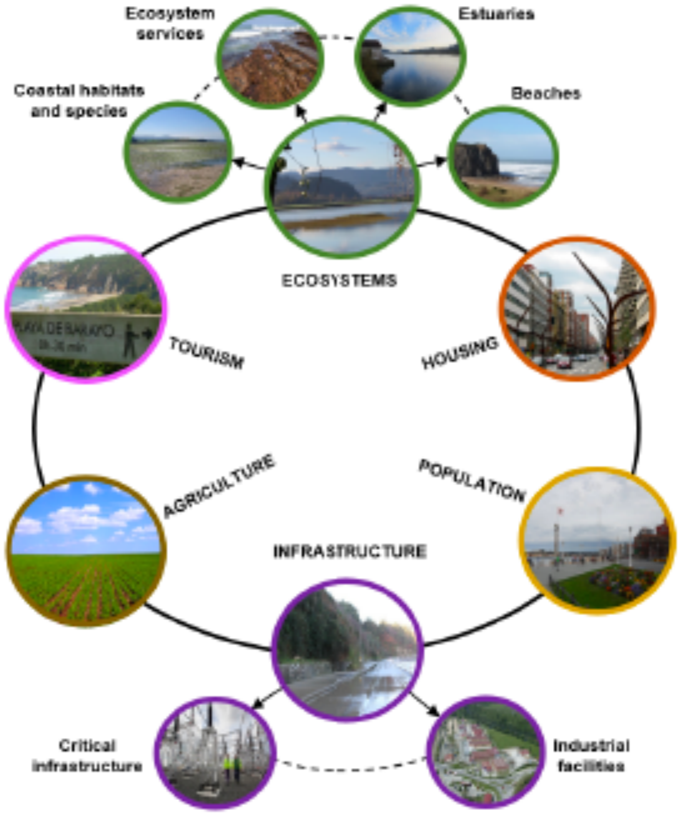


Figure SPM.1.



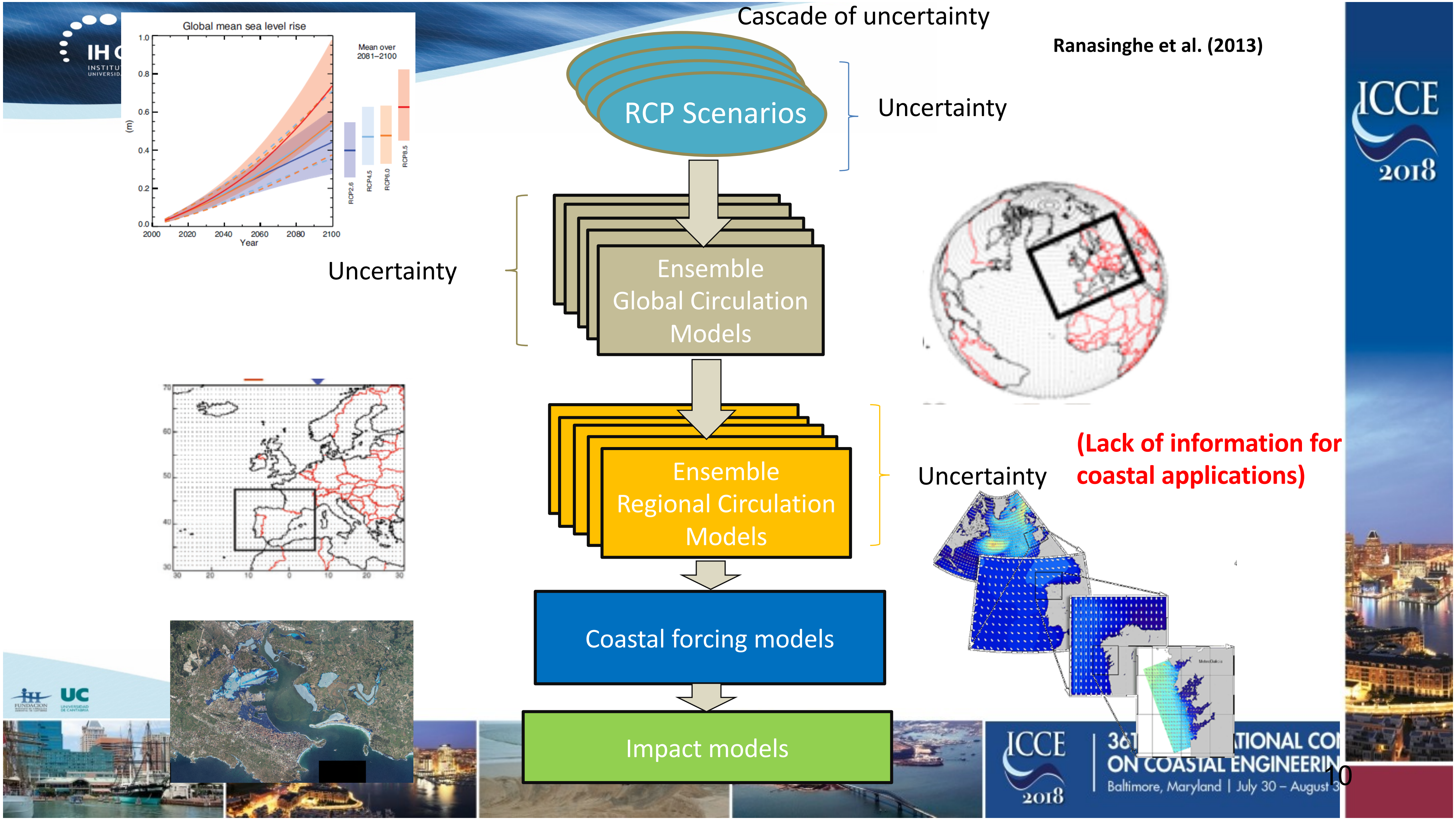
Risk framework: multi-hazard, multi-risk

- **Multi-impact**: impacts occurring at the same time or shortly following each other which overlap, accumulate or cascade; different impacts threatening the same exposed elements (with or without temporal coincidence)
- **Multi-hazard**: different drivers that combine to produce an impact; simultaneous or sequential occurrence of extreme or non-extreme events that may lead to an impact.
- **Multi-sectoral and multi-vulnerability**: A variety of exposed sensitive targets (e.g. natural systems, population, infrastructure, cultural heritage, etc.) with possible different vulnerability against the various hazards
- **Time-dependent vulnerabilities**: vulnerability of a specific class of exposed elements may change with time as a consequence of different factors (e.g. the occurrence of other hazardous events)

- **Multi-risk**:
  - it is related to multiple risks such as economic, ecological, social etc.
  - It determines the whole risk from several impacts, taking into account possible hazards and vulnerability interactions among sectors, hence entailing **multi-impact**, **multi-hazard, multi-sectoral and multi-vulnerability** perspective.

Risk framework: horizon and time evolution

- What is the **baseline period** for your risk assesment?
- **Horizons**? **Projections must cover a range of timescales relevant for planning purposes**: <20-year: payback period for an investment; 20-50 year: lifetime of infrastructure projects >100 years? lifetime of "nature based solutions" (saltmarsh/mangrove forest restoration-managed realignment, etc) → Different degree of uncertainty
- What are the RCPs or scenarios to be selected?
- Time evolution of risk is strongly dependent on the evolution of hazard, impacts, exposure and vulnerability. Nonstationary approach is needed!
  (time evolution of the return period of various damage levels; time-evolution of the mean and variance of annual damages)
- Timing: Present and future resilience of coastal systems is to be determined. Timing of storms/impacts has an important effect on risk. Similar to the introduction of adaptation measures in the analysis.



Cascade of uncertainty
Ranasinghe et al. (2013)
Global mean sea level rise
Mean over 2081–2100
(m)
Year
RCP2.6
RCP4.5
RCP6.0
RCP8.5
RCP Scenarios
Uncertainty
Ensemble Global Circulation Models
Uncertainty
Ensemble Regional Circulation Models
Uncertainty
(Lack of information for coastal applications)
Coastal forcing models
Impact models
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Appropriate spatial scale should be identified based on the magnitude and spatial distribution of the phenomena to tackle and the questions to be answered

Need for downscaling methods

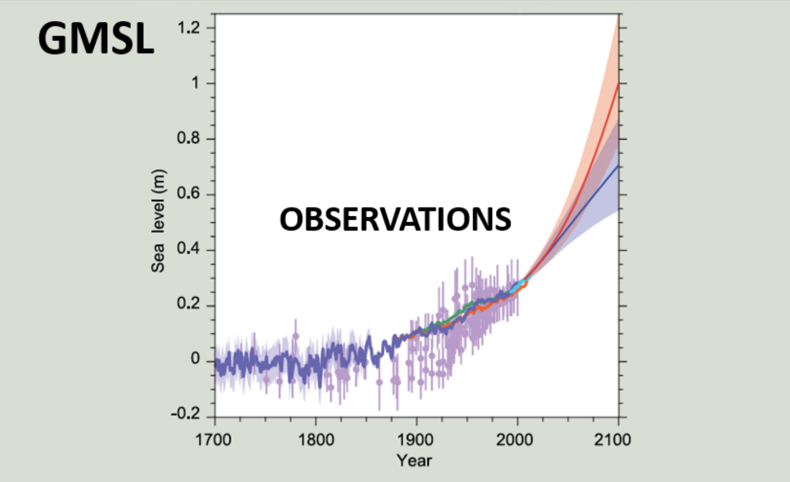
Downscaling methods are strongly dependent on the framework

- probabilistic vs non probabilistic
- Processed based models vs simplified methods/indicators
- Computational and economic resources

Drivers

Statistical Downscaling	Dynamic Downscaling
Strengths	
Computationally efficient Requires only monthly or daily GCM output Can relate GCM output directly to impact-relevant variables not simulated by climate models	Explicitly consists of both large-scale and small-scale physical processes, up to the resolution of the model Regional climate response is consistent with global forcing
Can be applied to any consistently- observed variable Can provide site-specific estimations	Provides data that is coherent both spatially and temporally and across multiple climate variables
Can be used to generate a large number of realizations in order to quantify uncertainty	Can be used in regions where no observations are available ?
Weakness	
Based on the essentially unverifiable assumption that statistical relationships between predictors and predictands remains stationary under future change	Assumes that sub-grid parameterization schemes remain stationary in the altered climate
Sensitive to choice of predictors and GCM ability to simulate these predictors	Sensitive to initial boundary conditions from GCMs
Tends to underestimate temporal variance Requires long-term observed data	Highly computationally demanding Difficulty to generate multiple scenarios

RELATIVE SEA-LEVEL RISE



TFE.2, Figure 2 | Compilation of paleo sealevel data (purple), tide gauge data (blue, red and green), altimeter data (light blue) and central estimates and *likely* ranges for projections of global mean sea level rise from the combination of CMIP5 and process-based models for RCP2.6 (blue) and RCP8.5 (red) scenarios, all relative to pre-industrial values. (Figures 13.3, 13.11, 13.27)

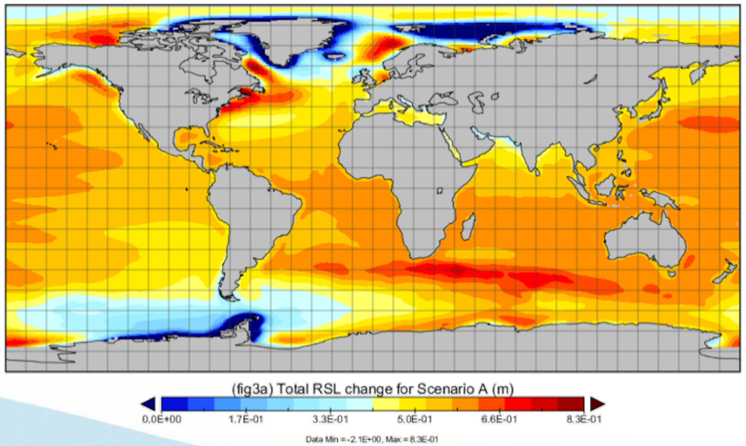
IPCC (2014)

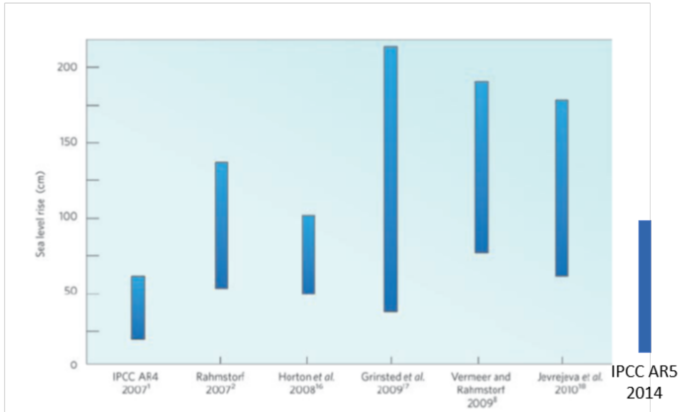
Table 5-2 | Projections of global mean sea level rise in meters relative to 1986–2005 are based on ocean thermal expansion calculated from climate models, the contributions from glaciers, Greenland and Antarctica from surface mass balance calculations using climate model temperature projections, the range of the contribution from Greenland and Antarctica due to dynamical processes, and the terrestrial contribution to sea levels, estimated from available studies. For sea levels up to and including 2100, the central values and the 5–95% range are given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available and the high scenario includes projections based on RCP6.0 and RCP8.5. Source: WGI AR5 Summary for Policymakers and Sections 12.4.1, 13.5.1, and 13.5.4.

Emission scenario	Representative Concentration Pathway (RCP)	2100 CO_2 concentration (ppm)	Temperature increase (°C)	Mean sea level rise (m)					
			2081–2100	2046–2065	2100	Scenario	2200	2300	2500
Low	2.6	421	1.0 [0.3–1.7]	0.24 [0.17–0.32]	0.44 [0.28–0.61]	Low	0.35–0.72	0.41–0.85	0.50–1.02
Medium low	4.5	538	1.8 [1.1–2.6]	0.26 [0.19–0.33]	0.53 [0.36–0.71]	Medium	0.26–1.09	0.27–1.51	0.18–2.32
Medium high	6.0	670	2.2 [1.4–3.1]	0.25 [0.18–0.32]	0.55 [0.38–0.73]	High	0.58–2.03	0.92–3.59	1.51–6.63
High	8.5	936	3.7 [2.6–4.8]	0.29 [0.22–0.38]	0.74 [0.52–0.98]				

Global vs. Local

RSLR RCP4.5 (Slangen et al. 2014)





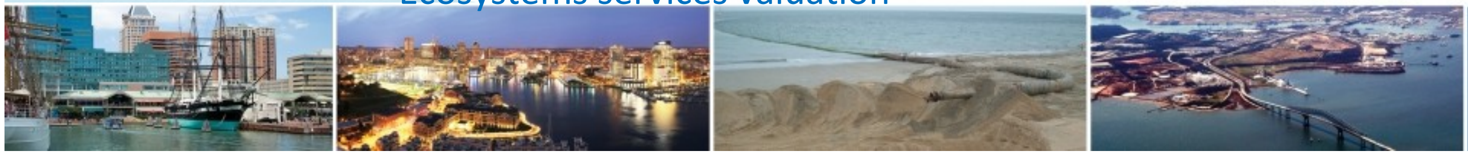
Rahmstorf (2010). Science

Probabilistic projections of RSL (Kopp et al., 2014)

Drivers

- Most of the work already developed neglecting waves may be appropriate for regional scales BUT not everywhere
- Local implementation (adaptation projects) requires **the full range of dynamics to be considered** with the relevant resolution (RSLR, astronomical tide, storm surge, waves, river discharge and local precipitacion)
- RSLR projections must be extended **beyond 2100** to understand real effects on long-lived infrastructure investments.
- Scenarios must account for **the full range of RSLR, including H++**
- **Not only extreme SLR projections matter**! High probability RLSR in combination with spring tides or non extreme SS/waves, may become already a problem for coastal management.

  Functional design
  Operations thresholds
  Maintenance strategies
  Capital Expenditure (CAPEX) vs OPEX (Operation expenses)
  Ecosystems services valuation



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IMPACTS

Based on historical events; direct mapping; expert assessment

PHYSICAL models and NUMERICAL models

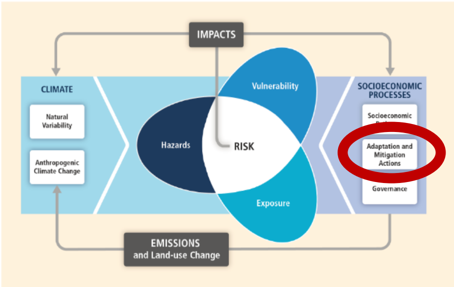
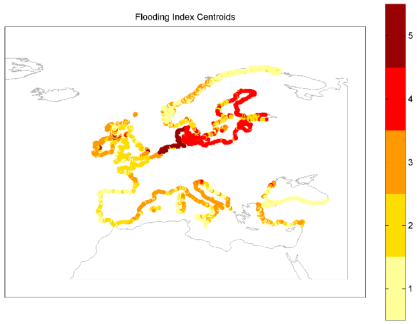


Figure SPM.1.

INDEX-BASED APPROACHES



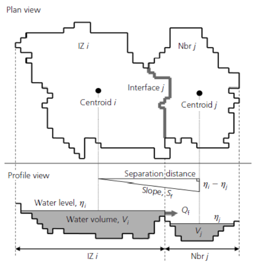
$$FloodingIndex = Coeff_{manning} \times \frac{TWL_{100YRP} \times (\alpha_{GOS} + \alpha_{SETUP})}{Slope_{mdt}}$$

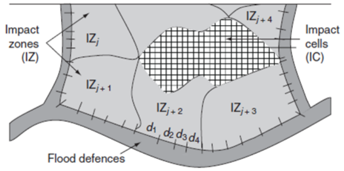
SEMI-EMPIRICAL FORMULATIONS

$$Set\text{-}up = \alpha\sqrt{H_s L_0}$$

Stockdon et al. (2006)

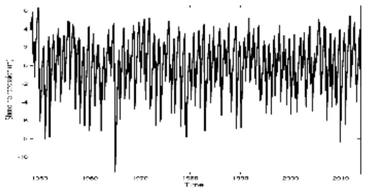
EFFICIENT HYDRAULIC MODELS





Jamieson et al. (2012)

SHORELINE EVOLUTION MODELS



Miller and Dean (2004)

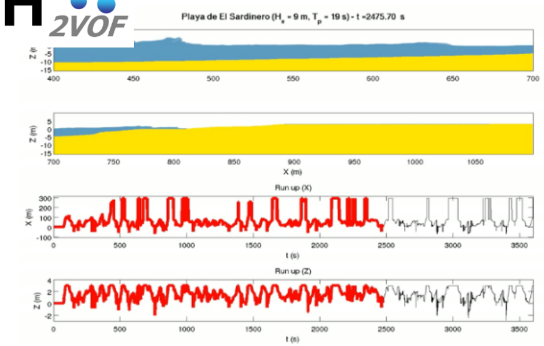
BRUUN RULE

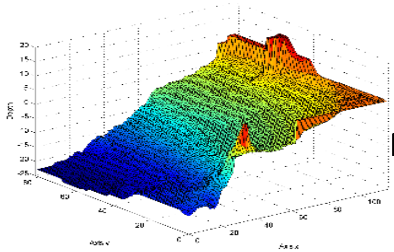
$$R = -W^* \frac{SLR}{B+h^*}$$

Bruun (1962)

PROCESS-BASED MODELS

IH 2VOF





Roelvink (2009)

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Climate change-induced coastal flooding

WHAT HAS BEEN DONE SO FAR?

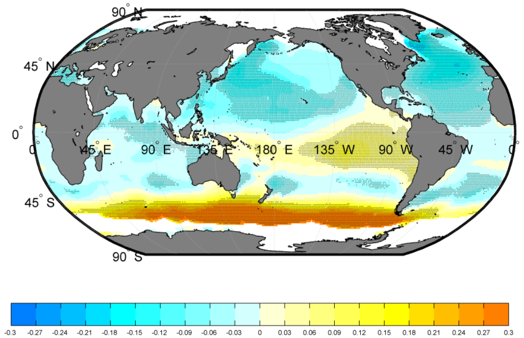
	Dawson et al. (2009)	Rosenzweig et al. (2011)	Hallegate et al. (2013)	Hinkel et al. (2014)	Muis et al. (2015)	Reguero et al. (2015)	Toimil et al. (2017)
SCALE	Regional O(10km)	City scale	Global	Global	Regional O(1000km)	Continental	Regional O(100km)
MODELING APPROACH	2D flood modeling	Bathtub	Bathtub	Bathtub	Bathtub	Bathtub	2D flood modeling
STATISTICAL APPROACH	Probabilistic	Deterministic	Deterministic	Deterministic	Probabilistic	Deterministic	Deterministic
CURRENT COASTAL FLOOD DRIVERS	Waves, tides	Storm surge, astronomical tide (DIVA, Vafeidis et al., 2008)	Storm surge, astronomical tide (DIVA, Vafeidis et al., 2008)	Storm surge, astronomical tide (DIVA, Vafeidis et al., 2008)	Storm surge, astronomical tide (DIVA, Vafeidis et al., 2008), river flow	Waves, storm surge, astronomical tide	Waves, storm surge, astronomical tide
CLIMATE CHANGE PROJECTIONS CONSIDERED	Waves, SLR	SLR	SLR	SLR	SLR, River flow	SLR	Waves, storm surge, SLR
CLIMATE CHANGE INTRODUCED	Waves, SLR	SLR	SLR	SLR	SLR, River flow	SLR	SLR

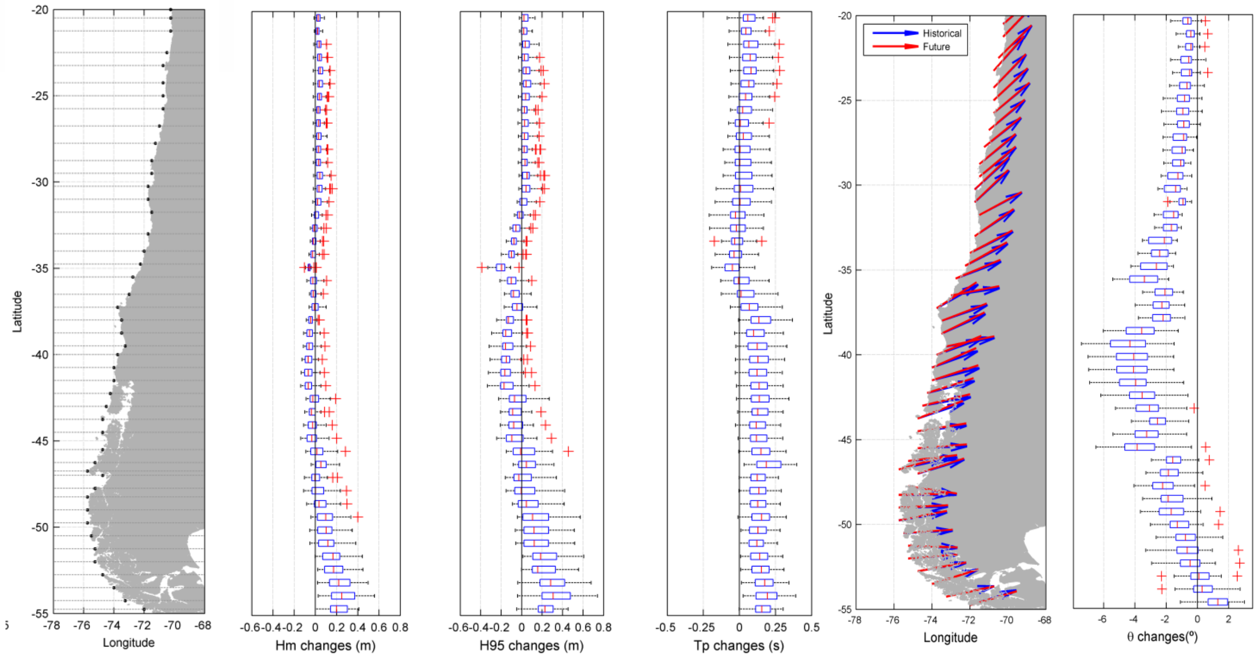
IMPACTS

PROJECTED CHANGES IN WAVES

RCP8.5 scenario – Multi-model Ensemble (30 GCMs)

For the period **2070-2099** relative to the period 1979-2008



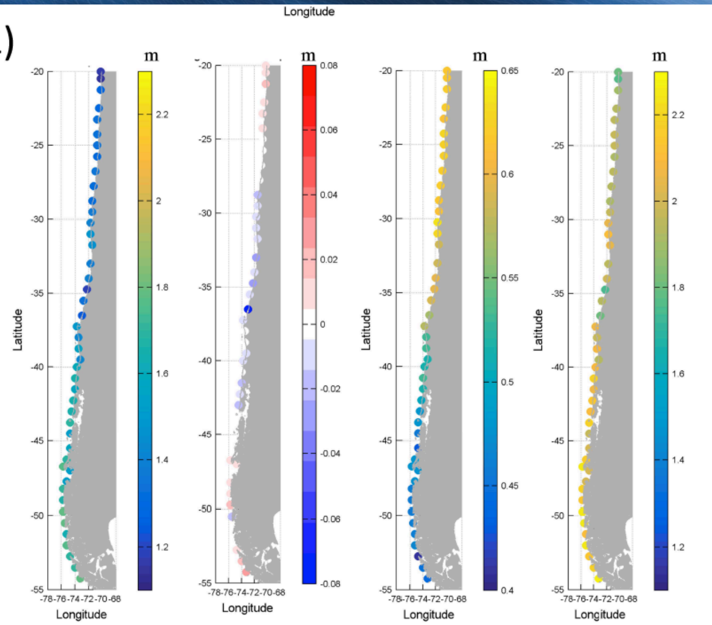


Camus et al. (2017)

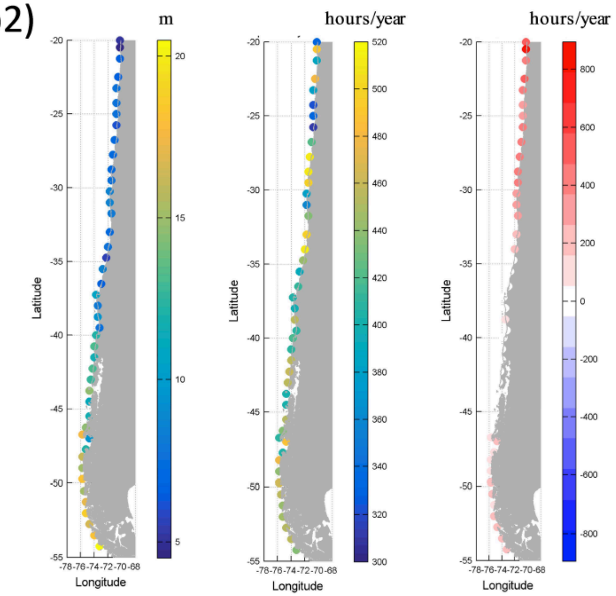
Regional multi-model projections (RCP8.5, 2071-2099 with respect 1979-2005) for wave statistics along the Coastline of Western South America (locations, intermodel changes of Hs, H95, Tp and $\boldsymbol{\theta}$)

IMPACTS

b1)



b2)



CHANGES IN PORT OPERABILITY DUE TO OVERTOPPING

b1) (1) 99th percentile of the TWL for (1979-2005) (2) multi-ensemble indicator changes only due to changes in waves and storm surge (3) regional sea level rise (from Slangen et al. (2014)) by 2100 (4) multimodel future TWL (period 2070-2099) taking into account wave, storm surge changes and SLR for RCP8.5 Scenarios).

b2) (1) coastal structure freeboard for an operability near 95% (2) hours/year exceeding the overtopping rates for pedestrians safety (3) multi model operability changes in hours/year for future period relative to present period

Climate change-induced probabilistic erosion

WHAT HAS BEEN DONE SO FAR?

	Bruun (1962)	Cowell et al. (2006)	Revell et al. (2011)	Ranasinghe et al. (2012)	Ranasinghe et al. (2013)	Casas-Prat et al. (2016)	Toimil et al. (2017b)
EROSION MODELING APPROACH	Static equilibrium formulation	Parametric modeling	Index-based approach	Wave impact modeling	Static equilibrium formulation	Empirical formulation	Dynamic equilibrium modeling
STATISTICAL APPROACH	Deterministic	Probabilistic	Deterministic	Probabilistic (JPM, Callaghan et al., 2008)	Deterministic	Deterministic	Probabilistic
CURRENT EROSION DRIVERS	-	Wave and sediment supply	TWL (SWL, waves)	Waves (storm events)	River flow and sediment supply	Waves	Waves, storm surge and astronomical tide
CLIMATE CHANGE PROJECTIONS CONSIDERED	SLR	SLR	SLR	SLR	SLR, Rainfall/Runoff	Waves	Waves, storm surge, SLR
CLIMATE CHANGE INTRODUCED	SLR	SLR	SLR	SLR	SLR, Rainfall/Runoff	Waves	SLR

IMPACTS

- Coastal flooding: there are still open questions on how projected drivers need to be statistically combined to feed process-based models considering their non-stationarity

- Coastal erosion: it is not clear how to model morphodynamics including non-linear process interaction and multi-scale coupling beyond a few days

- Impacts on ports: lack of observations and lack of design standards; the way forward must prioritize the assessment of functionality and stability of port’s structures considering non-stationary reliability and resilience

- Saltwater intrusion: lack of monitoring to improve process understanding and mixing zone changes mapping; modeling efforts need to be focused on uncertainty analysis

- Waste releases from eroded/flooded historical landfill sites: lack of monitoring, lack of methods to assess the extent of pollution and lack of knowledge of the behaviour and environmental impact of solid waste release in the coastal zone

IMPACTS

DETECTION AND ATTRIBUTION OF IMPACTS TO CLIMATE CHANGE AND SLR PROVIDES A FORM OF VALIDATING AND REFINING PREDICTIONS ABOUT FUTURE CHANGES.

HOWEVER, THE CHALLENGE IS DAUNTING:

- Lack of high-resolution, continuous and long-term observations
- Systems are affected by many factors other than CC and SLR → double constraint: 1) non-linear, non-local and trans-regional effects difficult to understand and quantify; 2) the adaptive capaitcy of the systems enhances the challenge
- Need to improve existing techniques and develop new methods that allow addressing attribution with greater confidence

Observations play a fundamental role!!

1. Risk framework and uncertainties
2. Climate drivers/hazards: projections and downscaling
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ADAPTATION

SOLUTIONS SPACE: ONE OPTION, MANY LAYOUTS

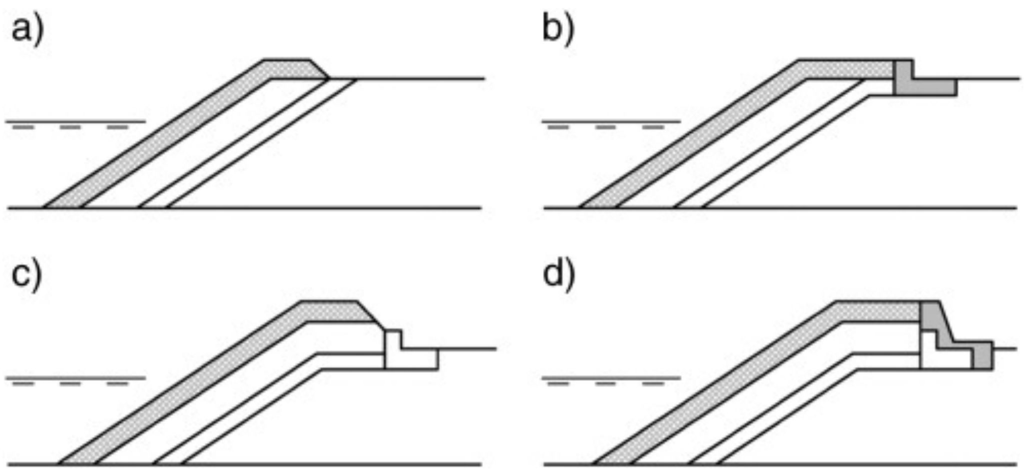
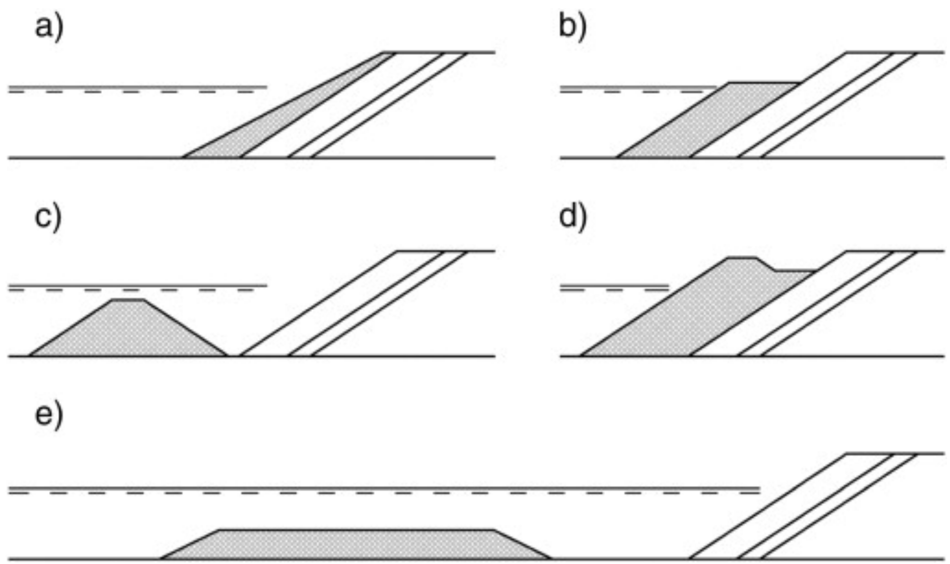


Fig. 1 Concepts of upgrading in which an increase in crest level is acceptable.



RESIDUAL RISK

Hans F. Burcharth , Thomas Lykke Andersen , Javier L. Lara (2014)

Upgrade of coastal defence structures against increased loadings caused by climate change: A first methodological approach

ADAPTATION

<u>SOLUTIONS SPACE:</u> ONE OPTION, MANY LAYOUTS

Figure 4.21: Basic wet flood-proofing measures for a residential structure

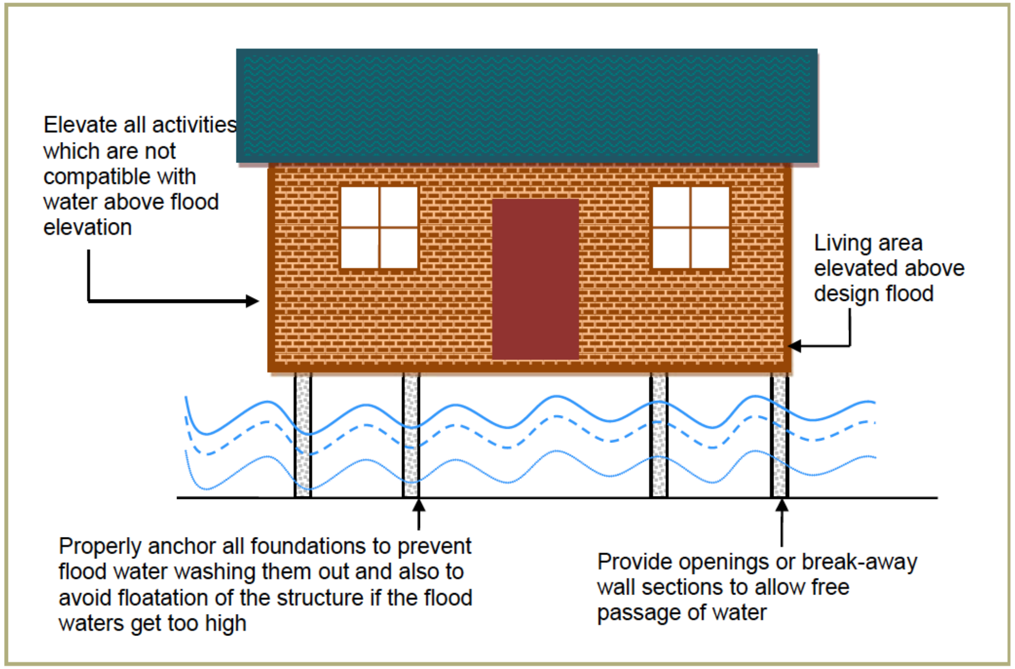
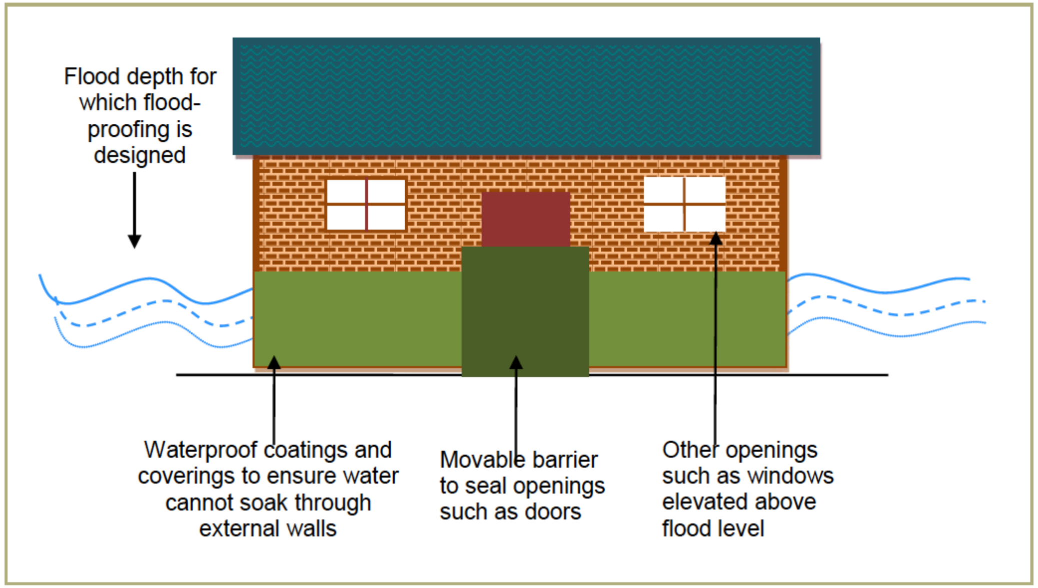


Figure 4.22: Basic dry flood-proofing measures for a residential structure



ADAPTATION

<u>SOLUTIONS SPACE</u>:

COMBINATION OF OPTIONS

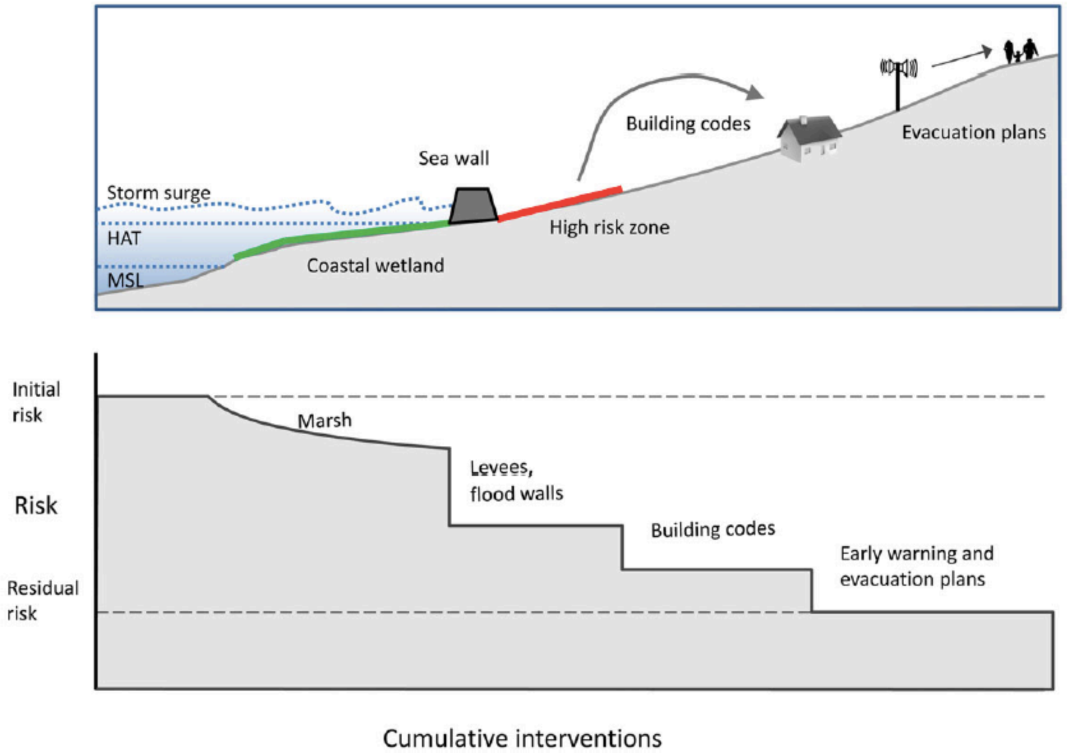


Figure 2 Ecosystems can form an important part of risk reduction, which is typically achieved through a combination of environmental, engineered, social, cultural, and legal approaches as illustrated in the upper figure. Cumulative interventions (lower figure) cannot remove risk, but rather reduce it to an acceptable level of residual risk.

Spalding *et al.* (2014)

ADAPTATION

<u>SOLUTIONS SPACE</u>:

NATURE-BASED SOLUTIONS

"The best NBS is the one that already exists"

ADAPTATION

Engineered structures have a design life, typically 20–50 years, and are built for design environmental, climatic, and anthropogenic conditions over that period.

Ecosystems remain in place for much longer periods of time depending on climate and human drivers. **How do we measure the variability of the expected service over time, especially during the expected service life of our NBS or hybrid solution?**

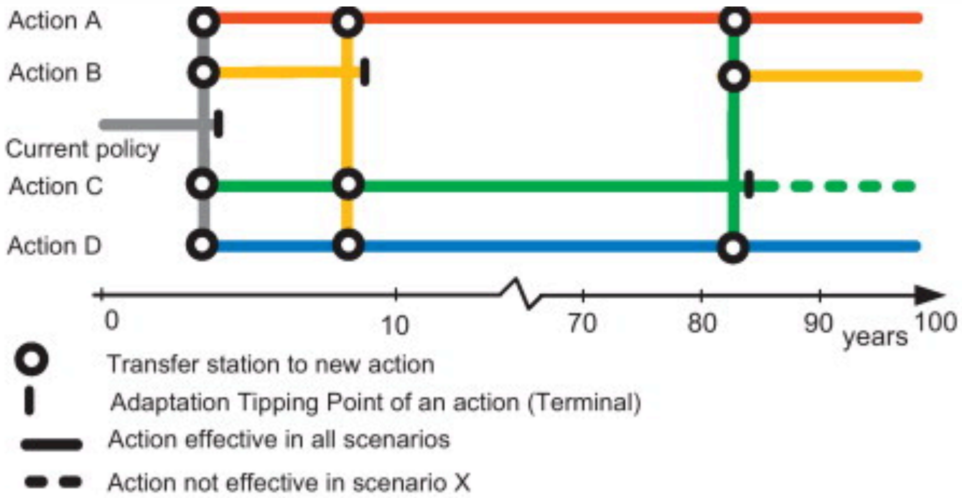
How do we evaluate time to performance of a new NBS and residual risk evolution in time?

A major difference between NBS and conventional engineered structures is that ecosystems are highly dynamic and may be able to recover and regenerate following damage. Engineered structures do require human intervention for maintenance and repair after damage.

Can we estimate regenerative/adaptive capacity and overall ecosystem resilience during the expected service life? Can we maintain or restore underperformance of NBS by human intervention?

What are the failure modes, tipping points or operating thresholds for a given NBS performance?

ADAPTATION



Adaptation Pathways Map

	Path actions	Relative Costs	Target effects	Side effects
1		+++	+	0
2		+++++	0	0
3		+++	0	0
4		+++	0	0
5		0	0	-
6		++++	0	-
7		+++	0	-
8		+	+	- - -
9		++	+	- - -

Scorecard pathways

An example of an Adaptation Pathways map (left) and a scorecard presenting the costs and benefits of the 9 possible pathways presented in the map. In the map, starting from the current situation, targets begin to be missed after four years. (Haasnoot et al 2013)

<u>ADAPTATION</u>: HOW MUCH, HOW, WHEN?

How do we determine the **Acceptable level of risk/ Residual risk/ Adaptation goal?**

What is the right time for adaptation ?

What is the right adaptation metrics?

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CONCLUSIONS

- **Uncertainties** in temporal and spatial distribution of risk component projections **are still too large. Probabilistic approaches are required**.
- The need of **climatic and non-climatic information** may vary considerably **depending on time horizon, spatial scale, impacts** to be considered, **sector** to be addressed and **decision level** (planning, design, implementation, operation)
- **Attribution is hampered by lack of observations** and methods **and the non-linear behaviour of the systems**
- **Observations** cannot be replaced by numerical modelling but are **essential to constrain and validate the models developed to project future changes**
- There is still **a long way to go for implementing** adaptation projects in coastal areas using a full engineering framework accounting for time variations (resilience, reliability) or **adaptive pathways.**
- **Flexible adaptation** allows to **cope with uncertain information**. Different possible sequences of adaptation measures combined with explicit learning about future climate based on monitoring
- Even more **open questions for considering NBS or hybrid solutions** as part of our solutions space

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** *Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Southampton, UK*