Is-it worth investing in NBS aiming at reducing water risks? Insights from the economic assessment of three European case studies

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Philippe Le Coent[a,*], Nina Graveline[b], Monica A. Altamirano[c], Nabila Arfaoui[d], Camilo Benitez-Avila[c], Thomas Biffin[e], Javier Calatrava[f], Kieran Dartee[e], Ali Douai[g], Amandine Gnonlonfin[h], Cécile Hérivaux[i], Roxane Marchal[j], David Moncoulon[j], Guillaume Piton[k]

[a] G-EAU, BRGM, University Montpellier, Montpellier, France
[b] Innovation - University of Montpellier - INRA, CIRAD, Montpellier SupAgro, Montpellier, France
[c] DELTARES, Delft, The Netherlands
[d] Catholic Univ. of Lyon, ESDES, Lyon, France
[e] Field Factors - 3016CH Delft, The Netherlands
[f] Universidad Politécnica de Cartagena, Cartagena, Spain
[g] Groupe de recherche en droit, économie et gestion (GREDEG), Université Côte d'Azur, CNRS, Sophia Antipolis, France
[h] IMREDD, Université Côte d'Azur, Nice, France
[i] G-EAU, BRGM, University of Montpellier, Montpellier, France
[j] Caisse Centrale de Réassurance, Paris, France
[k] Univ. Grenoble Alpes, INRAE, ETNA, Grenoble, France

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ABSTRACT

Economic narratives are largely put forward as an argument for the promotion of Nature Based Solutions (NBS). However, integrated economic evidence, taking into account direct and opportunity costs, avoided damages and the multiplicity of co-benefits generated by NBS are still needed to support this argument and convince decision makers to invest in these solutions. To address this gap, we develop a methodological framework for the economic assessment of NBS for water related risks and present its application to three European case studies. We find that the cost of implementation and maintenance is lower for NBS strategies than for grey solutions for the same level of risk reduction, thereby confirming the cost-effectiveness advantage of these solutions. Benefits in terms of avoided damages are however generally not sufficient to cover these costs. Co-benefits represent the major share of the monetary value generated by NBS strategies. Finally, the results of the cost-benefit analysis reveal context-specific results on the overall economic efficiency of NBS. These results urge decision makers to tailor funding strategies to the specificity of NBS economic value.

Introduction

In Europe, climate change is expected to increase the frequency of extreme weather events. The IPCC indeed predicts that annual damages due to climate risk will rise by 77% in 2030 (IPCC 2014). Water related risks will be particularly affected with an increased occurrence of droughts and floods. For example, the number of centennial floods is expected to double in the next three decades [3]. Engineered solutions or so-called grey infrastructure (e.g. floodwall) have been historically largely used to manage flood risks. The reliance on these solutions has nevertheless showed limits: limited adaptability in front of the expected modification of risks due to climate change [41], adverse environmental effects through the modification of ecosystems [54], the limited capacity of sewer systems to manage urban flooding with negative effects on water quality and the transfer of flood management risk downstream [30,60] and the tremendous investment and maintenance costs they generate [58].

There is a growing recognition and awareness that nature can help provide protection to humans through risk reduction properties of ecosystems [5,14,32]. The EU Floods Directive of 2008 already opened the way for more integrated flood management and a plurality of measures including the resort to Nature-Based-Solutions (NBS). River restoration, the restoration of wetlands and flood plains in rural context and a number of green infrastructure in urban contexts such as

* Corresponding author.
E-mail address: p.lecoent@brgm.fr (P. Le Coent).

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bioswales, green roofs, and vegetated open retention basins are increasingly considered as alternative or complementary solutions, to manage flood risks. Besides their impact on water risks, ecosystems generate a wide diversity of ecosystem services essential to human life, understood as the benefits people obtain from ecosystems [35]. Recently in urban contexts, the need for services provided by ecosystems, has been increasingly highlighted [51]. For example, urban trees included in many NBS for water risks have been estimated to have an impact on carbon storage and sequestration. An estimated 2,367,000 tonnes (approximately 15t/ha) of carbon is stored in London's trees [52]. Zinzi and Agnoli [61] estimate a 10-14% energy saving for buildings with green roofs in Barcelona due to reduced heating in winter and cooling effect in summer. Aevermann and Schmude [2] provide a review of amounts for air pollution removal associated with urban green ranging from 1.97 to 3.80 g/m^2/yr of O_3. Other examples of ecosystem services generated by NBS include twater cycle regulation, the creation of new habitats for biodiversity and recreational services [26]. The need for these services is expected to become even stronger in the context of climate change, with for example the expected increase in occurrence of heat waves [28,37]. However, the production of these services is increasingly threatened due to the degradation of ecosystems resulting from urban sprawl, pollution and climate change.

The terminology used to denominate these solutions is diverse: *ecosystems based adaptation, green infrastructure, ecosystem based disaster risk reduction, natural water retention measures* [32] and *sustainable urban drainage systems (SUDs)* [19]. More recently, the concept of *Nature Based Solutions* (NBS) has gained momentum. NBS can be considered as an umbrella term for these approaches that is defined by the EC[1] as "solutions to societal challenges that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience".

Interestingly, the economic advantage of NBS is generally assumed, as in the EC definition, with limited evidence to support this "fact". The economic assessment of NBS is however a key step in the evaluation of NBS. Indeed, assessing the value of costs and benefits of NBS and being able to compare them to alternative strategies such as business as usual grey solutions is fundamental for decision makers to develop these solutions and eventually turn them into implementable projects. The limited adoption of NBS aiming at reducing water risks may actually be attributed to uncertainties regarding their economic performance, as in the case of SUDs [47,53]. Some evidence mainly focused on SUDs actually show that risk reduction benefits may often not exceed the costs they generate [30,33,34,47]. But one particularity of NBS is their capacity to generate a multiplicity of co-benefits [51], such as biodiversity conservation, water availability and quality, air pollution, the regulation of air temperature. Economic assessment frameworks that accounts for the multifunctional impacts of NBS are thus required. The aim of this paper is to develop this framework for the economic assessment of NBS including specific methodologies to assess costs and benefits. We then apply our methodology to three case studies of the H2020 "NAture Insurance value: Assessment and Demonstration" (NAIAD) project, two in France and one in the Netherlands, in order to bring new evidence on the economic efficiency of NBS projects.

The cost-benefit balance of NBS for water-related risks requires the comparison between the cost of implementing and maintaining these solutions, and their opportunity costs, with the multiple benefits they generate: i) the cost of damages they prevent due to the reduction of water risks and ii) the co-benefits they provide. The evaluation of benefits of these NBS therefore calls for the combination of state of the art methods for the estimation of flood damages prevented by NBS solutions with methods for the estimation of the monetary value of the diversity of co-benefits they generate. In the scientific literature, previous studies tend to focus on either one benefit or the other. Some papers carry out a thorough evaluation of the impact of NBS on the reduction of risks, based on physical modelling mainly focusing on the impact on hazard [16,36,38,56] and in some cases on the reduction of damages they generate [57]. Other authors rather focus on the advanced valuation methods of ecosystem services generated by different types of NBS or of combinations of NBS: river restoration (Arfaoui and Gnonlonfin, [4] for a meta-analysis), urban parks (e.g [2]), Sustainable Urban Drainage Systems [30], green roofs [6,46], façade greening [50] and a meta analysis of stated preference valuation of blue and green Nature in cities [8]. Studies that combine both type of assessments generally have a simplified approach of risk reduction or ecosystem services, using only value transfer methods.

This study therefore brings a novel contribution in the sense that it provides a methodological framework for an advanced assessment of both NBS benefits on the reduction of water-related risk and for their co-benefits. The evaluation of the reduction of water risk is based on physical models of the impact of NBS on the reduction of flood hazard and on the use of sophisticated damage valuation methods (in two case studies out of 3). This evaluation is combined with thorough assessment of co-benefits that does not only rely on value transfer but rather on stated preferences or direct valuation methods (see the methods section for details). Finally, the paper presents the application of this common methodological framework to different scales in three sites in two European countries: from the city neighbourhood (Dutch case), to the river catchment level mixing urban, peri-urban and rural contexts (two French cases).

The paper describes in section 2 the economic assessment framework and its application to the case studies. Section 3 presents the main results that can be drawn from the economic assessment carried out in the three case studies. In section 4, we discuss the results and conclude.

Economic assessment methodology of NBS aiming at reducing water risks

General methodology of the economic assessment

The aim of the economic assessment methodology is to assess the relative economic value of alternative strategies, through a Cost benefit Analysis (CBA). The relative economic value provides an evaluation of the economic efficiency of a programme. CBA was initially developed to support policy development and justify environmental regulations in the US [48]. The method aims at ascertaining that benefits (gains in human well-being) exceed costs (losses in human well-being) before implementing projects or programmes and if investable funds are limited, which one of these projects or programmes should be selected [42,48]. The monetary value of these benefits and costs, revealed through choices in markets, is expected to reflect human preferences [49]. Its application to environmental economics has raised the need to assign a monetary value to environmental externalities, with methods mentioned in section 2.6.

In our context, the CBA aims to compare alternatives to manage water risks. Depending on the case study, one or several alternatives are compared which incorporate different levels of NBS and traditional grey infrastructure. NBS strategies are here the alternative projects we evaluate that may incorporate a combination of NBS and grey infrastructure. The CBA performed compares strategies without NBS (considered as the Business as Usual (BAU) strategy) with one or several strategies including NBS measures.

The CBA requires the estimation of all direct and indirect costs and benefits for the different NBS strategies under study in monetary value. The following typology of monetary values associated with NBS strategy are considered:

- Cost of implementation are those that are necessary for the implementation and maintenance of the NBS included in the NBS strategy;

[1] https://ec.europa.eu/research/environment/index.cfm?pg=nbs.

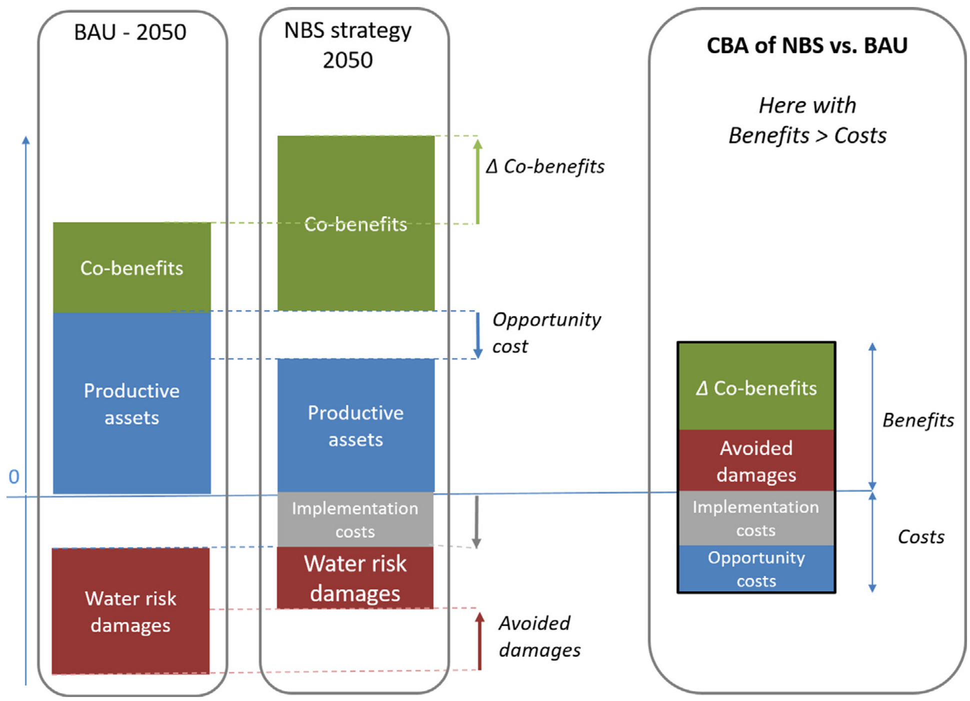

Fig. 1. description of the cost-benefit analysis approach for the economic valuation of NBS within NAIAD (modified from Graveline et al [22])

- Opportunity costs are those that are foregone with the NBS strategy, for instance areas that are taken out of production, or land that is used for NBS and that cannot be used for other purposes such as the construction of building. They are the indirect costs of the NBS strategy.
- Avoided Damage Costs are the damages avoided due to the reduction of water risks[2] generated by NBS strategies. Avoided costs are the primary benefit generated by NBS strategies aiming at reducing water risks.
- Co-benefits are the additional environmental, economic, and social benefits generated by NBS. In the CBA, we will focus on the ones that can be evaluated monetarily although they cover only part of the co-benefits generated by NBS strategies or only a portion of their overall value.

The methods used to estimate the monetary value of these different costs and benefits are described in details in section 2.4 to 2.6. In Fig. 1, we present a schematic representation of the CBA method applied to the evaluation of NBS aiming at reducing water risks.

Several indicators can be calculated to carry out a CBA. In this study, we mainly report on the Benefit Cost Ratio that is estimated with the following formula, where CB_t is the Co-benefits in year t, AD_t is the Avoided Damage in year t, r[3] is the discounting factor, C_t and OC_t are Implementations Costs and Opportunity Costs in year t and T is the time horizon of the assessment.

$$BCR = \frac{\sum_{t=0}^{T}\left[\frac{AD_t + CB_t}{(1+r)^t}\right]}{\sum_{t=0}^{T}\left[\frac{C_t + OC_t}{(1+r)^t}\right]}$$

A BCR superior to 1 means that a project is economically efficient, i.e. that it improves the economic welfare and that it should be eligible for investment by public funds. Decision makers may want to invest in the alternative that present the highest BCR among different courses of action.

In this study, we also look at partial CBA indicators in which we focus on the primary benefit and consider only the direct cost of implementation. Although partial in economic terms, this indicator provides indicators that may be contemplated by decision makers specifically interested in the risk reduction challenge.

$$\text{Avoided damage/Cost (rate)} = \frac{\sum_{t=0}^{T}\left[\frac{AD_t}{(1+r)^t}\right]}{\sum_{t=0}^{T}\left[\frac{C_t}{(1+r)^t}\right]}$$

Finally, we also report on a cost effectiveness indicator, which indicates the cost incurred to achieve an output, expressed by a physical indicator. This physical indicator is a proxy of the effectiveness of the measure such as m^3 of water retention for flood management. This indicator is compiled only for individual NBS measures and not for NBS strategies.

$$\text{Cost effectiveness} = \frac{\sum_{t=0}^{T}\left[\frac{C_t}{(1+r)^t}\right]}{Indicator\ of\ effectiveness}$$

The stepwise approach

A stepwise approach was used for the economic assessment of NBS in this project. This approach could be replicated in other contexts.

1. Set scale and time horizon. The time horizon at which the strategies are evaluated defines the number of years for which the benefits

[2] In this paper, the NBS considered are designed to reduce damages arising from pluvial and fluvial flooding (see section 2.3 for case study description). The general approach could nevertheless apply also to reduce other types of water risks such as coastal flooding or drought.

[3] Discounting arises because of the underlying value judgement in CBA taken from welfare economics, that individuals give a higher value to a present benefit or cost than to a future one. The discounting factor is thus determined by the rate at which individuals express. this "time preference" (Pearce *et al.*, 2006b). The European Commission recommends a discount factor ranging from 3 to 5% (European Commission, 2014) whereas the French Quinet report recommend a value of 2.5% (CGSP, 2013). In practice, the discounting factor varies in the different case studies (2.5% to 3%) considering the value prevailing in the evaluation of investment projects at the country level. The value of the discounting factor may affect negatively the benefits associated with long-term sustainability, since long term benefits will be discounted strongly especially when high discount factor are used.

and costs are taken into account in the economic analysis. This time horizon varies depending on the type of investment and is usually set at the expected lifetime of the considered investment.
2. Define and describe strategies. This step is crucial for the analysis. The identification of NBS strategies is undertaken using a participatory process involving stakeholders of the territory. NBS strategies are identified as a response to the main territorial challenges in terms of water risks and other territorial issues that may be addressed by NBS.
3. Impact assessment. The impacts of NBS strategies must be established against a reference scenario in order subsequently assess the economic value of these impacts. This requires first that NBS strategies be translated into usable inputs for modelling. Either this can be done through a simple quantification of some physical variables that characterize strategies (such as the number of trees planted in the different NBS strategies) or by developing maps that locate the different NBS and associated variables (land use change, retention volume). This quantification of NBS strategies is then used to estimate their impact using a diversity of models. Given the focus of this study on water risks, detailed hydrologic and hydraulic models are developed to estimate the impact of NBS strategies on flood damage. Other simplified models have been mobilized to estimate the physical impact of NBS on co-benefits.
4. Assessment of costs and benefits: The details of the economic assessment methods are presented in section 2.4 to 2.6.
5. Cost Benefit Analysis: Finalization of the CBA by compiling the benefits and costs defined above.

Description of the case studies

This paper reports on the economic assessment of NBS in three case studies: the Brague and the Lez case in southern France and the Rotterdam case in the Netherlands. The results presented here are based on original data collected during the H2020 Naiad Project by the authors of this article. The paper presents a cross-caste studies analysis of the results presented in project deliverable 6.3 of the H2020 NAIAD Project [11–13,21]. A diversity of contexts in terms of water risk, scale and urban/rural setting were selected in order to increase the robustness of the economic results: a neighbourhood scale with pluvial flooding issues in urban context (Rotterdam), a watershed scale with pluvial flooding issues in an urban context (Lez Catchment) and a watershed scale with a river flooding issue in an urban-rural context (Brague River catchment).

The Lez catchment in France (746 km^2) is characterized by a rapid urbanization around the city of Montpellier and pluvial flooding risks (78% of damages in the last major event of 2014 [11]. The catchment also faces typical challenges of large Mediterranean cities: heat island effects, air pollution, water scarcity and biodiversity loss mainly due to urban sprawl. Two NBS strategies based on two levels of development of green infrastructures in cities were designed to address these issues based on a stakeholder consultation process: i) “NBS 1” includes small bioswales, city deproofing and permeable pavement, and ii) “NBS 2” includes NBS1 measures plus green roofs, open retention basins, larger vegetated bioswales. The paper presents the results of the economic assessment of these strategies compared to a business as usual strategies with no intervention.

The Brague River catchment in France (68 km^2) meets the Mediterranean Sea in the city of Antibes. The catchment mid part is hilly and forested while the upper part is a plateau with a suburban land use. The flat floodplain of the lowlands experiences high flood risks, e.g., in Oct. 2015, an extreme flash flood caused 4 casualties and triggered dozens M€ of damages. The grey strategy initially proposed was to build large flood retention dams. The NBS strategy under study relies on small natural retention measures spread in the catchment over 200 ha, along with an ambitious river corridor restoration to give room to the river in the lowlands. It consists in building five light structures aiming to trap woody debris, widening the channel by 50–100%, modifying 3 bridges and restoring 13 ha of riparian forest and 11 ha of wetlands. It would also require buying and demolishing 50 to 70 houses.

The Rotterdam case study focuses on Spangen, a low-lying neighbourhood in the West of the city, spanning roughly 65 ha with around 10,000 inhabitants. With the low elevation and shortage of pervious surface area due to intense urbanisation, the neighbourhood has been suffering frequent pluvial flooding during heavy rain events. To add retention capacity to the area for dealing with these rain events, and to sustain a reliable supply of fresh water in times of droughts, a so-called Urban Waterbuffer (UWB) was realised on the square next to the Sparta Stadium in 2018. As the Rotterdam case study is interlinked with this implemented piece of hybrid infrastructure, it provides important insights that may not have been gleaned from modelling and forecasting alone. The Rotterdam case study also constitutes a comparison of three (green – grey – hybrid) neighbourhood wide strategies to address the economic impact of NBS approaches for the area.

Assessment of implementation and opportunity costs

The evaluation of implementation costs was estimated following the Life cycle costs (LCC) principles, also named Total Cost of Ownership (TCO). It considers the total cost of acquisition, use/administration, maintenance and disposal of a given item/service [17]. The accurate identification of LCC provides the information to assess the magnitude of investments for maintaining socio-technical system functionality over time. This methodology focuses on identifying the generating activities and cost determining factors to maintain the main functionality of NBS: avoiding water-related risks. Cost generating activities can be grouped into six LCC components namely: 1) capital expenditures, 2) operating and minor maintenance expenditures, 3) capital maintenance, 4) expenditure on direct support, 5) expenditure on indirect support and 6) cost of capital.

In the Rotterdam case study, the full LCC method was mobilized to directly estimate cost figures for costs related to measures and activities related to the realized UWB, as data could be collected in the pilot project. For the other NBS included in Rotterdam and in the Lez and Brague case studies, cost were estimated based on reference values from the scientific literature, national databases of market prices and expert opinions. Cost per units of surface (or volume) of individual NBS measures, composing NBS strategies were first evaluated, then these costs were extrapolated at the NBS strategy levels, to estimate the overall cost associated with NBS strategies. The estimation of costs based on value transfer presents large range of uncertainty, which is reported.

The opportunity costs are those costs associated with the foregone alternative, which can be measured by the net foregone benefit (because the resources that provide the services cannot be used in their next beneficial use, [55]). NBS implementation because of its relatively large spatial footprint usually requires large-scale land use changes from productive uses to other uses. When NBS are implemented on private land, the cost can be integrated in the capital expenditure related to land purchase, but when NBS are mainly implemented on public owned land, opportunity cost should be considered [18][4]. However, in urban cases NBS are implemented on marginal spaces, such as on a share of the sidewalk or even on concrete spaces, without specific use or value (roundabouts, forecourts, plaza etc.). Sometimes the use value will not be altered (e.g. greening parking spaces) so there are no opportunity costs. Sometimes the question of whether a change of land use generates an opportunity

[4] “*Many public investment projects use land as a capital asset, which may be state-owned or purchased from the general government budget. Whenever there are alternative options for its use, land should be valued at its opportunity cost […]. This must be done even if land is already owned by the public sector. If*it is reasonable to assume that market price captures considerations about land’s utility, desirability and scarcity, then it can generally be considered reflective of the economic value of land.”

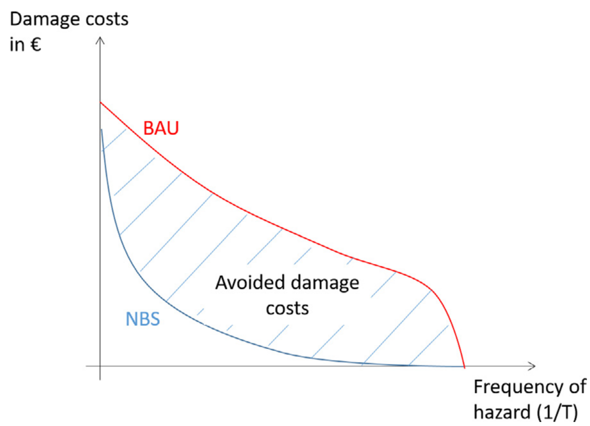

Fig. 2. The principle for assessing avoided damage costs

cost is subject to interpretation when public road or parking space is concerned.

In the Lez and Rotterdam case, we applied a conservative approach, which is to consider land market prices as a proxy of opportunity costs, although alternative possible use of this land is uncertain. We therefore estimate an upper bound of opportunity costs. In Brague, NBS strategies involve privately owned land use change. In this case, following recommendations from the water agency[5], land acquisition costs were included in investments costs while additional opportunity costs were estimated based on profits private landowners could have obtained from the use of this land (estimated by revenues they could have perceived over this land).

Assessment of avoided damages

Overall approach to the assessment of avoided damages

The overall approach to the estimation of the avoided damage associated with NBS strategies comprises two main steps: 1) estimation of the relation between water related hazards and damages (catastrophe risk models (CAT) model) and 2) estimation of the impact of NBS strategies on the modification of hazard (droughts or floods) through physical models[5]. The combination of these two steps leads to the estimation of damages under different NBS strategies and without these (BAU) (Fig. 2). The difference between damages in the BAU and NBS strategies provides an estimation of the avoided damage, which is expressed in Mean Annual (Avoided) Damage (MA (A) D) and can be integrated in the overall economic evaluation. The general approach was adapted to each case study according to specificities and data availability.

Estimating the relation between hazard and damage costs: the CAT model framework

The CAT model aims to establish the costs of an event based on its magnitude, its spatial distribution (event intensity), and the vulnerability of the elements at risk [44]. This involves the following steps [20,39]:

- Mapping of event's hazard intensity.
- Assessment of the exposure of the assets/elements at risk.
- Definition of damage functions/models.
- Calculation of the value of the damage cost.

Consequently, the structure of CAT models relies on three units: hazard, vulnerability and damage (Fig. 3).

[5] AERMC (2011). *Elaboration d'un outil de détermination des coûts de restauration hydromorphologique des cours d'eau du bassin versant local et des bassins RMC.* Agence De l'Eau Rhone Mediterranee Et Corse.

Overall the total damage computed for one event is:

$$D_E = \sum_{i=1}^{N_E} V_i(H_E(X_i, Y_i))$$

Where D_E is the damage of event E, N_E is the number of assets at risk for event E, i is the index of each asset, X_i Y_i are the coordinate of asset i, H_E is the hazard intensity for event E and V_i is the vulnerability of asset i which is usually computed using a damage curve, i.e., a curve relating the vulnerability to the hazard intensity H_E. This approach was followed in the Lez and Brague cases, while a simplified approach was used in the Rotterdam case to better suit the small scale of the focus area. The strategies in the Rotterdam case were designed to all provide a similar level of flood risk reduction to assess which is the most favourable choice in terms of associated costs and co-benefits provided, when comparing a grey, a hybrid and a green strategy for mitigating a T10-rain event (52,9 mm of rain over 12 h) in Spangen. An estimation of the magnitude of avoided damages was derived from another recent study on climate risk mitigation in the neighbourhood of Spangen [1].

The characterisation of the flood hazard event (H_E) in the different case studies has been done by using or adapting hazard models. In the Lez a 25 m-resolution runoff model developed at the French scale by the CCR [43] has been adapted to integrate the local information about land use and slopes taking into account water heights on each mesh. This method sprawls water along short watercourses, instead of being blocked in the banks and is possible in terms of calculation duration. It was calibrated on the Oct. 2014 event. In the Brague, a 2D model computed on a 2 m mesh represented the flooding in the whole floodplain [7]. The model was built using topographical data and land use maps. It includes bridges and culverts. It was calibrated on the Oct. 2015 event and validated on the Nov. 2011 event

Estimating the impact of NBS on hazards

This step involves modelling how NBS strategies would change the intensity and location of the hazard (hazard unit). For the Lez case, the hydraulic model used could not directly model the impact of NBS on flood hazards because of model limitations: too large resolution of the model and underlying equations (description of flow not integrating small-scale obstacles). An inverse approach was thus undertaken to approach the avoided damages related to NBS. Various values of runoff reduction (in %) were forced in the model and their effects in terms of damage reduction was computed. A relationship between the reduction of runoff and the reduction of damage was therefore estimated. The reduction of runoff (in %) resulting from NBS strategies was estimated simply by considering it equal to the % of rainfall stored in NBS (due to water retention capacity). Both, these estimations provided the building block to assess avoided damages due to NBS.

In the Brague case, the NBS strategy was directly included in the model by modifying bridge geometries, widening the river channel, lowering ground level on wetlands, changing the roughness coefficients where land use changed and removing effects of woody debris

Assessing avoided damages

The Mean Annual Avoided Damages (MA(A)D) is evaluated by estimating the reduction of damages obtained with NBS strategies for different return period and by summing the product of the avoided damages multiplied by the probability of occurrence of each rainfall event.

In the Lez and Brague case studies, the calibrated damage curves on residential houses has been used to simulate the effect of runoff reduction (Lez) and flow depth reduction (Brague) on damage. Damage was computed for several return periods (10, 20, 50 and 100 years in the Lez, 20, 100 and 500 years in the Brague) and then averaged. Differences between BAU and strategies enabled to compute the avoided damages. In the Lez case, an increase of 28% was subsequently applied as compared to residential damages to account for total direct damages (This ratio was estimated for the 2014 events).

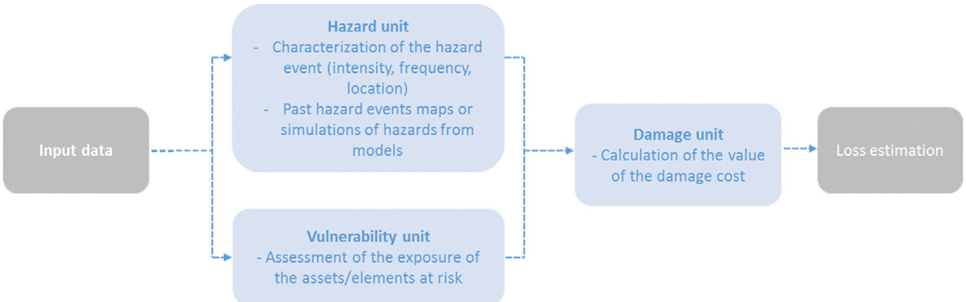

Fig. 3. Structure of any CAT models (adapted from [20,39]).

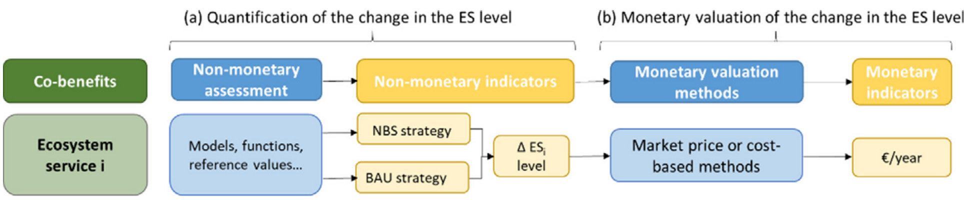

Fig. 4. Stepwise approach for ES valuation when direct valuation approaches are used [25]

Co-benefits assessment

The co-benefits assessment was carried out with a two-stage approach with (1) the identification of co-benefits and (2) the monetary valuation of those co-benefits. As recommended by Nesshöver et al. [45], a strong involvement of local stakeholders was organised throughout the process in order to integrate their perceptions and knowledge.

Identification of co-benefits

In the three case studies, the identification of co-benefits relied on the organisation of focus groups in which potential benefits of NBS strategies were discussed with local stakeholders. Three existing co-benefits classifications and frameworks were used as a basis for discussion: (i) the Millennium Ecosystem Assessment [40], (ii) the common international classification of ecosystem services (CICES) [23], (iv) the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) framework [15] for the identification ecosystem services. The EKLIPSE framework was used [51] for the identification of challenges in urban contexts.

These frameworks were finally combined in order to embrace a wide range of potential co-benefits and specific local issues. In the Lez case study, for instance -a watershed with 50% of natural areas and 30% of agricultural areas- ecosystem services classifications (MEA and IPBES) were used, while in the Rotterdam case study – an urban neighbourhood - the EKLIPSE framework was used as a core framework for co-benefits identification due to its comprehensive coverage of urban issues. In the Brague, the co-benefit list was tailored after three focus group meeting dedicated to flood protection, environment and quality of life.

Co-benefits valuation

Despite our acknowledgement of the diversity of values associated with NBS co-benefits [29], we focus in this paper only on the monetary valuation of co-benefits with the view to carry out the CBA. Two different valuation techniques were used to undertake a monetary valuation of co-benefits in the different case studies: direct valuation approaches and stated-preference approaches.

Direct valuation approaches (market price and cost-based methods) were used in the Rotterdam case study, to valuate seven co-benefits, namely climate mitigation through carbon storage, air quality regulation, water cycle regulation, urban regeneration, human health and wellbeing, and aesthetic amenities. These approaches rely on two main steps (Fig. 4):

- Step 1: the quantification of the level of ecosystem services provided by the NBS strategy (compared with the baseline) with biophysical indicators (e.g., annual carbon sequestration expressed in t-eqCO2/year; water availability expressed in m3/year) derived from models, functions or reference values obtained in similar contexts;
- Step 2: the monetary valuation of the change in the ecosystem service level derived from market prices (when market exists), replacement costs (costs required to provide a similar ecosystem service with a human engineered solution) or avoidance costs (costs that would occur if the ecosystem service were lost).

These approaches provide biophysical and monetary indicators for each ecosystem service. However, they do not reflect the total economic value of these ecosystem services, as they only capture direct use values. Results should thus be considered as lower bound estimates.

Stated preference approaches, namely the Contingent Valuation Method and the Discrete Choice Experiment [31], were used in the Brague and the Lez case respectively. These approaches rely on representative surveys of the population to estimate people's willingness to pay for a hypothetical modification of the environment (400 respondents in the Lez and 405 in the Brague), here the implementation of NBS strategies. In both cases, the survey aims at evaluating residents' Willingness to pay for different NBS strategies. They allow the estimation of total monetary values of NBS strategies and associated bundles of ecosystem services, without seeking to evaluate ecosystem services one by one. The stated preferences surveys are detailed in Gnonlonfin et al. [21] and Hérivaux and Le Coent [24].

Cost-Benefit Analysis of NBS in the three case studies

The results of the monetary assessment in the three case studies are summarized in Table 1 and Fig. 5.

In Brague and Rotterdam the cost of implementation and maintenance of grey solutions is higher than the cost of NBS strategies for the same level of risk management (grey alternatives were not evaluated in the Lez case). This confirms statements mentioning that NBS may be more cost effective solutions than grey solutions as they are less costly. Indeed, for the same level of avoided damage, the NBS solutions are 15% and 63% less costly than the grey solutions, in the Rotterdam and the Brague case study respectively.

The cost effectiveness of individual NBS measures has also been investigated in the Lez. In this case, the cost of different measures is compared with a proxy of the level of service: here the cost per m^3 of water retention. This analysis shows a very large heterogeneity of cost-effectiveness of individual NBS measures. For example, in the Lez case study, the cost-effectiveness of green roofs is extremely low because of

Table 1
Overview of results of the economic analysis in net present value in millions € discounted over the time horizon of the evaluation. Average values are indicated in bold and value ranges reflecting uncertainty (when evaluated) are indicated in italic between brackets.

Case study	Brague		Rotterdam			Lez	
Strategy	Grey	NBS	Grey	Hybrid	Green	NBS 1	NBS 2
Time Horizon	2070	2070	2070	2070	2070	2040	2040
Discount rate	2.5%	2.5%	3.0%	3.0%	3.0%	2.5%	2.5%
Implementation Cost of NBS scenarios (M€)	**169** *(87–270)*	**61** *(45–97)*	**8.2**	**8.1**	**6.9**	**52** *(39–65)*	**120** *(92–148)*
Opportunity cost (M€)	**0.6** *(0.5–0.7)*	**19** *(14–35)*	**0**	**4.9**	**13.0**	**210** *(135–285)*	**318** *(239–396)*
Avoided damages (M€)	**13** *(5–19)*	**14** *(6–21)*	**0.7** *(0.4–0.9)*	**0.7** *(0.4–0.9)*	**0.7** *(0.4–0.9)*	3.4	29
Co-benefits (M€)	–	**68** *(25–103)*	**0.004**	**6.0**	**10.7**	**287**	**363**
Avoided damage/ Cost (rate)	**0.1** *(0.1–0.1)*	**0.2** *(0.1–0.2)*	**0.08** *(0.05–0.11)*	**0.08** *(0.05–0.11)*	**0.09** *(0.06–0.13)*	**0.07** *(0.05–0.09)*	**0.24** *(0.2–0.3)*
BCR	**0.1** *(0.1–0.1)*	**1.0** *(0.2–2.1)*	**0.08** *(0.05–0.11)*	**0.50** *(0.46–0.53)*	**0.57** *(0.56–0.58)*	***1.3*** *(0.8–1.7)*	**1.0** *(0.7–1.2)*
BCR exc opportunity costs	**0.1** *(0.1–0.1)*	**1.3** *(0.3–2.8)*	**0.08** *(0.05–0.11)*	**0.82** *(0.79–0.85)*	**1.65** *(1.61–1.68)*	**6.0** *(4.5–7.5)*	**3.5** *(2.7–4.3)*

the large cost of green roofs as compared to their limited water storage capacity with 1282–1582€ of investment/m^3 of retention while vegetated bioswales cost 102–131 of investment/m^3 of water retention. This large difference of magnitude is confirmed in the Rotterdam case (See Appendix A)

In urban areas, taking into account the opportunity costs of NBS can totally change the estimation of their cost advantage. Considering that NBS require a large spatial extent as compared to traditional grey strategies, the inclusion of opportunity costs has a strong weight in the overall cost estimation, especially in urban areas where land value is high. As mentioned in the methodological section, we however estimate higher bound of opportunity cost. This point is discussed in the last section.

In the three cases, avoided damages benefits are not sufficient to cover investment and maintenance costs, as can be seen in the three case studies. This result needs to be nuanced because our estimations only accounts for a share of the avoided damages, with a restriction on direct damages. Indirect damages, such as the macro-economic impact of floods, due to their effect are not considered, although they can be significant. The assessment also does not consider the potential of protection measures on other non-monetary but essential indicators such as the capacity to reduce the exposition (number of residents in flood prone areas), limiting risk of deaths, injuries or post-traumatic stress.

Co-benefits represent the largest share of the value generated by NBS strategies in all three studies. This result does not depend on the method used for the estimation of co-benefits, since revealed preference methods have been used in the Lez and Brague case studies while direct valuation has been used in Rotterdam.

There are no clear-cut conclusions on the overall economic efficiency of NBS in our assessments. Indeed, NBS strategies have a BCR close to 1 or slightly superior on average in Lez and Brague and below one in Rotterdam whatever the strategy. The picture is more positive if we exclude opportunity costs from the economic analysis. Interestingly however, for Brague and Rotterdam, the economic efficiency of NBS strategies is nevertheless much higher than the one of grey strategies.

The Benefit Cost ratio should however not be the only criteria considered. For example, the level 1 NBS strategy in the Lez has the highest Cost-Benefit ratio however, the rate of avoided damages on implementation cost is extremely low, since this strategy has very limited effect on flood protection and is thus not satisfactory to reach flood risk reduction goals. Although this strategy may be cost-efficient if all benefits are considered, it could not be considered a valid alternative for municipalities aiming at addressing flood risks and should therefore be combined with other flood management strategies.

Discussion and conclusion

This article presents a methodological approach for the evaluation of NBS aiming at water risk and the results of its application to three case studies. This process has led to the identification of lessons learnt on the methodology.

The economic valuation of NBS strategies first requires a large effort for the design of strategies. This step requires the participation of stakeholders and preliminary modelling approaches. It is fundamental because the quantification of the physical characteristics and impacts (e.g. retention capacity, number of trees) is the basis for the estimation of their costs and benefits. The design of alternatives is also a key step in the economic assessment of any project. The innovative nature of NBS strategies as compared to traditional solutions nevertheless requires an additional effort in that aspect, since knowledge is not always available; participants need to be informed and engineering capacity for the design of option may not be available.

Second, cost estimates mainly rely on the transfer of existing values evaluated in other projects except in the Rotterdam case in which specific cost evaluation was undertaken for some NBS measures. This reliance on a diversity of sources gives rise to a high level of uncertainty. Costs can indeed vary greatly depending on the exact feature of the NBS and on local contexts. In order to reduce uncertainty, costs should either be directly valued locally or rely on local references presenting the same technical specifications.

Third, on opportunity cost, the approximation we used to estimate opportunity costs is relatively coarse and may lead to an overestimation of this cost. In Lez and Rotterdam, two urban cases, land price is used as a proxy of opportunity costs, even though NBS are developed on public areas. It provides an estimation of the fact that this space cannot be used for other profitable uses. Whether all public space may have other profitable use, such as sidewalks for example, is unclear. This area may need further investigation in the future.

Forth, in order to assess the avoided damages granted to NBS strategies, both simple, straightforward methods and advanced models are necessary to estimate fully the effect of NBS on the intensity and spa-

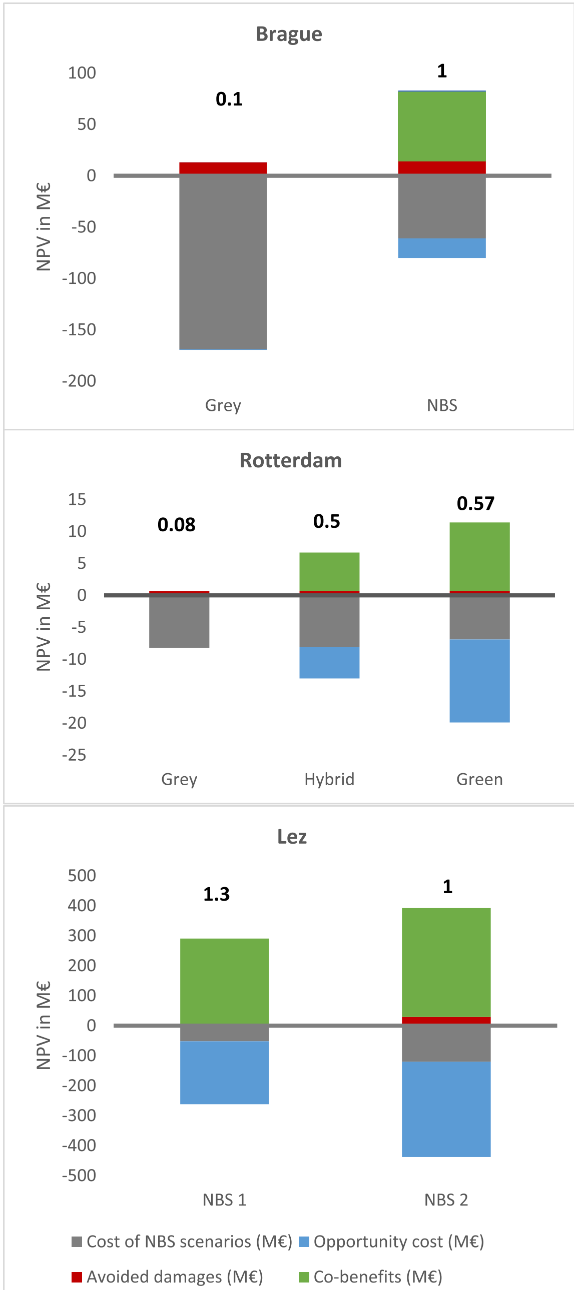

Fig. 5. Net Present Value of the costs and benefits included in the CBA of Brague, Rotterdam, Lez and Medina for the various strategies. The average BCR is indicated above histograms.

tial extent of hazards, especially when assessments are carried out at the catchment scale. The evaluation of avoided damages depends on the availability of data to be able to link the reduction of hazard to a reduction of damages. The synthetic character of this paper presenting multiple case studies should not mask the important disciplinary and interdisciplinary work behind each economic analysis [11].

Fifth, we report on the assessment of co-benefits through monetary approaches. The valuation of nature or ecosystem with monetary approaches is a highly divisive question among scholars. These last years, there is a growing number of scientists and practitioners who explore how combinations of ecological, socio-cultural and economic valuation tools can support environment valuation and land-use decision-making. In fact, there is a growing body of literature, which argues that valuation approaches of ecosystem services that target single value-types, be it economic, ecological or socio-cultural values fail to capture the importance of nature and to represent fully the society and its world-views, interests and preferences. As a response, integrated valuation approaches are increasingly put forward (Gómez-Baggethun and Barton, 2013; [29]). In this article, we only report on the monetary valuation of co-benefits that could be integrated in the CBA, although other valuation methods of co-benefits using socio-cultural or ecological methods could be integrated.

Finally, our economic assessment methodology bears the limits inherent to every economic analysis with ecological or environmental variables. The multiplicity of models required for the estimation of the different costs and benefits increases their overall uncertainty. Only the magnitude of costs and benefits should be compared rather than the precise values we have presented. In addition, only indicators that could be evaluated monetarily are included in this study. Other indicators such as non-monetary impacts on flood risk, co-benefits that could not be or partially be valued monetarily such as social and environmental indicators are important in the decision making process for the development of NBS. Their inclusion would require the development of a Multi Criteria Decision Analysis framework.

Some recommendations can be drawn from the main results of this study. First, NBS aiming at reducing water risks cannot be assumed to improve systematically economic welfare, since BCR lie between 0.5 and 1.3. It is therefore fundamental to carry out thorough case-specific economic valuations of a diversity of strategies, involving NBS, grey and hybrid solutions, in order to identify the most adequate strategy for water risk management and to address territorial challenges. In a context of limited public resources, economic valuation can help identifying the adequate solution to address water risks.

A preliminary step to screen measures to improve the overall economic efficiency of NBS strategies would be to carry assessments of the cost effectiveness (in terms of risk reduction) of the individual measures constituting these strategies. This preliminary assessment could help designing economically efficient NBS strategies, with combinations of cost-effective NBS measures (e.g. [9,10]). This rule of thumb should however not overlook the importance of co-benefits in the value of NBS. For example, small bioswales with simple plant cover may be more cost effective for water retention than large bioswales planted with trees but their production of co-benefits is also very limited; in this case, public money available for biodiversity or nature in city might help decide upon the two strategies.

The large share of co-benefits in the overall value of NBS aiming at reducing water risks combined with the limited avoided damages has strong implications on NBS funding and business models. Indeed, support from sectoral policies is generally conditioned to a positive cost-benefit analysis on the specific benefit they target, such as for example flood risk reduction in our cases. However, NBS appear to be economically efficient only when all the benefits they generate are considered. Implications for project set up and financing are very significant. Rules applying for the public funding of NBS should therefore be adapted in order to take into account cross-sectoral benefits of NBS. This requires modifications of the silo approach currently still prevailing in the application of public water risk policies. On the other hand, considering the significance of co-benefits for NBS economic value, it is important to ensure that the co-benefits are maximized during NBS design and implementation. For example, if an open retention basin is created in an urban environment, the vegetation included as well as its facilities for recreational activities should be considered with as much care as the technical specifications required for flood management. This conclusion invites decision makers to consider non-built environment, especially in urban environment, as rare multifunctional space for which the production of overall benefits should be maximized (risk reduction and "co"-benefits). This also suggests developing research methodologies that facilitate the identification of optimal spatial layout of NBS in a constrained urban environment [27,59].

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

LE COENT Philippe, GRAVELINE Nina, ALTAMIRANO Monica, ARFAOUI Nabila, BENITEZ-AVILA Camilo, CALATRAVA Javier, DOUAI Ali, GNONLONFIN Amandine, HERIVAUX Cécile, MARCHAL Roxane, MONCOULON David, PITON Guillaume

Thomas Biffin and Kieran Wilhelmus Jacobus Dartée, hereby declare that Field Factors B.V., nor their personal affiliation with Field Factors B.V. as employees raise any pecuniary or other conflicting interests, direct or indirect, in any matter with their contribution to the research conducted for the paper "*Is-it worth investing in NBS aiming at mitigating water risks? Insights from the economic assessment of NAIAD case studies.*"

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Supplementary materials

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