River flooding risk prevention: A cooperative game theory approach

Xana Álvarez[1], María Gómez-Rúa[2], Juan Vidal-Puga[3]

[1] Escola de Enxeñaría Forestal. Universidade de Vigo.
Campus A Xunqueira. 36005 Pontevedra. Spain.
E-mail: xaalvarez@uvigo.es

[2]Corresponding author.
Economics, Society and Territory (ECOSOT - ECOBAS) and
Facultade de Ciencias Económicas e Empresariais. Universidade de Vigo.
Campus Lagoas-Marcosende, 36310 Vigo. Spain.
Phone: +34986813506. E-mail: mariarua@uvigo.es.

[3] Economics, Society and Territory (ECOSOT - ECOBAS) and
Facultade de Ciencias Sociais e da Comunicación. Universidade de Vigo.
Campus A Xunqueira. 36005 Pontevedra. Spain.
E-mail: vidalpuga@uvigo.es

Published in *Journal of Environmental Management*[*]

Abstract

Socio-economic development combined with changing hydrological factors represents a challenge for extending flood protection. In particular, land owners should be encouraged to use their land in a way that improves its water retention capacity. However, problems of fairness may arise because a landowner can benefit or lose

[*]DOI: 10.1016/j.jenvman.2019.109284.

out depending on the use of other lands. This paper sets out to study the possibility of applying game theory through a cooperative game to solve this problem. Specifically, we look for a sharing rule function to help the planners to distribute the total benefit among landowners, taking into account a principle of stability. We concentrate on enhancing upstream water retention and focus on the role played by forests as natural water retention features. This is a methodological contribution that analyzes land use management for flood retention. Land planners, governments and landowners could use cooperative games as a flood risk management tool. With this method, compensations and benefits could be established to raise awareness and encourage land owners to cooperate.

Keywords: game theory, land management, flood mitigation, land use, compensations.

1 Introduction

According to Directive 2007/60/EC, "flood is the temporary covering by water of land not normally covered by water" (European Commission, 2007). If we take into account the risk concept defined by IPCC (2014) in this natural process,"flood risk" is a combination of flood probability and potential adverse consequences for human health, environment, cultural heritage, and economic activity (European Commission, 2007). Recent studies (Jongman et al., 2015; Cook, 2017) indicate that the risk of flooding and economic damage in Europe will increase in the near future. This may be due to human influence causing unnatural disasters. In this case, risk results from the interaction of vulnerability, exposure, and hazard (Mechler et al., 2014).

Various factors can lead to damaging floods. Damage is attributed in particular to increasing exposure due to high population growth and economic development in areas prone to floods (Bouwer, 2011; Neumayer and Barther, 2011; Field et al., 2012; Visser et al., 2014). A study conducted by Alfieri et al. (2015) concludes that the socio-economic impact of river floods in Europe could increase by an average of 220% due to climate change by the end of the 21st century. Therefore, it is important to evaluate flood risk. Lyu et al. (2019) conduct a comprehensive review of current research on regional flood risk assessment methods. Geographic Information System (GIS) is a very useful tool for spatial flood risk modelling. Some examples are Lyu et al. (2016, 2018a); Jalayer et al. (2014). GIS is also useful for scenario-based inundation analysis (Yin et al., 2013) and numerical modelling (Shen and Xu, 2011). However, assessing floods is difficult to evaluate, especially when there is an evolution of vulnerability from natural, economic and social systems to flood impacts, as well as their exposure. Multi-model and multi-discipline approaches are recommended to further advance into this research field (Teng et al., 2017).

On the other hand, there are measures to control and contain flood risk. There is a type of actions that can be seen as protective measures. Such measures have traditionally been based on the so-called *grey infrastructure*, such as dikes, dams, and other concrete structures (Rasid and Paul, 1987; Roth and Winnubst, 2014; Balica et al.; 2015). However, the increase in land use by human populations means that this grey infrastructure is no longer sufficient to cope with dynamic flood risk (Tempels and Hartmann, 2014; Nquot and Kulatunga, 2014; Mustafa et al., 2018). A promising alternative is the use of nature-based solutions such as the so-called *Natural Water Retention Measures* (NWRM) as a complement to grey infrastructure (Zeleňáková et al., 2017; Brody et al., 2017; Bhattacharjee and Behera, 2017, 2018). The challenge is to consider multifunctional land uses which have the potential to provide temporary flood retention and storage, stimulating the provision of other ecosystem services.

NWRM are usually implemented mainly on private land, so a compromise between flood risk management and land exploitation is needed (Scherer, 1990; Hartmann, 2016; Thaler et al., 2016). Management through an integrated approach combining structural and land use planning measures (Rezende, 2010; Barbedo et al., 2014) is an efficient way of reducing flooding (Miguez et al., 2012). According to various experts (e.g., Directorate-General for Environment (European Commission) (2016); Machac et al. (2018)), policies such as Directive 2007/60/EC and the "Blueprint to Safeguard Europe's Water Resources" (European Commission, 2007), and The Working Group F on Floods (2012), there are two main options for flood protection: controlling and retaining floods upstream and seeking to adapt land use downstream. The latter option has been widely analyzed (e.g., Temmerman et al. (2013); Aerts et al. (2014)), mainly because of the urgency of protecting the safety of people. However, increasing water retention capacity in the headwaters of river basins may be a more effective flood protection measure because downstream areas usually contain a greater volume of water, and their topography is normally flat, which does not help drainage.

In this study, we explore flood reduction through actions that incentivize water retention upstream. In particular, we ask what can be done to make landowners voluntarily decide to change their land uses to reduce the risk of flooding? The main challenge is to reach the best agreements between upstream and downstream (Machac et al., 2018). To that end, we have selected game theory as a negotiation tool. In particular, we need to take into consideration multiple aspects such as economic issues (i.e., how to reward or incentivize flood retention services), property rights (e.g., how to allow temporary floodwater storage on private land), public participation (e.g., how to ensure the involvement of private landowners), and issues of public subsidies (e.g., how to integrate flood retention into agricultural subsidies).

Out of all these issues, this paper focuses on one key question: How can land owners be encouraged to adapt (or compensated for adapting) the use of their land and its management strategies in a way that increases their water retention capacity? In this, we apply cooperative game theory, a mathematical tool, first developed in a seminal book by von Neumann and Morgenstern (1944). This enables us to analyze and solve allocation situations where two or more agents (or players) have different interests. Unlike decision theory, where those interests are unique or coincide, or zero-sum games, where they are incompatible, cooperative game theory focuses on situations where a mutually beneficial compromise is possible. It also differs from non-cooperative game theory in that the allocation can be made from a centralized point of view, rather than through non-cooperative bargaining among the players.

In this paper, we check that there are stable rules for sharing the benefit of building NWRM in upland areas. By "stability" we mean that no group or coalition of landowners can improve their aggregate benefit by acting against the proposed share. Our proof is constructive: We provide three ways of computing three respective ways of sharing the benefits of cooperation. One of them is optimal for upstream landowners who build MWRM, another one is optimal for downstream landowners who take advantage of those MWRM, and the third one is a compromise value between the first two.

2 The model

2.1 Cooperative games

A *cooperative game* is a pair (N, v) where N is a finite set of *agents* (or *players*) and $v : 2^N \longrightarrow \mathbb{R}$ is the *characteristic function* of the game, where $v(S)$ represents the *worth* of *coalition* $S \subseteq N$. The interpretation is that the worth of S is the benefit that agents in S can generate by themselves, without the help of the other agents. As usual, we assume $v(\emptyset) = 0$.

A cooperative game (N, v) is *superadditive* if $v(S \cup T) \geq v(S) + v(T)$ for all $S, T \subset N$ with $S \cap T = \emptyset$. The interpretation is that two different coalitions can obtain at least as much benefit working together as by themselves. A cooperative game (N, v) is *monotonic* if $v(S) \leq v(T)$ for all $S \subseteq T \subseteq N$. The interpretation is that no coalition can obtain less by adding new members. A cooperative game (N, v) is *additive* if $v(S) = \sum_{i \in S} v(\{i\})$ for all $S \subseteq N$. The interpretation is that there is no benefit from cooperation, since no coalition can improve on what its members can achieve by themselves.

One main objective of cooperative game theory is to select an allocation, or a set of allocations, admissible to the players for every cooperative game. At this point, two main approaches are possible: One is based on stability, where the aim is to find stable allocations in the sense that no coalition of players can improve by itself. The second is based on fairness and seeks to find fair allocations based on an idea of justice.

Let (N, v) be a cooperative game. An *imputation* of (N, v) is an allocation $x \in \mathbb{R}^N$ satisfying $\sum_{i \in N} x_i = v(N)$ (i.e. the worth of the whole coalition is fully allocated among its members), and $x_i \geq v(\{i\})$ for all $i \in N$ (i.e. no agent gets less than he/she would get by him/herself). We denote by $I(N, v)$ the set of imputations of (N, v). The *core* of (N, v) is the set of stable imputations, defined as:

$$Core(N, v) = \left\{ x \in I(N, v) : \sum_{i \in N} x_i \geq v(S) \text{ for all } S \subset N \right\}. \tag{1}$$

The interpretation of the core is intuitive: We look for payoff allocations that no coalition of agents can improve by itself. The main problem with the core is that it may be empty, as can be seen in Example 2.3 below. Another (minor) problem is that the core may be huge, which makes it necessary to find criteria for picking up a core allocation. However, if (N, v) is an additive game, both problems are avoided, since the core is a singleton given by $Core(N, v) = \{x\}$ where $x_i = v(\{i\})$ for all $i \in N$.

A *sharing rule* is a function that assigns to each cooperative game (N, v) in a class of games a vector $\phi(N, v) \in \mathbb{R}^N$ such that $\sum_{i \in N} \phi_i(N, v) = v(N)$. A sharing rule can then be used to state how compensation should be given in order to assure a core allocation. The best known sharing rule in cooperative game theory is the Shapley value (Shapley, 1953). To define it formally, we introduce the following notation: Given a finite set N, let Π_N denote the set of all orders in N. Given $\pi \in \Pi_N$, let $Pre(i, \pi)$ denote the set of elements of N which come before i in the order given by π, i.e.,

$$Pre(i, \pi) = \{ j \in N | \pi(j) < \pi(i) \}.$$

The Shapley value of the cooperative game (N, v) is defined as:

$$Sh_i(N, v) = \frac{1}{n!} \sum_{\pi \in \Pi_N} \left[v(Pre(i, \pi) \cup \{i\}) - v(Pre(i, \pi)) \right] \tag{2}$$

for all $i \in N$.

2.2 River flood games

Assume a finite number of land owners on a river basin. These are the agents, i.e. N is the set of land owners. We denote these agents by $N = \{1, \ldots, n\}$. On the other hand, we assume that agents are only affected by actions taken by upstream owners, considering the natural direction of run-off. This refers to the amount of water from rainfall that runs over the land surface or through the soil to groundwater and streamflow.

Hence, "upstream" and "downstream" are defined by a directed graph $\mathcal{G}$ with no cycles, whose nodes are the agents. In particular, $(i, j) \in \mathcal{G}$ is interpreted as meaning that agent i is an upstream agent j, so that water falling on region i eventually ends up on agent j's land.

Forest decreases risk of flooding in downstream land, and is itself also less affected by flooding (Laurance, 2007; Van Dijk et al., 2009) because water retention potential tends to increase with the extent of forest cover in a water basin (Tyszka, 2009; European Environment Agency, 2015). Taking into account the objective of this study, and in order to keep the model simple, we regroup the uses into two types: "*Forest*", which retains floodwaters, and "other uses", which *accelerate* them. For this particular study, we define "forest" as a large tract of land covered with trees and underbrush (woodland). "Other uses" means all other natural and artificial land cover, characterized by the absence of vegetation and trees.

The benefit of having a forest is given by a vector $f \in \mathbb{R}^N_+$, and that of "other uses" that accelerate floods is given by a vector $a \in \mathbb{R}^N_+$, i.e. when agent $i \in N$ has a forest on his/her land, he/she obtains $f_i \in \mathbb{R}$, and otherwise $a_i \in \mathbb{R}$.

Moreover, the positive externality for land $j \in N$ due to the presence of a forest on land $i \in N$ is given by a matrix $B = (b_{ij})_{i,j \in N}$ such that $b_{ij} > 0$ when $(i, j) \in \mathcal{G}$ and $b_{ij} = 0$ otherwise (*"water flows downstream"*).

A *river flood problem* is a tuple $(N, \mathcal{G}, f, a, B)$ with the properties given above.

Finally, the expected damage gradually increases downstream (Petts and Amoros, 1996; Graf, 1998; Begum et al.; 2007; Serra-Llobet et al., 2018). This has been demonstrated by studies in specific river basins such as that of te Linde et al. (2011) in the Rhine basin and Papathanasiou et al. (2013) in the Ardas basin. These areas are the floodplains, characterized by their flatness and as being the final evacuation point of all the water that infiltrates into the river basin, concentrating the highest water flows. In addition, the larger the forest cover, the more water is retained (Petts and Amoros, 1996; Tyszka, 2009; European Environment Agency, 2015). This again lowers the amount of water flowing as surface run-off and at the outlets of catchment. For both these reasons, we assume that the larger a forest is, the more beneficial its effects are.

The simplest way to factor this assumption into the model is the following:

Assumption 1 $(i, j), (j, k) \in \mathcal{G}$ implies $(i, k) \in \mathcal{G}$ and $b_{ik} \geq b_{jk}$.

A *river flood game* is a cooperative game (N, v) generated by a river flood problem, where the worth of a coalition S is given by the maximization problem:

$$v(S) = \max_{F \subseteq S} \Psi(F, S, f, a, B) \tag{3}$$

where

$$\Psi(F, S, f, a, B) = \left\{ \sum_{i \in F} f_i + \sum_{j \in S \setminus F} a_j + \sum_{i \in F, j \in S \setminus F} b_{ij} \right\}.$$

In particular, we say that any set in $\arg\max_{F \subseteq N} \Psi(F, S, f, a, B)$ is an *optimal configuration* for S.

Notice that $\sum_{i \in F} f_i$ is the benefit from having forests, $\sum_{j \in S \setminus F} a_j$ is the benefit from other uses, and $\sum_{i \in F, j \in S \setminus F} b_{ij}$ is the benefit from externalities.

Regarding the notation, we apply the convention of using i for a generic element F (i.e. agents with forests) and j for a generic element of $N \setminus F$ (i.e. agents with other uses). When it is not defined whether an agent is a forest or not, we use either term indistinguishably.

The examples below represent diverging extreme situations, i.e. they are not necessarily the most plausible for real life situations, but they cover the broadest range of possibilities.

Example 2.1 *Let* $N = \{1, 2, 3\}$, $f = (1, 0.99, 2)$ *and* $a = (2, 1, 1)$. *Moreover, the graph is given by* $\mathcal{G} = \{(1, 2), (2, 3), (1, 3)\}$, *i.e. player* 1 *is upstream, player* 3 *is downstream, and player* 2 *is between the other two (see Figure 1). We assume that the benefit from lands* 2 *and* 3 *increases by* 2 *each when land* 1 *is a forest, and the benefit from land* 3 *increases by* 1 *if land* 2 *is a forest. Hence,* $b_{12} = b_{13} = 2$, $b_{23} = 1$, *and* $b_{ij} = 0$ *otherwise.*

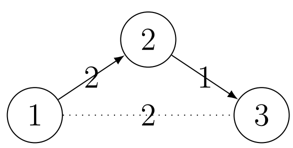

Figure 1: Example of a river basin.

The worth of each coalition and the optimal configuration that produces it, are shown in Table 1.

S	$v(S)$	forest	other uses
$\{1\}$	2	-	$\{1\}$
$\{2\}$	1	-	$\{2\}$
$\{3\}$	2	$\{3\}$	-
$\{1,2\}$	4	$\{1\}$	$\{2\}$
$\{1,3\}$	4	$\{1\}$	$\{3\}$
$\{2,3\}$	2.99	$\{2\}$	$\{3\}$
N	7	$\{1\}$	$\{2,3\}$

Table 1: Cooperative game that arises from the river flood problem presented in Example 2.1.

Notice that the river flood game given in Example 2.1 satisfies Assumption 1, because $b_{13} > b_{23}$, i.e. agent 1 is more effective at keeping a forest as a retention area. In this example the core is nonempty, as for instance the Shapley value $Sh(N, v) = (2.83, 1.83, 2.33) \in Core(N, v)$. This allocation is achieved by a two-step procedure: Firstly, optimal configuration $F = \{1\}$ (i.e. only agent 1 is a forest) is implemented, so that the direct benefit is $(1, 3, 3)$. Secondly, in compensation for agent 1 being a forest, agent 2 transfers 1.17 units of utility and agent 3 transfers 0.67 of utility to agent 1.

To emphasize the advantage of considering a centralized model such as the one proposed here, we briefly compare it to the situation in which agents act non cooperatively, i.e., with no compensation to one another.

We represent the problem given in Example 2.1 as follows. Assume that there are two 2×2 matrices (Table 2) so that agent 1 chooses the row, agent 2 chooses the column, and agent 3 chooses the matrix.

3 is a forest		
	2 forest	2 other uses
1 forest	$(1, 0.99, 2)$	$(1, 3, 2)$
1 other uses	$(2, 0.99, 2)$	$(2, 1, 2)$

3 other uses		
	2 forest	2 other uses
1 forest	$(1, 0.99, 4)$	$(1, 3, 3)$
1 other uses	$(2, 0.99, 2)$	$(2, 1, 1)$

Table 2: Non cooperative game that arises from the river flood problem presented in Example 2.1.

To compute the final payoff allocation in this example, we describe the final payoff allocation as follows: The first component of each vector is the payment to agent 1, the second component is the payment to agent 2, and the third component is the payment to agent 3. Each agent has two possible strategies: use his/her land as a forest or put it to other uses.

In this situation, we have the so called *iterated elimination of strictly dominated strategies* (Aumann, 1976), which enables us to predict the final outcome assuming some mild rationality in the agents.

Firstly, agent 1 should choose other uses, since that would provide a larger final payoff (2) than choosing a forest (1), whatever the other agents do. Knowing that, agent 2 should choose other uses, since that would provide a larger final payoff (1) than choosing a forest (0.99), whatever agent 3 does. Knowing that, agent 3 should choose to have a forest, since that would provide a larger final payoff (2) than choosing other uses (1).

Thus, the only rational choices in this game are for agents 1 and 2 to devote their land to other uses and agent 3 to have a forest, resulting in a final payoff allocation of $(2, 1, 2)$, which means that each agent is worse off than with the Shapley value $(2.83, 1.83, 2.33)$.

The Shapley value does not always belong to the core, as the next example shows:

Example 2.2 *Let* $N = \{1, 2, 3, 4, 5\}$*,* $f = (0, 0, 0, 0, 1)$*,* $a = (1, 0, 0, 0, 0)$*. Moreover, the graph (see Figure 2) is given by* $\mathcal{G} = \langle\{(1, 2), (1, 3), (1, 4), (1, 5), (2, 5), (3, 5)\}\rangle$*, and* $b_{ij} = 1$ *for all* $(i, j) \in \mathcal{G}$*.*

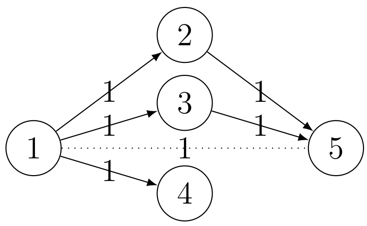

Figure 2: Example of a river flood game with the Shapley value outside the core.

The maximum aggregate benefit that agents can achieve in this example is 4*, which can be achieved in many ways. Formally, there are multiple optimal configurations, such as* $F = \{1, 5\}$ *and also* $F' = \{1, 2, 3\}$*.*

In the first case ($F = \{1, 5\}$*), nodes* 1 *and* 5 *are forest, so players* 1*,* 2 *and* 3 *benefit from the forest in node* 1 *and get a total of* 3 *units of benefit (*$b_{1i} = 1$ *for each* $i \in \{2, 3, 4\}$*) whereas node* 5 *gets* $f_5 = 1$ *for having another forest.*

In the second case ($F = \{1, 2, 3\}$*), nodes* 1*,* 2 *and* 3 *are forests, so player* 4 *benefits from the forest in node* 1 *and gets a total of* $b_{14} = 1$ *units of benefit, whereas player* 5 *gets* $b_{15} + b_{25} + b_{35} = 3$ *units of benefit from forests in nodes* 1*,* 2 *and* 3*.*

In both cases, the total benefit is 4*, and no other configuration can improve on this.*

Let (N, v) be the cooperative game generated by this river flood game. Then, $v(N) = 4$. Similarly, it is straightforward to check that $v(\{1, 2\}) = 1$, $v(\{1, 5\}) = 2$, and so on. In this case, $Sh(N, v) = (1.5, 0.5, 0.5, 0.42, 1.08)$. This payoff can be achieved by implementing $F = \{1, 5\}$, i.e. forests in 1 and 5, and making agents 2, 3 and 4 compensate 1 and 5 in order to achieve this payoff allocation. However, $v(\{1, 2, 3, 4\}) = 3 > 2.92 = \sum_{i=1}^{4} Sh_i(N, v)$. Hence, $Sh(N, v) \notin Core(N, v)$. Notice, in fact, that player 5 receives an unjustifiable compensation. Nonetheless, $Core(N, v)$ is nonempty, as for example $(1, 0, 1, 1, 1) \in Core(N, v)$. This payoff can be achieved by implementing $F = \{1, 5\}$ and making agent 2 pay 1 unit to agent 1 in exchange for having a forest. No coalition of agents can improve by itself on what this payoff allocation assign to it.

In following Sections, we propose a method for finding core allocations.

Given the private ownership of the land, any allocation that does not belong to the core can be blocked by a group of agents, leading to potential loss of efficiency in the location of forests.

In general, the assumption "the further the forest, the greater its beneficial effect" is key for the emptiness of the core, as the next example (which does not satisfy Assumption 1) shows:

Example 2.3 *Let $N = \{1, 2, 3, 4, 5\}$, $f = (0, 0, 0, 0, 1)$, $a = (1, 0, 0, 0, 0)$. Moreover, the graph (see Figure 3) is given by $\mathcal{G} = \langle\{(1, 2), (1, 3), (2, 5), (3, 4), (4, 5)\}\rangle$, $b_{12} = b_{13} = b_{25} = b_{34} = b_{45} = 1$ and $b_{ij} = 0$ otherwise.*

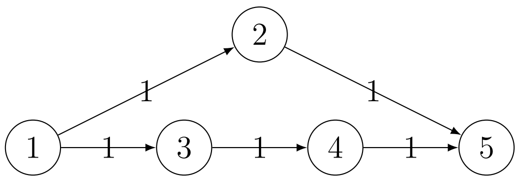

Figure 3: Example of a graph that induces a cooperative game with an empty core.

The worth of some coalition and their respective optimal configuration are given in Table 3.

S	$v(S)$	forest	other uses
$\{1,2,3,4\}$	2	$\{3\}$	$\{1,2,4\}$
$\{1,2,3,5\}$	3	$\{1,5\}$	$\{2,3\}$
$\{1,2,4,5\}$	3	$\{2,4\}$	$\{1,5\}$
$\{1,3,4,5\}$	3	$\{3,5\}$	$\{1,4\}$
$\{2,3,4,5\}$	2	$\{3,5\}$	$\{2,4\}$
N	3	$\{1,5\}$	$\{2,3\}$.

Table 3: Cooperative game that arises from the river flood problem presented in Example 2.3.

For $S = N$, it is irrelevant whether agent 4 has a forest or not. Notice that a core element x in the river flood game given in example 2.3 should satisfy $x_1 + x_2 + x_3 + x_4 \geq 2$, $x_2 + x_3 + x_4 + x_5 \geq 2$, and $x_i + x_j + x_k + x_l \geq 3$ otherwise, which implies that $x_1 + x_2 + x_3 + x_4 + x_5 \geq 3.25$. This is not possible because $v(N) = 3$, so the core is empty for this game.

2.3 Saturated river flood games

To analyze the nonemptyness of the core in general river flood games, we use the concept of *saturated river flood games*, defined as follows:

Definition 2.1 *We say that a river flood game is* saturated *if the two following conditions hold:*

- *For each pair of adjacent lands, there is an optimal configuration in which* both *are forests.*
- *For each pair of adjacent lands, there is an optimal configuration in which* neither *is a forest.*

It is not difficult to check that the river flood problem given in Example 2.3 is saturated. By contrast, the river flood problem (N, v) presented in Example 2.1 is not saturated, since the only optimal configuration is $F = \{1\}$. However, there is a saturated river flood game (N, w) that satisfies $v(S) \leq w(S)$ for all $S \subset N$ and $v(N) = w(N)$. In view of definition (1), this implies that $Core(N, w) \subseteq Core(N, v)$. Hence, the nonemptyness of $Core(N, w)$ implies the nonemptyness of $Core(N, v)$, and any core allocation in (N, w) is also a core allocation in (N, v).

Notice that, as with the examples given above, saturated river flood games are not necessarily expected to represent real life scenarios. Our methodology is, in fact, the following: We first mathematically check that if our result holds for saturated river flood games, then it holds for all river flood games; we then show by exhaustive sampling of random river flood games that our hypothesis holds true.

Next, we show how to generate a possible (N, w) from (N, v) in Example 2.1. We follow these steps:

1. Reduce b_{12} from 2 to 0.99 and increase f_1 from 1 to 2.01. With these changes, $v(\{1\})$ and $v(\{1,3\})$ increase, while the rest of $v(S)$ (including $v(N)$) remain unchanged. Furthermore, $F = \{1, 2\}$ becomes a new optimal configuration.

2. Reduce b_{23} from 1 to 0, removing arc $(3, 4)$; and increase f_2 from 0.99 to 1.99. With these changes, $v(\{2\})$ and $v(\{2,3\})$ increase, while the rest remain unchanged. Moreover, agent 1 and 3 become adjacent.

3. Reduce b_{13} from 2 to 1, and increase f_1 from 2.01 to 3.01. With these changes, $v(\{1\})$ and $v(\{1,2\})$ increase, while the rest remain unchanged. Furthermore, N and $\{1, 3\}$ become two new optimal configurations.

4. Reduce b_{12} from 0.99 to 0, removing arc $(1, 2)$; and increase a_2 from 1 to 1.99. With these changes, each $v(S)$ remains the same.

5. Reduce b_{13} from 1 to 0, removing arc $(1, 3)$, and increase a_3 from 1 to 2. With these changes, the river flood problem becomes trivially saturated (because there are no adjacent nodes).

Let (N, w) be the resulting river flood game. Thus, (N, w) is both saturated and additive (since there are no externalities). In particular, $Core(N, w) = \{(3.01, 1.99, 2)\}$. It can then be deduced that $(3.01, 1.99, 2) \in Core(N, v)$.

In general, this procedure can be replicated to generate a saturated river flood game from each non-saturated one, as the following proposition shows:

Proposition 2.1 *For each river flood game (N, v), there is a saturated river flood game (N, w) with at most as many arcs and such that*

- $v(S) \leq w(S)$ *for all* $S \subset N$.
- $v(N) = w(N)$.

Moreover, if (N, v) satisfies Assumption 1, it is possible to find such a (N, w) that also satisfies Assumption 1.

Proof. Let (N, v) let be a river flood game defined by f, a, and B. We check that there is a saturated river flood game (N, w) with at most as many arcs as $\mathcal{G}$ and such that the conditions of the Proposition are fulfilled. We proceed by double induction on the cardinality of $\mathcal{G}$, $|\mathcal{G}|$, and the cardinality of

$$\Omega = \left\{ (i, j) \in \mathcal{G} : i, j \text{ adjacent and } \max_{F \subseteq N : |F \cap \{i,j\}| \neq 1} \Psi(F, N, f, a, B) < v(N) \right\}, \tag{4}$$

the set of adjacent nodes for which there is no optimal configuration with both or none of them as forests. If $\mathcal{G} = \emptyset$ then there are no externalities and (N, v) is saturated, so $w = v$. Assume then the result holds when the cardinality of the graph is $|\mathcal{G}| - 1$ or lower. If $\Omega = \emptyset$, then (N, v) is saturated, and we take $w = v$. Now assume $\Omega \neq \emptyset$. W.l.o.g. it can be assumed that $(1, 2) \in \Omega$, so 1 is before 2 in the graph. Assume that there is no optimal configuration with both 1 and 2 as forests (the case in which neither of them is a forest is analogous). We define (N, v') as follows. Let

$$F' \in \arg \max_{F \subseteq N : \{1,2\} \subseteq F} \Psi(F, N, f, a, B) \tag{5}$$

be a configuration with the highest value of those in which both 1 and 2 are forests. By assumption, this configuration is not optimal, which implies that there is some optimal configuration $F'' \subset N$ with $\alpha = \Psi(F'', N, f, a, B) - \Psi(F', N, f, a, B) > 0$. Since 1 and 2 are adjacent with 1 before 2 in the graph, it is deduced that $b_{12} > 0$. Hence, $\alpha' = \min\{\alpha, b_{12}\} > 0$. Now, define (N, v') by taking $f_1' = f_1 + \alpha'$, $b_{12}' = b_{12} - \alpha'$, and $b_i' = f_i$, $a_j' = a_j$, and $b_{ij}' = b_{ij}$ otherwise. Since, 1 and 2 are adjacent, it is deduced that (N, v') satisfies Assumption 1 when (N, v) does. It is straightforward to check that F'' is still optimal in (N, v'), and so $v'(N) = v(N)$. Moreover, for each $S \subseteq N$, there is also $v(S) \leq v'(S)$, with strict inequality when $1, 2 \in S$ and there exists an optimal configuration in S in which both 1 and 2 are forests. There are two cases:

1. When $\alpha' = b_{ij}$, agents 1 and 2 are not adjacent in (N, v').

2. When $\alpha' = \alpha$, F is optimal in (N, v').

In the first case, we apply the induction hypothesis on $|\mathcal{G}|$. In the second case, we apply the induction hypothesis on $|\Omega|$. In both cases, the induction hypothesis tells us that there is a saturated river flood game (N, w) that satisfies Assumption 1 if (N, v) does, and such that $v'(S) \leq w(S)$ for all $S \subset N$ and $v'(N) = w(N)$. Since $v(S) \leq v'(S)$ for all $S \subset N$ and $v'(N) = v(N)$, we deduce our result. ■

The relevance of Proposition 2.1 is that $Core(N, w) \subseteq Core(N, v)$, and hence it suffices to study the nonemptyness of the core for saturated river flood games. Obviously, Assumption 1 plays a role in this study, since Example 2.3 shows that there are saturated river flood games with empty cores when Assumption 1 does not hold.

In Example 2.1 the resulting saturated game has no externalities and is hence trivially additive, which enables us to identify a core element. In general this is not the case, as following example shows:

Example 2.4 *Let $N = \{1, 2, 3\}$, $f = (0, 0, 1)$ and $a = (1, 0, 0)$. Moreover, the graph is given by $\mathcal{G} = \{(1, 2), (2, 3), (1, 3)\}$, as in Example 2.1 (see Figure 1). Let $b_{12} = b_{13} = b_{23} = 1$.*

The worth of each coalition and the optimal configurations that generate them are given in Table 4.

S	v(S)	optimal configurations
$\{1\}$	1	$\emptyset$
$\{2\}$	0	$\emptyset, \{2\}$
$\{3\}$	1	$\{3\}$
$\{1,2\}$	1	$\emptyset, \{1\}, \{2\}$
$\{1,3\}$	2	$\{3\}$
$\{2,3\}$	1	$\{2\}, \{3\}, \{2,3\}$
N	2	$\{1\}, \{2\}, \{3\}, \{1,2\}, \{1,3\}, \{2,3\}$

Table 4: Cooperative game that arises from the river flood problem presented in Example 2.4.

It can be checked from Table 4 that this river flood problem is saturated. To see why, notice that, for any pair of agents, there exists an optimal configuration that contains both of them, and another optimal configuration that contains none of them. For example, for players 1 and 2, both {1,2} and {3} are optimal configurations.

3 Stable sharing rules

The river flood problem presented in Example 2.4 is saturated. Moreover, it has externalities that cannot be reduced by increasing a or f, because that would increase $v(N)$.

However, it is still possible to remove an adjacent arc (in this case, either $(1, 2)$ or $(2, 3)$) without changing the associated river flood game. We claim that this is true in general:

Claim 3.1 *Under Assumption 1, each saturated river flood problem $(N, \mathcal{G}, f, a, B)$ satisfies one of the following conditions:*

1. $\mathcal{G} = \emptyset$, *or*
2. *there is some $(i, j) \in \mathcal{G}$ such that $v(S) = v^{-ij}(S)$ for all $S \subseteq N$, where (N, v) is the river flood game generated by $(N, \mathcal{G}, f, a, B)$ and (N, v^{-ij}) is the river flood game generated by $(N, \mathcal{G} \setminus \{(i, j)\}, f, a, B')$ with $b'_{kl} = b_{kl}$ for all $(k, l) \in \mathcal{G} \setminus \{(i, j)\}$.*

Although we do not have a formal proof, we have checked that this is true in more than 640,000 randomly generated river flood games taking natural restrictions. The algorithm used is described in the Appendix.

Claim 3.1 enables us to find core allocations.

Theorem 3.1 *Under Claim 3.1, the core is nonempty in any river flood game that satisfies Assumption 1.*

Proof. Under Proposition 2.1, for any river flood game (N, v) that satisfies Assumption 1, a saturated river flood game (N, w) can be found with $v(S) \leq w(S)$ for all $S \subset N$ and $v(N) = w(N)$ that also satisfies Assumption 1. Since $v(S) \leq w(S)$ for all $S \subset N$ and $v(N) = w(N)$, $Core(N, w) \subseteq Core(N, v)$ and it suffices to check that $Core(N, w) \neq \emptyset$. If (N, w) has no externalities, it is additive and hence $Core(N, w) = \{x\}$ where $x_i = w(\{i\})$ for all $i \in N$. Hence, $x \in Core(N, v) \neq \emptyset$. In case (N, w) has externalities, under Claim 3.1.2, the cardinality of the graph can be reduced and repeat the process repeated until the game becomes additive. ■

Nonemptyness of the core is an important property. It implies that shares in the benefit can be found that no coalition of players can improve by itself.

Given that core allocations can be found, we look for a way to choose a reasonable one, i.e. we look for a sharing rule in the class of river flood games. The Shapley value seems a natural candidate, but it may be outside the core (Example 2.2), even when the core is nonempty.

We next present three alternative core sharing rules.

The first (x in Table 5 and Algorithm 1 in the Appendix) applies the procedure used in the proofs of Proposition 2.1 and Theorem 3.1 in the most favorable way for agents located upstream. The second one (y in Table 5 and Algorithm 2 in the Appendix) applies the algorithm in the most favorable way for agents located downstream. Finally, we propose an intermediate sharing rule that balances the two approaches (z in Table 5 and equation (1) in the Appendix) .

Example 3.1 *Following the same procedure used above to obtain a saturated game in Example 2.1, we compute the three rules for all the examples in the paper. The results are shown in Table 5.*

	x	y	z
Example 2.1	$(3.01, 1.99, 2)$	$(2, 2, 3)$	$(2.505, 1.995, 2.5)$
Example 2.2	$(1, 1, 1, 0, 1)$	$(1, 1, 1, 0, 1)$	$(1, 1, 1, 0, 1)$
Example 2.4	$(1, 0, 1)$	$(1, 0, 1)$	$(1, 0, 1)$

Table 5: Three proposed sharing rules.

Example 2.1 represents a river basin with three land owners. If they cooperate, they can get a total benefit of 7 *units. To get that benefit, the planner should state that agent* 1 *devotes her/his land to have a forest, and agents* 2 *and* 3 *to other uses (see Table 1). In that case, the provisional benefit that the agents would receive is the following: agent* 1 *would receive* 1 *unit (the benefit for having a forest), agent* 2 *would receive* 3 *units (*1 *unit for devoting the land to other uses plus* 2 *units due to the externality caused by agent* 1 *for having a forest), and agent* 3 *would also receive* 3 *units (for the same reason as agent* 2*). If the planner plans to apply the sharing rule y, for instance, the final distribution of the benefit will be different from the provisional one. Agent* 2 *should compensate agent* 1 *with* 1 *unit, so agent* 1 *will finally receive* 2 *units and agent* 2 *will get also* 2 *units. The payoff of agent 3 will not change with respect the previous one, that is, she/he receives* 3 *units. Then, the final payoff allocation is* $(2, 2, 3)$*, as stated by rule y.*

Notice that the payoff allocation changes in Example 2.1 but not in Examples 2.2 and Example 2.4. This is because the latter describe saturated problems, whereas in Example 2.1 there is some freedom to build the associated saturated problem, depending on which agents it is intended to favor more.

4 Discussion

In this paper we assess the potential of game theory through cooperative games applied to flood risk reduction. We assess what benefits/costs would result from changes in land use in the upper areas of the catchment. It is a methodological contribution that analyzes land use management for floodwater retention. The result is positive in the sense that we show that cooperative games are indeed a useful tool. We consider it important to apply this model to different study areas as a future research line, after carrying out a flood risk assessment of the selected areas as some authors have already done (Lohani et al., 2011; Lyu et al., 2016, 2018b, a). It is advisable a practical application where we make use of the cooperative game theory to establish possible agreements among land owners. We plan to test our model in different types of basins to make comparisons and check if it works for different basins types. This would enable comparisons of different types of river basins to be made and would serve check how the model works depending on the particular characteristics of each basin. Finally, costs / benefits can be established according to land uses and their potential for reducing the risk of flooding.

Our study shows the possibility of continuing to progress in the reduction of flood risk through new alternatives such as incentives to owners to change land use upstream in the river basin, agreements between managers and owners, and allocation of benefits in uses that enhance water retention. This means progress at a scientific, technical, political, social, and environmental levels in this field.

Firstly, the purpose of European Floods Directive (European Commission, 2007) is to establish a framework for the assessment and management of flood risks, seeking to reduce adverse consequences for human health, environment, cultural heritage and economic activity associated with floods. Accordingly, the Directive requires Member States to draw up flood risk management plans. Public bodies must carry out specific plans to detect the main risks of flooding in the catchments that they manage, and to locate the areas with the highest risks of flooding. Flood risk management plans seek to improve territorial planning and flood zone management. In this sense, many studies have sought to model different situations depending on hydrological and weather data. Examples include Lyu et al. (2018c), Kourgialas and Karatzas (2011) and Levy (2005), and the studies listed in the review by Sanyal and Lu (2004). Other authors have sought to predict future conditions, so as to learn what the natural response will be if something is changed. For example, Purvis et al. (2008) offer a methodology for estimating the probability of future coastal flooding given uncertainty over possible sea level rise.

Moreover, the EU Water Framework Directive (European Parliament and Council, 2000) and the Blueprint to Safeguard Europe's Water Resources (European Commission, 2012) also recognize the potential of rural land use change for supporting water management objectives. In addition, the Directorate-General for Environment of the European

Commission highlights the role of natural approaches for protecting water resources and managing flood risks. It emphases that NWRM are multi-functional measures that seek to protect and manage water resources and have the potential to provide multiple benefits, such as flood risk reduction, water quality improvement, groundwater recharge, and habitat improvement (European Commission, 2014).

There seems to be a wide range of different techniques, analyses and studies that enable situations to be modeled, estimations made and risk areas detected. In addition, there are various recommendations on techniques for land use management to safeguard and enhance the water storage potential of landscape, soil, and aquifers. Therefore, it is recommended that work continue on learning how to avoid these natural risks. This knowledge needs to be shared in different areas and sectors more frequently. To that end, there are other types of tools not currently used in the field of flood risk which have great potential, such as the cooperative game theory applied in this paper.

Taking into account all these advances, the prospect of replacing "flood control" with "risk management" opens up. This can be done by influencing aspects that can reduce flood risk instead of striving for total control. In addition, this implies social and economic aspects that require the collaboration of all stakeholders and especially that of the landowners. One such strategy is to improve water retention in territories by controlling, as far as possible, the generation of runoff, which sometimes results in catastrophic floods. It is important to learn about and simulate the floods in cities, because they result in human, economic and environment damage. That means considering all the factors that influence the flow of water into cities. Those factors are present throughout river basins, no just in downstream areas. Changes, upsets and other situations upstream influence what happens downstream. Despite the growing literature on flood risk management, our paper presents, to our knowledge, the first cooperative game theory model specifically applied to incentive, from an economic point of view, the needed implication of land owners in this process.

5 Conclusions

This study shows a framework for allocating compensation amounts between participants based on cooperative game theory, taking into account a principle of stability. We show that it is possible to establish distribution rules that encourage stable payments for landowners. Specifically, we present three optimal stable methods for compensation payments between land owners that show that our model is applicable in real life. The assumptions made are examples of situations that can be found in a basin, so the method can be used to solve real life problems with flood risks. Game theory, such as our application of cooperative games here, can be applied in real life by managers to solve flood problems. There is a possibility of establishing cost / benefit sharing rules. For example, if public bodies wish to create subsidies to encourage forest use over other uses which are less beneficial for water retention they could use game theory to ensure fairness in the granting of such subsidies and the distribution of the relevant amounts. As another example, land that has a use that favors water retention and therefore reduces the risk of flooding could pay less taxes. One aspect to be noted is the computational time necessary to perform the calculations in case studies with a high number of nodes. When there are many nodes, the problem becomes intractable due to speed limits. Still, algorithms are quick and work well for up to 60 nodes, which is a reasonable number for many river basins. Moreover, it can also be used in larger river basins, since not all landowners have the possibility to change their land use and hence we can exclude them as players.

Cooperation between different public agencies would also be very positive in this case because, if places with a high potential for water retention are recognized, they can then be considered by the public administration as areas of special interest in territorial planning (protected areas, avoiding construction and infrastructures, promotion of certain land uses, etc.). This allows to take into account flood mitigation and ecosystem-based adaptation. In this case, we reduce vulnerability and increase resilience against climate risks through biodiversity and ecosystem services (Nesshöver et al., 2017; Ferrario et al., 2014; Schuerch et al., 2018; Getzner et al., 2017; Bianchi et al., 2018).

Finally, awareness in society in general and among landowners in particular is fundamental. They must be aware that the use of their land has repercussions for the risks of flooding, not only from their own land but also from land far from their location. They also need to be aware of the importance of land uses for society and the environment.

With the methodology, alternatives and assumptions considered in this study, a more comprehensive and basin-wide approach is analyzed to highlight the importance of retaining water in river catchment and upstream areas and to improve such retention. This is done by applying cooperative game theory. We explore a little-used tool to solve allocation issues in flood risk negotiations. Our results are positive in the sense that they show that stable incentives are possible in order to encourage landowners to contribute to flood risk reduction. Moreover, our proofs are constructive. We present two algorithms which actually implement stable compensation allocations. One or the other can be used depending on which kind of landowner (upstream or downstream) is to be more favored.

An average of the two can also be used to provide a more balanced allocation. A sensible policy can take these allocations into consideration in establishing a fair way to charge downstream areas. The idea is to incentivize upstream areas to adapt flood ecosystems without having to resort to tax or other external incentives. Territory planners, governments, and landowners could use cooperative game theory as a flood risk management tool. With this method, compensations and benefits are established to raise awareness and encourage land owners to cooperate.

Acknowledgements

The authors thank Andrea Janeiro, Lars Ehlers and Loe Schlicher, and the participants at the 14th European Meeting on Game Theory in Bayreuth (Germany), the XXXVII Congreso Nacional de Estadística e Investigación Operativa in Oviedo (Spain), and the LAND4FLOOD Workshop and Working Group meeting in Riga (Latvia) for their useful comments.

The authors acknowledge funding and networking support from COST Action CA16209: Natural Flood Retention on Private Land (LAND4FLOOD). Financial support from the Spanish Ministerio de Economía y Competitividad (ECO2014-52616-R), Ministerio de Economía, Industria y Competitividad (ECO2017-82241-R), and Xunta de Galicia (GRC 2015/014) is also gratefully acknowledged.

References

Aerts, J.C., Botzen, W.W., Emanuel, K., Lin, N., De Moel, H., Michel-Kerjan, E.O., 2014. Evaluating flood resilience strategies for coastal megacities. Science 344, 473-475. https://doi.org/10.1126/science.1248222

Alfieri, L., Feyen, L., Dottori, F., Bianchi, A., 2015. Ensemble flood risk assessment in Europe under high end climate scenarios. Global Environ. Chang. 35, 199-212. https://doi.org/10.1016/j.gloenvcha.2015.09.004

Aumann, R.J., 1976. Agreeing to disagree. Ann. Stat. 1236-1239. Stable URL: http://links.jstor.org/sici?sici=0090-5364%28197611%294%3A6%3C1236%3AATD%3E2.0.CO%3B2-D

Balica, S.F., Dinh, Q., Popescu, I., 2015. Vulnerability and exposure in developed and developing countries: Large-scale assessments, in: Hydro-Meteorological Hazards, Risks and Disasters Elsevier, Boston, pp. 125-162. https://doi.org/10.1016/B978-0-12-394846-5.00005-9

Barbedo, J., Miguez, M., van der Horst, D., Marins, M., 2014. Enhancing ecosystem services for flood mitigation: a conservation strategy for peri-urban landscapes? Ecol. Soc. 19. https://doi.org/10.5751/ES-06482-190254

Begum, S., Stive, M.J., Hall, J.W. (Eds.), 2007. Flood risk management in Europe: Innovation in policy and practice (Vol. 25). Springer, Dordrecht.

Bhattacharjee, K., Behera, B., 2017. Forest cover change and flood hazards in India. Land Use Policy 67, 436-448. https://doi.org/10.1016/j.landusepol.2017.06.013

Bhattacharjee, K., Behera, B., 2018. Does forest cover help prevent flood damage? Empirical evidence from India. Global Environ. Chang. 53, 78-89. https://doi.org/10.1016/j.gloenvcha.2018.09.004

Bianchi, E., Accastello, C., Trappmann, D., Blanc, S., Brun, F., 2018. The economic evaluation of forest protection service against rockfall: A review of experiences and approaches. Ecol. Econ., 154, 409-418. https://doi.org/10.1016/j.ecolecon.2018.08.021

Bouwer, L.M., 2011. Have disaster losses increased due to anthropogenic climate change? B. Am. Meteorol. Soc. 92, 39-46. https://doi.org/10.1175/2010BAMS3092.1

Brody, S.D., Highfield, W.E., Blessing, R., Makino, T., Shepard, C.C., 2017. Evaluating the effects of open space configurations in reducing flood damage along the Gulf of Mexico coast. Landscape Urban Plan. 167, 225-231. https://doi.org/10.1016/j.landurbplan.2017.07.003

Cook, H.F., 2017. The protection and conservation of water resources. John Wiley & Sons. New Jersey.

Directorate-General for Environment (European Commission), 2016. A guide to support the selection, design and implementation of Natural Water Retention Measures in Europe. https://publications.europa.eu/en/publication-detail/-/publication/a6de1b15-d277-4753-bc37-3b746b09ef9f. (Accessed 06-11-2018).

European Commission, 2007. Directive 2007/60/EC of the European Parliament and of the Council on the assessment and management of flood risks. https://www.eea.europa.eu/ds_resolveuid/225ca7718f284bb088d18344a23240d8. (Accessed 12-07-2018).

European Commission, 2012. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Commiteee and the Committee of the Regions, A Blueprint to Safeguard Europe's Water Resources (COM/2012/0673).

European Commission, 2014. EU policy document on Natural Water Retention Measures by the drafting team of the WFD CIS Working Group Programme of Measures. Technical Report. https://circabc.europa.eu/sd/a/2457165b-3f12-4935-819a-c40324d22ad3/Policy%20Document%20on%20Natural%20Water%20Retention%20Measures_Final.pdf. (Accessed 06-11-2018).

European Environment Agency, 2015. Water retention potentials of Europe's forests. a European overview support to natural water retention measures. https://www.eea.europa.eu/publications/water-retention-potential-of-forests. (Accessed 06-11-2018).

European Parliament and Council, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal (OJ L 327), pp. 1-73. https://www.eea.europa.eu/ds_resolveuid/e2e9a06d22054287afa97e82e95913fc. (Accessed: 12-07-2019).

Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., Airoldi, L., 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat. Commun. 5, 3794. https://doi.org/10.1038/ncomms4794

Field, C.B., Barros, V., Stocker, T.F., Dahe, Q., 2012. Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge.

Getzner, M., Gutheil-Knopp-Kirchwald, G., Kreimer, E., Kirchmeir, H., Huber, M., 2017. Gravitational natural hazards: Valuing the protective function of alpine forests. For. Policy Econ. 80, 150-159. https://doi.org/10.1016/j.forpol.2017.03.015

Graf, W.H., 1998. Fluvial hydraulics: Flow and transport processes in channels of simple geometry. Number 551.483 G7. John Wiley and Sons, Chichester.

Hartmann, T., 2016. Clumsy foodplains: Responsive land policy for extreme floods. Routledge.

IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 169-194.

Jalayer, F., De Risi, R., Giugni, M., Manfredi, G., Gasparini, P., Cavan, G., 2014. Probabilistic gis-based method for delineation of urban flooding risk hotspots. Nat. Hazards 73, 975-1001. https://doi.org/10.1007/s11069-014-1119-2

Jongman, B., Winsemius, H.C., Aerts, J.C., de Perez, E. C., van Aalst, M.K., Kron, W., Ward, P.J., 2015. Declining vulnerability to river floods and the global benefits of adaptation. Proc. Natl Acad. Sci. 201414439.

Kourgialas, N.N., Karatzas, G.P., 2011. Flood management and a GIS modelling method to assess flood-hazard areas - a case study. Hydrol. Sci. Journal - Journal des Sci. Hydrol. 56, 212- 225. https://doi.org/10.1080/02626667.2011.555836

Laurance, W.F., 2007. Environmental science: Forests and floods. Nature 449, 409. https://doi.org/10.1038/449409a

Levy, J.K., 2005. Multiple criteria decision making and decision support systems for flood risk management. Stoch. Environ. Res. Risk Assess., 19, 438-447.

Lohani, A.K., Goel, N.K., Bhatia, K.K.S., 2011. Comparative study of neural network, fuzzy logic and linear transfer function techniques in daily rainfall-runoff modelling under different input domains. Hydrol. Process. 25, 175-193. https://doi.org/10.1002/hyp.7831

Lyu, H.-M., Shen, J.S., Arulrajah, A., 2018a. Assessment of geohazards and preventative countermeasures using AHP incorporated with GIS in Lanzhou, China. Sustainability, 10, 304-. https://doi.org/10.3390/su10020304

Lyu, H.-M., Shen, S.-L., Zhou, A., Yang, J., 2019. Perspectives for flood risk assessment and management for mega-city metro system. Tunn. Undergr. Sp. Technol. 84, 31-44. https://doi.org/10.1016/j.tust.2018.10.019

Lyu, H.-M., Sun, W.-J., Shen, S.-L., and Arulrajah, A. 2018b. Flood risk assessment in metro systems of mega-cities using a GIS-based modeling approach. Sci. Total Environ. 626, 1012-1025. https://doi.org/10.1016/j.scitotenv.2018.01.138

Lyu, H.-M., Wang, G.-F., Shen, J.S., Lu, L.-H., Wang, G.-Q., 2016. Analysis and GIS mapping of flooding hazards on 10 May 2016, Guangzhou, China. Water 8, 447. https://doi.org/10.3390/w8100447

Lyu, H.-M., Xu, Y.-S., Cheng, W.-C., and Arulrajah, A. (2018c). Flooding hazards across southern China and prospective sustainability measures. Sustainability 10, 1682. https://doi.org/10.3390/su10051682

Machac, J., Hartmann, T., Jilkova, J., 2018. Negotiating land for flood risk management: upstream-downstream in the light of economic game theory. J. Flood Risk Manag. 11, 66-75. http://dx.doi.org/10.1111/jfr3.12317

Mechler, R., Bouwer, L. M., Linnerooth-Bayer, J., Hochrainer-Stigler, S., Aerts, J.C.J.H., Surminski, S., Williges, K., 2014. Managing unnatural disaster risk from climate extremes. Nat. Clim. Chang. 4, 235-237. https://doi.org/10.1038/nclimate2137

Miguez, M. G., Veról, A. P., Carneiro, P. R. F., 2012. Sustainable drainage systems: an integrated approach, combining hydraulic engineering design, urban land control and river revitalisation aspects, in: Drainage systems. InTech.

Mustafa, A., Bruwier, M., Archambeau, P., Erpicum, S., Pirotton, M., Dewals, B., Teller, J., 2018. Effects of spatial planning on future flood risks in urban environments. J. Environ. Manage. 225, 193-204. https://doi.org/10.1016/j.jenvman.2018.07.090

Nesshöver, C., Assmuth, T., Irvine, K.N., Rusch, G.M., Waylen, K.A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., Külvik, M., Rey, F., van Dijk, J., Vistad, O.I., Wilkinson, M.E., Wittmer, H., 2017. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. Sci. Total Environ. 579, 1215- 1227. https://doi.org/10.1016/j.scitotenv.2016.11.106

Neumayer, E., Barthel, F., 2011. Normalizing economic loss from natural disasters: a global analysis. Glob. Environ. Chang. 21, 13-24. https://doi.org/10.1016/j.gloenvcha.2010.10.004

Nquot, I., Kulatunga, U., 2014. Flood mitigation measures in the United Kingdom. Procedia Econ. Financ. 18, 81-87. 4th International Conference on Building Resilience, Incorporating the 3rd Annual Conference of the ANDROID Disaster Resilience Network, 8th - 11th September 2014, Salford Quays, United Kingdom. https://doi.org/10.1016/S2212-5671(14)00916-2

Papathanasiou, C., Serbis, D., Mamassis, N., 2013. Flood mitigation at the downstream areas of a transboundary river. Water Util. J. 3, 33-42. https://www.ewra.net/wuj/pdf/WUJ_2013_05_04.pdf.(Accessed: 12-07-2019).

Petts, G.E., Amoros, C., 1996. The Fluvial Hydrosystem. Springer, pp.1-12. https://doi.org/10.1007/978-94-009-1491-9_1

Purvis, M.J., Bates, P.D., Hayes, C.M., 2008. A probabilistic methodology to estimate future coastal flood risk due to sea level rise. Coast. Eng. 55, 1062-1073. https://doi.org/10.1016/j.coastaleng.2008.04.008

Rasid, H., Paul, B.K., 1987. Flood problems in Bangladesh: Is there an indigenous solution? Environ. Manage. 11, 155-173. https://doi.org/10.1007/BF01867195

Rezende, O., 2010. Avaliação de medidas de controle de inundações em um plano de manejo sustentável de águas pluviais aplicado à baixada fluminense. Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia (COPPE), Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil.

Roth, D., Winnubst, M., 2014. Moving out or living on a mound? jointly planning a Dutch flood adaptation project. Land Use Policy 41, 233-245. https://doi.org/10.1016/j.landusepol.2014.06.001

Sanyal, J., Lu, X.X., 2004. Application of remote sensing in flood management with special reference to monsoon Asia: a review. Natural Hazards 33, 283-301. https://doi.org/10.1023/B:NHAZ.0000037035.65105.95

Scherer, D., 1990. Upstream/downstream: Issues in environmental ethics. Temple University Press.

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D.,Mc Owen, C. J., Pickering, M. D., Reef, R., Vafeidis, A. T., Hinkel, J., Nicholls,R. J., Brown, S., 2018. Future response of global coastal wetlands to sea-level rise. Nature 561, 231-234.

Serra-Llobet, A.S., Kondolf, G.M., Schaefer, K., Nicholson, S., 2018. Managing flood risk: innovative approaches from big floodplain rivers and urban streams. Springer. https://doi.org/10.1007/978-3-319-71673-2

Shapley, L.S., 1953. A value for n-person games, in: Kuhn, H., Tucker, A. (Eds.), Contributions to the theory of games, volume II of Annals of Mathematics Studies. Princeton University Press, Princeton NJ., pp. 281-304.

Shen, S.-L., Xu, Y.-S., 2011. Numerical evaluation of land subsidence induced by groundwater pumping in Shanghai. Can. Geotech. J. 48, 1378-1392. https://doi.org/10.1139/t11-049 te Linde, A.H., Bubeck, P., Dekkers, J.E.C., de Moel, H., Aerts, J.C.J.H., 2011. Future flood risk estimates along the river Rhine. Nat. Hazard Earth Sys. 11, 459-473. https://doi.org/10.5194/nhess-11-459-2011

Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nature 504, 7478-7479.

Tempels, B., Hartmann, T., 2014. A co-evolving frontier between land and water: dilemmas of flexibility versus robustness in flood risk management. Water Int. 39, 872-883. https://doi.org/10.1080/02508060.2014.958797

Teng, J., Jakeman, A. J., Vaze, J., Croke, B. F., Dutta, D., Kim, S., 2017. Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. Environ. Modell. Softw. 90, 201-216. https://doi.org/10.1016/j.envsoft.2017.01.006

Thaler, T.A., Priest, S.J., Fuchs, S., 2016. Evolving inter-regional co-operation in flood risk management: distances and types of partnership approaches in Austria. Reg. Environ. Change 16, 841-853. https://doi.org/10.1007/s10113-015-0796-z

The Working Group F on Floods, 2012. Flood risk management, economics and decision making support. http://ec.europa.eu/environment/water/flood_risk/pdf/WGF_Resource_doc.pdf. (Accessed: 06-11-2018).

Tyszka, J., 2009. Estimation and economic valuation of the forest retention capacities. J. Water Land Dev. 13, 149-159. https://doi.org/10.2478/v10025-010-0025-6

Van Dijk, A.I., Van Noordwijk, M., Calder, I.R., Bruijnzeel, S.L., Schellekens, J., Chappell, N.A., 2009. Forest-flood relation still tenuous-comment on 'global evidence that deforestation amplifies flood risk and severity in the developing world' by CJA Bradshaw, NS Sodi, KS-H. Peh and BW Brook. Global Change Biol. 15, 110-115.

Visser, H., Petersen, A.C., Ligtvoet, W., 2014. On the relation between weather-related disaster impacts, vulnerability and climate change. Climatic Change 125, 461-

477. https://doi.org/10.1007/s10584-014-1179-z

von Neumann, J., Morgenstern, O., 1944. Theory of Games and Economic Behavior, first ed. Princeton UP.

Yin, J., Yu, D., Yin, Z., Wang, J., Xu, S., 2013. Multiple scenario analyses of Huangpu River flooding using a 1D/2D coupled flood inundation model. Nat. Hazards 66, 577-589. https://doi.org/10.1007/s11069-012-0501-1

Zeleňáková, M., Diaconu, D.C., Haarstad, K., 2017. Urban water retention measures. Procedia Engineering 190, 419-426. https://doi.org/10.1016/j.proeng.2017.05.358