CEE 206 Final Project

Evaluation of The Potential of Building Hurricane Storm Surge Levees for New York City

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[Table of Contents]

[Executive Summary]

Storm surge protection has become a major concern of New York City due to its geographical low-lying coastline, and inadequate current protection. The American Society of Civil Engineers has proposed several conceptual designs on levees for various water inlets in New York City. In this report, we evaluate the costs and benefits of these conceptual designs, assuming the levees' lifespan is from 2014 to 2114.

In order to decide on the construction and the height of the storm surge levees, we performed a series of decision analysis that includes multi-objective analysis, modeling of the monetary loss, terminal analysis and sensitivity analysis on the risk aversive-ness. Three action spaces were identified: 1) do not build a levee, 2) build a 15’ levee, and 3) build a 30’ levee. The associated states of nature are as follows: for action 1 the storm height is less than 50’, for action 2 the storm height is either less than 15’, or between 15’ and 50’, for action 3 the storm height is either less than 30’, or between 30’ and 50’. We view the objectives of the state department of New York as being: economic damage, environmental impact, risks to citizens, reputation of the city to tourists and political issues. After carrying out a multi-objective analysis, action 3 was found to best meet all of the above-mentioned objectives.

To compute the expected utility for each of our actions, we need to first compute the expected economic loss, and the estimated construction cost associated with each action.

On the economic loss side, we computed the expected annual loss for each action, which is the sum product of the mean loss due to flood height and the annual likelihood of occurrence of flood height. The annual likelihood of occurrence of flood height depends on the number of storm surges, and the surges' flood heights. The occurrence of storms is assumed to be a Poisson process, and the resultant surge height is assumed to be normally distributed; in return, both distributions depends on the storm severity associated with a particular return period being considered.

On the cost side, the estimated construction cost for the 15’ and 30’ levee were modeled with linear functions. The 15’ levee cost $13.7 Billion while the 30’ levee cost $27.4 Billion. The total monetary cost was obtained by summing the construction cost and cost due to loss. We further note that the majority of the loss is contributed by high-frequency-low-severity events (which are of return periods in the order of magnitude of less than 15 years).

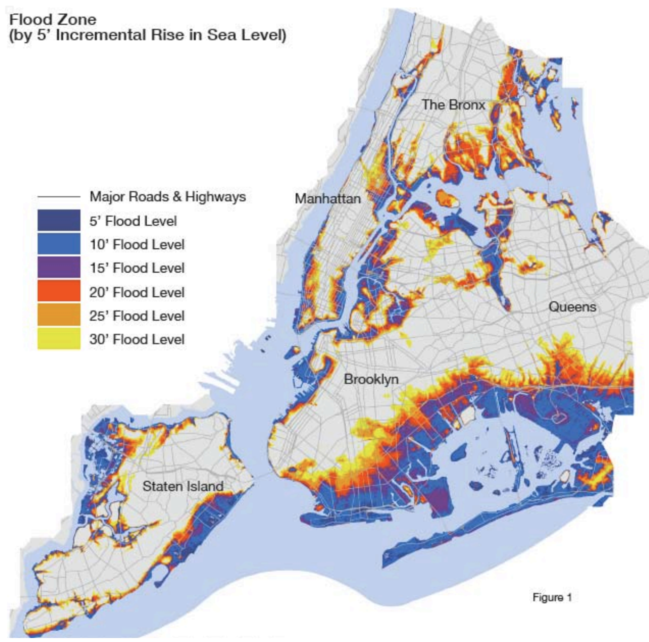
As for decision marking, we used a risk averse utility function to determine the optimal action. Sensitivity studies were performed to evaluate how the decision changed with varying degrees of risk aversion. The decision did not change as we altered the degrees of risk aversion. At the end, the action with the highest utility was the optimal decision. Based on our analysis, we decided to build the 15’ levee (action 2) because it had the highest monetary value (-$ 271.2 B) and utility value (63).

Finally, we recommend adding another action to our decision tree – to build a 20’ levee – because we realized that building a 30’ levee has a poor economic tradeoff due to its high construction costs. After calculating the expected loss of a 20’ levee we concluded it would be a more favorable action than both the 15’ and 30’ levee due to its lower construction cost compared to the 30' and the higher value it can protect compared to the 15'.

[Full Report]

[A] Motivation --

Storm surge protection has become a major concern of New York City due to its geographical low-lying coastline, and inadequate current protection. The American Society of Civil Engineers has proposed several conceptual designs for various water inlets in New York City. We wanted to analyze if we should build a levee or not, and if we build a levee, what height should it be. Our data source is from the 2010 and the 2013 report by the New York City Panel on Climate Change (NPCC). The figure on the right shows the level of inundation in the event of storm surges of height 5' to 30', in 5' increments (the results shown herein as well as those on the levees' construction cost and on the expected economic loss due to various surge heights are from a previous independent study by Deodatis, Hatzikyriakou, and Wong).



[B] Decision Model: --

Actions, A = {a_1, a_2, a_3}:

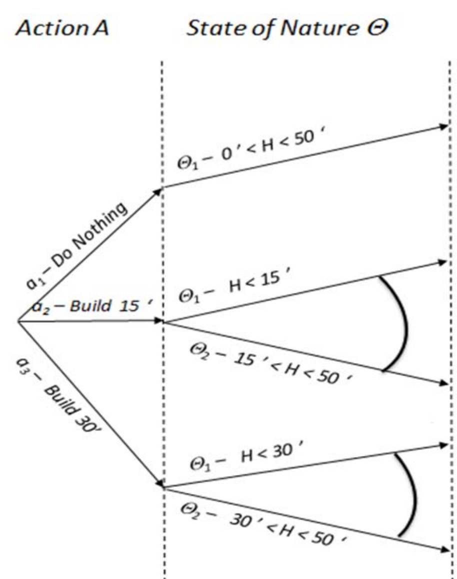
- a_1: do nothing, at cost $c_1 = 0$
- a_2: build a h_b = 15' storm surge levees, at cost c_2
- a_3: build a h_b = 30' storm surge levees, at cost $c_3 = 2c_2$

Outcomes, Θ = {θ_1, θ_2, θ_3}:

- θ_1: Storm Height<50'
- θ_2: Storm Height<Levee Height
- θ_3: 50>Storm Height>Levee Height

Objectives, O = {O_1, O_2, O_3, O_4, O_5}:

- O_1: Economic Damage
- O_2: Environmental Impact
- O_3: Risk to Citizens
- O_4: Reputation of New York City to Tourists
- O_5: Political Issue



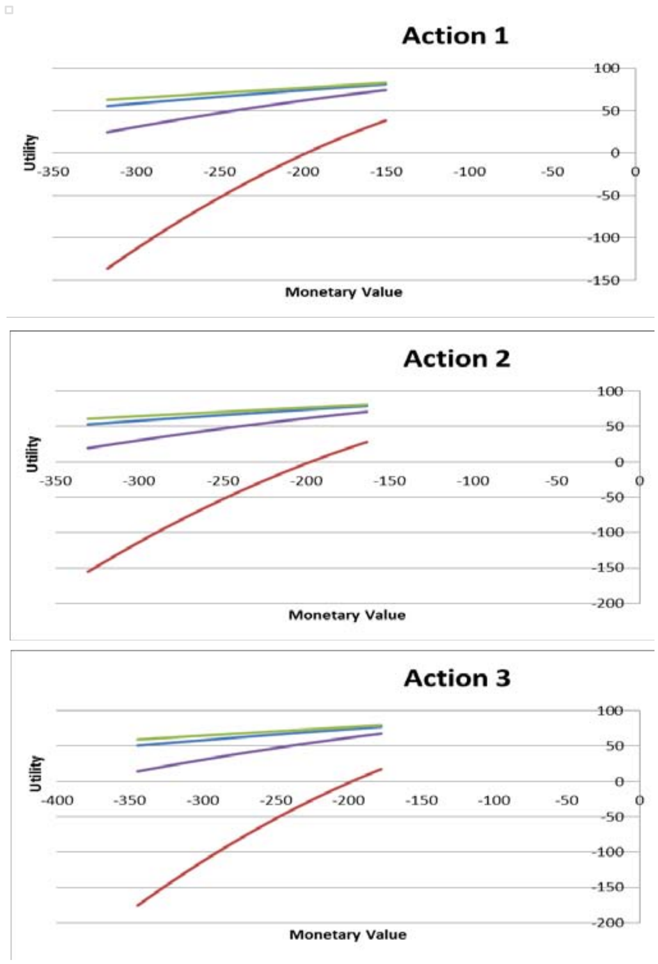
Different relative weights are assigned to each objective based on the importance of the objective, and the probabilities of the actions achieving every objective are determined subjectively.

Relative Weight	100	60	20	5	5	Overall Utility
	O1	O2	O3	O4	O5	
A1	0.1	0.4	0.1	0.6	0.3	40.5
A2	0.7	0.9	0.65	0.75	0.4	142.75

A3	0.9	0.95	0.8	0.85	0.5	169.75

After the multi-objective has been conducted, we found that action 3 has the highest overall utility and will best meet all of our objectives.

[C] Utility Model: ---

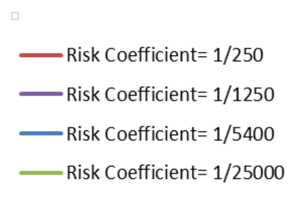


Given the significant amount of unprotected land despite the implementation of our levee, we chose a utility function that minimizes risk and thereby loss to New York City. The utility function uses the total monetary value, which is the sum of construction cost and cost due to loss: U(C+ L). We assumed the following risk aversion utility function, with a degree of risk aversion of 1/5400.

$$U(M) = -M^2/10{,}800 + M/9 + 100$$

$$M = Total\ Monetary\ Value = C + L$$

We performed a sensitivity analysis on the utility function to ensure it was sufficiently risk averse and also to test how it changed our decision. The analysis showed that changing the degree of risk aversion did not change the decision. It also showed that increasing the degree of risk aversion did not improve the utility of any given action. Plots of our sensitivity analysis on the utility function are shown in the appendix.



[D] Construction Cost Model: ---

We assumed a linear construction cost model, based on data from a previous cost benefit analysis on New York City storm surge levees. In other words, the construction cost is assumed to vary linearly with the levee's height. Below is the model and costs for the 15’, 20’, and 30’ levee.

Levee Height	15'	20'	30'
Construction Cost ($ Billion) = 0.913 x Levee Height (ft)	$ 13.7B	$ 18.3 B	$ 27.4 B

[E] Expected Economic Loss Model: --

We are interested in computing the expected annual loss (AAL) for each action (1), which is the sum product of the mean loss due to flood height, $E[L|a_i, h]$, and the annual likelihood of occurrence of flood height, v_H (AAL has the same meaning as v_L – the expected rate of loss per year). v_H depends on the number of storm surges, N, and the surges' flood heights, H (2). The occurrence of storms is assumed to be a Poisson process, and the resultant surge height is assumed to be normally distributed; in return, both distributions depends on the storm severity associated with a particular return period s_{RP} being considered, and thus $N \sim Poisson(v_{s_{RP}})$, and $H \sim N(\mu_{H|s_{RP}}, \sigma_{H|s_{RP}})$.

While we do not have the likelihood of the storm severity associated with a particular return period, $f_{s_{RP}}(s_{RP})$, we have the values of the return periods, and the expected number of hurricanes associated with a particular return period can be computed: $v_{s_{RP}} = 1/Return\ Period$. Since hurricane occurrence is a Poisson process, the probability of seeing a hurricane more severe than said return period carries an exponential distribution (4).

In numerical integration terms, we choose to terminate the integration at RP=1000 and at h=50, since the probability beyond these ranges are negligible (5). We choose to start the integration at RP=2 for ease of computing the $\Delta(1 - e^{-v_{RP}})$.

$$AAL = v_L = E[L|a_i] = \int E[L|a_i, h] \cdot d(v_H) \tag{1}$$

$$v_H = \int \int f_{H|RP}(h|rp) \cdot f_{RP}(rp) \cdot dh \cdot drp \tag{2}$$

$$v_L = \int \int E[L|a_i, h, rp] \cdot f_{H|RP}(h|rp) \cdot f_{RP}(rp) \cdot dh \cdot drp \tag{3}$$

$$\begin{aligned} f_{RP}(rp) &\approx P\left[X \geq x_{rp-1}\right] - P\left[X \geq x_{rp}\right] \\ &\approx (1 - e^{-v_{RP}(rp-1)}) - (1 - e^{-v_{RP}(rp)}) = \Delta(1 - e^{-v_{RP}}) \end{aligned} \tag{4}$$

$$v_L = \sum_{RP=2}^{1000} \sum_{h=0}^{50/\Delta h} E[L|a_i, H] \cdot f_{H|RP}(h|rp) \cdot \Delta h \cdot \Delta(1 - e^{-v_{RP}}) \tag{5}$$

$$E[L\ in\ 100\ years] = \sum_{t=1}^{100} \frac{v_L}{(1+r)^t} = \sum_{t=1}^{100} \frac{v_L}{(1.1)^t} \tag{6}$$

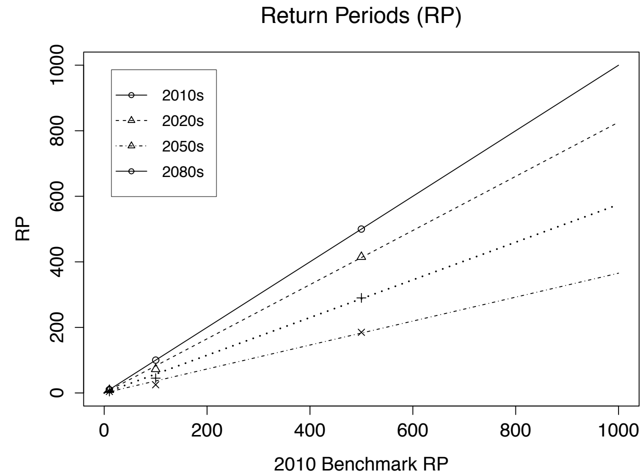
Finally, the expected loss in 100 years is the summation of the discounted expected annual loss for 100 years (at rate r). From asking our friends in the construction program, we establish that the discount rate for construction projects is roughly 10% (6). Here we also assume the time from the decision to build to the completion of construction is (miraculously) 1 year. Additionally, we note that this model could potentially involve many more considerations, such as the various distributions' time dependency, the uncertainty associated with the return period, and the construction time. More on this topic and other model assumptions in the following description of each model input.

To compute the expected annual loss, we need inputs for $v_{s_{RP}}$ $f_{H|s_{RP}}(h|s_{RP})$, and $E[L_H|h]$.

[i] Occurrence Rate for Hurricane with Severity Associated with a Particular Return Period: $v_{s_{RP}}$

Time Slice	1-in-10years storm		1-in-100years storm		1-in-500years storm	
	Mean (yrs)	Sd	Mean (yrs)	Sd	Mean (yrs)	Sd
2010 Benchmark	10	0	100	0	500	0
2020s	9	1	72.5	7.5	415	35
2050s	4.5	1.5	45	10	290	40
2080s	4.5	1.5	25	10	185	65

The 2010 NPCC report provides the return periods for 1-in-10years, 1-in-100years and 1-in-500years category hurricanes for the 2010 benchmark, the 2020s, the 2050s, and the 2080s. We note that the return periods decrease for hurricanes in the same category as the year increases; that means that hurricanes of the same severity are occurring more frequently.

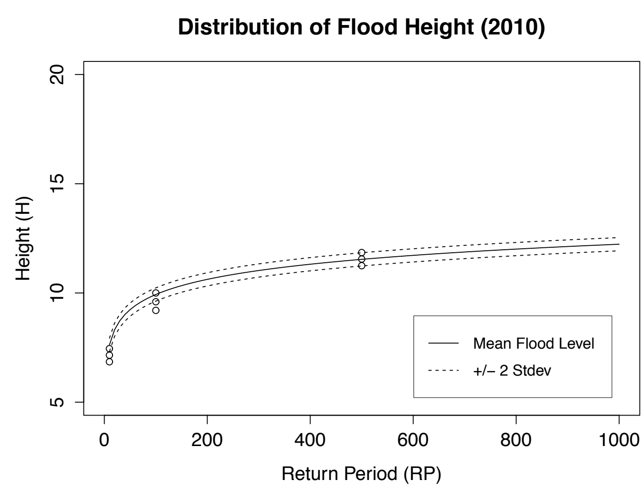


Return period is the inverse of the expected number of occurrences per year, which is the rate of occurrences per year for a Poisson process: v_{RP}=1/$Return\ Period$. Thus, to compute the hurricane occurrence rate, we need to determine the associated return periods. To do so, we fit a linear curve to extrapolate the in-between return periods (appendix contains trend coefficients and significance). For simplicity, we model the expected loss based only on the 2050s return periods, and thereby ignoring the time-dependency of the return periods. 2050s is chosen because it is about halfway between 2014 and 2114 – the expected life span for our surge levees.

[ii] Flood Height Distribution: $f_{H|s_{RP}}(h|s_{RP})$

Time Slice	1-in-10years storm		1-in-100years storm		1-in-500years storm	
	Mean (ft)	Sd	Mean (ft)	Sd	Mean (ft)	Sd
2010 Benchmark	6.3	0	8.6	0	10.7	0
2020s	6.65	0.15	8.9	0.1	11.05	0.15
2050s	7.15	0.15	9.4	0.2	11.55	0.15
2080s	7.8	0.4	10.05	0.45	12.2	0.4

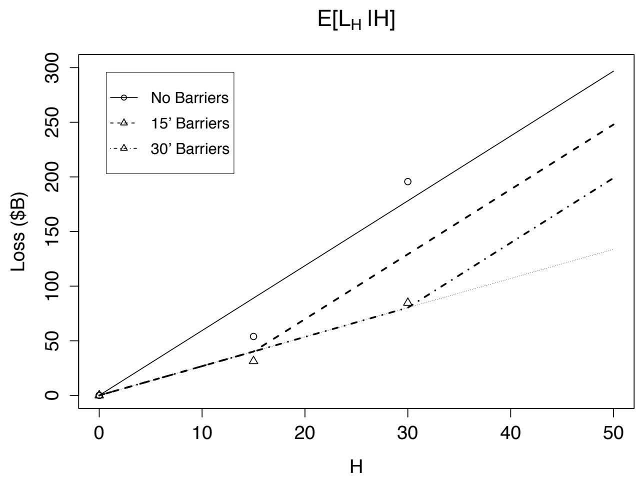
The 2010 NPCC report also provides the flood height distribution for 1-in-10years, 1-in-100years and 1-in-500years category storms for the 2010 benchmark, the 2020s, the 2050s, and the 2080s. As with our decision for the hurricane occurrence rate, we only focus on the distribution for 2050s, and thereby also ignore the time-dependency of the flood height distribution.



The flood height is assumed to have a normal distribution, with the mean and the standard deviation dependent on the storm's severity associated with each return period: $H \sim N(\mu_H(s_{RP}), \sigma_H(s_{RP}))$. To compute the distribution of the flood height for all return periods, we fit a logarithmic curve (appendix contains trend coefficients and significance). We note that the values do not go beyond 15' for any flood.

[iii] The Expected Loss due to Flood Height: $E[L_H|h]$

From a previous study using Hazus's hurricane module, the economic loss for the five boroughs of New York City were computed for 15' and 30' storm surges (appendix contains the values' geographic distribution). In order to extrapolate the economic loss for other surge heights, we assume a deterministic linear relationship between the surge height above the barrier and the economic loss. Further, we fit the regression through $(0', \$0B)$, since there should be no loss associated with no surge height (appendix contains trend coefficients and significance). Lastly, since the proposed barriers do not protect the entire New York City, there would still be economic loss associated with storm surges below the barrier heights; the barrier's benefit is in maintaining a lower rate of increase in economic loss for surges below the barrier's height.



$$E[L_H|H] = \begin{cases} 5.94h & no\ barriers \\ \begin{cases} 2.6765h & h < h_d\ and\ h_d = 15' \\ 40.148 + 5.94h & h \geq h_d\ and\ h_d = 15' \end{cases} \\ \begin{cases} 2.6765h & h < h_d\ and\ h_d = 30' \\ 80.296 + 5.94h & h \geq h_d\ and\ h_d = 30' \end{cases} \end{cases}$$

We do note that the regressions are based on a very limited set of sample points, and thus future studies would benefit from additional Hazus analysis to provide more sample points. That said, their significance at the 10% level tells us that we can reject the null hypothesis that there is no relationship between surge height and economic loss (which is intuitively obvious).

Putting everything together, we can compute the expected loss for each action (algorithm and code shown in the appendix):

$$v_L = \sum_{RP=2}^{1000} \Delta(1 - e^{-v_{RP}}) \sum_{h=0}^{50/\Delta h} E[L|a_i, H] \cdot N(\mu_H(s_{RP}), \sigma_H(s_{RP})) \cdot \Delta h$$

The results based on the 2010 NCPP report shows that building 30' levees provides no additional protection from expected economic loss. This result can be explained by the fact that the distribution of surge and thus flood height is below 15'. We will touch on, in a later chapter, the expected utility of these economic losses and how the expected economic loss is distributed amongst the various surge heights.

Action	a_1: do nothing	a_2: build 15' levees	a_3: build 30' levees
$E[L\|a_i]$	\$ 313.6B	\$ 152.9B	\$ 152.9B

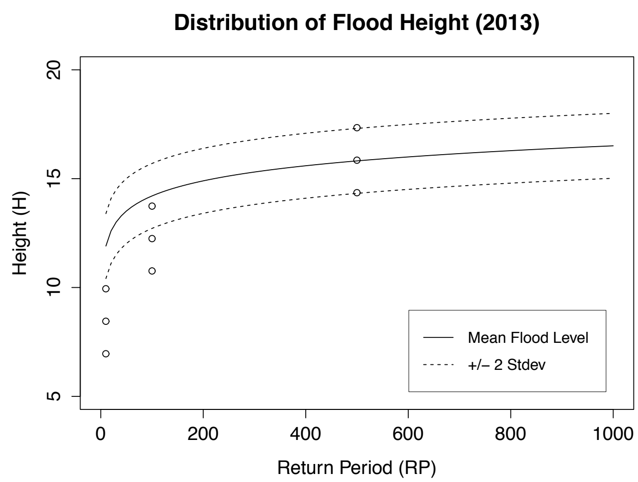
[F] Terminal Analysis: ---

Between NPCC's 2010 and 2013 report, the distribution of the flood height is adjusted while that of the return period remains largely the same.

Time Slice	1-in-10years storm		1-in-100years storm		1-in-500years storm	
	Mean	Sd	Mean	Sd	Mean	Sd

2010 Benchmark	6.3	0	8.6	0	10.7	0
2050s	8.45	0.7457	12.25	0.7458	15.85	0.7458

As with the 2010 data, we fit a logarithmic curve using the 2050s height distributions (appendix contains trend coefficients and significance). We note that the flood height's distribution resulted from the 2013 study has an increased mean, and carries more uncertainties, compared to the 2010 study.



The 2010 report provided prior parameters for the mean and standard deviation of the storm heights associated with the 1-in-10years, 1-in-100years, and 1-in-500yrs storm. The 2013 report provided posterior parameters for the mean and standard deviation. We conduct terminal analysis to solve for the hyper parameters that were used to find the updated 2013 values.

$$n = n'' - n'$$

$$n\bar{x} = n''\bar{x}'' - n'\bar{x}'$$

$$(n-1)s^2 + n\bar{x}^2 = [(n''-1)s''^2 + n''\bar{x}''^2] - [(n'-1)s'^2 + n'\bar{x}'^2]$$

10 year storm		
Prior (2010)	Posterior (updated 2013)	Solve for Hyper Parameters
n' = 2	n" = 70	n = 68
$\bar{x}$' = 7.15	$\bar{x}$" = 8.45	$\bar{x}$ = 8.49
s' = 0.15	s" = 0.7457	s = 0.72
100 year storm		
Prior (2010)	Posterior (updated 2013)	Solve for Hyper Parameters
n' = 2	n" = 70	n = 68
$\bar{x}$' = 9.4	$\bar{x}$" = 12.25	$\bar{x}$ = 12.33
s' = 0.2	s" = 0.7458	s = 0.57
500 year storm		
Prior (2010)	Posterior (updated 2013)	Solve for Hyper Parameters
n' = 2	n" = 70	n = 68
$\bar{x}$' = 11.55	$\bar{x}$" = 15.85	$\bar{x}$ = 15.98
s' = 0.15	s" = 0.7458	s = 0.07

The results based on the 2013 NCPP report shows that building 30' levees does provide additional protection from expected economic loss. This result can be explained by the fact that the distribution of surge and thus flood height is above 15'.

Action	a_1: do nothing	a_2: build 15' levees	a_3: build 30' levees

$E[L\|a_i]$	\$ 506.9B	\$ 257.5B	\$ 247.0B

[G] Expected Loss, Cost and Utility: ---

We compute for the total monetary value and the utility for each action. The result using either the 2010 or the 2013 data is the same: a_2. We note that despite the 30'

$$Monetary\ Value\ =\ Expected\ Loss\ +\ Cost\ of\ Construction$$

Results (2010):

$E[M|a_1]$ = -\$313.2B $U[a_1]$ = 56.1
$E[M|a_2]$ = -(\$152.9B + \$13.7B) = **-\$ 166.6B** $U[a_2]$ = **79.05**
$E[M|a_3]$ = -(\$152.9B + \$27.4B) = -\$ 180.3B $U[a_3]$ = 76.9

Results (2013):

$E[M|a_1]$ = -\$506.9B $U[a_1]$ = 20.07
$E[M|a_2]$ = -(\$257.5B + \$13.7B) = **-\$ 271.2B** $U[a_2]$ = **63.0**
$E[M|a_3]$ = -(\$247.0B + \$27.4B) = -\$ 274.4B $U[a_3]$ = 62.5

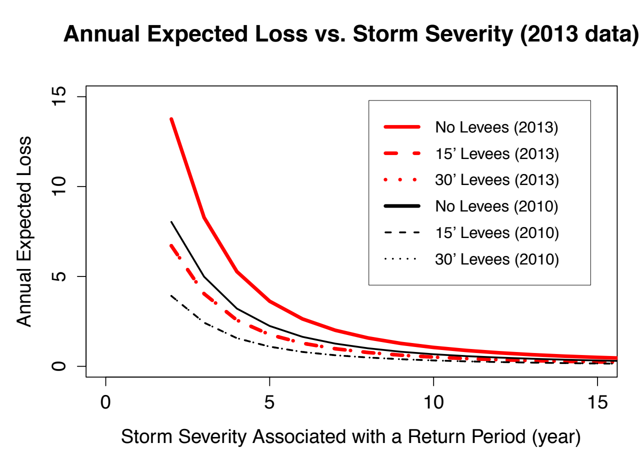
[H] Value of Information: ---

No information is available on the amount of money that the New York City Panel on Climate Change spent to create the 2013 report. We tried to estimate the value of the information provided by the 2013 report by subtracting the expected monetary value of the optimal action from the 2010 report from the expected monetary values of the optimal action from the 2013 report. The optimal action from the 2010 report is a_1, build a 15' levee, and the optimal action from the 2013 report is also a_1. The value of information, as seen through a static decision problem's lens, turns out to be negative, and thus effectively zero: $VI = E(T) - E(a^*) = -\$\ 166.6\text{B} - (-271.2\text{B}) < 0$.

However, we cannot calculate the value of information for this project using the conventional VI equation because the value of new information involves more than just the reported losses between the first and second report. We came to the conclusion that there is definite value in the information from the 2013 report, though the value is obscured by the changes in mean, standard deviation as well as associated costs. Further, this decision analysis involves dynamic parameters, and is thus not a static problem.

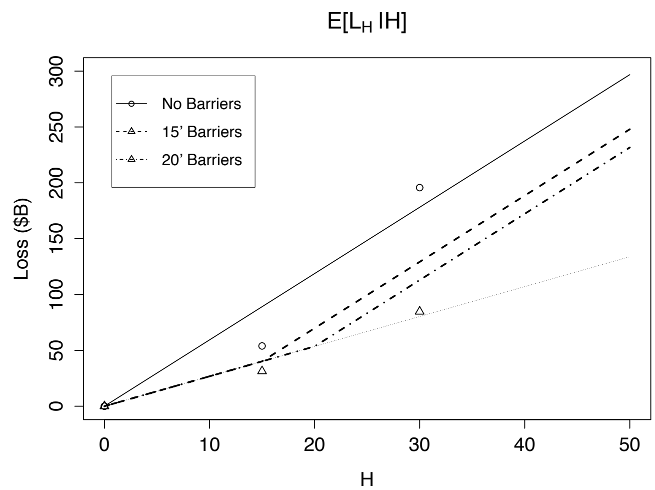
[I] Source of Economic Loss: ---

Even though the purpose of this study is to protect New York City from extreme storm surges, we note that these low-frequency-high-severity events are not the main contributor to the annual expected economic loss due to flood. The graph on the left shows that higher frequency events contribute to the majority of the loss (the graph tails off quickly for events associated with return periods of 15 years or greater).



This result implies that despite each high frequency event incurring a minor expected loss, the sheer number of these events per year render their annual aggregate loss to be very significant in value. Conversely, despite each low frequency event incurring a major expected loss, the low probability of seeing it on an annual basis render its expected value very low.

[J] Recommendation/Proposed Future Work: ---



After conducting our study we realized that building a 30' levee is not an economically feasible action. It is often hard to define a comprehensive action space without sufficient prior knowledge; therefore, at the beginning of our project we thought comparing a 15' and 30' levee would provide interesting results.

We would recommend adding a new action, to build a 20' levee, to our decision tree. We computed the expected loss of a 20' levee to see if this action would be favorable. The loss associated with a 20' levee is the same as that of the 30' levee (-$247.0B) because the storm surge height is not expected to go above 18' under the 2013 values (see graph in the section on terminal analysis); however, the construction cost of building the levee will be lower for the 20' levee. Under out construction cost model, it is expected to cost $27.4B to build a 30' levee, but only $18.3B to build a 20' levee. Thus the overall monetary value of a 20' levee is -$265.3B, which turns out to be lower than the expected overall monetary value of both the 30' (-$274.4B) and the 15' (-$271.2B) levee.

Results Summary:

$E[M|a_1]$ = -$506.9B
$E[M|a_2]$ = -($257.5B + $13.7B) = -$ 271.2B
$E[M|a_3]$ = -($247.0B + $27.4B) = -$ 274.4B
$E[M|a_3]$ = -($247.0B + $18.3B) = **-$ 265.3B**

In the future we propose conducting an optimization study to find the levee height that would minimize the loss caused by storms while also minimizing the construction cost of the levee.

[K] Contribution of Group Members: ---

Simone Fobi: Multi-objective Analysis, Utility Function and Sensitivity Analysis, Construction Cost Estimates, Powerpoint Presentation.
Claire (Hsaio-Hsuan) Lin: Multi-objective Analysis, Utility Function and Sensitivity Analysis, Construction Cost Estimates, Powerpoint Presentation.
Christy Nelson: Prior and Posterior Values of Storm Surge Heights, Terminal Analysis, Value of Information, Powerpoint Presentation.
Steven Wong: Modeling Loss Function, Value of Information, Powerpoint Presentation.

[Appendix]

[i] References: --

[1] Horton, Radley, Vivien Gornitz and Malcolm Bowman. "New York City Panel on Climate Change 2010 Report". 2010. Page 55.

[2] "New York City Panel on Climate Change: Climate risk Information 2013". June 2013.

[3] Jansen, Peter and Piet Dircke. "Verrazano Narrows Strom Surge Barrier. Presentation". New York City: ASCE Met Section Infrastructure Group Seminar, 2009.

[4] Abrahams, Michael J. "Conceptual Design of an East River Storm Surge Barrier. Presentation". New York City: ASCE Met Section Infrastructure Group Seminar, 2009.

[5] Murphy, Lawrence J. and Thomas R. Schoettle. "Arthur Kill Storm Surge Barrier Design Concept". Presentation. New York City: ASCE Met Section Infrastructure Group Seminar, 2009.

[6] Baker, Jack W. "An Introduction to Probabilistic Seismic Hazard Analysis". Stanford, 2008

[ii] Coefficients and Statistical Significance from Trend-Fitting: --

Return Periods:

Coefficients (2050s):

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*
RP$RP	*0.57495*	*0.01776*	*32.38*	*0.000953 ****

Flood Height Distribution (2010):

Coefficients:

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*
height$RP	*205.220*	*8.216*	*24.98*	*0.0016 ***

Expected Loss:

Coefficients (no barriers):

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*
loss$flood	*5.9367*	*0.8268*	*7.18*	*0.0189 **

Coefficients (infinitely high barriers):

	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*
loss$flood	*2.6765*	*0.2076*	*12.89*	*0.00596 ***

Flood Height Distribution (2013):

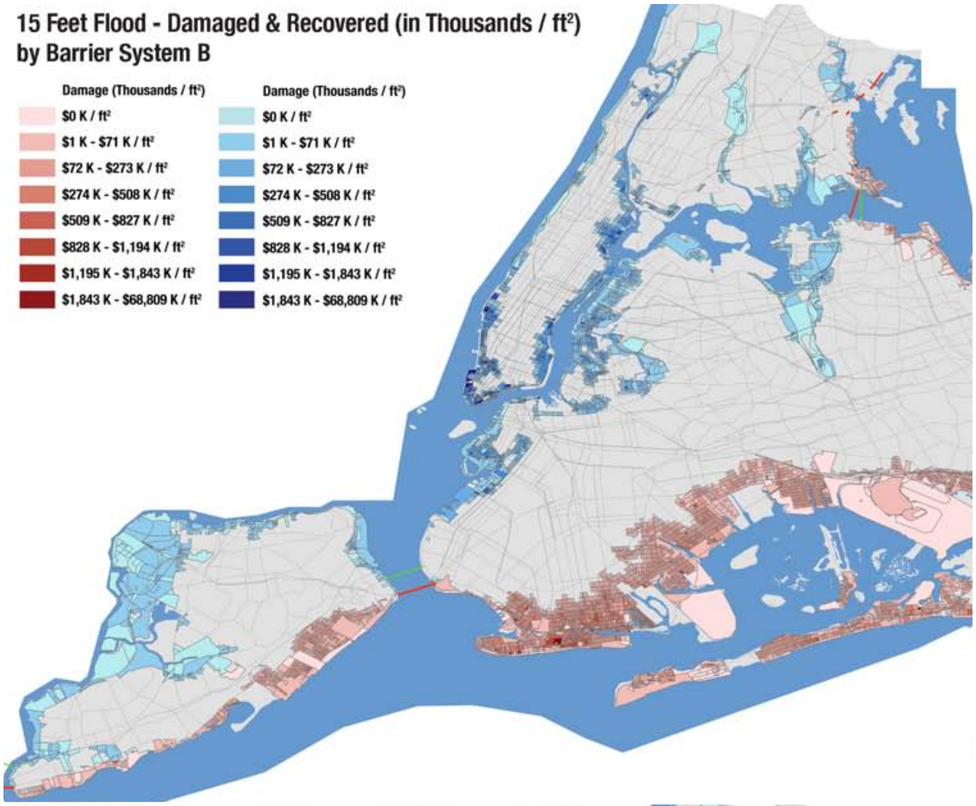
Coefficients:

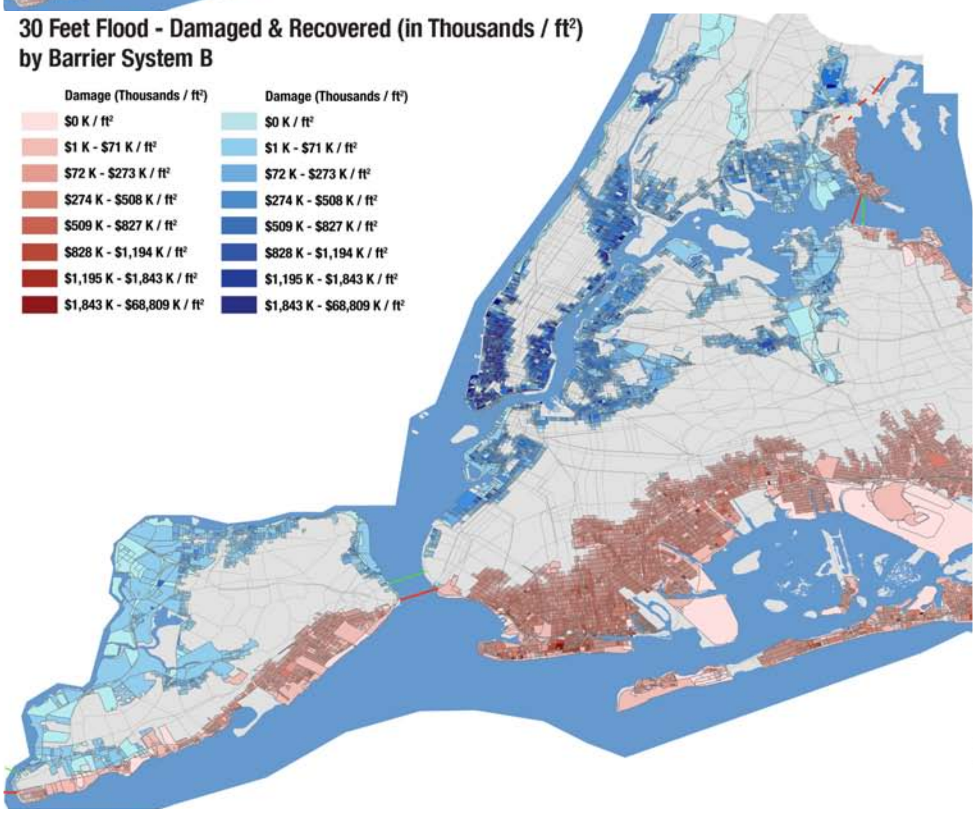
	Estimate	*Std. Error*	*t value*	*Pr(>|t|)*
height$RP	*14783*	*1806*	*8.183*	*0.0146 **

[iii] Numerical Integration Algorithm: ---

```
for each action, a:
    for each hurricane strength associated with each return period, rp:
        for each flood height, h:
            1. compute probability of h, given rp and a
            2. multiply the probability of h by the expected loss E[L], given a:
                if a = a0
                    E[L] = 5.94h
                if a = a1
                    if h < 15
                        E[L] = 2.6765h
                    if h ≥ 15
                        E[L] = 40.148 + 5.94h
                if a = a2
                    if h < 30
                        E[L] = 2.6765h
                    if h ≥ 30
                        E[L] = 80.296 + 5.94h
            3. sum all the expected losses for each h
        end
         sum the product of expected losses from each hurricane associated with each rp and its differential
         rate of each rp
    end
end
```

[iv] Economic Damage & Recovery Due to Levees for 15' and 30' Storm Surges: ------------------------





```
# CEE 206 - Final Project
# Steven Wong | SUNI: stywong
rm(list = ls())
setwd("~/desktop/cee 206 final project/")
par(mfrow = c(1,1))
source("save_as_eps.r")

#################### RP  ###################

# read data
RP = read.csv("ReturnPeriod2010.csv", header=TRUE)

# regression fit
# fit.2010 = lm((RP$Mean2010) ~ RP$RP+0)
# summary(fit.2010)
# fit.2020 = lm((RP$Mean2020) ~ RP$RP+0)
# summary(fit.2020)
fit.2050 = lm((RP$Mean2050) ~ RP$RP+0)
summary(fit.2050)
# fit.2080 = lm((RP$Mean2080) ~ RP$RP+0)
# summary(fit.2080)

# # plot
# plot(0,0, xlim = c(0,1000), ylim = c(0,1000), pch="",
#      xlab="2010 Benchmark RP", ylab="RP", main="Return Periods (RP)")
# curve((fit.2010$coef[1]*x),0,1000, lty=1, add=TRUE)
# curve((fit.2020$coef[1]*x),0,1000, lty=2, add=TRUE)
# curve((fit.2050$coef[1]*x),0,1000, lty=3, add=TRUE, lwd=2)
# curve((fit.2080$coef[1]*x),0,1000, lty=4, add=TRUE)
# points(RP$RP, RP$Mean2010, pch=1)
# points(RP$RP, RP$Mean2020, pch=2)
# points(RP$RP, RP$Mean2050, pch=3)
# points(RP$RP, RP$Mean2080, pch=4)
# legend("topleft",legend=c("2010s","2020s","2050s","2080s"),
#        lty=c(1,2,4),pch=c(1,2,2),cex=0.8,inset=0.05,bty="o",,box.lwd=0)
# save_as_eps("rp.eps",6,9)

# values
RP = 1:1000
RP.2050 = fit.2050$coef[1]*RP
v.2050 = 1/RP.2050

#################### H ###################

# read data
height = read.csv("FloodHeight2010.csv", header=TRUE)
# height = read.csv("FloodHeight2013.csv", header=TRUE)

# regression fit
fit.2050 = lm(exp(height$Mean2050) ~ height$RP+0)
summary(fit.2050)
fit.2050.Usd = lm(exp(height$Mean2050+2*height$Sd2050) ~ height$RP+0)
summary(fit.2050.Usd)
fit.2050.Lsd = lm(exp(height$Mean2050-2*height$Sd2050) ~ height$RP+0)
summary(fit.2050.Lsd)
fit.2050.Usd1 = lm(exp(height$Mean2050+1*height$Sd2050) ~ height$RP+0)
summary(fit.2050.Usd1)
fit.2050.Lsd1 = lm(exp(height$Mean2050-1*height$Sd2050) ~ height$RP+0)
summary(fit.2050.Lsd1)

# plot
```

```
plot(0,0, xlim = c(0,1000), ylim = c(5,20), pch="",
     xlab="Return Period (RP)", ylab="Height (H)", main="Distribution of Flood Height
(2010)")
# plot(0,0, xlim = c(0,1000), ylim = c(5,20), pch="",
#      xlab="Return Period (RP)", ylab="Height (H)", main="Distribution of Flood Height
(2013)")
curve(log(fit.2050$coef[1]*x),0,1000, lty=1, add=TRUE)
curve(log(fit.2050.Usd$coef[1]*x),0,1000, lty=2, add=TRUE)
curve(log(fit.2050.Lsd$coef[1]*x),0,1000, lty=2, add=TRUE)
points(height$RP, height$Mean2050, pch=1)
points(height$RP, height$Mean2050-2*height$Sd2050, pch=1)
points(height$RP, height$Mean2050+2*height$Sd2050, pch=1)
legend("bottomright",legend=c("Mean Flood Level","+/- 2 Stdev"),
       lty=c(1,2),cex=0.8,inset=0.05,bty="o",,box.lwd=0)
save_as_eps("height10.eps",6,9)
# save_as_eps("height13.eps",6,9)

# values
RP = 1:1000
mu.2050 = log(fit.2050$coef[1]*RP)
sd.2050 = log(fit.2050.Usd1$coef[1]*RP)-log(fit.2050$coef[1]*RP)

#################### E[L|H] ####################

# read data
loss = read.csv("LossLevels.csv", header=TRUE)
colnames(loss) = c("flood.levels","no.bars","protected","ys.bars")

# regression fit
fit.no.bars = lm((loss$no) ~ loss$flood+0)
summary(fit.no.bars)
fit.ys.bars = lm((loss$ys) ~ loss$flood+0)
summary(fit.ys.bars)

# # plot
# plot(0,0, xlim = c(0,50), ylim = c(0,300),
#      xlab="H", ylab="Loss ($B)", main=expression("E[L"[H]~"|H]"))
# # none
# curve((fit.no.bars$coef[1]*x),0,50, lty=1, add=TRUE)
# points(loss$flood.levels, loss$no.bars, pch=1)
# curve((fit.ys.bars$coef[1]*x),0,50, lty=3, lwd=0.5, add=TRUE)
# points(loss$flood.levels, loss$ys.bars, pch=2)
# # 15'
# curve((fit.ys.bars$coef[1]*x),0,15, lty=2, lwd=2, add=TRUE)
# curve((fit.no.bars$coef[1]*(x-15)+fit.ys.bars$coef[1]*15),15,50, lwd=2, lty=2,
add=TRUE)
# # 20'
# curve((fit.ys.bars$coef[1]*x),0,20, lty=4, lwd=2, add=TRUE)
# curve((fit.no.bars$coef[1]*(x-20)+fit.ys.bars$coef[1]*20),20,50, lwd=2, lty=4,
add=TRUE)
# legend("topleft",legend=c("No Barriers","15' Barriers","20' Barriers"),
#        lty=c(1,2,4),pch=c(1,2,2),cex=0.8,inset=0.05,bty="o",,box.lwd=0)
# # 30'
# curve((fit.ys.bars$coef[1]*x),0,30, lty=4, lwd=2, add=TRUE)
# curve((fit.no.bars$coef[1]*(x-30)+fit.ys.bars$coef[1]*30),30,50, lwd=2, lty=4,
add=TRUE)
# legend("topleft",legend=c("No Barriers","15' Barriers","30' Barriers"),
#        lty=c(1,2,4),pch=c(1,2,2),cex=0.8,inset=0.05,bty="o",,box.lwd=0)
# save_as_eps("loss_new.eps",6,9)

#################### E[L] ####################
max.h = 50
```

```
d = 0.5
h.d = seq(from = 0, to = max.h, by=d)

exp.loss = array(0, dim=c(3))
exp.loss.a = array(0, dim=c(3,length(RP)))
exp.loss.rp = array(0, dim=c(3,length(RP),length(h.d)))
exp.rp = array(0, dim=c(3,length(RP),length(h.d)))

for (a in 1:length(exp.loss)){
  for (rp in 2:length(RP)) {
    for (h in 1:length(h.d)) {
        if (a == 1) { # no barriers
            exp.loss.h = 5.49*h.d[h]
        } else if (a == 2){ # 15' barriers
          if (h.d[h] < 15) {
            exp.loss.h = 2.6765*h.d[h]
          } else {
            exp.loss.h = 40.148 + 5.94*h.d[h]
          }
        } else if (a == 3) { # 20' barriers
          if (h.d[h] < 20) {
            exp.loss.h = 2.6765*h.d[h]
          } else {
            exp.loss.h = 53.53067 + 5.94*h.d[h]
          }
#         } else if (a == 3) { # 30' barriers
#           if (h.d[h] < 30) {
#            exp.loss.h = 2.6765*h.d[h]
#           } else {
#            exp.loss.h = 80.296 + 5.94*h.d[h]
#         }
        }
      exp.rp[a,rp,h] = (pnorm(h.d[h]+d/2,mu.2050[rp],sd.2050[rp])-pnorm(h.d[h]-
d/2,mu.2050[rp],sd.2050[rp]))
      exp.loss.rp[a,rp,h] = exp.rp[a,rp,h]*exp.loss.h
    }
    exp.loss.a[a,rp] = ((1-exp(-v.2050[rp-1]))-(1-exp(-
v.2050[rp])))*sum(exp.loss.rp[a,rp,])
#     exp.loss.a[a,rp] = (v.2050[rp-1]-v.2050[rp])*sum(exp.loss.rp[a,rp,])
  }
  exp.loss[a] = sum(exp.loss.a[a,])
}

# discount
time = 1:100
df = array(1,dim=c(3,length(time)))
for (a in 1:dim(df)[1]) {
  for (t in 1:dim(df)[2]) {
    df[a,t] = exp.loss[a]/(1.1)^t
  }
}
exp.loss.100 = rowSums(df)

#################### Distribution of E[L] ####################

# # EP 2010
# plot(0,0, xlim = c(0,50), ylim = c(0,10), pch="",
#      xlab="Storm Severity Associated with a Return Period (year)",
#      main="Annual Expected Loss vs. Storm Severity (2010 data)", ylab="Annual Expected
Loss")
# points(RP[-1],exp.loss.a[1,-1],pch=20,cex=0.5)
# points(RP[-1],exp.loss.a[2,-1],pch=1,cex=0.5)
```

```
# points(RP[-1],exp.loss.a[3,-1],pch=2,cex=0.5)
# legend("topright",legend=c("No Barriers","15' Barriers","30' Barriers"),
#        pch=c(20,1,2),cex=0.8,inset=0.05,bty="o",,box.lwd=0)
# save_as_eps("rp_loss_2010.eps",6,9)

exp.loss.a.2013 = exp.loss.a

# 1, 2, 5; 19, 16, 18

# EP 2013
plot(0,0, xlim = c(0,15), ylim = c(0,15), pch="",
     xlab="Storm Severity Associated with a Return Period (year)",
     main="Annual Expected Loss vs. Storm Severity (2013 data)", ylab="Annual Expected
Loss")
lines(RP[-1],exp.loss.a.2013[1,-1],lty=1,lwd=4,col="red")
lines(RP[-1],exp.loss.a.2013[2,-1],lty=2,lwd=4,col="red")
lines(RP[-1],exp.loss.a.2013[3,-1],lty=3,lwd=4,col="red")
lines(RP[-1],exp.loss.a[1,-1],lty=1,lwd=2)
lines(RP[-1],exp.loss.a[2,-1],lty=2,lwd=2)
lines(RP[-1],exp.loss.a[3,-1],lty=3,lwd=2)
legend("topright",legend=c("No Levees (2013)","15' Levees (2013)","30' Levees (2013)",
                           "No Levees (2010)","15' Levees (2010)","30' Levees (2010)"),

lty=c(1,2,3,1,2,3),lwd=c(4,4,4,4,2,2,2,2),col=c("red","red","red","black","black","black"),

       cex=0.8,inset=0.05,bty="o",,box.lwd=0)
save_as_eps("rp_loss.eps",6,9)
```