Supplementary Materials: An Integrated Plan to Sustainably Enable the City of Riohacha (Colombia) to Cope with Increasing Urban Flooding, while Improving Its Environmental Setting

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1. The Cases Submitted to Simulation

Several combinations ("cases") of "scenarios" and "alternatives" were considered in order to produce the relevant information for decision-making. Table S1 summarizes the considered cases: a first group of three cases (1, 2, and 3) were set up just to investigate how the current system ("ALT_0") would react given either climate change or further urbanization, discovering that in this particular case, climate change would lead to the most relevant effects (once the urban area is already consolidated, the added stress caused by climate change would be more significant).

The second group concerns the comparative evaluation of the ALTs. Notice that each case actually involves three simulations, according to the three possible events considered (the design one, corresponding to T10, *i.e.*, a 10-year return period event, equivalent to the historical one of November 2011; T84, corresponding to the September 2011 historical event; and T100CC, the harshest event considered, referring to a return period of 100 years with climate change), together with their corresponding boundary conditions.

The set of alternatives basically considers: doing nothing; maintaining present actions; changing to a sustainable urban drainage approach; adopting an environmental approach; a combination of measures that maximizes the effects of flood control; and a realistic combination that considers the costs involved.

2. Evaluation Framework

Accompanying the creative exercise of conceiving and defining solution alternatives—each one being a compound combination of particular choices (size, number, and location) of each solution option—the multi-objective system approach is based on a powerful integrated evaluation framework.

This approach is basically the VALURI approach described in Nardini *et al.* [1]. In very simplified terms, it includes:

- Level I "objective evaluation": Measurement of each key objective: Risk (R), Costs (C) (implementation and operation, management and replacement (OMR)), Nature (N) (environmental value of the involved assets), and social Disturbance (D) (or benefit) to the local community because of a modification of the status quo (in particular because of a change of land use or delocalization).

Through this analysis, it is possible to conceive and identify candidate alternatives, which are submitted to the next level.

- Level II "conflict management": This is an evaluation–negotiation stage explicitly addressing the subjective points of view of stakeholders: for each interest group (stakeholder), a measure (evaluation index) of its satisfaction ("quality of life"), concerning the performance of the system, is built. The structure of such indices and the process of their construction have to be highly participatory to achieve, first of all, the trust of the people involved. This requires a number of specific interviews, which although quite demanding, lead to a very valuable social learning output on both sides: the people and the analyst and, as such, the whole decision process (see Keeney [2] and Renn [3]). The framework is multicriteria, but should not rely on complex mathematical techniques; rather, it aims at showing in the simplest way which gains and losses each interest group would experience according to each considered alternative, and with this basis, negotiating based on values and on thresholds to move towards a more accepted solution [4,5].

Among the alternatives passing this evaluation (denoted as "socially acceptable"), the decision maker can select the best according to the next step.

- Level III "strategic": Here, the idea is to synthesize, again in a multicriteria framework, the pros and cons as seen from a broader perspective, sensitive to the common good and sustainability. As such, it looks for two classes of outcomes:
  (1) *Quality of life*: A synthesis of the social satisfaction emerging from Level II; a proxy for this is the net social economic benefit (BN), because—according to economic theory—the higher it is, the more likely it will be that (scarce) resources are used efficiently and allocated according to consumers' preferences, while, on the other hand, it is a measure that is very well known and considered by decision makers. In addition, the financial, social and legal feasibility (without which no benefits can be reached) are relevant to this criterion.
  (2) *Justice:* In extremely simplified terms, this can be described by: (a) the equity in the allocation of economic loads amongst stakeholders; (b) the overall social disturbance (DM will prefer, *ceteris paribus*, the alternative which affects fewer people); and (c) the degree of conservation of natural capital (amenities, ecological integrity, biodiversity, *etc.*).

In the project described here for Riohacha, a simplified version of this approach was developed, where Level II was not explicitly addressed, and Level I and III were mixed.

The indicators adopted in practice are summarized in Table S2, with their meaning, which reflects one-to-one the above discussion of the objectives. In Table S3, the relevant cause–effect relationships among solution options and the effects (evaluation indicators) are shown.

Table S1: "Cases" (combination of a Scenario and an ALTernative) submitted to simulation.

No.	Name of "CASE"	Purpose	Scenarios						ALTernatives	
			Urban Develop	Land Use	Hydrological	No. of Events	Hydrological Details of the Considered Events	Boundary Condition	Name	Change from ALT_0
1	Zero	reference	current	U0	current	1	that with historical Tr	current	ALT_0	no
2	Climate Change (CC)effect	point out the effect of CC	current	U0	future	1	the same, but IDF modified because of CC	CC	ALT_0	no
3	urbanization effect	point out the effect of urbanization	future	U1	current	1	that with historical Tr	current	ALT_0	no
The following are to be evaluated in comparative fashion:										
4	Evalua_Base	provide a reference for the comparative evaluation	future	U1	future	3	(0) the historical Nov.2011_Tr10; (i) the historical_ Sept.2011_Tr84;(ii) that with Tr100 IDF modified by CC	(0), (i) current; (ii) with CC	ALT_Base	yes
5	Evalua_AMB	show what environmental options can do alone	future	U2	future	3	the same	the same	ALT_AMB	yes
6	Evalua_SUDS	ascertain whether SUDS technological options are enough	future	U1	future	3	the same	the same	ALT_SUDS	yes
7	Evalua_Max	set the upper reachable safety level	future	U2	future	3	the same	the same	ALT_MAX	yes
8	Evalua_R1	provide good performance,	future	U2	future	3	the same	the same	ALT_REAL_1	yes

9	Evalua_R2	avoiding options that are hard to implement the same, but with local adjustments to satisfy community suggestions	future	U3	future	3	the same	the same	ALT_REAL_2	yes
10	Evalua_R3	the same, optimized economically	future	U4	future	3	the same	the same	ALT_REAL_3	yes

Table S2. Evaluation indicators adopted.

No.	Component		Indicators	Units	Aggregation Over the Whole Set of Elements within a Given Alternative	Orientation	Maximum	Best	Minimum	Worst	Meaning of the Extremes	Relative Importance	Weight
1	Environmental value	a	Green area created (or preserved from urbanization)	ha	summation of all the elements present	+	75	75	0	0	immediate	3	0.375
		b	Continuity of the "*humedales*" system	-	holistic judgment over the whole set of elements	+	3	3	0	0	the whole system is perfectly connected	5	0.625
2	Social disturbance	a	Number of houses to be adapted	Units	summation of all the elements present	-	2000	0	0	2000	immediate	5	0.833
		b	Number of houses to be removed	Units	summation of all the elements present	-	25	0	0	25	immediate	1	0.167
3	Flood risk	a	Number of houses affected by the design event T10	Units	output of MODCEL simulation including the effects of all interventions	-	3000	0	0	3000	immediate	5	0.625

					taken within a given alternative								
		b	Number of houses affected by the extreme event T100 with CC	Units	the same	-	3000	0	0	3000	immediate	2	0.250
		c	Number of sensitive works (prone to failure)	Units	summation of all the elements present	-	350	0	0	350	immediate (remember: linear works are counted as unit to each 100m)	1	0.125
4	Cost	a	Investment cost of interventions	M$	summation of all the elements present	-	120	0	0	120	immediate	5	0.500
		b	Capitalized OMR cost	M$	summation of all the elements present	-	120	0	0	120	immediate	5	0.500
5	Administrative feasibility	a	Conflict area with respect to POT (urban land use plan)	ha	summation of all the elements present	-	300	0	0	300	immediate	5	1.000
6	Financial sustainability	a	Annual OMR cost	M$/ year	summation of all the elements present	-	3000	0	0	3000	immediate	-	1.000

Note: T10 indicates an event with a return period of 10 years; T100 indicates an event with a return period of 100 years.

Table S3. Relevant cause–effect relationships amongst solution options (columns, with vertical writings in the first row) and indicators (rows).

No.	Component		Indicators	Solution Options											Scenarios	
				Floodable Parks	Rain Gathering Roofs	Permeable Parking Areas	Green Corridor (Natural Hydraulic Connections)	Morphological Modification of Humedales	Surface and Subterranean Drainage Canals and Pipes	Subterranean Retention Tanks	Pumping Stations	Defense Works	Adaptation or Removal of Houses	Land Use Change	Urban Development	Hydrology & Climate Change
1	Environmental value	a	Green area created (or preserved from urbanization)	1	-	-	1	1	-	-	-	-	1	1	-	-
		b	Continuity of the "*humedales*" system	1	-	-	1	1	-	-	-	-	-	-	-	-
2	Social disturbance	a	Number of houses to be adapted	1	-	-	1	1	-	-	-	-	1	-	-	-
		b	Number of houses to be removed	1	-	-	1	1	1	-	-	1	1	-	-	-
3	Flood risk	a	Number of houses affected by the design event T10	x	x	x	x	x	x	x	x	x	1	x	x	x
		b	Number of houses affected by the extreme event T100 with CC	x	x	x	x	x	x	x	x	x	1	x	x	x
		c	Number of sensitive works (prone to failure)	-	-	-	-	-	x	x	x	x	-	-	-	-
4	Cost	a	Investment cost of interventions	x	x	x	x	x	x	x	x	x	x	(x)	x	x
		b	Capitalized OMR cost	-	-	-	-	-	x	x	x	x	x	-	-	-
5	Administrative feasibility	a	Conflict area with respect to POT (urban land use plan)	1	-	-	-	-	-	-	-	-	-	1	-	-
6	Financial sustainability	a	Annual OMR cost	-	-	-	-	-	x	x	x	x	-	-	-	-

Notes: 1: The solution option influences the corresponding row evaluation criterion just summing up the values of its elements (*i.e.*, the areas of floodable parks). x: means there is a relationship, but it is not that straightforward, so determining its impact requires some intermediate tools and steps (e.g., using a unit parametric cost, for the Cost impact; or performing a flood model simulation and corresponding GIS operations for what concerns the impact on Risk). (x): means that land use change would influence cost usually by reducing it; however, this is relevant only in a social cost–benefit analysis, while the Cost considered here has a financial perspective.

3. Simplified Cost-Benefit Analysis (CBA) of the Alternatives

The rationale of this analysis is to keep track of the economic criterion and to complement the multicriteria evaluation where no consideration of economic efficiency was included.

In a straightforward CBA approach, first costs (C) and benefits (B) are assessed and then compared; if B exceeds C, the alternative is economically viable (and *vice versa*). However, as it is quite hard to assess the damage itself, we proceed inversely: we determine which value should assume the parameter "unit damage c" in order to cause a given candidate alternative (as it is ALT_R3, in our case) to have at least a non-zero cost–benefit balance. Thereafter, the point is whether the found value makes sense or not, *i.e.*, whether the c value would be proportioned to the actual type of houses encountered in the area. If it is, that balance is meaningful and as a conclusion the candidate ALT is at least economically acceptable. This is indeed the strength of the approach presented here. The value c is hence a parameter to be determined.

Notice that the indicator "net social benefit" (B_N), representing the "economic efficiency"—to be included in the Level III strategic evaluation according to the VALURI approach presented before—is not included in the evaluation matrix, exactly because the actual damage value is not calculated; it rather plays an analytic role.

We are totally aware that actual damages are a function of several features characterizing the event, like water depth, velocity, and duration (see for instance [6–9]); but on the one hand, here we wanted just to exclude the doubt that the selected ALT_R3 could perform too poorly in economic terms; on the other hand, most of flooding in this areas occurs with water depth within a relatively narrow range (say 0.15 to 1.0 m) within which damages do not vary that much for the given typology of houses and goods involved. In any case, a further research is ongoing to explore the veracity of this assumption by trying to determine directly the damages as a function of at least water depth.

In summary, in the CBA carried out:

- The only benefit considered is the risk reduction.
- Only the direct, tangible risk component is assessed.
- No residual risk is considered.
- We assume that a house located in a flooded place always experiences the same damage, independently both of the hydraulic characteristics of the event (depth, duration, and velocity) and the type of house. This damage is denoted as "unit damage c". This is equivalent to adopting the average of a stage–damage curve for any stage value. This is a heavy assumption, since reducing water levels (in this approach) does not minimize losses (which could be expected). Only eliminating floods counts positively.

We treated stochasticity with an events-based approach. Accordingly, within a given year, the occurrence probability of any of the considered events is the difference between the exceedance probability of that event and that of the following (bigger) one, as shown in Figure S1:

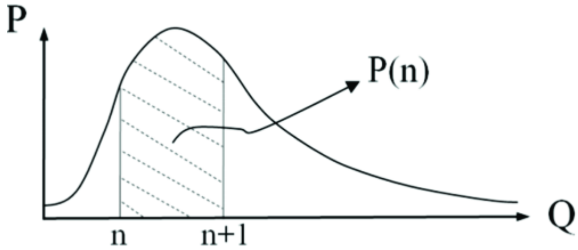

Figure S1. Computation of the probability of occurrence associated with an event with return period T_R.

The expected damage in that year is the weighted summation, with such probabilities P(n), for the considered events, of the corresponding damage D(n); in formulas and considering just 3 TR (T10, assumed as a reference event; T84, corresponding to the historical September 2011 event; and

T100 with climate change, considered as an upper extreme event to ascertain the robustness of the solution):

$$P(n) = P^N(n + 1) - P^N(n) \quad (S1)$$

where n is the index of the generic T_R; a bi-univocal correspondence between n and $T_R(n)$ exists; M is the number of elements T_R considered (n = 1, 2, …, M); $P^N(n)$ is the non-exceedance probability of the n-th event; and $P^N(n) = 1 - 1/T_R(n)$; $P^N(M+1) = 1$, by convention.

Hence the annual risk r is:

$$r = P(1)D(1) + P(2)D(2) + P(3)D(3) \text{ (money/year)}, \quad (S2)$$

where: $D(n) = V(n) \times c$; c = unit damage (parameter to be determined); snd V(n) = number of houses affected by event with the n-th T_R.

In other words, the damage D(n) associated with event of return period $T_R(n)$ is the number V(n) of affected houses (those lying in the flooded zone, larger for higher T_R, as determined by a MODCEL simulation and the application of the flooded zone GIS tool developed) multiplied by the unit damage c of any single house. Hence, the annual risk will be such damage times the probability P(n) of occurrence of events falling in the corresponding class n. Then, all events are considered and their expected damages summed.

To obtain the overall expected damage over the whole planning horizon T, the annual values are simply summed after being adjusted by the discount factor corresponding to the associated year:

$$R_T = r + r\,d^1 + r\,d^2 + ... + r\,d^{(T-1)} = r\,(1 + d + d^2 + ... + d^{(T-1)}) \text{ (money)} \quad (S3)$$

With the discount factor $d = 1/(1 + s)$, and where R_T is the overall risk (expected damage) over the T years with social interest rate "s". As noted, this formulation only includes the direct, tangible component of damages and disregards the residual risk. With the data already presented and this approach, the following Table S4 is obtained, where calculation of direct, tangible risk is made assuming that the value of 19.9 M$/house/event is given to parameter "c". This is the value that indeed nullifies the B_N for ALT_R3 (see below Table S5). The first part of the table shows the number of affected houses V(n) corresponding to the three different events considered; while the second part of the table shows the expected damage values (*i.e.*, the risks), again associated with the three events, for each alternative (columns). The last part of the table, and particularly the bold lines, provides the inputs for the simplified Cost–Benefit Analysis:

Table S4. Calculation of direct, tangible risk, when the particular value of 19.9 (M $/house/event) is given.

Return Time	Non Exceed. Probab.	Event Probability	Number of Affected Houses				
T_R (n)	**P^N(n)**	**P(n)**	**Base**	**R1**	**R2**	**R3**	**Viviendas**
10	0.9000	0.0881	2062	0	0	0	0
84	0.9881	0.0019	2459	450	453	453	219
100	0.9900	0.0100	2808	635	463	463	492
Return Time	**Non Exceed. Probab.**	**Event Probability**	**Expected Damage Values (M$col)**				
T_R (n)	**P^N(n)**	**P(n)**	**Base**	**R1**	**R2**	**R3**	**Viviendas**
10	0.9000	0.0881	3610.2	0	0	0	0
84	0.9881	0.0019	93.1	17.0	17.1	17.1	8.3
100	0.9900	0.0100	558.1	126.2	92.0	92.0	97.8

This is the value that indeed nullifies the B_N for ALT_R3 (see below Table S5).

Table S5. Risk and Cost calculations (given the 19.9 (M$col/house/event) of parameter c).

Risk and Cost	Units	Base	R1	R2	R3	Viviendas
Annual expected Risk	(M$col/year)	4261.3	143.2	109.3	109.3	106.1
Capitalized Risk	(M$col)	**81,683.8**	**2745.6**	**2092.6**	**2092.6**	**2033.2**
Total Cost	(M$col)	**7376**	**164,582**	**161,859**	**161,859**	**76,436**

The CBA structure is always differential, in this case with respect to the ALT_Base, as it just assesses whether the increment of benefits overcomes those of costs. The basis is therefore the following matrix (Table S4), which can be obtained straightforwardly from the previous information (for the same value of the parameter c 19.9 (M$col/house/event)):

Table S6. Cost–benefit calculations (given the 19.9 (M$col/house/event) of parameter c).

Costs and Benefit	Units	Base	R1	R2	R3	Viviendas
Differential Costs	(M$col)	0	157,206	154,483	79,591	69,061
Differential Benefit	(M$col)	-	78,938	79,591	79,591	79,651
Net Benefit $B_N = B–C$	**(1000 M$col)**	-	**−78**	**−75**	**0**	**11**
c leading to $B_N = 0$	(M$col/house/event)	-	39.5	38.6	19.9	17.2

The last line presents the values of the parameter c (unit damage) for which the corresponding alternative would present a zero net benefit B_N, but all costs and benefits are here calculated based on the assumed value 19.9 as a reference (this is why B_N is zero for R3 and non-negative for the others).

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