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Chapter 13

Giving Room to the River: A Nature-Based Solution for Flash Flood Hazards?

The Brague River Case Study (France)



Guillaume Piton, Nabila Arfaoui, Amandine Gnonlonfin, Roxane Marchal, David Moncoulon, Ali Douai, and Jean-Marc Tacnet

Highlights

- Flash floods were studied with a multiscale hazard modelling approach including effects of Nature-based protection measures
- Relevant strategies are based on combinations of headwater natural water retention measures and of giving-room-to-the-river in the lowlands to increase ecological status and decrease flood levels
- Benefits were assessed with top-down approaches interesting for national and regional supporting stakeholders and also locally by survey to benefit from local dwellers' vision and willingness to contribute

13.1 Introduction

The Brague River is located in the region between Nice and Cannes along the French Mediterranean coast (Fig. 13.1). In the region, a quite dense urban belt is located aside the shore, where many hilly catchments finish their way to the sea. On

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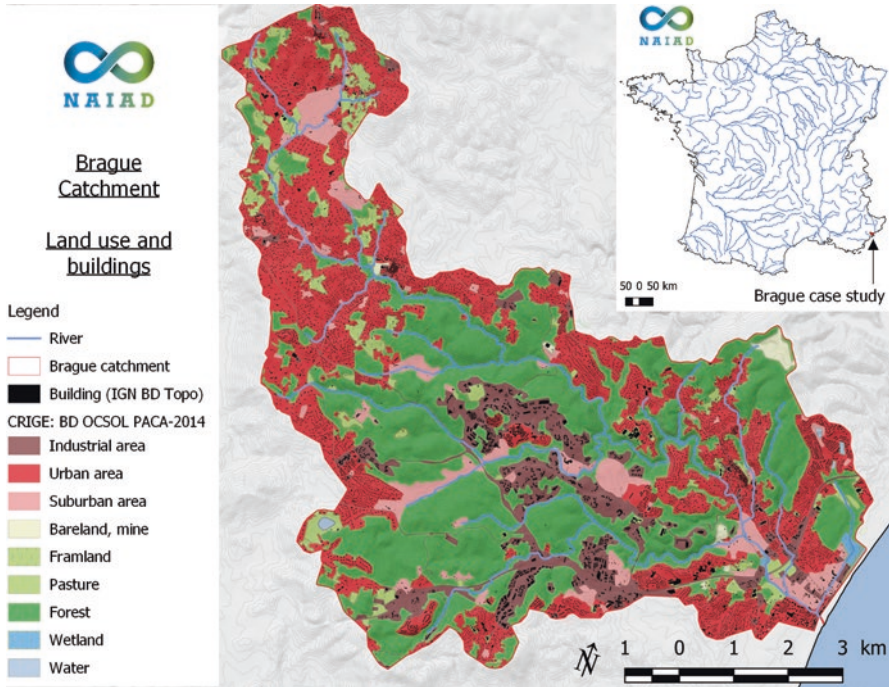


Fig. 13.1 Brague River catchment land use and location in France

third October 2015, severe rainfalls triggered extreme flash floods in three catchments: Brague (area: 68 km²), Grande Frayère (22 km²) and Riou de l'Argentière (47 km²) as well as generalized urban runoff in the cities of Cannes and Nice and in the villages in between. Twenty people died, about €M 550–650 of losses were observed all over the area, as well as cascading hazards and failures on transportation, communication and energy networks (Préfecture des Alpes-Maritimes 2016).

The Brague River catchment was selected to perform an in-depth analysis. Its catchment has rural headwaters, a forested central part where is located both the Sofia-Antipolis activity area and natural parks, and finally lowlands occupied by urbanized areas, though pastures prevail in the lowlands' central area (Fig. 13.1).

On Oct. 2015, the basin was severely hit by an extreme flash flood (time return period >100 years). Numerous data on the event features were later collected by the local authorities (Préfecture des Alpes-Maritimes 2016). The disaster resulted in four fatalities within the catchment. More than 50 million € of damage were recorded in both the Biot and Antibes municipalities. Several campsites were flooded and later closed by the administration for safety reasons. Access roads to the Sophia-Antipolis activity area were cut. Building hosting business activities were damaged in number. It is worth mentioning that huge volumes of large wood (i.e., logs longer than 1 m) were released from the natural park forests causing bridges obstruction and, thus aggravating flooding (Fig. 13.2). This event was used as a calibration case to study flash flood hazards and risks and their effects on ecosystems.

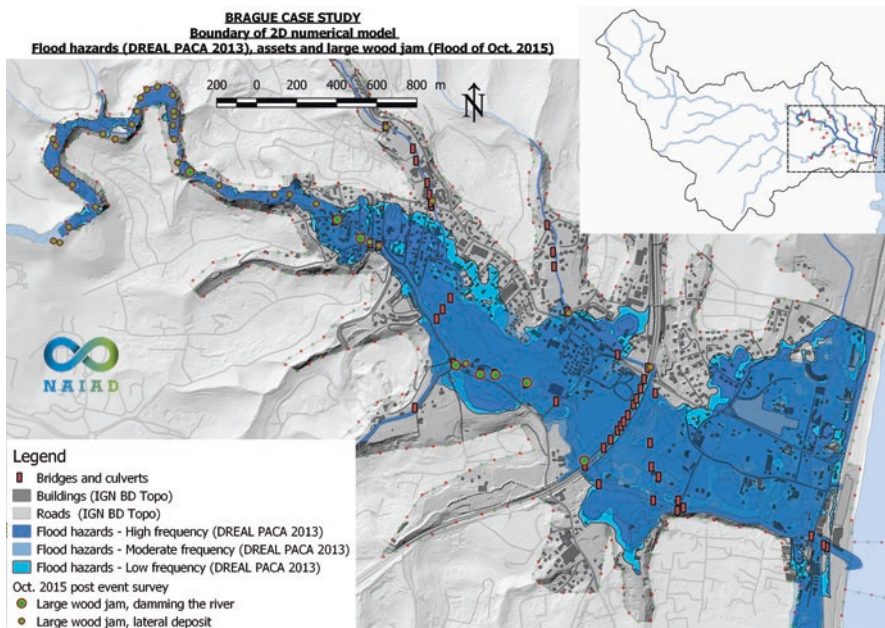


Fig. 13.2 Map of the Brague lowlands with location of bridges and large wood jams inventoried after the oct. 2015 disaster and flood hazard map (DREAL PACA 2013)

In essence, flood risk is still very high in the area and social demand for new infrastructure works aiming at protecting the remaining people living in residential areas and working in industrial areas is extremely high. The Brague River was selected to perform a comprehensive flood risk analysis and to study the performance of flood protection measures either grey (i.e., civil engineering) and/or green and blue (i.e., Nature-based solutions – NBS). This chapter synthesizes the key lessons learnt after 3 years of research by five research teams working together. More details can be found in Pengal et al. (2018) on the main catchment features, Piton et al. (2018a) on hazards, Gnonlonfin et al. (2019) on the economical assessment and Tacnet et al. (2019) on integration of methods. The chapter first provides a short description of the methods used to assess flood hazards. It secondly describes how the protection strategies were defined, valued (costs and benefits) and how their protection efficacy was assessed. It finally discussed the lessons learnt from this case-study and their possible replication and transfer to other sites.

13.2 Risk Assessment

Two modelling approaches were implemented in the Brague case study to address different scales relevant with risk assessment needs and types of planned NBS (Fig. 13.3):

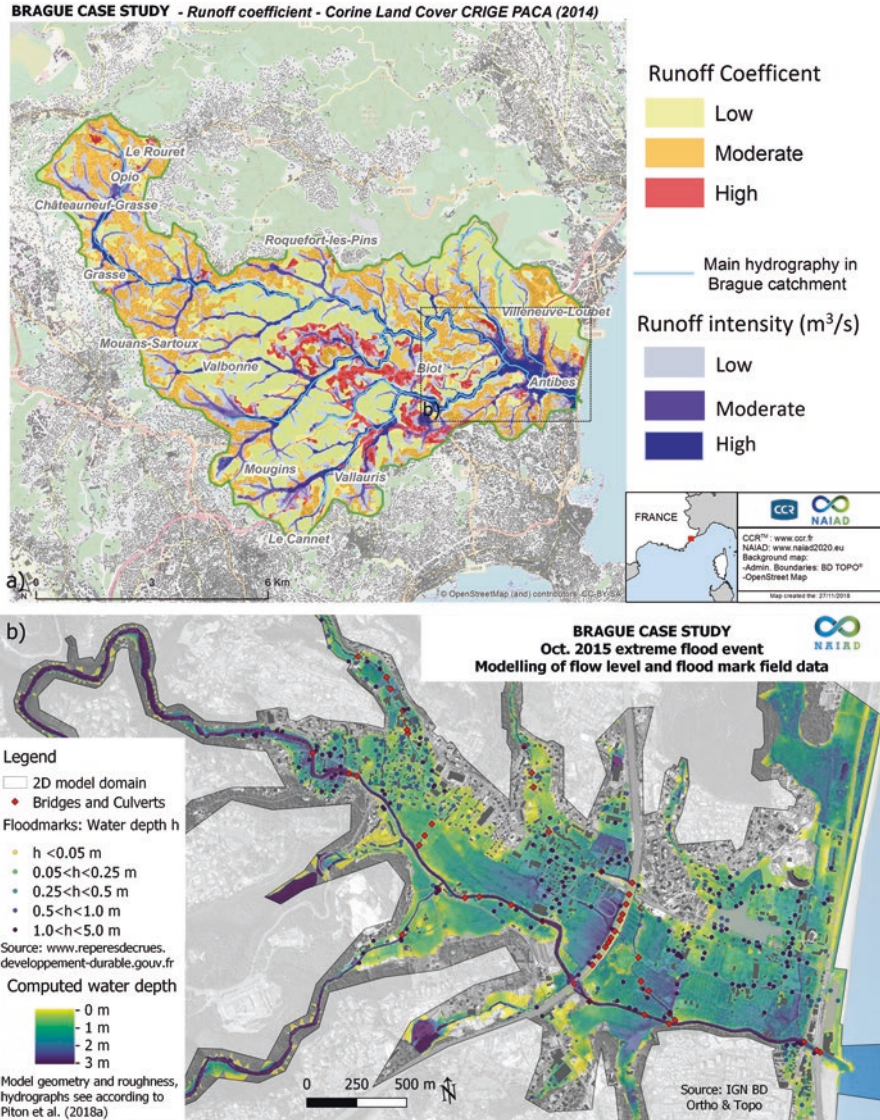


Fig. 13.3 Multi-scales Hazard modelling: calibration results of (a) the CCR surface runoff hazard at catchment scale and (b) of the Iber flood hazard in the lowlands

- Surface runoff hazards were modelled by CCR (Caisse Centrale de Réassurance) at the catchment scale with their own models working on regular grids with pixel size of 25 m (Moncoulon et al. 2014),
- Flood hazards were modelled only on the lowlands with IBER (Bladé et al. 2014). This open-source software solves the shallow water equations in 2D on an irregular mesh. In our case study, elements were typically of size 1–3 m in urban

area or channels, and up to ten time bigger in pastures and forests, thus much finer than the CCR's model but providing results on a smaller area.

The catchment-scale modelling enabled to compute damages in the upper part of the catchment and eventually efficacy of small natural water retention measures (Strosser et al. 2015) spread in the catchment. However, a 25 m pixel size was too coarse to capture precisely hazards at house scale in the catchment lowlands, or effects of large wood jams or the protection efficacy of the measures planned to be studied in the lowlands. That is why the focus on the lowlands was performed with another more accurate tool, i.e., the 2D model. A satisfying calibration of both models was performed on the Oct. 2015 event (Fig. 13.3, details in Gnonlonfin et al. 2019). For instance the computed value of runoff-related damage at catchment scale in current situation is only 2% higher compared to the actual damage observed on Oct. 2015.

Both models computed the spatial distribution of hazard intensity of either historical events (e.g., Oct. 2015 flood) or theoretical events of known time return (e.g., 20 years, 100 years and 500 years). They were then coupled with methods to compute the related damages. In a second stage, models were tuned to include protection measures (see later) and re-run to assess the related avoided damages.

13.3 Evaluation of Protection Strategies

13.3.1 Tailoring Protection Strategies

The design of strategies was inclusive to integrate different knowledge from stakeholders. Stakeholders represent all the actors whose interests can be affected, positively or negatively, by the strategies. They include public actors, representatives of civil society (institutional stakeholders) and the population (individual stakeholders). In a first step, the design of strategies has aimed for the integration of experts and institutional stakeholders' knowledge. The strategies were defined by INRAE (previously Irstea) during years 2017 and 2018 based on:

- (i) Past engineering reports, previously planned measures and actually implemented measures, e.g., on the tributaries of the Brague called Vallon des Combes and Vallon des Horts;
- (ii) Feedbacks from Oct. 2015 and Nov. 2011 events on suitability of existing works and problems related to large wood;
- (iii) Five stakeholders workshops that were organized by Univ. Côte d'Azur where needs, possible protection measures and policies were debated; and
- (iv) Expert knowledge trying to tailor to the catchment peculiarities these local knowledge with the know-how and state-of-the-art in design of NBS and flash flood protection.

In a second step and in the perspective to integrate individual stakeholders' knowledge and preferences, alternative protection strategies were proposed by 405 citizens during a survey performed by Univ. Côte d'Azur on 2019 (see later).

It was first envisioned to rely on water retention measures, i.e., flood retention basins and small natural water retention measures. The total rainfall volume related to the Oct. 2015 event on the Brague catchment was about 8.6 Mm³, more than half of it flowed to the sea within the event (Préfecture des Alpes-Maritimes 2016). A quick analysis was performed using the FEV (Flood-Excess-Volume) framework of Bokhove et al. (2019, 2020). It enabled estimating the cumulated retention volume that would be necessary to protect Biot and Antibes. For an equivalent event, the FEV would be 1.3–2.7 million m³ at the catchment scale (see detailed estimation for a subcatchment in Bokhove et al. 2019).

During stakeholder workshops, citizens asked that classical flood retention dams be studied. It would represent quite large structures considering the retention volume required. This option became strategy Grey #2 (see later) and was studied objectively to be compared to NBS strategies. Storing the FEV in smaller natural areas requires room: 1.3–2.7 million m³ is equivalent to a lake, 2-m deep, with a square shape of side length 800–1160 m. This virtual object helps assimilating the huge excess of water during extreme flash floods and is to be compared with the catchment topography. The conclusion is straightforward: if huge dams are not used, there is no room in the catchment to store such a great amount of water, as a whole or split in smaller volumes.

An inventory of areas eventually suitable to implement natural water retention measures (NWRM – Strosser et al. 2015) in the Brague catchment was reviewed (Fig. 13.4). Then, hypothesis regarding the average water depth that could be stored in each measure were performed (Gnonlonfin et al. 2019). It provides a first order estimate of the cumulated retention volume of all NBSs and existing retention dams. Overall, about 100 ha have a high potential to host NWRM and more than 200 ha should be further studied but could also be relevant sites. On these more than 300 ha, it seems reasonable to plan buffering at least 100,000 m³ of water and up to 3–5 times this volume providing that all potentially viable areas would be used.

In essence, the potential of retention by NBS varies in the range 0.1–0.5 million m³ while extreme flood events involve excess of several millions m³. These first order estimates merely demonstrate that upstream retention by NBS could be non-negligible but is certainly not sufficient to manage the flood and runoff risk: increasing channel capacity in the lowlands would also be necessary.

In addition, measures should be taken to prevent adverse consequences of NBS side effects, e.g., wilder rivers means more large wood in river channels during floods. Hybrid, i.e., green – grey strategies were consequently thought to be the most suitable for flash flood-prone rivers. Regarding grey measures, the most promising were:

- Replacement of existing bridges prone to trigger large wood jams or high back-water; and/or
- Racks to trap large wood during floods upstream of bridges likely to be clogged;
- Retention dams with large outlets enabling the reservoir to be dry in normal time and to fill only for severe floods, i.e., higher than 10 years return period events.

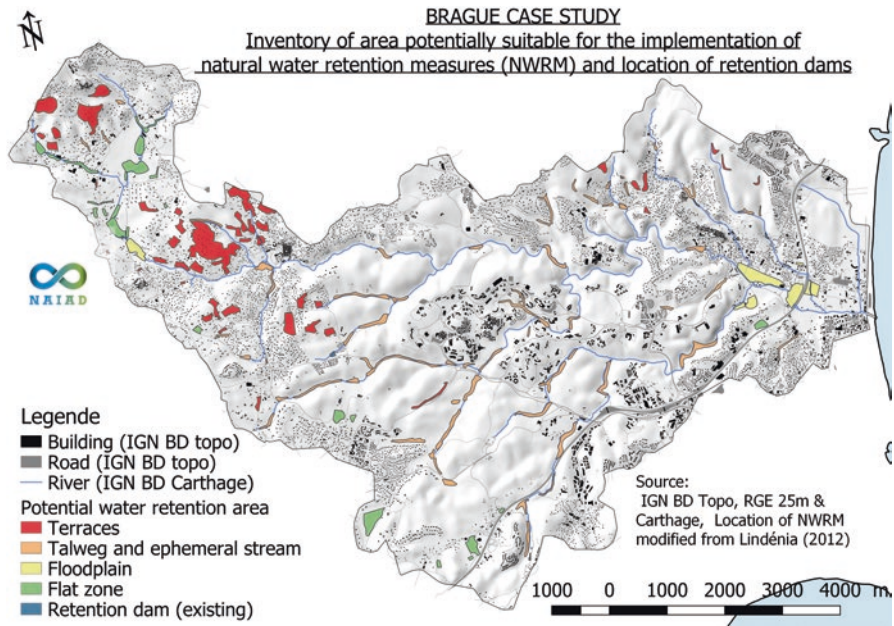


Fig. 13.4 Map of areas suitable to implement retention measures (grey or NBSs) (Source: adapted from Lindénia 2012)

Regarding green measures, the most promising were:

- Small NWRM implemented in flat lands that would be transformed in wetlands and in talwegs were leaky dams could be built;
- An integrated floodplain management called “giving-room-to-the-river” gathering river channel widening, aquatic and riparian vegetation restoration, restoration of secondary arms and small tributaries connecting the main channel bed to restored wetlands in the floodplain.

During stakeholders workshops and a survey performed in the catchment in 2019, citizens were asked to choose between various ambitions of using green or grey measures (Arfaoui and Gnonlonfin 2020a). Four strategies were proposed (Table 13.1 and Fig. 13.5):

- Grey #1 was simply the building of large wood traps;
- Grey #2 was the wood traps plus very large retention dams on the two mains sub-catchments;
- NBS #1 merged NWRM and a scenario giving-room-to-the-river on its current axis;
- NBS #2 was based on NBS #1 but more ambitious by adding a large bridge on the highway to prevent the clogging of the current culverts and also moving a road located along the river further in the floodplain to reconnect several natural patches.

Table 13.1 Summary of measures implemented in each strategy

	Grey #1: Large wood traps	Grey #2: Large retention dams	NBS #1: <i>Reopening a river corridor</i>	NBS #2: <i>Restoring an integrated floodplain to the river</i>
Principle	Preventing bridges to be clogged by large wood transported during floods and aggravating flood levels	As Grey #1 plus building of two large flood control dams on the Brague River and Valmasque River. The dams are design to store the Oct. 2015 flood hydrograph	Implementing small natural water retention measures in the upper part of the catchment and giving-room-to-the-river in the lowlands by widening the bed, restoring the riparian forests and wetlands	As NBS #1 plus removing more lateral and longitudinal constraints (road, highway culverts), recreating a wide natural bed in the central natural area of the lowlands
Key measures	Building of 5–7 racks made of steel pipes with space 2–3 m between each other, 2–5 m high above ground level and founded deep in the sediment. Creating pedestrian paths out of private lands. No building expropriation required.	Flood control dam on the Brague River: retention capacity 880,000 m ³ . Outlet letting normal flows pass, up to the 10 years return peak discharge; Flood control dam on the Valmasque River: retention capacity 560,000 m ³ . Outlet letting normal flows pass, up to the 10 years return peak discharge; 200 m of dikes to build on the Brague River right bank, close from the train line. No building expropriation required.	Small natural retention areas, cumulated area ≈ 200 ha 10–40 m of widening of the Brague river bed; Restoring riparian forests (13 ha); 3 bridges to demolish and rebuild wider and without central pile (bridge Brejnev, bridge Murator and golf course first pedestrian bridge); 3 bridges to demolish and rebuild wider and without central pile (bridge Brejnev, bridge Murator and golf course first pedestrian bridge); 5 Large wood trapping structures on the Brague River (3) and Valmasque River (2), height above ground level: 2–5 m; 20 ha of wetland restoration; 55–75 demolitions of houses; Continuous bicycle tracks along all banks. Building a new high bridge for the highway #A8 and create a second channel in the natural central part of the floodplain with better connectivity with wetlands; Removing and rebuilding further from the river 1.4 km of the departemental road RDS04 between roundabouts of route des Colles (access to Sophia-Antipolis) and of chemin de la Romaine (Pont Brejnev); rebuilding behind the golf course at the hillslope toe and through or close to the quarry.	Small natural retention areas, cumulated area ≈ 200 ^{ha} 10–40 m of widening of the river bed; Restoring riparian forests (13 ha); 3 bridges to demolish and rebuild wider and without central pile (bridge Brejnev, bridge Murator and golf course first pedestrian bridge); 5 Large wood trapping structures on the Brague River (3) and Valmasque River (2), height above ground level: 2–5 m; 20 ha of wetland restoration; 55–75 demolitions of houses; Continuous bicycle tracks along all banks. Building a new high bridge for the highway #A8 and create a second channel in the natural central part of the floodplain with better connectivity with wetlands; Removing and rebuilding further from the river 1.4 km of the departemental road RDS04 between roundabouts of route des Colles (access to Sophia-Antipolis) and of chemin de la Romaine (Pont Brejnev); rebuilding behind the golf course at the hillslope toe and through or close to the quarry.

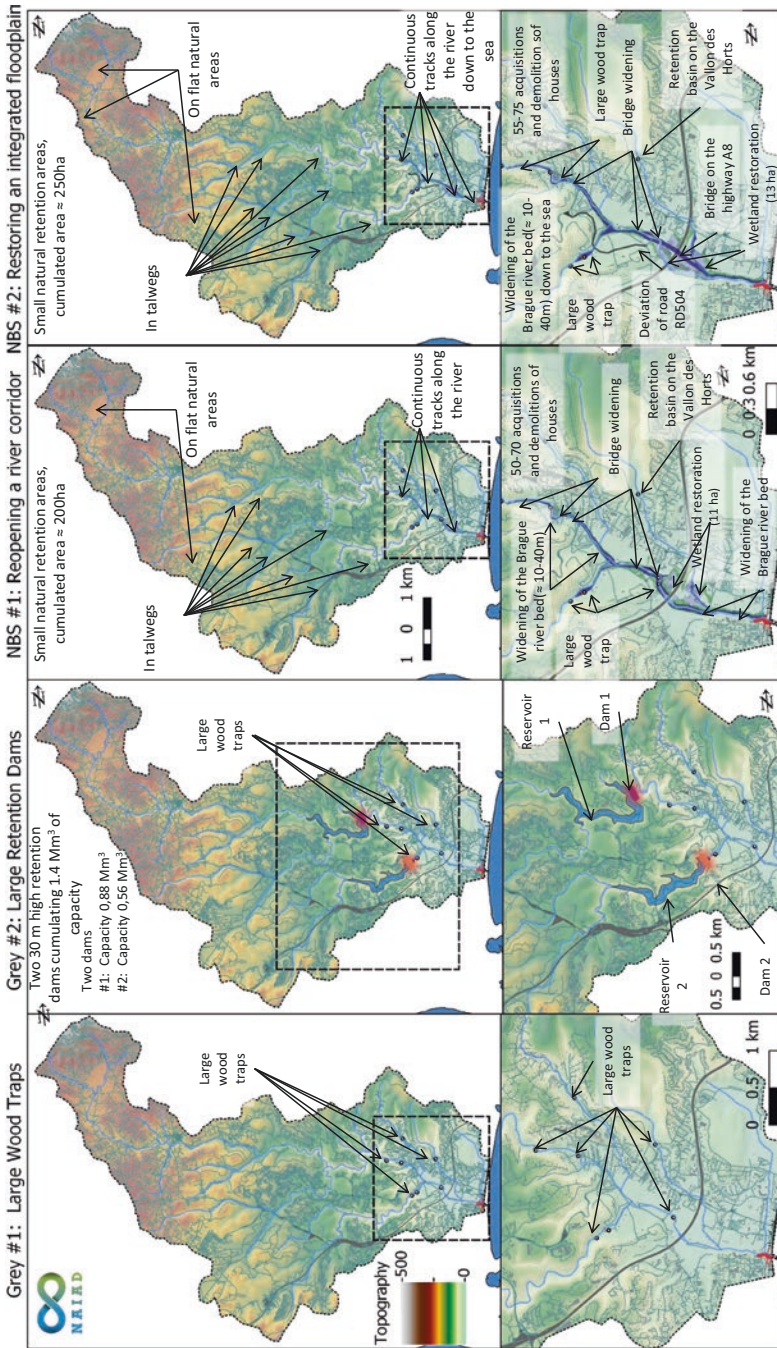


Fig. 13.5 Maps of the four strategies. (Source: IGN BD Carto, BD Topo and BD Alti)

Table 13.2 Discounted costs of strategies of a 50 years lifetime: mean (min; max)

Strategy	Grey #1: Large wood traps	Grey #2: Large retention dams	NBS #1: Reopening a river corridor	NBS #2: Restoring an integrated floodplain to the river
Investment [M€]	3.6 (2.5; 5.4)	171 (89; 270)	76 (56; 128)	119 (90; 206)
Maintenance [M€]	3.7 (2.8; 4.7)	105 (63; 147)	4 (3; 5)	4 (3; 5)
Total [M€]	7.3 (5.3; 10.1)	66 (26; 123)	80 (59; 133)	12 (3; 211)

13.3.2 Costs of Strategies

Table 13.2 presents the costs of the four strategies over a 50-year life cycle (see guidelines in Chap. 6 – Le Coent et al., [this volume](#)). The cost estimates were made from a literature review and local surveys. They comply with the national recommendations, including a 2.5% discount rate (Langumier et al. 2014; CGDD 2018). These costs include investment and maintenance costs. The investment costs include: (i) the costs of acquisition and compensation of the land and residences affected estimated from the market price of real estate (PERVAL database, prices of 2018) and (ii) the costs of studies and works. Maintenance costs include estimates of maintenance and repair costs. Due to the uncertainties in the cost estimates, three values are provided: an average followed by a lower and upper bounds. The details of the costs estimations can be found in Gnonlonfin et al. (2019).

13.3.3 Estimating Physical Efficacy for Hazard and Risk Reduction

13.3.3.1 Protection Efficacy of Small Natural Water Retention Measures

A computation was performed with the catchment-scale model to study the effect of upstream retention in reducing damages. Modelling accurately NWRMs in the catchment-scale model with its 25 m size pixels was complicated. A simpler inverse procedure was thus followed: runoff coefficients were reduced, the model on the Oct. 2015 event was then run and it was checked how much overall damages were reduced (Fig. 13.6).

This straightforward analysis was performed to check how much should the runoff be reduced (whatever be the measures to do so) to reduce the runoff-related damage by a certain amount. It was actually performed through the runoff coefficient, i.e., a virtual way to say that more water is retained in the catchment. It was concluded that a reduction of 20% of runoff reduced insured damages by $\approx 7\%$ while a reduction of 50% of runoff reduced insured damages by 45%. The conclusion of this modelling is consistent with the FEV analysis stressing that if upstream

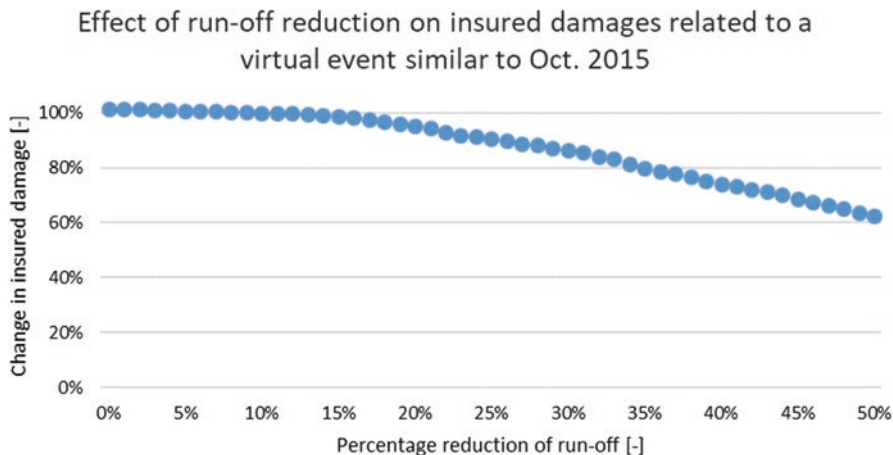


Fig. 13.6 Effect of hazard reduction (reduced runoff coefficients) in case of Oct. 2015-type runoff events on insured losses for residential homeowners of the Brague River catchment

retention measures can be useful, they are not sufficient to achieve satisfying protection needs.

It is worth being stressed that the numbers provided in Fig. 13.6 are not mean annual values but values related to the Oct. 2015 event, which was rather extreme. The protection efficacy would be higher for events of smaller magnitude but this analysis was not performed.

13.3.3.2 Protection Efficacy of Large Dams and Giving-Room-to-the-River

Strategies Grey #2 (large dams) and NBS #1 emerged early in the project, during 2017, and were studied with more advanced models (Iber flood model and CCR runoff model). Strategy Grey #1 came out during the survey performed during autumn 2019, its protection efficacy was assessed by expert knowledge. Strategy NBS #2 also emerged during discussion with stakeholders in 2019. It could not be modelled as accurately as NBS #1 and its performance is also partially based on expert assessment.

The estimation of the avoided damages followed the standard protocol recommended by the French state (CGDD 2018 and Chap. 6, Le Coent et al., [this volume](#)):

- (i) Modeling of the flood levels related to several flood events of known return period, this, in the current state and with protection strategies;
- (ii) Assessment of damage to buildings using damage curves, i.e., relationship between damage and hazard intensity (e.g., flood level) for each asset;
- (iii) Estimate of the mean annual avoided damage by difference between the mean damage in the current state and that assuming the strategy implemented.

Several damage curves provided by French guidelines and calibrated by CCR were used to provide low, medium and high damage estimates (Table 13.3).

One could be surprised that both Grey #2 and NBS #1 strategies only reduce damage by roughly one third. As the works to be carried out are extensive, the modelled reduction of 30% is less than expected. Figure 13.7 shows areas where significant influence on flood level are modelled with the proposed works in the NBS #1 strategy (results are quite similar with Grey #2 works). Cautious inspection of the model results demonstrate that although flow level are effectively reduced in the upstream area (green zone on Fig. 13.7), numerous assets are also located in the downstream part of the lowlands where the studied works have much less influence. There are several reasons to this situation, reasons that should be used later to optimize the strategies:

Table 13.3 Damage per events and mean annual (avoided) damage

Scenario	Current situation			Grey #2			NBS #1		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Damage related to $Q_{20\text{years}}$ [M€]	6.0	15.0	23.2	4.9	12.1	19.0	4.1	10.2	16.1
Damage related to $Q_{100\text{years}}$ [M€]	11.4	27.5	42.5	7.0	17.2	26.8	7.2	17.5	27.8
Damage related to $Q_{500\text{years}}$ [M€]	15.4	37.2	52.4	9.8	23.8	37.4	12.1	29.3	43.0
Mean annual damage [M€]	0.6	1.6	2.4	0.5	1.1	1.7	0.4	1.1	1.7
Mean annual avoided damage [M€]				0.2	0.5	0.7	0.2	0.5	0.7
Avoided/mean annual [-]				30%	29%	28%	32%	32%	31%

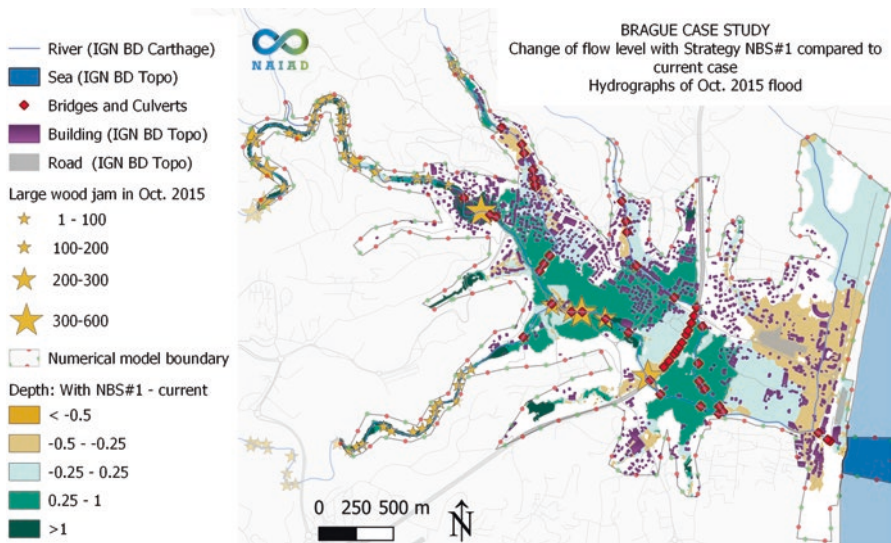


Fig. 13.7 Changes in flood level with NBS#1 compared with current case. Large wood jam observed in Oct. 2015 are assumed trapped by large wood trap in NBS #1 strategy. Color code depends on decrease or increase of water depth

- Most measures being located on the main stems of the Brague River and its Valmasque tributary, flows coming from the numerous small tributaries are still present and generate their share of damage;
- The culverts at the highway A8 and the bridge constraining the river width at the sea mouth (and their associated backfill) are key bottleneck sections on the Brague main stem. They dam the flow and slow down the lowland drainage. Thus even though the upstream and eventual downstream sections of the river are widened, remaining bottleneck sections trigger extensive backwater and dramatically reduce the flood hazard protection efficacy.

Strategies Grey #1 and NBS #2 were not studied in such details. Based on the knowledge gained during the project on the river functioning, we consider that Grey #1 can only very locally reduce flooding. Consequently, its effect on damage reduction is considered to be negligible: the areas where flood level would be reduced are spatially limited and limited to the close vicinity of bridges and culverts.

NBS #2 is more ambitious than NBS #1 in terms of removing barriers formed by road networks. It should be optimized at a later stage to address the previously mentioned bottleneck section near the sea mouth (the other one at the highway if fixed by a new large bridge). The railway and roads bordering the coast actually dam the valley. This is the main reason of the aggravated flood level in the downstream area (orange zone in Fig. 13.7). These obstacles should be equipped with several discharge structures or culverts to prevent this side effect of a higher channel capacity upstream. The cost related to these structures were not included in estimates of Table 13.2. Although removing the barrier related to the highway culvert will reduce flood levels in the upstream part of the lowlands, it is difficult to predict how downstream flood levels will change. They will likely decrease if sufficient discharge capacity is found through the railway and road backfills but we cannot be sure without further detailed modelling. The avoided damage for NBS#2 are consequently not accurately estimated, just expected to be higher than for NBS#1.

It is worth noting that, a dual strategy combining the strategies Grey #2 and NBS #2 was proposed by citizens during the survey. Large civil engineering structures degrading nature in forested parks upstream of an ambitious project of river restoration seem a bit inconsistent. In France, it is now mandatory both to protect river environment and to mitigate flood risks in projects to be consistent with the EU Water Framework Directive and the EU Flood Directive (somehow merged in the “GEMAPI law”, see Marchal et al. [this volume](#); Vigier et al. 2019). This dual strategy cannot be considered an integrated strategy because the environmental alterations related to the large dams would only be partially offset by the environmental improvements associated to strategy NBS #2. Its protection efficacy would conversely be higher than each strategy taken alone. The issue related to the flows coming from the small tributaries would nonetheless remain but the main stems would be much less prone to flooding. Overall, the avoided damages would be higher than the 30% computed for each single strategy but would not reach 100% of the 1.6 (0.6; 2.4) M€/year (mean (min; max)).

13.3.4 *Co-benefit Estimations*

Two different methods were used and compared to estimate co-benefits: a top-down approach based on the transfer of values published in literature and a bottom-up approach based on a survey.

13.3.4.1 **Top-Down Approach**

A benefit transfer method developed by Arfaoui and Gnonlonfin (2020b) was used to estimate the economic value of the co-benefits of environmental restoration. For this, a meta-regression of 49 studies of restoration of river ecosystems, conducted from 1996 to 2018 in Europe, East Asia and America, was carried out. A value transfer function from NBS strategies and their co-benefits was built upon an analysis of 187 values of willingness to pay (WTP) for ecological restoration measures. Input parameters are (i) the type of measures implemented (management of the riparian forest, restoration of the river bed, restoration of the floodplain, agricultural practices), (ii) the ecosystem services provided by the strategies and (iii) an indicator of the ambition of the project (normal or strong).

The estimation of the value of co-benefits in the different strategies at the scale of the Brague basin was estimated by WTP per year and per household. The methodological variables and the co-benefits were set at the average value of the database and the upper and lower bounds were estimated through the uncertainty of the statistical adjustment whose correlation coefficient was $R^2 = 0.38$. For strategy NBS #1 and NBS #2, the resulting WTPs were 28 (2; 353) and 75 (4; 608) €/household/year (mean (min; max)), respectively. Grey strategies are not restoration strategies and have consequently no co-benefits.

13.3.4.2 **Bottom-Up Approach**

Unlike a top-down approach, the bottom-up approach incorporates additional knowledge from different stakeholders on a representative scale. In this perspective, our approach follows the three conditions recommended by Carolus et al. (2018): (i) definition of strategies by local stakeholders, (ii) participation of key players concerned by the environmental problem and (iii) relevant geographic scale.

Key stakeholders represent all the actors whose interests can be affected, positively or negatively, by the strategies. We distinguish public actors, representatives of civil society and the population. With semi-structured interviews and focus groups conducted between July 2017 and December 2018, stakeholders participated in the identification of co-benefits and in the preparation of the survey questionnaire. The survey was conducted face-to-face from September 6, 2019 to October 15, 2019 in a representative sample of 405 people (Gnonlonfin and Douai 2019; Arfaoui and Gnonlonfin 2020a). Respondents were recruited using a random

sampling procedure in public places in order to independently respect three representativeness criteria: geographic location, gender and age.

The survey aimed at evaluating the WTP for strategies using the contingent valuation method in the perspective to measure the social preference for NBS and/or grey strategies and the willingness of the population to financially contribute to their implementation. For the sake of simplicity and because of the method constraints, both the risk reduction effect and co-benefits related to environmental and life quality improvement were merged in this WTP estimate.

Respondents were first asked to select their preferred level of ambition in the two strategy categories (grey and NBS). Respondents were informed about the level of socio-economic costs (investment and maintenance, expropriation and demolition of houses) and the ranges of potential benefits of all the measures (reduction of the risk of flooding and co-benefits). In a second step, the respondents had to indicate, on the one hand, whether they were willing to financially contribute for the preferred strategy and, on the other hand, to express their level of “bounded WTP” to take into account uncertainties related to the purchasing decision (Pondorfer and Rehdez 2018). In addition, respondents who refused to contribute financially were asked to justify their choice in order to identify the protest responses.

The survey demonstrated the preferred strategies were (Table 13.4): NBS #1 for 44% of respondents, Grey #1 (28%), and NBS #2 (10%). No respondent prefers the Grey #2 strategy alone but 18% of respondents preferred that all measures be implemented to the highest possible ambition, i.e., that both Grey #2 and NBS #2 be done. We also observed that 69% of respondents refuse to contribute financially to their preferred strategy. However, the analysis of the reasons justifying this refusal showed that 31% were responses to protests linked to local governance and the methodology of the survey (Gnonlonfin and Douai 2019). This rate is similar to those reported in the literature (Meyerhoff and Liebe 2010). The Heckman (1976) model was used to correct the selection bias and predict the empirical mean of the WTP (Table 13.4).

13.3.5 Cost-Benefit Analysis (CBA) to Assess Strategy Efficiency

The WTP estimated by both approaches were aggregated at the scale of the watershed considering 28,874 households (INSEE database, inventory of 2014).

Table 13.4 Preferences and willingness to pay per strategy in euros/household/year according to the bottom-up estimated by survey

Strategy	Grey #1	Grey #2	Grey#2 + NBS#2	NBS #1	NBS #2
Preference rate	28%	0%	18%	44%	10%
Willingness to pay: mean (min; max) in €/household/year	57 (31; 81)	0	156 (63; 240)	83 (31; 125)	116 (2; 173)

Table 13.5 Cost benefit analysis on a 50 year time window: **mean estimate** [min; max]

Strategy	Costs	Top down analysis			Bottom-up analysis	
	Total costs (M€)	Avoided damage (M€)	Co-benefits by transfer method (M€)	B/C (-)	Contingent analysis of total economic value (M€)	B/C (-)
GREY #1	7	≈ 0	0	≈ 0	47	6.7
	[5; 10]				[25; 66]	[2.5; 13.2]
GREY#2	170	13	0	0.1	0	0
	[88; 271]	[5; 19]	[0; 0]	[0; 0.2]		
GREY#2 + NBS#2	294	<45	≈ 0	<0.15	128	0.4
	[182; 481]				[57; 200]	[0.1; 1.1]
NBS #1	80	14	23	0.5	68	0.9
	[59; 132]	[6; 21]	[6; 34]	[0.1; 0.9]	[25; 103]	[0.2; 1.7]
NBS #2	122	14+	40	>0.4	95	0.8
	[93; 211]	[6+; 21+]	[3; 498]	[>0.1; >5.6]	[51; 142]	[0.2; 1.5]

Table 13.5 summarizes the cost-benefit estimates over a 50-year period and presents the benefit/cost ratios (B/C) in the two approaches. With the exception of the bottom-up estimate of the Grey #1, all strategies have an average values of B/C < 1. Strategy Grey #1 has a relatively low cost. Its supporters gave quite high WTP for it, thus its high B/C ratio. To the opinion of the authors, this result is related to an overestimated protection efficacy of large wood trap in the perception of local citizens. The trauma related to large wood obstructing bridges on October 2015 was often reported during interviews and stakeholder workshops.

Avoided damage are in any case much lower than total costs. Financing the works just based on the risk reduction potential appears to be economically inefficient. Co-benefits actually weight more in the cost-benefit balance. They consequently deserve effort to quantify them. It is worth stressing that estimation of the WTP varies greatly depending on the method used. Much higher WTP values were provided in the preliminary analysis of Gnonlonfin et al. (2019) resulting in ratio B/C > 1 for both NBS strategies. The key difference was that we used the results coming from stakeholder workshops, i.e., the list of ecosystem services that stakeholders considered relevant in the catchment. On the contrary, values in Table 13.5 were computed assuming a fully top-down analysis performed without stakeholder workshops. Using such an approach decreases dramatically the weight given to ecosystem services and consequently the WTP. In essence, the transfer method used in the top-down approach is highly sensitive to stakeholder feedback: if ecosystem services are reported to be important in the citizen perception, the computed WTP might be multiplied by 3–5.

Another parameter that could be discussed is the number of households considered. The rigorous way to determine it would be by estimating the critical distance from the site above which households no longer benefit from the project. We had neither time nor funds to gather sufficient data to do so. In such case an area has to

be chosen somewhat arbitrarily. Administrative limits are usually considered in the literature (Logar et al. 2019). Computing the social benefit at the scale of the 11 municipalities intersecting the Brague basin would increase the number of households and thus the co-benefit estimates by a factor 3.4. This would result in a $B/C > 1$ balance for the NBS strategies in the two approaches. We used the conservative assumption that only households residing within the catchment geographical limit represents the population impacted by the strategies, thus ignoring the large population visiting the catchment to work, hike, play golf, camp or come in the parks. The level of aggregation of social benefit is therefore determinant for the output of a CBA.

13.4 Lessons Learnt and Replication/Scaling/ Re-scaling Issues

13.4.1 *Should We Perform Top-Down or Bottom-Up CBA or Both?*

One can wonder if it is worth performing all these modelling if a survey is sufficient to provide elements to perform a CBA. We think that both approaches worth being performed because elements on avoided damages and co-benefit in the light of a standard method or based on local perception are used to aid several different decisions taken nationally, regionally and locally.

The top-down CBA first covers the risk reduction by demonstrating the impact of strategies on risks without taking into account local perceptions. It is used by the French State, in addition to other criteria, to decide whether or not the strategy can be funded with the Barnier Funds (a national fund for natural hazard protection, see Chap 3 – Marchal et al., [this volume](#); CGDD 2018). The top-down approach also allows to provide economic value to environmental impacts (highly uncertain but useful in some contexts, see Kallis et al. 2013) and to provide additional information for the decision-making of regional actors such as the Water Agency, whose financing decision relies on the environmental impact of strategies.

Our results show that, from a top-down perspective, no strategy is worth the investment from an economical point of view. Therefore, other criteria e.g., safety or indirect damage to the environment, will be decisive in the financing decision under the Barnier Funds (CGDD 2018). Economical valuation of co-benefits are not as standardized as for avoided damages. So far, the Water Agency relies more on other criteria related to environmental quality and restoration potential of strategies to support and finance strategies (e.g. Piton et al. 2018b). It can also be noted that other frameworks such as multicriteria decision-making methods have been developed to aid decisions on such situation involving multiple benefits and values. It allows for instance to consider global effectiveness of NBS combining e.g.,

physical, environmental, economic and social values. The implementation should be based on a close collaboration with stakeholders (Philippe et al. 2018; Tacnet et al. 2018, 2019). In this case-study application, the process was not advanced enough to implement it in practice but it will be possible to implement the methodology if needed in the future.

Conversely, the bottom-up approach provides information on local perception and the social acceptability of the strategies. The basin agency, in charge of the river management is responsible of both risk reduction and river restoration. The recent GEMAPI law enables basin agencies to raise a tax of a maximum of 40 €/person/year to finance their mission of managing watercourses. The survey provides information on the social acceptability of the tax. It gives clues on (i) the strategies for which the local population is ready to contribute financially and (ii) the amount of the socially acceptable contribution. Indeed, the median WTP is considered to be a good indicator of the acceptable financial contribution for the majority of the population (OECD 2018). For the Brague case study, the WTP for the sole Grey #2 strategy is null highlighting the social unacceptability of a financial contribution for this strategy despite its benefits as avoided damage. On the other hand, the median WTP (lower than the mean values provided in Table 13.4) are estimated at 27 (7; 47) €/household/year for the strategy NBS#1 (uncertainty range between brackets); 75 (38; 100) €/household/year for the strategy NBS#2 and 59 (8; 100) €/household/year for the dual strategy Grey#2 + NBS#2, i.e., 0.8–2.1 M€/year at the catchment scale. Basin agency have thus potentially significant funding opportunity, although the support of other actors as the French State and the Water Agency are still necessary.

Hence the three key partners with financial power, namely the regional Water Agency, the State, and the local basin agency need three assessments, namely avoided damages, environmental restoration ambition and local perception of both for each of them to take the decisions to support a given strategy.

13.4.2 Evidence of the Importance to Give Room to Rivers Prone to Flash Floods

A broad lesson learnt on this case study is that, in rivers hit by Mediterranean thunderstorms of high magnitude, even high ambition on retention measures in the upper and mid-catchment is insufficient to prevent flooding of downstream lowlands. Therefore, a sufficiently large corridor must be maintained for such rivers to convey flows down to the sea or to the downstream bigger river. Such corridor can be natural and/or comprise several flood resilient activities; however, built assets in those corridors create long lasting constraints. Stakeholder involvement and news in media demonstrate that people working and living there, initially not informed or unaware of the risks, regret that the authorities enabled them to settle. Then,

protecting such areas is extremely expensive and regularly not feasible regarding high magnitude events. Buying such assets to remove them is another very expensive solution.

Maintaining on the contrary large corridors is certainly more resilient and provide numerous co-benefits. From a broader point of view, evidences of physical effectiveness and limits of NBS appeared as an essential criteria for their mainstreaming. NBS have co-benefits but their real physical effect on hazards reduction (storing a water volume, reducing runoff) had first to be demonstrated before moving to decision-aiding approaches such as economic approaches presented above. That is why some modelling is usually required to demonstrate the rational in the ambition of the strategy compared to the magnitude of the flooding. The FEV approach is a simple yet powerful tool to do so (Bokhove et al. 2019, 2020).

13.5 Conclusion

This chapter synthesizes some conclusions of 3 years of work involving five multidisciplinary research teams. Stakeholder participation through workshops and surveys helped us to define several protection strategies against flash floods in the Brague River catchment. A multi-scale modelling approach was implemented to compute flood hazards at the catchment scale and in the lowlands with a higher accuracy. The effects of NBS and grey measures involved in the various strategies were assessed in term of hazard reduction and avoided damages through model tuning. Total costs of each strategies were evaluated as well as co-benefits. Co-benefits were both locally assessed by survey (bottom-up approach) and valued using transfer functions (top-down approach). Cost benefit analysis were performed using both the top-down and the bottom-up approaches. Both are useful because they provide different perspectives usable by the great variety of stakeholders involved in flood risk and river management, notably the local basin agency, the regional Water Agency and the French State.

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