Flood Risk Management Model to Identify Optimal Defence Policies in Coastal Areas Under Climate Change Uncertainties: Pontina Plain Case Study

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Abstract

Coastal areas are highly vulnerable to flooding, due to hydrological extreme events such heavy rainfalls and/or storm surges which are supposed to be increasing in the next future due to the emission in atmosphere of anthropogenic greenhouse gases. In this study, in order to assess the future hydraulic risk in coastal regions, as well as, to identify optimal defense/adaptation policies, a risk analysis model is developed to calculate the present day and future flood risk, accounting for climate change uncertainties and mitigation measures. Such model juxtaposes a number of coupled/nested models as: a) a stacking daily rainfall downscaling model which combines simulations from multiple predictive models, as Random Forest, extreme gradient boosting and Non-homogeneous Hidden Markov Model (NHMM) (Cioffi et al. 2018); b) a Bivariate Point Process model (BPPM) (Zheng et al., 2014) that calculates Joint probability density function between extreme daily rainfall amount and daily extreme storm tide depth; c) a simulation-optimization model - in which multi-objective GA optimization model (Deb et al., 2002) and 2D hydraulic model are combined (Cioffi et al. 2018) - calculates sets of Pareto optimal solutions which are obtained by defining two optimality criteria consisting in: minimizing both the cost of the flood defense infrastructure system and the flooding hydraulic risk. ; d) a mathematical decision model which is aimed to identify the best policies of mitigation of hydraulic risk and the timing, taking into account the uncertainties in hydrological extreme event predictions. The risk analysis model is applied to the study case of Mazzocchio area which is the most depressed area (about 10000 ha) within the Pontinia Plain, a large reclamation region in the south of Lazio (Italy), particularly vulnerable to extreme events - as extreme rainfall amount and sea level rise due to storm surge at the sea outfall of the river- which in the past caused the crisis of hydraulic network system with flooding of large areas and collapse of levees. XXI Century projections of daily rainfall amount and sea level for the RCP 8.5-IPCC scenarios were performed using ensemble of 35 GCM simulations (CESM1 CAM5 BGC 20C + RCP8.5 Large Ensemble) (Kay et al., 2015).

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Introduction:

Coastal areas are highly vulnerable to flooding, due to hydrological extreme events such heavy rainfalls and/or storm surges which are supposed to be increasing in the next future due to the emission in atmosphere of anthropogenic greenhouse gases. In this study, in order to assess the future hydraulic risk in coastal regions, as well as, to identify optimal defense/adaptation policies, a risk analysis model is developed to calculate the present day and future flood risk, accounting for climate change uncertainties and mitigation measures. Such model juxtaposes a number of coupled/nested models as:

a) a simulation-optimization model - in which multi-objective GA optimization model (Deb et al., 2002) and 2D hydraulic model are combined (Cioffi et al. 2018) - calculates sets of Pareto optimal solutions which are obtained by defining two optimality criteria consisting in: minimizing both the cost of the flood defense infrastructure system and the flooding hydraulic risk. ;
b) a stacking daily rainfall downscaling model which combines simulations from multiple predictive models, as Random Forest, extreme gradient boosting and Non-homogeneous Hidden Markov Model (NHMM) (Cioffi et al. 2018);
c) a Bivariate Point Process model (BPPM) (Zheng et al., 2014) that calculates Joint probability density function between extreme daily rainfall amount and daily extreme storm tide depth;

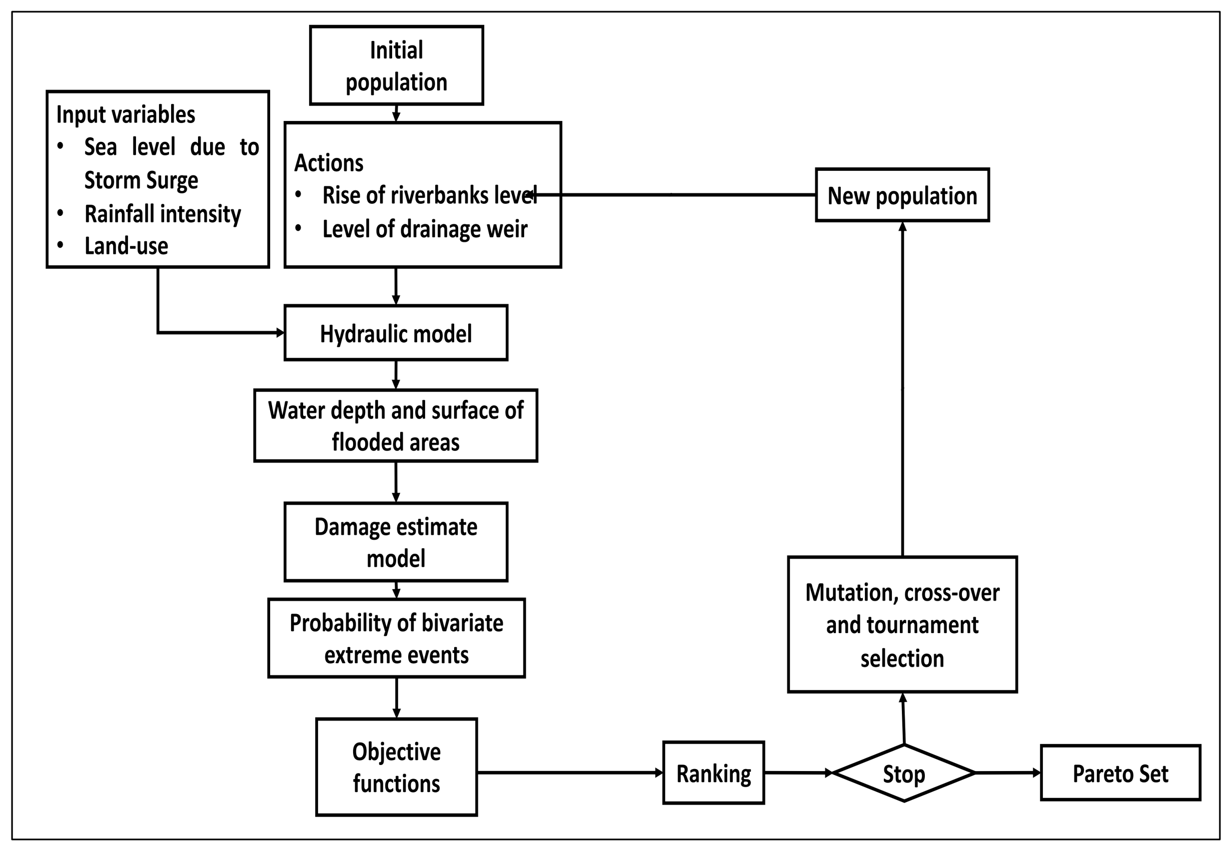
The risk analysis model is applied to the study case of Mazzocchio area which is the most depressed area (about 10000 ha) within the Pontinia Plain, a large reclamation region in the south of Lazio (Italy), particularly vulnerable to extreme events - as extreme rainfall amount and sea level rise due to storm surge at the sea outfall of the river- which in the past caused the crisis of hydraulic network system with flooding of large areas and collapse of levees.

Methodology:

Simulation – optimization model

Objective functions

- Minimize hydraulic risk (**R**):
  - $Of_1 = \min(R)$
  - $R(\xi_1, \xi_2, \vec{l}) = \int_{\Xi} \left[\int_S \left(\sum_{i=1}^{I} D_i(\xi_1, \xi_2, \vec{l}, h, c, s)\right) ds\right] p(\xi_1, \xi_2) d\xi$
- Minimize the costs of interventions ($\mathbf{C_s}$)
  - $Of_2 = \min(C_s)$



Two functions are involved in defining the probabilistic hydraulic risk (Nardini et al, 2012):

- The economic damage $D = f(\vec{\xi}, \vec{l}, h, c, s)$
- The joint probability density function $p(\xi_1, \xi_2)$ of occurrence of rain and storm surge events

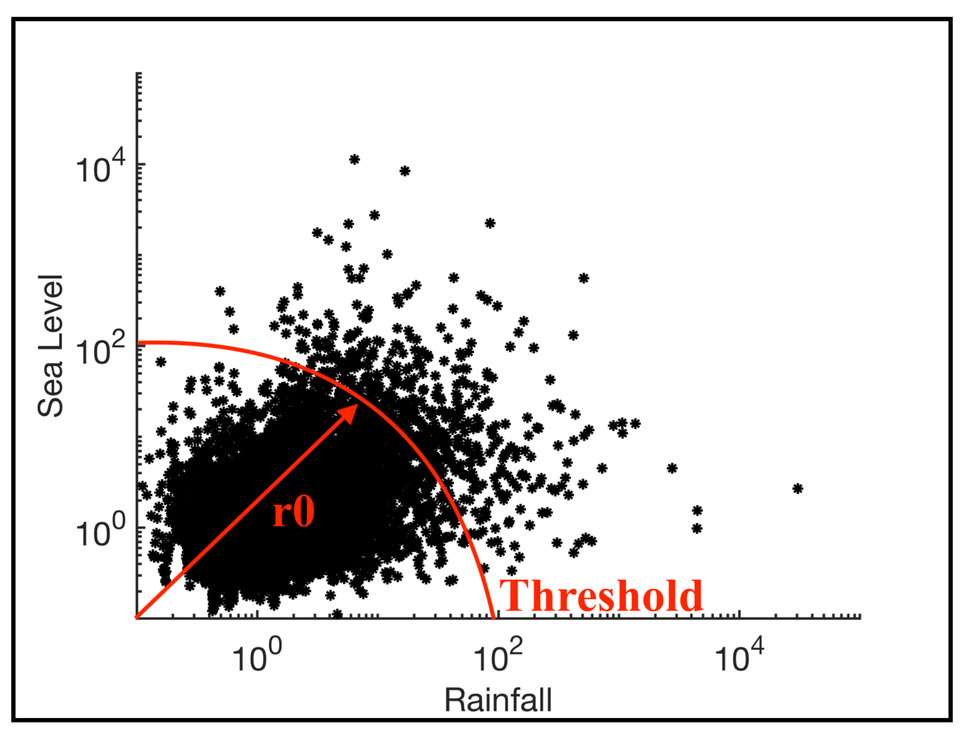
$$HR(\xi_1, \xi_2, f)_{annual} = \int_{\Xi} \left[\int_X \int_Y D(\xi_1, \xi_2, f, x, y)\, dxdy\right] p(\xi_1, \xi_2) d\xi$$

Bivariate Point Process Method

- The risk of flooding in a coastal area is influenced by the combination of intense rains along with storm surge phenomena along the coast and at the mouth of the rivers.
- Even a weak dependency can have significant implications in estimating hydraulic risk (Lian et al., 2013, Zheng et al., 2013).
- Point process can handle situations where only a single variable is extreme, as well as when both variables are simultaneously extreme (Zheng et al., 2014).
- There are several methods of multivariate statistical analysis to estimate the dependence of such events, among which the Point Process Method (Coles, 2001). For the estimation of the probability distribution G (x, y), the "logistic model" (Tawn, 1988) was applied.

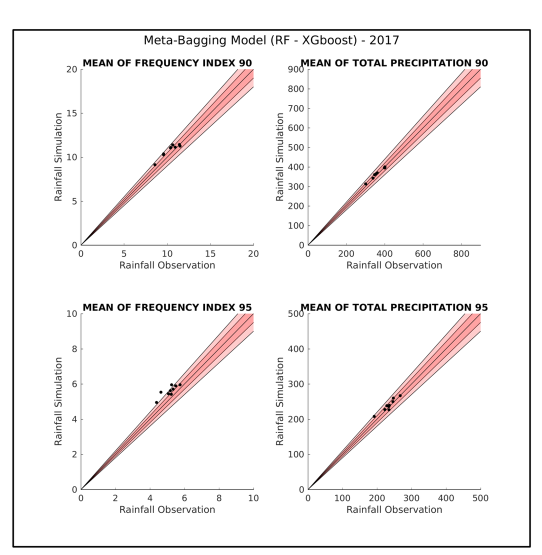
$$G(x, y) = \exp\{-(x^r + y^r)^{1/r}\}$$

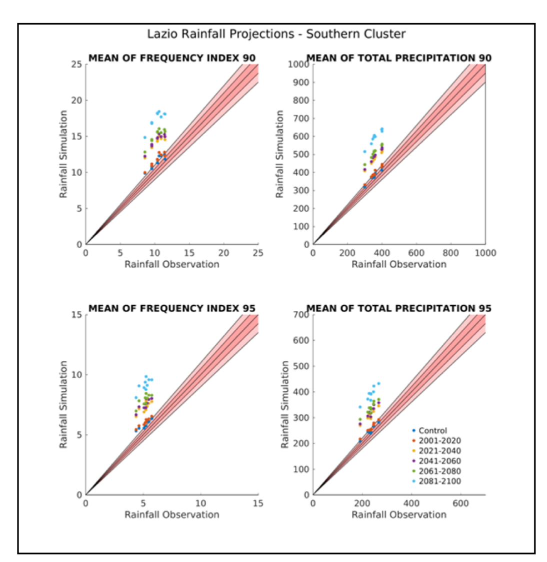
  - Independence and complete dependence correspond to r=1 and r=+∞
  - x and y are margins of the bivariate vector following the standard Fréchet distribution.



Stacking daily rainfall downscaling model

Causes of rainfall regime changes are global but effects are local
Because of the coarse spatial resolution of general circulation models (GCMs), the statistics of precipitation at the local scale can be strongly biased in retrospective simulations
GCM simulations of large-scale upper-air fields (geopotential height, winds, etc…) are generally better constrained than those for precipitation, and an appropriate selection of these variables can provide an effective set of predictors for statistical downscaling.
We investigated on the potentiality of the Non-homogeneous Hidden Markov model (NHMM) in simulating realistically the local daily rainfall occurrence and intensity in different regions of the world: Tanzania and Agro Pontino (Italy).





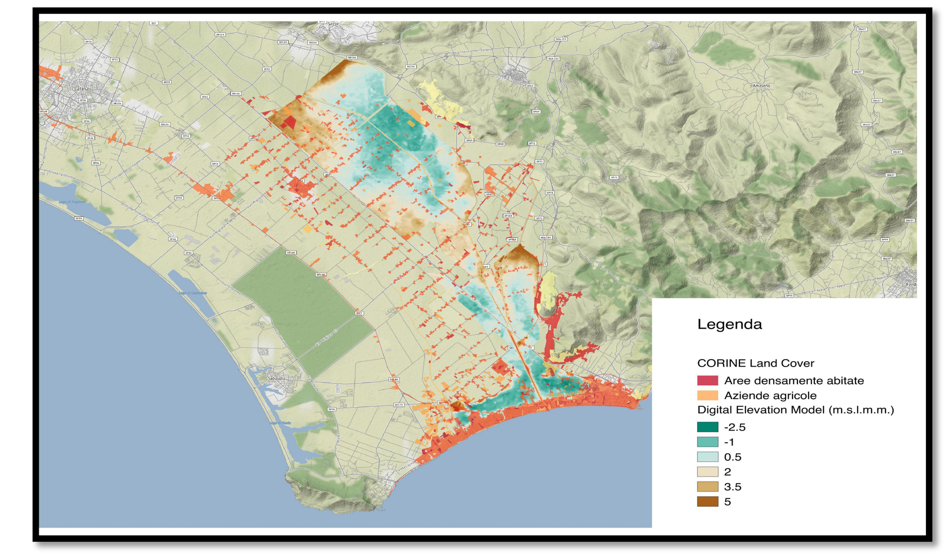
F. Cioffi, F., Conticello, F., Lall, U., Marotta, L., & Telesca, V. (2017). Large scale climate and rainfall seasonality in a Mediterranean Area: Insights from a non-homogeneous Markov model applied to the Agro-Pontino plain. Hydrological Processes, 31(3), 668-686.
Cioffi, F., Conticello, F., & Lall, U. (2016). Projecting changes in Tanzania rainfall for the 21st century. International Journal of Climatology, 36(13), 4297-4314.

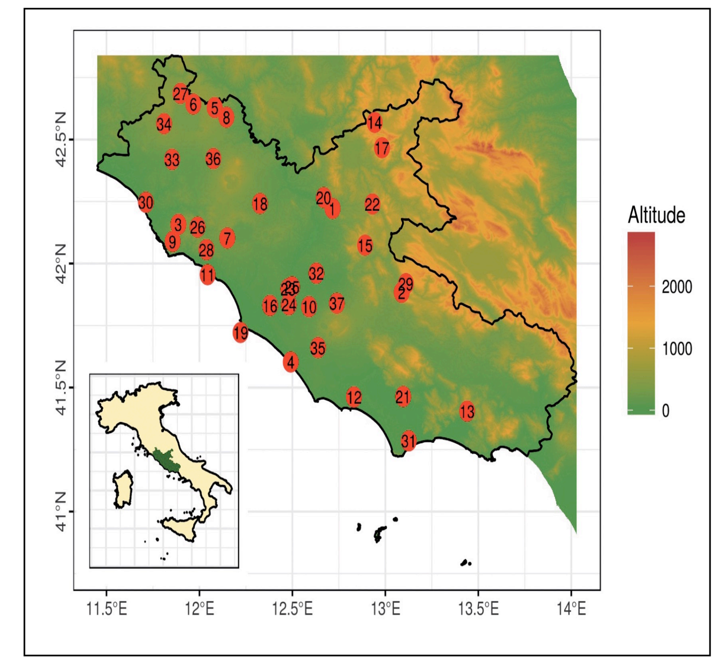
Results:

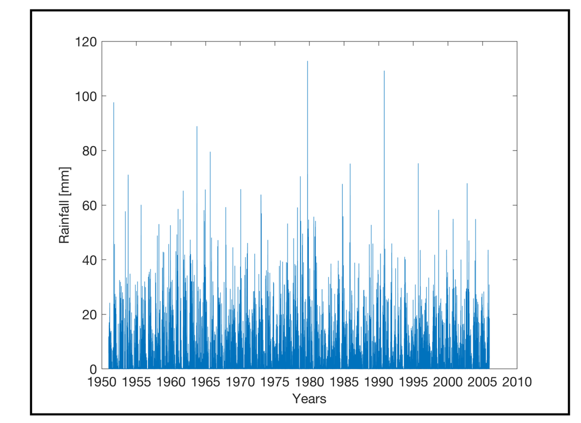
The data used came from a group of 4 stations located in the study area.

The extremes are then defined as events that occur above a high radial threshold r_0.

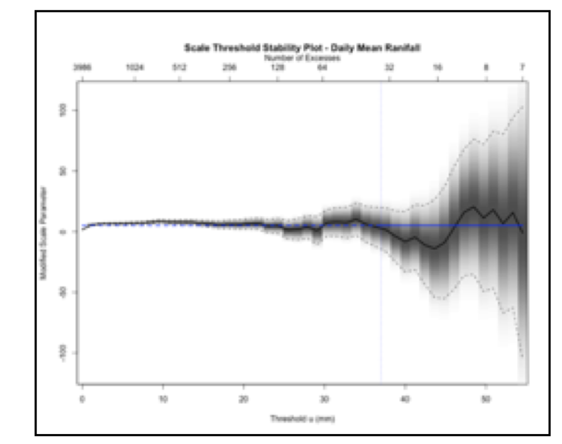
1) 20 years rainfall records are analysed
2) Mean excess and mean residual life plots are examined to validate the choice of threshold
3) Generalized Pareto Distribution fitting mode







1



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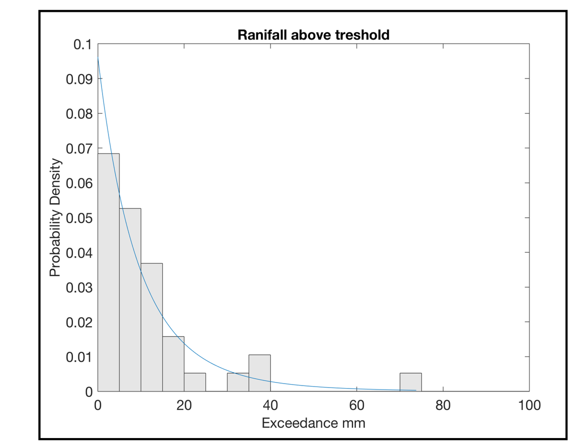

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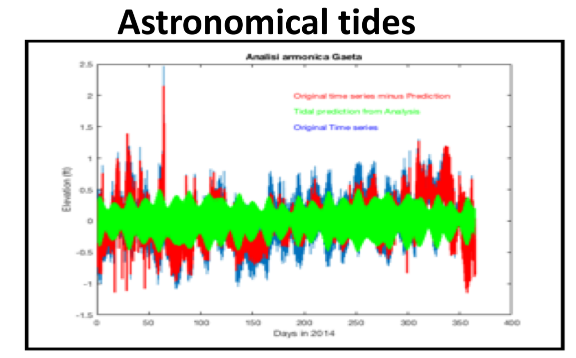
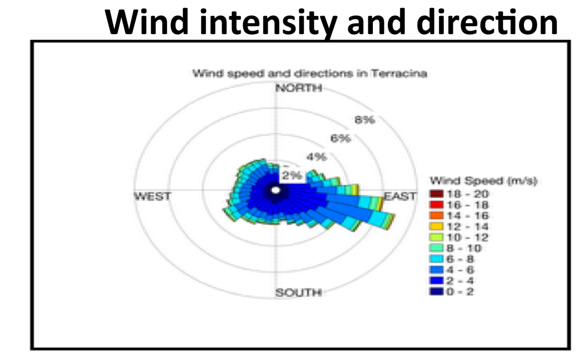
Storm surge level is a sum of 3 components:

Astronomical tides



1

Wind intensity and direction



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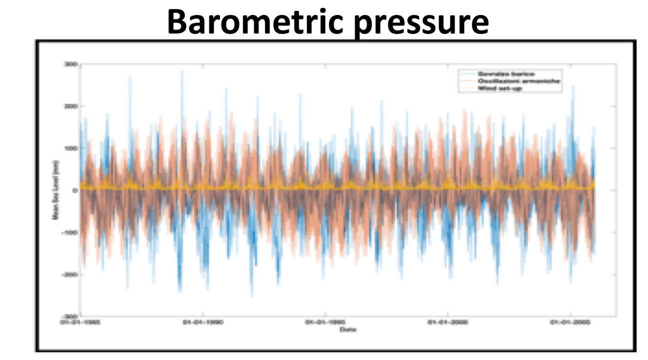
Barometric pressure

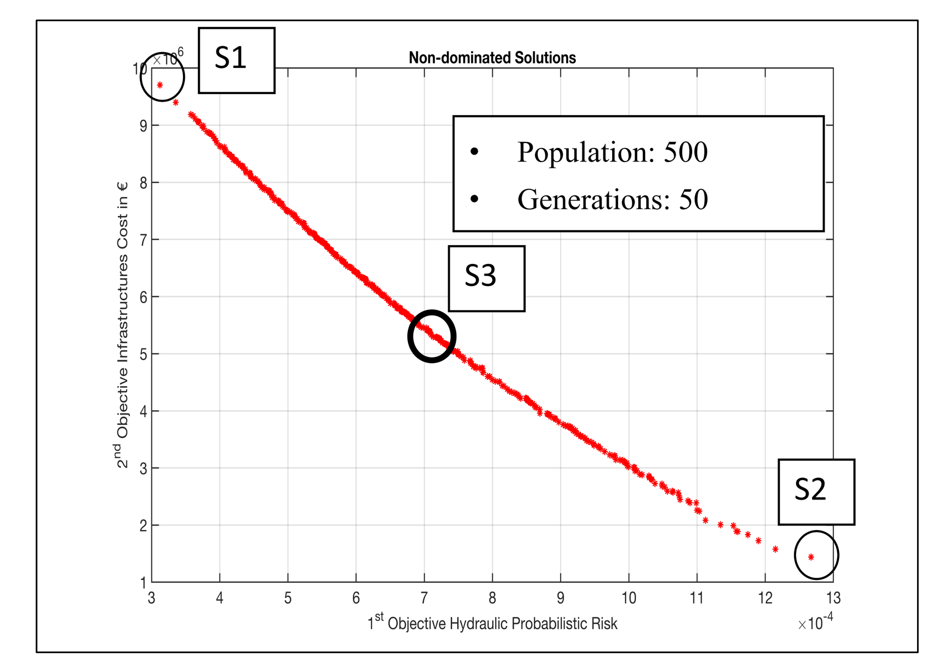


3

To estimate the damages we developed a model that integrate satellite land use data (CORINE Land Cover) with results of hydraulic simulations in terms of water depth. The corrispondent damage is calculated iterpolating water dept data with depth – damage functions.

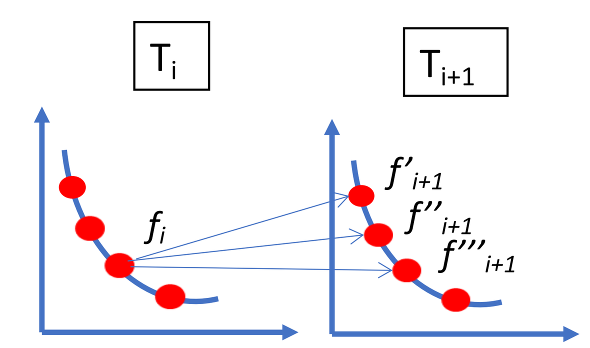
Simulation-optimization model is used to obtain a Pareto Set of possible interventions, in this case increase of fluvial embankments and level of the drain are considered as interventions. The three solutions highlighted refer to:

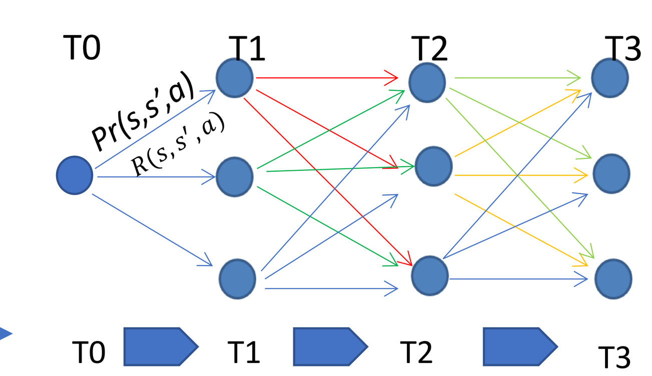
- Higher cost and lowest risk (**S1**)
- Higher risk and lowest cost (**S2**)
- Balanced solution (**S3**)



Dynamic Programming – Markov Decision Process:

A mathematical decision model which is aimed to identify the best policies of mitigation of hydraulic risk and the timing, taking into account the uncertainties in hydrological extreme event predictions is needed. This objective can be achieved through a dynamic programming technique called Markov Decision Process, which, for each time horizon, calculates the choice of the best intervention considering the probability of passingfrom one state to another.
XXI Century projections of daily rainfall amount and sea level for the RCP 8.5-IPCC scenarios can be obtained using ensemble of 35 GCM simulations
(CESM1 CAM5 BGC 20C + RCP8.5 Large Ensemble) (Kay et al., 2015).





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