Process-based flood damage modelling relying on expert knowledge: a methodological contribution applied to agricultural sector

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Abstract. Flood damage assessment is crucial for evaluating flood management policies. In particular, properly assessing damage to the agricultural assets is important because they are complex economic systems particularly exposed to floods. The modelling approaches used to assess flood damage are of several types and can be fed by damage data collected post-flood, from experiments or based on expert knowledge. The process-based models fed by expert knowledge are subject of research and also widely used in an operational way. Although identified as potentially transferable, they are in reality often case-specific and difficult to reuse in time (updatabililty) and space (transferability). In this paper, we argue that process-based models, based on a rigorous modelling process, can be suitable to be applied in different contexts. We propose a methodological framework aiming at verifying the conditions necessary to develop these models in a spirit of capitalisation by relying on four axes which are: i/ the explicitation of assumptions, ii/ the validation, iii/ the updatability, iv/ the transferability. The methodological framework is then applied to the model we have developed in France to produce national damage functions for the agricultural sector. We show in this paper that the proposed methodological framework allows an explicit description of the modelling assumptions and data used, which is necessary to consider a reuse in time or a transfer to another geographical area. In this sense, this methodological framework constitutes a solid basis for considering the validation, transfer, comparison and capitalisation of data collected around models based on processes relying on expert knowledge. In conclusion, we identify research tracks to be implemented to pursue this improvement in a spirit of capitalisation and international cooperation.

1 Introduction

Worldwide, flooding generate huge damage (van Loenhout et al., 2020) estimated at 58 billion EUR (75 billion USD) per year (Alfieri et al., 2017). The EU Floods Directive (Directive 2007/60/EC) requires Member States first, to map flood extent and assets at risk; second to coordinate measures to reduce this flood risk. Every Member States are confronted to this challenge to decrease total flood damage while urban assets keep on developing in flood prone area (Rojas et al., 2013). To face this challenge, flood management usually mix several types of approach at river basin level. Agricultural areas globally generate less damage than urban ones (1% only of the total damage in Europe (Alfieri et al., 2017)). As a consequence, protection measures such as dykes are usually dedicated to protect urban areas. Farmers are rather seen as potential contributors to reduce flood risk either by changing their practices (O'Connell et al., 2007; Posthumus and Morris, 2010) or by using agricultural lands to give more room for water flooding which involves increasing their exposure (Morris et al., 2010). However, the second type of measures raises many questions on acceptability and compensations (Zandersen et al., 2020; Erdlenbruch et al., 2009; Posthumus et al., 2008, 2010). Then properly evaluate flood damage on agriculture becomes a real issue for two reasons. First, evaluating flood damage on agriculture is necessary to justify the efficiency of the policy and then the choice that can be done between several options. This is usually done by performing Cost-Benefit Analysis which requires developing flood damage functions (Jonkman et al., 2008; Merz et al., 2010). Second, even if the project is efficient, the acceptability of those measures requires involving farmers (Posthumus et al., 2008) and introducing compensation payments (Erdlenbruch et al., 2009). To reach this goal, developing a comprehensive model to evaluate flood damage on farms is necessary. In particular, to discuss and build a trusting relationship with farmers that may be over exposed, this model needs to reflect as much as possible what happens to them in case of flooding.

Several classifications of the methods used to model flood damage can be found in the literature (Jongman et al., 2012; Davis and Skaggs, 1992; Merz et al., 2010; Molinari et al., 2020; Malgwi et al., 2021). However, these classifications are not operative because they mix the modelling methods and the data necessary to feed the models. Presenting the modelling methods separately from the data needed to feed them provides greater clarity. The strategies generally adopted to model flood damages are: (i) data driven modelling, (ii) conceptual modelling, (iii) process-based modelling. To feed these models, different types of data can be used: (i) damage observation data, (ii) data from expert knowledge, (iii) data from experiments. Data driven modelling approaches requires damage observation data. Conceptual modelling are more often used to evaluate indirect damage with input-output (IO) models (Hallegatte, 2008; Van der Veen et al., 2003; Hallegatte, 2014; Crawford-Brown et al., 2013; Xie et al., 2012) or computable general equilibrium (CGE) models (Xie et al., 2014; Rose and Liao, 2005; OCDE, 2014). They are appropriate for indirect and large scale damage evaluation but not for sectoral damage evaluation at micro and meso scales. Process-based modelling can be fed by expert knowledge or experimental data. Experiments require very significant monetary and time investments. Most often process-based modelling approaches are fed with expert knowledge. To do so, it is recommended to have experienced interviewers, who also have some knowledge of making damage estimates (Davis and Skaggs, 1992). To illustrate these categories of modelling approaches, let us take the example of flood damage assessment models developed in Germany and the United Kingdom. In Germany, a huge effort to collect post-flood damage data has been carried out (Thieken et al., 2017) and the models developed for residential (FLEMO-ps) (Thieken et al., 2008a) and economic assets (FLEMO-c) (Kreibich et al., 2010) are data driven models. On the contrary, the flood damage functions that have been established in United Kingdom by the Flood Hazard Research Center (FHRC) are process-based models fed with expert knowledge (Penning-Rowsell and Chatterton, 1977; Penning-Rowsell et al., 1992, 2005, 2013; Priest et al., 2021b). The flood damage model INSYDE (Dottori et al., 2016) in Italy or **floodam.building** (Grelot and Richert, 2019) in France are also part of this category. Each of these methods has its advantages and drawbacks. For data-based approaches, it remains difficult to systematically collect individual data on a large scale. For process-based approaches, the understanding of processes often remains too incomplete (Merz et al., 2010; Meyer et al., 2012, 2013). Moreover, process-based modelling approaches are often pointed out as being context specific and not allowing capitalisation of modelling efforts to other contexts.

For agricultural sector, no data driven models was found in the literature. In Germany, no model such as FLEMOps or FLEMOc exists for agriculture (Thieken et al., 2008b). To evaluate agricultural damage in the MEDIS project, Forster et al. (2008) extrapolated yield loss estimation based on one specific flood in Germany. This can be explained by the fact that little sinistrality data is available for the agricultural sector. The penetration rate of private insurance for flood crop losses is low (Priest et al., 2021a; Browne, 2000; Vozinaki et al., 2015) and no private insurance for overall agricultural damage exist as for example for soil erosion. Conceptual models are not suitable for assessing damage at the watershed or farm level (Meyer et al., 2013). Flood damage on economic activities such as farms is classically estimated by the loss of added value (Penning-Roswell et al., 2005; Brémond and Grelot, 2010) which corresponds to the decrease in product minus the variation in production costs due to flooding (Brémond et al., 2013). Due to flood impacts, the farmer will make some choices which will lead to variation in production costs. Some may be saved (harvest) while others may increase (treatment, tillage, for instance). Then, damage to agricultural assets results both from complex biophysical processes and from repair and recovery actions taken by farmers, which need to be explained in order to assess the damage (Brémond et al., 2013; Brémond, 2011; Durant et al., 2018; Priest et al., 2021a). For this purpose, a process-based modelling approach seems to be the most promising. As experimental data on flood damage on farms are scarce and context-specific (Satrapa et al., 2012), feeding expert knowledge into the models seems most suitable. However, a literature review on 42 studies on flood damage modelling for agricultural activities (Brémond et al., 2013) showed that many simplifications are usually done: (i) most methods considered only the loss of yield; (ii) the loss of yield was estimated in function of period of the year which hinder the transferability to other geographical context; (iii) the biophysical processes considered were not explicit; (iv) the implications of flooding on farmers' actions were not explicitly considered or not transferable; (v) the implications of flooding for perennial crops were not taken into account; (vi) the modelling assumptions were not validated.

In this article, we analyze and discuss the methodological aspects required to develop process-based damage assessment models in a spirit of capitalisation. We propose a framework for the development of damage assessment models based on expert knowledge and illustrate its use around the model **floodam.agri** that we have developed and used to produce flood damage functions for the agricultural sector in France. Two questions are addressed: (i) Is the methodological framework we propose useful for developing flood damage assessment models in the spirit of capitalisation? (ii) What methodological efforts are needed to develop process-based models that are not only context specific in this capitalisation and cooperation perspective? In section 2, based on a state of the art, the proposed methodological framework is detailled around its four axis: (i) explicit assumptions, (ii)validation, (iii) updatability and (iv) transferability. In section 3, the case study, i.e the context and main steps of development of **floodam.agri** are presented. Then, in section 4, the methodological framework is applied to **floodam.agri**. In the section 5, the usefulness and limitations of the framework are discussed. Finally, the section 6 concludes by outlining the research avenues to be developed for the improvement of process-based models.

2 Methodological framework for capitalizing on modeling efforts

2.1 Proposition of a methodological framework

Based on a review of the literature as well as on our own modeling experience, we propose the methodological framework presented in the table 1. It is presented in the form of questions that are as many conditions to be respected for the development of process-based models in a capitalisation perspective. We detail the conditions of each axis in the sections 2.2 to 2.5.

2.2 Axis 1: Explicit Assumptions: system boundaries, biophysical processes and decisions

Gerl et al. (2016) reviewed 47 flood damage models (process-based or data driven) in order to create a basis for harmonization and benchmarking. One of their main conclusion is that this requires profound insight into the model structures, mechanisms and underlying assumptions. In the following, we highlight which assumptions need to be explicited.

Flood damage are usually classified in four types: direct tangible (e.g. physical damage due to contact with water), indirect tangible (e.g. loss of production and income), direct intangible (e.g. loss of life) and indirect intangible (Jongman et al., 2012; Merz et al., 2010; Priest et al., 2021b). To evaluate flood damage on economic activities, defining the limits of the system considered is crucial to distinguish between direct and indirect damage since the flood affects not just the property directly affected. As an example, on agricultural assets, Brémond and Grelot (2012) identified induced damage at farm scale due to the links between farm plots and buildings. Nortes Martínez et al. (2020) shows the importance of interactions betweens farms and the cooperative at a winery cooperative scale and the consequences on flood damage estimation. So first, clearly defining the limits and the components of the system under consideration is necessary to avoid problems of double counting or forgetting damage. This refers to the condition EA1 in the table 1.

Then, process-based models try to reflect physical or biophysical processes that occurs on the considered system and which generate flood impacts. Those processes are numerous, depend on the component of the system considered and may depend on different flood parameters (Kelman and Spence, 2004). Explicit assumptions on which are the processes considered, on which component of the system and which are the flood parameters involved are essential in

Table 1. Methodological framework for the development of process-based flood damage models

Axis 1 : Explicit assumptions	
EA1	What are the boudaries and components of the system considered ?
EA2	What are the biophysical processes that cause the damage considered?
	Are the biophysical processes that cause the damage taken into account in the model explicitly considered?
	Are the links between biophysical processes and flood parameters clearly defined?
EA3	Which are the assumptions on farmers' decisions?
	Are the links between the farmers' decisions and impacts made explicit?
Axis 2 : Validation	
V1	Is it possible to compare the model results with sinistrality data?
V2	Is it possible to compare the results of the model with other similar models?
V3	Does the model meet stakeholders' expectations?
V4	Has the model been tested on several application cases?
V5	Has the model been presented and discussed with the experts involved for the development?
	Are modeling assumptions about processes and actions validated with the experts involved?
	Are the monetization values validated with the experts involved?
	Are the results of the models validated with the experts involved?
Axis 3 : Updatability	
U1	Are all the data used in the model and their sources made explicit?
U2	Are the vintages of the data used in the model specified?
U3	Are the data used tracked over time?
Axis 4 : Transferability / improvements	
T1	Are the conditions for adaptations, improvements and transfers described?
T2	Has the model been transferred to another context?

process-based models (Davis and Skaggs, 1992). Condition EA2 (table 1) is developed in sub-conditions that helps to detail how the biophysical processes due to flood on the considered system taken into account.

Finally, flood damage results of interaction of flood impacts and human behaviour (Middelmann-Fernandes, 2010). At the end, evaluating the damage in monetary terms requires knowing the repair and restoration choices made by the people affected and their costs. In data-driven modelling those choices are implicitly included in the damage data collected. In process-based models, the property damage avoided technique is used (Shabman and Stephenson, 1996). The repair choices and their costs are hypothetical and fed with expert knowledge. As a consequence, explicit assumptions on the decision rules considered are also critical to properly describe a process-based damage model. This refers to the condition EA3 (table 1).

2.3 Axis 2: Validation

Although the research community has put a lot of efforts into improving flood damage models, Molinari et al. (2019a) point the lack of validation and identify three modalities for the validation of flood damage models which are: (i) the comparison with observed data, (ii) the comparison with other models, (iii) the use of expert judgement. In the methodological framework (table 1), the condition V1 questions the possibility to compare the outputs with observed damage data and the condition V2 to compare the models between them. However, for all sectors, and especially for the agricultural one, a lack of data to fully implement the first modality is commonly observed. In addition, sinsitrality data should be considered with caution as it may only represent part of the damage that one wishes to compare. The insurance coverage of the different types of damage, in particular in agriculture, is not complete. As for the second one, a lot of work is being done to compare the different existing models (Gerl et al., 2016; Molinari et al., 2020; Malgwi et al., 2021) in order to have a better idea of the uncertainties. However, the difficulties encountered are often related to the lack of explicit assumptions used in the approaches and modeling choices which brings us back to the importance of properly addressing axis 1 of our methodological framework. The third modality is a validation related to the operationality and use of the model. We state that two perspectives should be distinguished:(i) the adequacy with the stakeholders' expectations (condition V3) which is related to the use of the model in practice (V4), (ii) the validation with the experts involved in the modelling process (V5). As for the second point, few experience and methodology has been found. Let us mention the experience of Dias et al. (2018) who discussed with experts the data collected for the construction of damage functions on buildings. The methodology for validating the models with experts remains to be consolidated. Based on our own experience, we detail in the V5 condition, the sub-conditions which seem to us necessary for the validation by the experts involved in the modeling process in the following steps: (i) discussion of the modeling assumptions about processes and recovery actions, (ii) discussion of the monetization values; (iii) discussion of the outputs.

2.4 Axis 3: Updatability

Although some research exists on updating flood hazard models, for example by integrating climate change (Hattermann et al., 2016), the update of flood damage models remains little investigated although necessary (Comiskey, 2005). Updatability is defined as the possibility of updating and should be understood as the anticipation in the modeling process of the possibility of updating the calibration data of the model. This notion is different from the update which corresponds to updating the model outputs. It can be achieved through the updatability of the source data or through simplified methods of actualization of the outputs. The update when it is addressed, concerns the values allowing the monetization as for example, in the last version of the multi-coloured handbook (Priest et al., 2021b). In general, the databases used are rarely made explicit and even less so the vintages. It is therefore important to verify whether the types of data and their sources are made explicit (condition U1, table 1), whether the database vintages used are specified (condition U2), whether the databases are tracked over time (condition U3).

2.5 Axis 4: Transferability

Transferring flood damage model is a challenging issue (Molinari et al., 2020; Jongman et al., 2012; Cammerer et al., 2013). As we dealt with updating in the section 2.4, we focus here on transfer in space and improvements of the model. Improving modelling techniques to transfer data driven flood damage models has been largely explored (Wagenaar et al., 2018, 2021). But, the transfer of process-based model is very challenging mainly because it requires a great understanding of origin, calibration, assumptions, field of application which brings back again to the central issue of explicit modelling assumptions (section 2.2). Although process-based modeling approaches seem to be the most promising in terms of transferability, the lack of explicit assumptions hinders this and models developed remains context-specific (Vozinaki et al., 2015). For example, for the development of AGRIDE-c (Molinari et al., 2019b; Scorzini et al., 2020), **floodam.agri** was partially transferred. In particular, the yield loss coefficients were directly used after discussions with local experts. However, the part concerning the validation by experts remains poorly detailed in Molinari et al. (2019b); Scorzini et al. (2020). We are not sure that all the central assumptions of **floodam.agri**, namely biophysical processes and farmers' decisions, were sufficiently detailed in Agenais et al. (2013) to allow transferability. Condition T1 (table 1) checks whether the adaptation, improvement or transfer conditions have been taken into account and described at the time of the model design. Condition T2 refers to the effective transfer of the model.

3 Case study: the development of floodam.agri to produce national damage functions for agriculture in France

3.1 Context of development and implications

In France, since 2011, it is mandatory for local flood risk managers to conduct cost-benefit analysis (CBA) of their flood management projects, to make them eligible for financial support from the State. Meanwhile, as a support, the French Ministry in charge of Environment proposed a methodology to fulfil CBA (Rouchon et al., 2018). A working group of engineers and researchers of which we were part was charged to develop damage functions usable on a national scale. The idea was that the consulting firms in charge of the realization of CBA for local flood risk managers could use these resources whatever the context. Two strategies were possible: reuse and adapt damage functions to the French context or develop our own functions. For the agricultural sector, among existing process-based models, the AGDAM model developed by the USACE (1985) and the model developed by the FHRC (Hess and Morris, 1988; Morris and Hess, 1988; Penning-Roswell et al., 2005; Priest et al., 2021a) standed out as being the most advanced. The possibility of adapting AGDAM or the FHRC damage functions was investigated. However, a review of the literature (Brémond et al., 2013) revealed that no existing damage function could meet the operational needs. Indeed, the Ministry needed ready to use French National Damage Functions: (i) that cover the vast majority of French agricultural crops and that were compatible with the databases used to locate them (Graphical Plot Register,

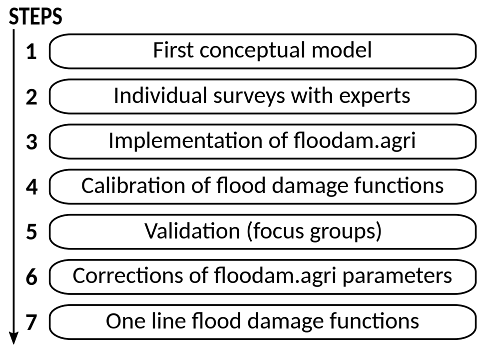


Figure 1. Development process of the national flood damage functions for agriculture

GPR, which is the french Land Parcel Identification System, LPIS,connected to the Common Agricultural Policy), (ii) that are applicable on a national scale but can be adjusted to local specificities if needed (specific culture, selling price. . .), (iii) that are updatable, i.e. based on values from identified databases that can be tracked over time as far as possible. Then, the option retained was to develop our own damage functions. As in other countries, the lack of sinistrality data quickly led us to choose process-based models based on expert knowledge. In this article, we focus on the **floodam.agri** model that we developed and that was used to produce the national damage functions. However, ready to use national flood damage functions have been developed for residential sector, public infrastructures, agricultural sector, and commercial and industrial sector. They are all available online[1]. In practice, since 2013, over 200 flood management projects have been analyzed by cost-benefit using this method and flood damage functions.

3.2 Methodology to develop floodam.agri and produce national damage functions

floodam.agri includes generic parts and can produce damage functions at different scales, depending on the calibration. We illustrate in this article the use of **floodam.agri** to produce damage functions at the national scale. This methodology has followed seven stages (figure 1).

First, the **conceptual framework** has been established. A crop category is broken down into elementary components and for each component, the damage is estimated based on the biophysical processes at work due to the flood and the actions carried out by farmers after the flood.

Second, to inform the conceptual framework, thirty **individual surveys** (figure 2) with agricultural experts working in regional technical institutes were carried out. They usually had expertise at the level of a crop family that encompasses several categories (appendix A, table A1). Some had expertise in several families of crops. Among the experts, six were specialists in grain and oleaginous crops, eight in vegetable crops, four in vines, three in fruit-trees, and eight in meadows and feeding crops. The experts worked in geographical areas where crops had been impacted by at least once flood since 2005. We focused on five areas that differ in terms of hydrological and

[1] https://www.ecologie.gouv.fr/levaluation-economique-des-projets-gestion-des-risques-naturels

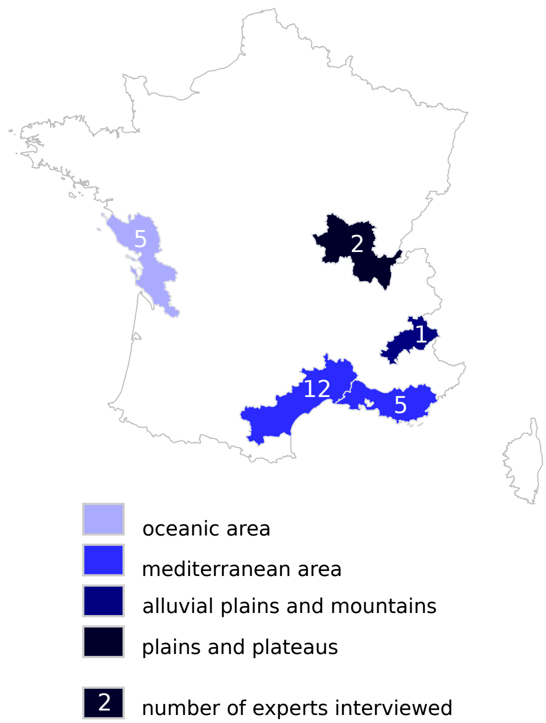


Figure 2. Geographic distribution of the experts interviewed

agricultural contexts: two Mediterranean areas, an area composed of alluvial plains and mountains, an oceanic area, and a rural area composed of plains and plateaus.

A questionnaire was designed (supplementary material 1) to conduct semi-structured interviews that lasted about one hour. It was structured in two parts in order to collect information: (i) on impacts on farm components, and (ii) on consequences on farmers' practices. Prior to every interview, production cycles in terms of physiological stages and agricultural work calendar were established based on literature, for the categories of crop corresponding to the expert interviewed. This information was presented and discussed with the experts too.

Third, **floodam.agri implementation** can be summarised as shown in the figure 3. The crops for which damage can be estimated with **floodam.agri** are defined in a three-level classification (appendix A, table A1). All the crops that belong to a same category are associated to a similar vulnerability to floods, but can differ in terms of their other characteristics (yield, selling price, crop calendar, intermediate consumption). For each component, based on the interviews, the sensitivity to flooding is modeled i.e a proportion of loss or level of deterioration of a component is associated to flood parameters; for example, for the crop component, the sensitivity determines a loss of yield in percent of the standard yield. Decision rules associate behaviours to the proportion of loss or level of deterioration of a component. **floodam.agri** model was implemented using R language.

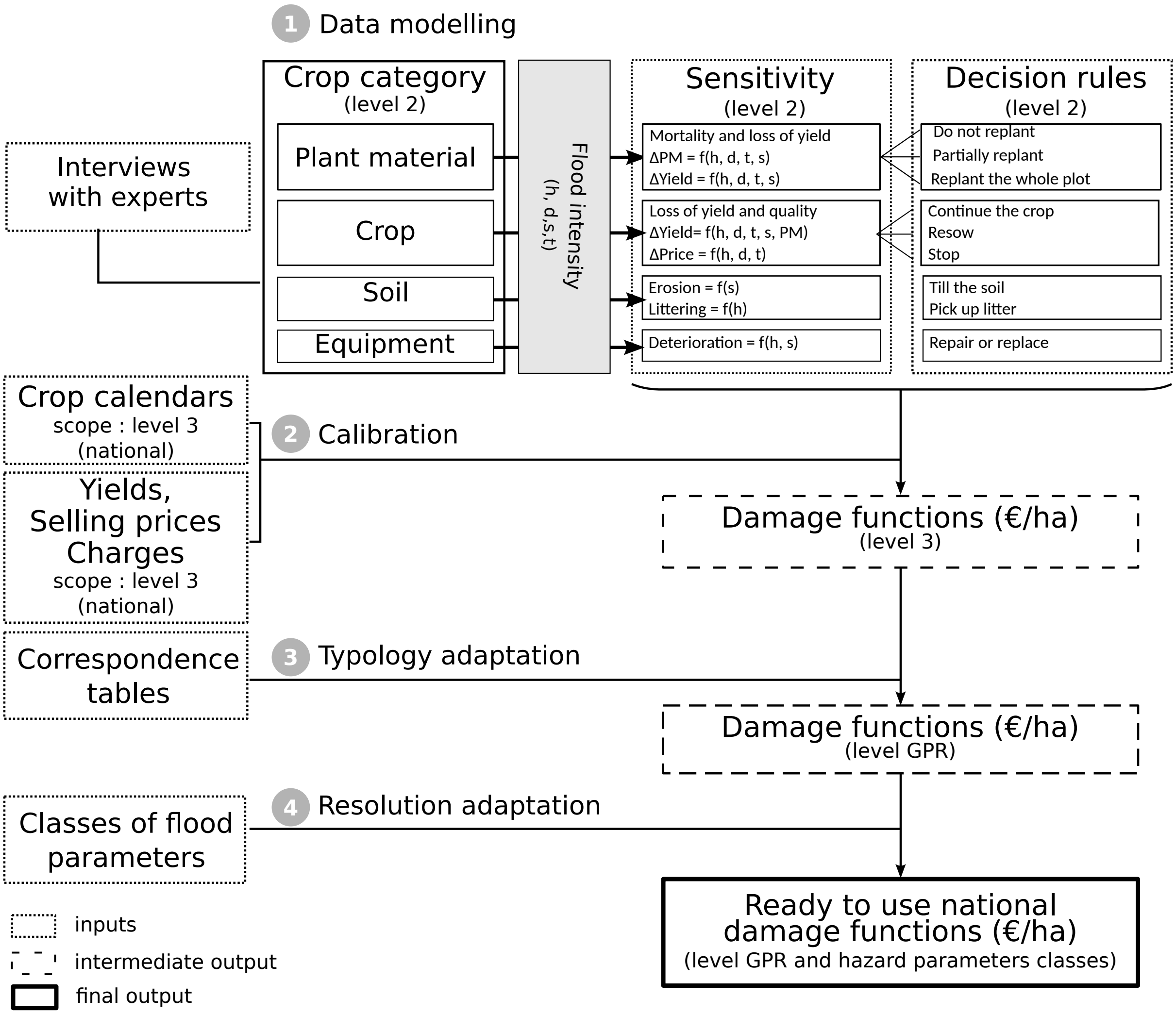


Figure 3. Production process of the national French flood damage functions with **floodam.agri**

Fourth, **floodam.agri** must be **calibrated** with data such as agricultural calendars, yields, and sales prices to produce flood damage functions. The level of data specification should be appropriate for the scale at which the damage functions are to be produced. For the national damage functions, we used data at the national level.

Fifth, a **validation** was carried out through focus groups bringing together the experts consulted in individual interviews for each crop family. This steps occurred in average one year after the first interview. In total, five focus group have been organised (see section 4.2).

Sixth, based on focus group discussions, some **corrections** have been done.

Seventh, the process resulted in **ready to use flood damage functions**. To produce them, two more steps (3 and 4 on figure 3) were achieved: (3) adapting the damage functions to fit the typology used to locate the crops (GPR), (4) adapting the resolution of the functions to fit the available data that pertain to flood parameters. The ranges of values considered for each parameter in **floodam.agri** and the grouping choices for the period of occurrence and flood duration categories chosen for ready to use damage functions are specified in appendix B (respectively tables B1, B3 and B2). In addition for the national application, to manage rotations if necessary on the application territory, we proposed to create a mixed function. For example, if the 3-year rotation is wheat, wheat, rape, the weight assigned to the wheat function is 2/3 and the weight assigned to rape 1/3.

3.3 Overview of French national damage functions

Ready to use national damage functions were produced for 15 of the 28 sorts of crop of the GPR typology (supplement material 2). These 15 sorts accounted for 89% of agricultural areas located in flood-prone areas in metropolitan France in 2010, according to the GPR database. They indicate the estimated expected value of damage in euros by hectare, depending on the water depth, submersion duration, season of occurrence of the flood, and flow speed. The maximum expected damage is the lowest by hectare for sunflower crops (1 611 Euros) and the highest for arboriculture and orchards (93 549 Euros) (table A2).

For illustrative purpose, the figure 4 shows the damage function of the arboriculture. How the hazard parameters were aggregated to produce these graphical outputs is specified in appendix B. The damage increases with the flow speed, the submersion duration, and the water depth. It is generally the highest in spring and the lowest in winter.

The threshold effects in the relationship between the damage and the water depth correspond to the water depths at which new types of plant organs are reached by water (e.g. leaves, fruits).

4 Application of the methodological framework to floodam.agri

In this section, the methodological framework (table 1) is applied to **floodam.agri**. The objective is to analyze the extent to which the framework makes the modelling process explicit and allows for the transfer of the model to other study cases. A detailed illustration is given for apple crop.

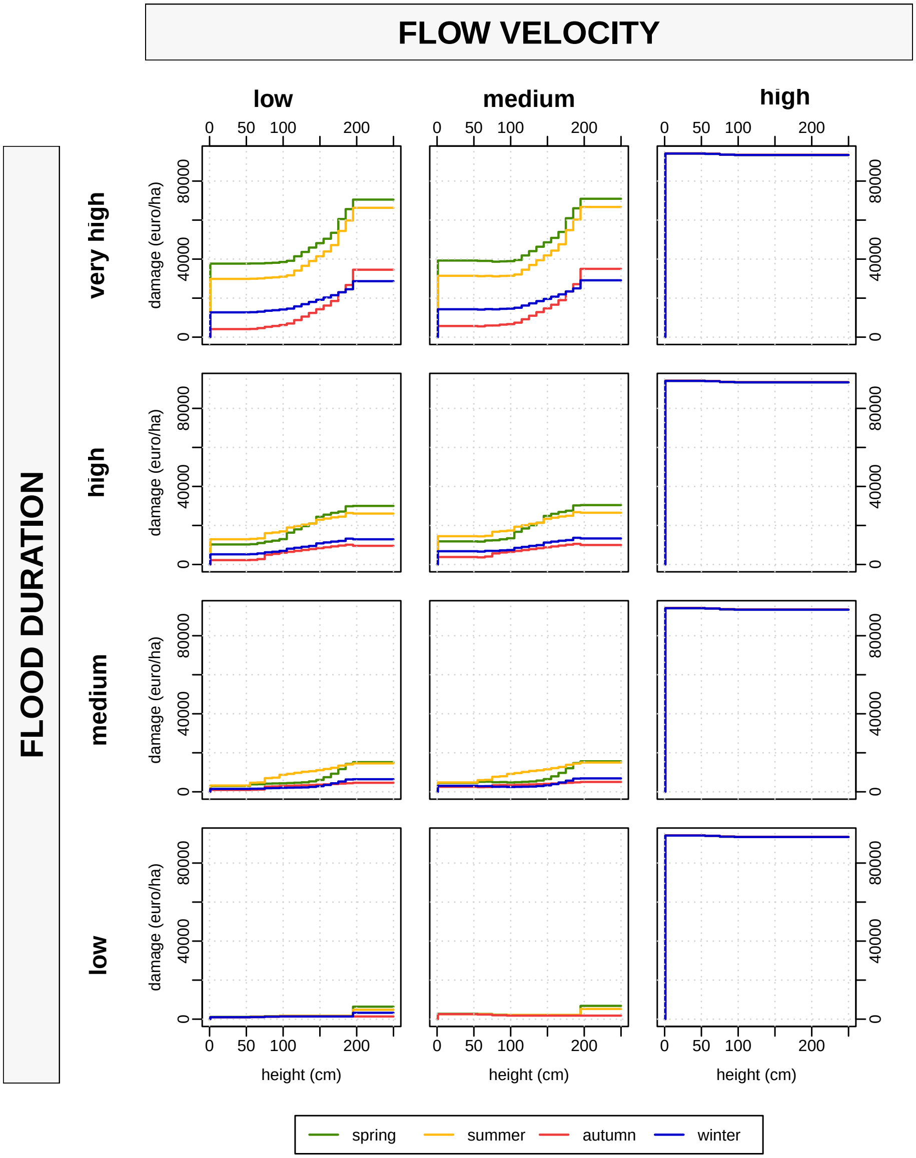


Figure 4. Example of the national flood damage function developped using **floodam.agri** for the category "arboriculture"

265 ## 4.1 Axis 1: Explicit assumptions

EA1: What are the boundaries and components of the system considered?

floodam.agri is based on a conceptual model developed on the basis of the literature and previous works (Brémond et al., 2013; Brémond, 2011; Nortes Martínez, 2019a). Flood impacts on the agricultural sector can be evaluated by

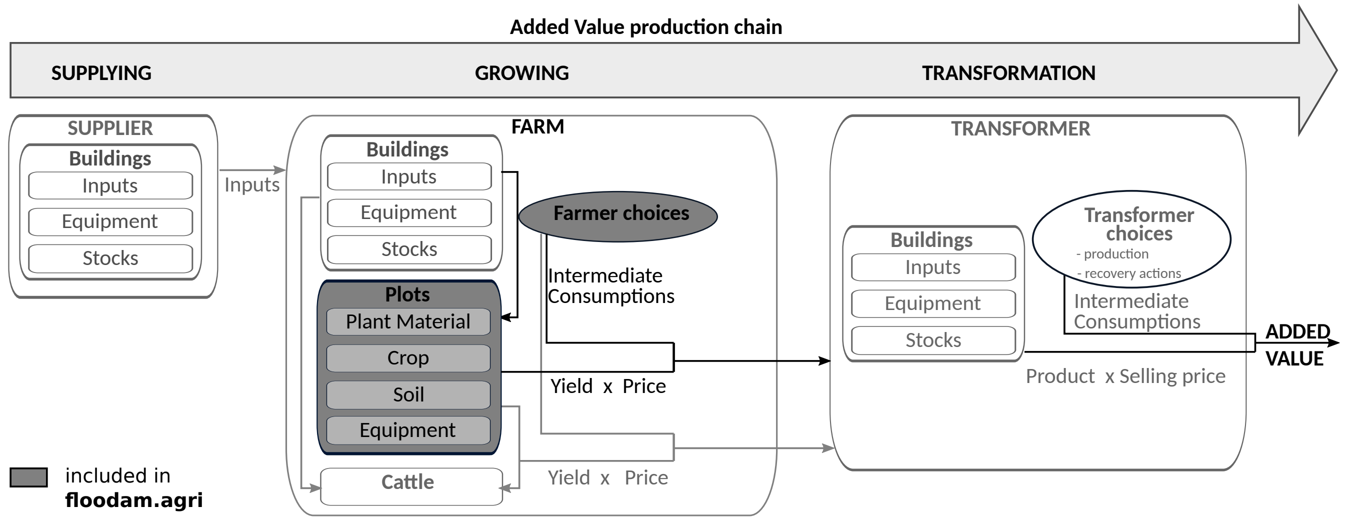


Figure 5. Boundaries and components considered in **floodam.agri**

the variation of added value through the production process. The figure 5 represents the links between economic entities that may impact the variation of added value. Each economic entity is composed of physical components such as building and parcels that can be directly affected by a flood. The farmer makes choices for the production process and recovery if a flood occurs. At farm level, the growing process can be impacted either directly by the flood or indirectly if farm's buildings are impacted. In the same way, flood impacts on suppliers may interferes on the production process. The components in dark grey are those that are currently considered in **floodam.agri**. It takes into account the physical components related to the land plots namely crops, plant material, soil and equipment such as irrigation systems, fences and trellis depending on the crop type. It also takes into account farmer's decision in terms of adaptation of production tasks (crop management sequence) and recovery tasks. Using **floodam.agri** requires specifying some data on these components to produce the damage functions. These assumptions represent a national vision for the development of national damage functions but can be specified at other scales. They were made in collaboration with the experts consulted. For example, we had to set the physiological stages to the weeks of the year (example for the apple in the figure 6). Similarly, assumptions were made about certain physical characteristics (trunk heights, first fruits). Finally, we also specified the crop management sequences for each crop (according to the physiological stages and based on the weeks of the year for the national application).

Interviews were conducted on the vulnerability of farm buildings and their contents (equipment and stock) as well as cattle. However, these elements have not been integrated into **floodam.agri** to date. **floodam.agri** also does not consider induced damage at the farm scale i.e damage induced on farm activity due to direct damage on farm equipment for example as evaluated in Brémond and Grelot (2012) or indirect damage at the scale of the area affected by a flood as for example damage propagation on cooperatives as evaluated in Nortes Martínez

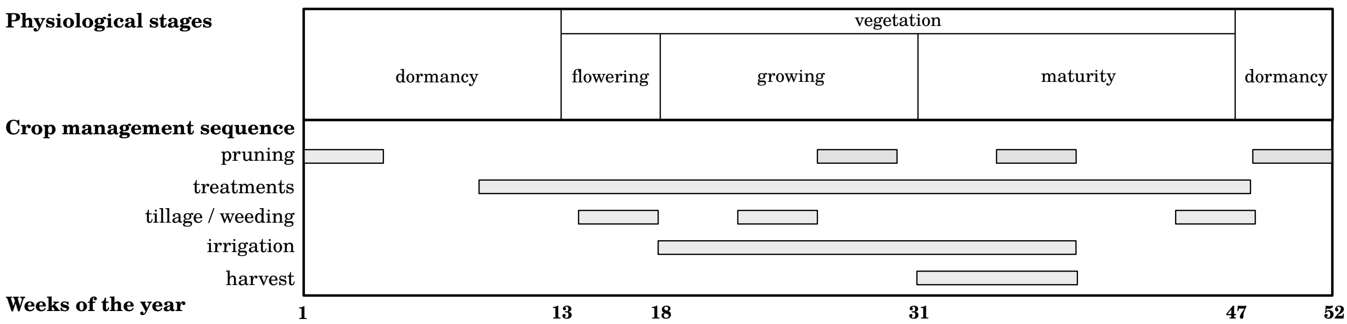


Figure 6. Distribution of the physiological stages and crop management sequence of apple crop over the weeks of a year selected for the national functions

(2019a) and described in Nortes Martínez (2019b). Indeed, in an operational way, it remains very difficult to obtain information concerning the links between farm buildings and parcels of the same farm or the links between farms and cooperatives.

Equations 1 to 4 describe the translation of this conceptual framework in economic terms. The total damage to a plot (D in €/ha) is the sum of the costs of the actions needed to restore the plot (C in €/ha) and of the loss of added value (ΔAV in €/ha). It is calculated as the sum of the damage to each component of the plot (D_c): (i) plant material (for perennial crops), (ii) the crop production, (iii) the soil, and (iv) equipment. The crop component is defined as the part of the plant that is harvested.

The added value is the difference between the outcome of the plot (O) and the intermediate consumption due to its management (IC). The outcome is the product of the yield (Y) and the selling price (P), while the intermediate consumption is the consumption in terms of input, material, and labour. The loss of added value is the difference between the usual added value and the added value following a flood.

$$D = \Delta AV + C = \sum_c D_c \quad (1)$$

$$AV = O - IC \quad (2)$$

$$O = Y * P \quad (3)$$

$$IC = Input + Material + Labour \quad (4)$$

$$\Delta AV = AV_{usual} - AV_{flood} \quad (5)$$

EA2: What are the biophysical processes that cause the damage considered?

The methodological framework proposes to discuss this following two sub-questions.

– Are the biophysical processes that cause the damage taken into account in the model explicitly considered?

– Are the links between biophysical processes and flood parameters clearly defined?

For each component, the table 2 summarises the processes at work in the formation of damage, the major flood parameters involved, whether the process is considered or not in **floodam.agri** and if yes how it is estimated. These processes have been identified based on literature and during the individual interviews.

The parameters used to characterise the floods are: (i) the height, (ii) the duration of submersion, (iii) the velocity, and (iv) the season. Flood impacts on crops were described in function of physiological stages instead of time of the year to maintain the adaptability of our model to different contexts. The relevance of the choice of these physiological stages to the sensitivity of the component to flooding was discussed with the experts. For apple, for example (figure 6), to qualify the sensitivity of the plant material (tree), two stages were defined (dormancy and vegetation) and for the crop, five stages (dormancy, bud-break, flowering, growing, maturity). The effects of water level are defined taking into account crop data (trunk height, fruit height and maximum height). For apple tree, the height of the trunk has been set at 80 cm and the maximum height of the trees at 200 cm.

Plant material

The table 2 shows that the main processes that cause plant material, i.e tree or vine, mortality are uprooting or asphyxia. The table 3 details how the processes discussed with the experts were modeled into a mortality rate (β) for a low velocity flood. For the example of arboriculture, trees are considered to be uprooted for high velocity. The diagrams represent the mortality rate (β) as a function of the flood parameters (duration and height) for the two physiological stages defined with experts. The proportion of trees suffering from asphyxia increases with the water depth and submersion duration. There is no uprooting for low or medium velocity.

Crop

For perennial crops, on a plot, the crop borne by the destroyed plant material (β) is considered destroyed as well. The crop loss (α) on the undamaged plant material ($1-\beta$) is then determined. The table 2 synthesizes the processes identified with experts which contribute to yield loss (α) or quality loss (γ) for annual and perennial crops. The table 4 illustrates for the apple crop how the processes were associated with yield loss. In addition to yield losses, flooding can cause a deterioration in the quality of the remaining fruit (e.g. reduced shelf-life potential) and generate a lower selling price. Based on the interviews with experts, it was considered for the example of apples that the selling price (P_u) is reduced by 10% when the flooding occurs at the maturity stage with a height of more than 80 cm and a duration of more than two days. This effect is added to the loss of yield as described in equation 11.

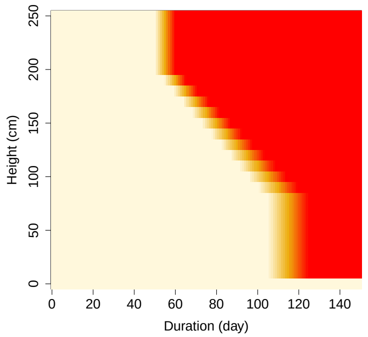
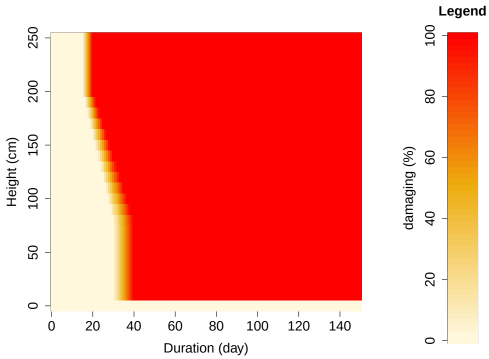
Soil

The flood impacts on the soil component taken into account in **floodam.agri** are erosion and littering (table 2). Erosion depends on the flow speed and the quantity of material carried by flood water depends on the water depth.

Table 2. Biophysical processes considered or not in the national flood damage functions produced with **floodam.agri**

Biophysical processes	Flood parameter	Considered	Estimation
Plant material			
mortality by uprooting	velocity, height	yes	replantation strategy
mortality by root asphyxia	season, duration, height	yes	replantation strategy
mortality by leaf asphyxia	sediment, height, duration	yes	replantation strategy
mortality by salinity	salinity	no	-
mortality by contamination	contamination	no	-
Crops			
poor flowering or fruiting by root asphyxia	season, duration, height	yes	loss of yield
destruction of buds, flowers, fruits by contact	season, duration, height	yes	loss of yield
increase in cryptogamic diseases	season, duration, height	yes	loss of yield
growth alteration by root asphyxia	season, duration, height	yes	loss of yield
growth alteration by crop laying down	velocity, height	yes	loss of yield
growth alteration by leaf asphyxiation	season, sediment, height	yes	loss of yield
growth alteration by salinity	season, salinity	no	-
growth alteration by contamination	season, contamination	no	-
excess of water in the fruits	season, duration, height	yes	price decrease
soiled fruits by sediment deposit	season, sediment, height	yes	loss of yield
soiled fruits by contamination	contamination	no	-
Soil			
deposits of debris and waste	velocity, height	yes	repair costs
erosion without loss of soil	velocity, height	yes	repair costs
erosion with loss of soil	velocity, height	yes	repair costs
soil contamination	contamination	no	-
soil salinisation	salinity	no	-
Equipment			
pulling out and moving irrigation pipes	height, velocity, season	yes	pipe reinstatement
fence degradation and debris build-up	height, velocity	yes	cleaning and repair costs
trellising torn off by the current	height, velocity	yes	replacement
damaged trellising	height, velocity	yes	repair costs

Table 3. Mortality of plant material for apple crop in function of the physiological stages and biophysical processes involved (low velocity)

	Dormancy	**Vegetation**
Mortality rate (β)		
Biophysical processes involved	The metabolism is paused and apple tree therefore have a low sensitivity to root asphyxiation. For a flood with less than 80 cm of water, i.e. the branches are not in contact with the water, the time before tree mortality occurs is 105 days. The mortality will be total after 125 days. With all the trees submerged (> 200 cm), tree mortality starts at 50 days and the orchard is completely lost at 60 days of flooding. Between these two heights, losses increase proportionally with the water height.	During the vegetation period, the sensitivity of trees to asphyxiation increases. For a flood with less than 80 cm of water, mortality starts for 30 days of flooding and is total at 40 days. With 200 cm of water, there can be losses of plant material as early as 15 days of flooding and they are total for 20 days.

How the damage processes were related to the flooding parameters based on the interviews for the arboriculture example is detailed in the table 8. For the moment, the phenomena of organic matter loss or pollution are not taken into account. This is mainly due to the fact that the experts we met have not been confronted with these problems in a systematic way. The salinisation phenomena are the subject of an adaptation which is in progress.

Equipment

Equipment on the plots (ie irrigation systems, fences, greenhouses, and trellis) can be deteriorated or destroyed (table 2). The deterioration or destruction of equipment depends on the flow speed, that influences the number of devices that move during the flood, and on the water depth that is linked to the number of devices immersed.

Table 4. Flood impacts on yield variation for apple crop in function of the physiological stages and biophysical processes involved

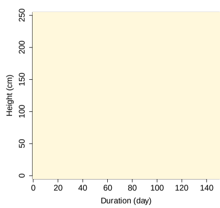
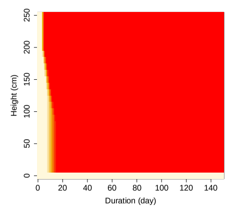
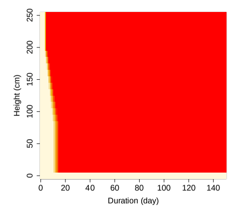
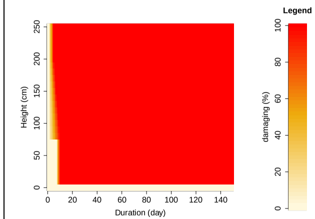
	Dormancy	**Flowering**	**Growing**	**Maturity**
Yield variation				
Biophysical processes involved	Apart from yield losses due to the loss of plant material, flooding during the dormancy phase does not cause yield losses.	Effects involved are asphyxiation on roots and foliage, water contact on the flowers, phytosanitary risk of scab infection. Without contact with leaves and flowers (less than 80 cm), yield loss due to root asphyxiation starts from 7 days and is total after 15 days.With all the trees submerged (< 200 cm), loss due to asphyxiation or water-flower contact begins after 3 days and is total after 5 days. For intermediate heights, the asphyxiation thresholds evolve linearly. In addition to this asphyxiation effect, there are yield losses due to scab. Scab can cause losses whatever the water level from 7 days of flooding, and total at 15 days.	Only the asphyxiation and water-flower contact effects are taken into account (the risk of scab infection is negligible). If flood height is < 80 cm, yield loss starts at 10 days and is total at 15 days. If flood height is > 200 cm, loss starts after 3 days of flooding and is total for 5 days of flooding. For intermediate heights, the thresholds of duration evolve linearly between 80 and 200 cm.	The main effect is the contact between water and fruit. If flood height is < 80 cm, yield loss starts at 7 days and is total at 10 days. If flood height is > 200 cm, yield loss starts at 1 day and is total after 5 days of flooding due to rotting of the fruit. For intermediate heights, the thresholds of duration evolve linearly between 80 and 200 cm.

Table 5. List of additional or cancelled tasks taken into account in **floodam.agri**

	Tasks	**Crops concerned**
Additional	Sowing	Grain crops and oleaginous
	Oversowing	Grain crops and oleaginous
	Treatment	All
	Chemical harvest	Fruit trees
	Replanting	Vegetable crops
Cancelled	Treatment	All
	Harvest	All

EA3: Which are the assumptions on farmers' decisions?

The assumptions made on the decision rules of farmers after the flood are linked to the damage endured and the physiological stage of the crops. They are explicited for each component below.

Behavior in standard situation

The behavior of farmers in standard situation is defined by the crop management sequence which is the logical and orderly sequence of tasks that must be performed to achieve the set yield (Sébillote and Soler, 1990). The periods in which tasks must be performed are defined on the basis of physiological stages (example for the apple, figure 6). These sequences of tasks were used as a basis to discuss with the experts the change in farmers behavior due to flood. The list of potential additional or cancelled tasks is presented in the table 5.

Decisions related to plant material

Direct (D_{PM}) and delayed (D^d_{PM}) damage to plant material are estimated. Direct damage to plant material do not depend on farmer's decisions and is estimated by the loss of outcome due to the loss of plants:

$$D_{PM} = \beta \times Y_u \times P_u \tag{6}$$

with β the proportion of plants lost by hectare, Y_u the mean usual yield by hectare, and P_u the mean usual selling price.

Then, delayed damage (D^d_{PM}) is estimated taking into account the farmer's decision. Depending on tree mortality rate (β), three possible strategies are considered in the table 6: (i) no replanting (equation 7), (ii) replant only the missing trees (equation 8), (iii) grubbing and replant the entire plot (equation 9). Each strategy is associated to costs and their mathematical formulation. The table 6 gives the values of (β) associated with the three strategies that were collected from the experts of arboriculture.

Table 6. Farmer's strategy for replantation in function of mortality of plant material (β) for the case of arboriculture

β	**Strategy**	**Associated costs**	**Equation**
$< 15\%$	No replanting	Loss of the corresponding production until the end of the orchard's life of the orchard.	$$D^d_{PM} = \sum_{i=1}^{A_{max}-A_{PM}} \frac{\beta \times Y_u \times P_u}{(1+r)^i} \quad (7)$$
$15 < \beta < 25\%$	Replanting of missing trees only	Loss of production corresponding to the end of the life of the orchard	$$D^d_{PM} = \beta \times C_{pl} \times \frac{A_{PM}}{A_{max}} + \sum_{i=1}^{A_{prod}} \frac{\beta \times Y_u \times P_u}{(1+r)^i} \quad (8)$$
$\beta > 25\%$	Grubbing and replanting of the entire plot	Replanting and maintenance costs for the entire area Loss of the corresponding production during the period of entry into production.	$$D^d_{PM} = C_{pl} \times \frac{A_{PM}}{A_{max}} + \sum_{i=1}^{A_{prod}} \frac{Y_u \times P_u - IC_h}{(1+r)^i} \quad (9)$$
with A_{max} the usual maximum age of the perennial plants considered A_{PM} the mean age of the plants at the time of the flood,[2] and r the discount rate. C_{pl} the cost of planting one hectare of the perennial plants considered A_{prod} the age at which the plants become productive IC_h the intermediate consumption related to the harvest, by hectare			

Decisions related to crops

The possible strategies following the loss of yield are different depending on whether the crop is perennial or annual. The table 7 summarized the possible strategies and the associated equation to calculate damage.

In **floodam.agri**, farmers of perennial crops have only two choices: continue (equation 11) or stop (equation 12) the crops. In all cases, the basic assumption is that of a continuity of the production of the current crop. That is to say that no radical change in the orientation of the farm's production is envisaged. Most of the time they decide to continue the crop management sequence also because leaving rotten fruit in the orchard or vineyard could lead to disease development. For example, for apple crops, the harvest is always carried out unless the total yield losses, i.e. combining yield losses alone and plant material losses, are : (i) more than 95% and the flooding took place before the maturity stage, (ii) above 75% and the flooding takes place at the maturity stage (a chemical treatment is then carried out). Moreover, if they continue, for the case of apple, there is no variation of intermediate consumptions because the treatments are already very regular in normal situation.

Table 7. Strategies for the continuation of the crop management sequence and associated equation

Strategy	Crop concerned	Equation
Continue the crop	Annual crop	$D_{crop} = \alpha Y_u \times P_u + (1-\alpha) \times Y_u \times \gamma P_u + IC_t$ (10)
	Perennial crop	$D_{crop} = (1-\beta)\left[\alpha Y_u \times P_u + (1-\alpha) \times Y_u \times \gamma P_u\right] + IC_t$ (11)
Stop the crop	Annual and perennial crops	$D_{crop} = Y_u \times P_u - IC_h$ (12)
Re-sow the same crop	Annual crops	$D_{crop} = \alpha_2 Y_u \times P_u + IC_s$ (13)
Sow another crop	Annual crops	$D_{crop} = Y_u \times P_u - (1-\alpha_2) Y_{new} \times P_{new} + IC_s$ (14)
IC_t the additional expenses in terms of treatments, by hectare IC_h the intermediate consumption related to the harvest, by hectare α_2 the yield reduction coefficient that takes into account the fact that late sowing can lead to smaller yields IC_s the intermediate consumption related to sowing, by hectare. IC_s the intermediate consumption related to sowing, by hectare.		

Regarding annual crops, farmers generally have to modify their usual crop management plan then the additional expenses in terms of treatments to avoid moisture-related diseases (equation 10). They can also decide to stop the crop (equation 12).

Two additional strategies are possible for annuals crops in function of the period of occurrence of the flood and the loss of yield. It is possible to re-sow the same crop if the flood occurs early enough in the crop's development cycle (e.g., up to the emergence stage for winter and summer field crops). In this case, the damage is expressed in terms of yield loss due to the later seeding plus the additional seeding costs (equation 13). The possibility of planting another catch crop is also being considered. This is particularly the case when the flooding occurs too late on a winter cereal for the same crop to be resown. The grain farmer may then consider planting a spring or summer cereal. This alternation is part of the crop rotation that he practices on a multi-year basis. In this case, the damage is expressed in terms of the possible loss of product linked to the realisation of this new crop to which is added the cost of a new sowing (equation 14).

Decisions related to the soil and equipment

As for the soil and equipment, the repair and replacement actions have been defined with experts in function of flood impacts on the component. The damage to the soil component (D_{soil}) relates only to the year of the flood. It is equal to the costs of tilling the soil to correct for erosion and picking up litter, which depend on the labour and mechanisation costs:

$$D_{soil} = (d_{tilling} + d_{cleaning}) \times (C_{labour} + C_{mecha}) \quad (15)$$

with $d_{tilling}$ the amount of time needed to till one hectare of soil, $d_{cleaning}$ the amount of time needed by hectare to pick up litter, C_{labour} the labour cost, and C_{mecha} the mechanisation cost.

For the case of orchard, the table 8 summarizes the actions to be carried out and the estimated work times that have been defined with the experts. The damage to the soil was defined in the same way for each crop family.

The damage to equipment (D_{eq}) relates only to the year of the flood. It is equal to the replacement and repair costs, which include labour and material costs:

$$D_{eq} = \sum_{i \in I} C_{mat}(i) + \sum_{j \in J} (C_{mat}(j) + d_{repair}(j) C_{labour}) \quad (16)$$

with I the set of devices that need to be replaced, J the set of devices that need to be repaired, C_{mat} the material cost to replace or repair a device, and d_{repair} the amount of time needed to repair a device.

Table 8. Illustration of assumptions elaborated with experts for soil damage for orchards for the national damage functions

Velocity	**Height**	**Biophysical processes**	**Recovery actions**		**Damage** (€/ha)
			Tilling workforce cost 12 €/h mechanization 19 €/h	**Cleaning** workforce cost 12 €/h mechanization 18 €/h	
Low	< 80 cm	Surface erosion and deposition of small plant debris	5 hours/ha (2 persons and equipment)	25 hours/ha (1 person and equipment)	965
Low	> 80 cm	Surface erosion and deposition of various debris with slight damage to the trellis and and irrigation equipment	5 hours/ha (2 persons and equipment)	45 hours/ha (1 person and equipment)	2105
Medium	-	Digging of small gullies (< 20 cm deep) and deposition of various debris with slight damage to trellis and irrigation equipment	15 hours/ha (2 persons and equipment)	45 hours/ha (1 person and equipment)	2535
High	-	Digging of medium-sized gullies (> 20 cm deep) and deposition of various debris with slight damage to trellis and irrigation equipment (as the orchard is being uprooted, cleaning up is not necessary). the orchard is uprooted, the is faster)	20 hours/ha (2 persons and equipment)	25 hours/ha (1 person and equipment)	2250

4.2 Axis 2: Validation

In this section, the methodological framework (table 1) is used to describe the validation process implemented for **floodam.agri**.

V1: Is it possible to compare the model results with sinistrality data?

As specified in the section 3, up to date, it is not possible to compare flood damage models developed for the agricultural sector with sinistrality data since no such data exists (Priest et al., 2021a; Vozinaki et al., 2015). In France, sinistrality data on the agricultural sector are very limited and unsuitable for comparison with the damage functions developed. Indeed, the penetration rate of private insurance is very low. Compensation is mainly paid through the National Agricultural Risk Guarantee Fund (FNGRA). However, this system compensates only part of the crop losses (for example, losses of grapes or cereals are not covered) and, moreover, it is a compensation system based on a declarative estimate of losses at the time of the flood. It does not take into account, as we have tried to do in this study, the deferred losses and the variations in expenses linked to farmers' decisions.

V2: Is it possible to compare the results of the model with other similar models?

Up to date, no comparison of **floodam.agri** has been done with other models. To our knowledge, this has not been done for any flood damage assessment model for agriculture. Comparing **floodam.agri** with existing flood damage model for agriculture such as the flood damage functions developed by the FHRC in the UK or AGDAM in the USA would required a common case study. No such initiative has been done yet. We hope that the effort of explicitness made in this article contributes to go in this direction. As a first step, the table C1 uses the methodological framework we propose to compare **floodam.agri**, FHRC method and AGDAM method. This comparison was made on the basis of the documents we had at our disposal, namely the agdam users manual (USACE, 1985) and the different versions of the mulitcouloured manual (Penning-Roswell et al., 2005; Priest et al., 2021b). On the basis of existing documents, a certain amount of information remains incomplete (the number of applications, transfers that may have not been published…). This table should not be considered as a result in itself but it highlights that the framework proposed in this article constitutes a basis for discussion for the comparison and transfer of process-based models.

V3: Does the model meet stakeholders' expectations?

The national flood damage functions that were produced using **floodam.agri** were used by stakeholders (engineering firms and project developers) between 2014 and 2022 in more than 200 Cost-Benefit Analysis (CBA). This proves that **floodam.agri** has met the expectations of the stakeholders involved in the process namely the Ministry of the Environment, the local authorities in charge of the project, the consulting firms that carry out the CBA.

V4: Has the model been presented and discussed with the experts involved for the development?

Within the framework of the development of **floodam.agri**, we implemented a specific methodology allowing to discuss and validate in group during workshops, the setting in model of the information collected in individual interviews. This qualitative research method is the focus group. The aim of these workshops is multiple. They allow the coherence of the information collected in individual interviews to be verified and discussed collectively. Above all, they allow the results of the overall modelling chain (loss of plant material, yield, associated behaviours) to be presented to the experts who were interviewed separately on the different components of the model and to allow them to readjust their assumptions if necessary.

The following topics were discussed using illustrations (figure 7):

- the biophysical processes considered for each component,
- the ranges of yield loss in function of flood parameter,
- the determination of impacts for each components in function of flood parameter,
- the farmers' strategies for crop continuation,
- the additional or cancelled tasks and as a consequence the variation in crop expenses,
- the replanting strategies,
- the list of recovery tasks and their estimated cost (hours of work, equipment).

Each assumptions has been discussed until all experts agreed to validate them. Following this work, the list of changes to be made was established (supplementary material 3) and implemented.

4.3 Axis 3: Updatability

In this section, the methodological framework (table 1) is used to describe the updatability of **floodam.agri**.

U1: Are all the data used in the model and their sources made explicit?

To produce flood damage functions, **floodam.agri** requires: (i) an estimate of usual yields, (ii) an estimate of selling prices, (iii) an estimate of intermediate consumptions, (iv) physiological stages and crop management sequence. The table 9 lists all the data and their source used in **floodam.agri**. There is no homogeneous database that provides information on all the technical and economic data of the crops. We had to collect this information from different databases depending on the crop and sometimes complete this information based on expert opinion. It is therefore all the more important to be rigorous about making the data used explicit.

U2: Are the vintages of the data used in the model specified?

The vintage used and the frequency of update are specified in the table 10. Since the databases used are heterogeneous, the vintages of the databases are also heterogeneous.

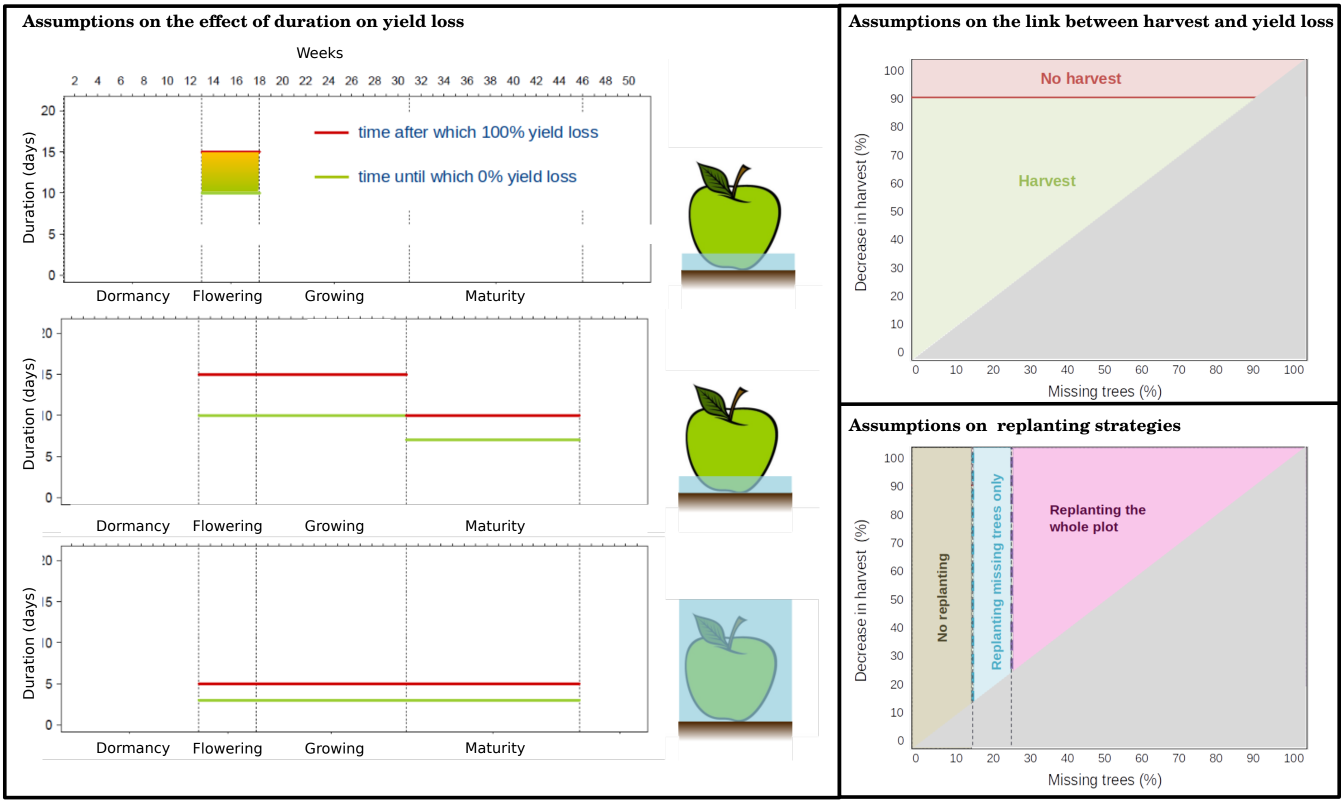


Figure 7. Example of illustrations used during the focus group of experts for the case of apple crops

Table 9. Data sources

Type of estimates	**Sources for:**				
	Meadows and feeding crops	Grain and oleaginous crops	Fruit trees	Grape vines	Vegetable crops
Localisation	GPR	GPR	GPR	GPR	GPR
Yields	AAS	AAS	AAS	AAS	AAS
Prices	SADs	ASB	IPPAC	LR data	IPPAC, SADs
Harvest	experts	SADs	SADs, LR data	experts	SADs
Sowing/Plantation	experts	experts	SADs	SADs	expert
Treatments	-	-	Eco-Phyto 2018	Eco-Phyto 2018	experts
Crop calendars	LR data, experts	LR data, experts	LR data, experts	LR data, experts	LR data, experts

GPR: Graphical Plot Register; AAS: Annual Agricultural Statistics database; SAD: Scales of Agricultural Disasters; ASB: Agricultural Situation Bulletin; IPPAC: Index of Producer Prices of Agricultural Commodities; LR data: technical and economic memento of the main agricultural productions in Languedoc-Roussillon and fact sheets on the Languedoc-Roussillon region

U3: Are the data used tracked over time?

The table 10 shows the update frequency of the databases used. Updating the data that are published annually is easy. On the other hand, to update data from documents whose publication frequency is not predetermined requires checking for each data if a new edition has been produced. If not, a validation with experts should be renewed.

Table 10. Vintage and update frequency of database used to apply **floodam.agri** at the national scale in France

data	database	vintage used	update frequency
localisation	GPR	2010	annual
yields	AAS	2009, 2010, 2011	annual
price	IPPAC	2009, 2010, 2011	annual
price	ASB	2009, 2010, 2011	annual
price	SADs	2007	occasional
price	TEMMAPL	2012 / experts	occasional
IC	SADs	2006, 2007 / experts	occasional
IC	TEMMAPL	2012 / experts	occasional
IC	Eco Phyto	2018	occasional
physiological stages	TEMMAPL	experts	occasional
crop management sequence	TEMMAPL	experts	occasional

To sum up, the tables 9 and 10 show that the updatability of data is not homogeneous. Three modalities can be distinguished:

- input data come from a single database which tracked over time (eg yields),
- input data come from different databases with different update frequencies (eg selling prices and intermediate consumptions),
- input data come from expert knowledge (eg physiological stages).

4.4 Axis 4: Transferability

In this section, the methodological framework (table 1) is used to describe the conditions on transferability.

T1: Are the conditions for adaptations, improvements and transfers described?

The possibility to adapt **floodam.agri** to different contexts was a requirement and has been anticipated in the modelling process. The different steps for adaptation from the simplest to the most demanding are identified according to the differences between the context in which **floodam.agri** was developed and the context in which it could be transferred. Methodological proposals are made for each of these steps (figure 8).

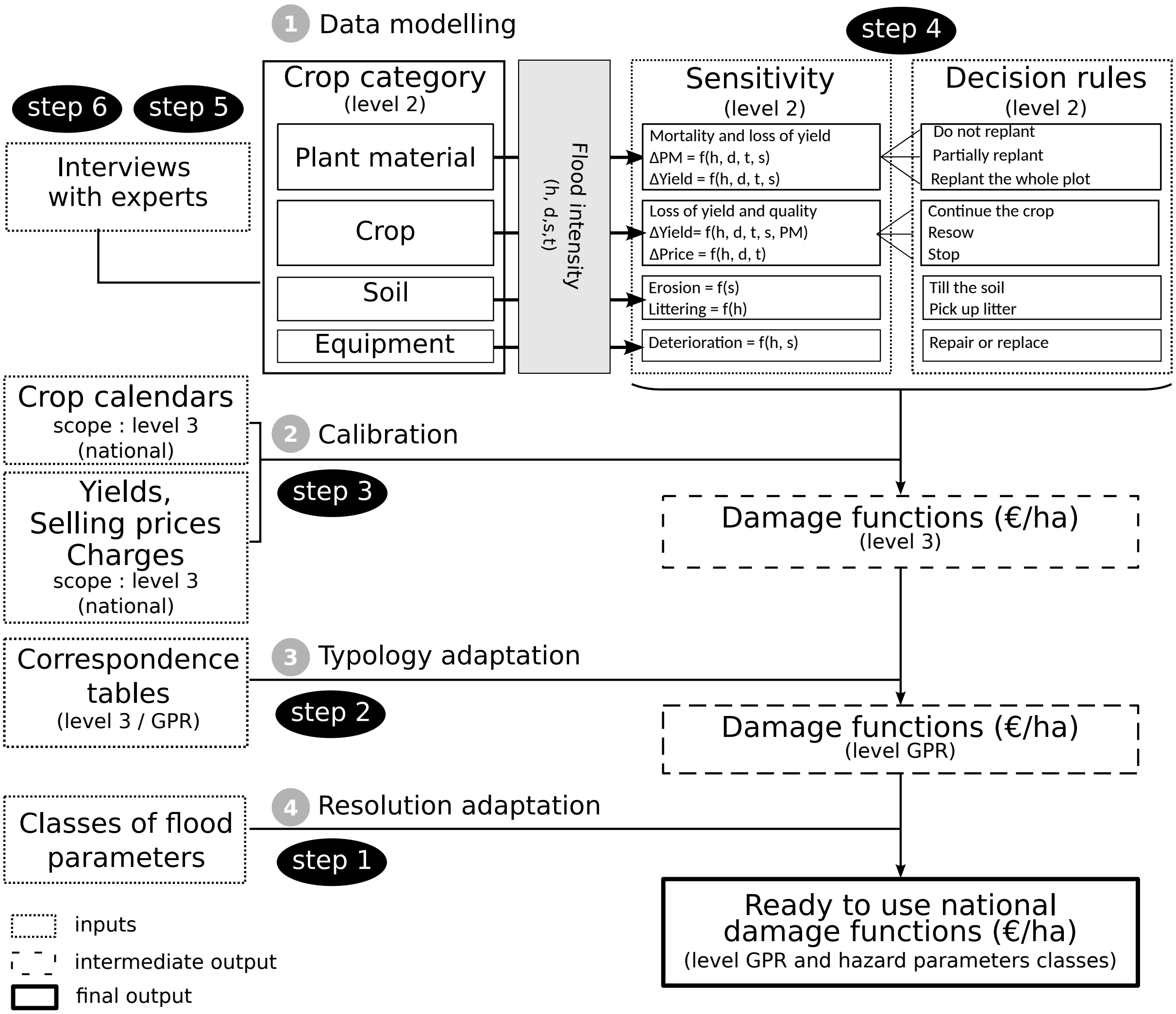


Figure 8. Steps of adaptation to transfer **floodam.agri**

Adjusting damage functions resolution (step 1)

The first possibility of adaptation concerns the compatibility between the flood damage functions produced with **floodam.agri** and existing hydraulic and hydrological models in terms of resolutions. As the resolution of flood parameters is higher in **floodam.agri**, it can generate flood damage functions with a higher resolution easily. For example, for the national application, it was proposed to simplify the season parameter and we defined four seasons (appendix B, table B1). If hydrological models gives a more precise definition of flood seasonality, given that the time step is the week in **floodam.agri**, adapted damage functions can be produced.

Adjusting the typology (step 2)

To generate national damage functions, we had to adapt the damage function typology developed in level 3 (appendix A, table A1) to make it compatible with the GPR (appendix A, table A2). It is possible to adapt this typology and make other crop categories from level 3.

Adjusting to local context (step 3)

This step encompasses two aspects. First, the adjustment of crop technical-economic data (yields or selling prices) requires to ensure that data listed in section 4.3 exists on the study area. The problems encountered in this case may be related to the typology of crops that will have to be adapted too. Second, locally, it will be necessary to adjust crop calendars (figure 6) of each crop. Since the physiological stages have been calibrated on a weekly basis, these calendars can be adapted to a new context on the basis of existing bibliographical and technical data on the area of application and/or on the basis of interviews with agricultural experts, taking care to cover the diversity of crops.

Adjusting sensitivity and decision rules in case of flooding (step 4)

In the context of application, some biophysical processes or particular behaviors of farmers in case of flooding that have not been considered in **floodam.agri** may appear. In this case, it will be necessary to consolidate the modeling (sensitivity and decision rules) with local experts.

Adding a new crop (step 5)

If a crop is to be added to the list of 53 existing crops in **floodam.agri**, two options should be considered. First, it is necessary to determine whether the crop can be assigned to a vulnerability category. If so, it is necessary to calibrate the physiological stages, crop management sequence, yield and price of the crop. If not, it will be necessary to create a new crop category and to add new sensitivity and decision rules functions. For this, data collection from agricultural experts will be necessary. Moreover, agro-economic data will have to be collected to calibrate the functions.

Taking into account new hazard parameters (step 6)

This is the most demanding level of adaptation because it requires to repeat for each crop category all the biophysical processes and the impact on farmers' decisions. This type of transfer necessarily requires work with experts.

T2: Has the model been transferred to another context?

To date, some adjustments have been done to adjust resolutions (step 1) or to adjust local data (step 2) in the frame of the mandatory CBA of flood management projects. In Mao (2019), an adaptation of the flood damage functions has been done at regional level (step 2) using regional data. Based on Agenais et al. (2013), **floodam.agri** has been partially transferred to the Italian context (Molinari et al., 2019b; Scorzini et al., 2020) but the way in which the experts' knowledge was collected and formalized for the transfer is not made explicit, particularly with regard to the assumptions made about the processes and behaviors of the farmers. Moreover, work is underway to adapt **floodam.agri** to coastal flooding (step 6).

5 Discussions

5.1 A crucial contribution to the clarification of assumptions

The proposed framework clarifies the components, interactions and decision entities that are or are not considered in the damage assessment model. In economic systems, added value is produced on spatial entities (plots in the agricultural case) and depends on production factors (material, labor, input) and decision rules. In the case of agriculture, the added value increases on the plots and is then stored and transformed in other spatial entities on or off the farm. Nortes Martínez et al. (2020) show the importance of these interactions for avoiding over and understimate in damage assessment. Because of the complexity of these mechanisms of localisation of added value in a production chain, the FHRC recommends, in an operational way, not to take into account the indirect effects (Penning-Roswell et al., 2005). However, making the limits of the modeled system explicit remains fundamental in the classification of damage between direct and indirect. The larger the system considered, the more it will include effects that could be considered indirect. Developing models that locate and characterise interactions between several components in the field is time demanding. Depending on operational needs, this approach may be required (resilience analysis of a sector affected by a project) or not (large-scale damage assessment on all the issues).

From the modeling experience presented in this article around **floodam.agri**, the proposed framework concerning the explicitation of assumptions appears to us to be effective for two main reasons. Firstly, the explanation of the assumptions facilitated the collection of information from the experts. Indeed, we found that the logic we proposed to deconstruct the biophysical processes and the decisions made by farmers was consistent with the cognitive approach of damage assessment of the experts. In this sense, the application of the framework reduces the uncertainties surrounding the collection of expert knowledge. Secondly, the explicitness of the assumptions appears to be a necessary condition for the implementation of the other axes, namely validation, updatability and transferability. For example, it is essential to know which processes have been taken into account in determining yield losses. Studies carried out in the context of drainage may only take into account processes such as root asphyxiation, which will be predominant, but in the case of floods with significant velocity effects, it is essential to integrate also the processes of uprooting or laying down. This effort to clarify assumptions is also necessary for capitalisation.

5.2 Consolidate the validation

The proposed framework allows for a clear improvement in the validation methodology with experts involved in the modelling process. However, we are aware of the need to consolidate this aspect. Two avenues are usually identified: first, the comparison of model results with each other; second, the comparison with claims data (Molinari et al., 2019a). A third avenue is to consider the geographical transfer of models as an opportunity to capitalise on expert knowledge by involving new experts and being able to clearly present the modelling assumptions to them. We consider that the clarification of the assumptions is a prerequisite for both avenues and the framework presented here is a step towards the possibility of comparing models with each other. We have made a first proposal in the table C1 based on existing literature. This should not be considered as a result but as a discussion support to allow exchanges on methods with a view to capitalization. Concerning the collection of ex post damage data, in particular for the agricultural sector, this is a real challenge that requires a long-term effort. Some interesting initiatives are to be highlighted, as for example, the validation carried out by Chau et al. (2015) or Shrestha et al. (2021). The modelling effort we have carried out to develop **floodam.agri** has highlighted the importance of acquiring knowledge both on biophysical and human processes in order to be able to assess damage in economic terms. This implies that the data to be collected post-flood in order to validate a model such as **floodam.agri** must be of different natures, ranging from biophysical impacts (yield loss, mortality of plant material, soil erosion. . .) to monetary damage, including the chain of behaviours of recovery and continuation of crop management sequence. But this type of post-flood data collection is very time consuming. Most of the time, on large-scale events, the primary objective will be to obtain an overall damage assessment fairly quickly and not to carry out a detailed characterisation of the damage formation processes. In this case, it could be used to estimate damage in monetary terms from hazard parameters. It could also be used to estimate damage in monetary terms from partial post-flood data collection such as yield losses, which corresponds to the practice of the insurance system in France. This type of use would provide a more complete picture of the damage on the basis of the current modelling assumptions, but would not or only partially validate the estimated values. On the contrary, such a characterisation makes sense for small-scale events for which, however, various levels of impact can be encountered on an individual scale. In this case, the collection of data allows for validation. For this, the implementation of observatories is an interesting approach.

5.3 Capitalise over time with updatability

The proposed methodological framework requires the specification of all the data used, their source and their vintage. This makes it possible to consider updating the models produced for a given context over time. This is the case, for the damage functions produced thanks to **floodam.agri**. This effort allows to consider the transfer by comparison of existing databases from one context to another. A difficulty persists for data that are not tracked over time, and in this case we recommend either updating the data on the basis of expert opinions, or using a discount rate whose value must be specified.

5.4 Anticipating the transferability to capitalise in space

Transferability needs to be anticipated right from the design stage. We are convinced that process-based models have generic parts that can be transposed and specified in other contexts. The methodological framework has proven useful to describe these aspects and their specification. In particular, we propose a reflection with experts on the basis of vegetative cycles rather than on a monthly basis as this was done by (Vozinaki et al., 2015) for the evaluation of yield losses due to flash floods in Greece. We believe that this approach has two major advantages. First, discussing biophysical impacts (yield and plant material losses) and decisions to continue cultivation, with experts on this basis fits better with their cognitive approach and reduce incertainty in data collection. Second, it makes it possible to transfer this method to other contexts, by calibrating vegetative cycles of crops.

5.5 Development prospects around process-based models

The proposed methodological framework also provides a basis for future improvements. In this sense, the explicitness of the assumptions (biophysical processes, decision rules) should not be fixed but should be fed. This suggests the possibility of pooling efforts on an international scale. The tracks of improvement which seem to us to be a priority concern the taking into account of: (i) other biophysical processes, (ii) agricultural buildings, (iii) breeding systems, (iv) adaptations of the trajectories of farms to floods.

Some biophysical processes such as pollution, salinization or degradation of soil quality remain little studied and should be consolidated.

As for agricultural buildings, a similar approach by breaking down the basic components of the farm building (structure, equipment, input) could be conducted using the model **floodam.building** (Grelot and Richert, 2019). It will then be necessary to specify the sensitivity and reparation costs of these components with experts. The challenge remains to determine the location associated with the use and technical orientation of buildings, which is not specified in existing databases in France.

Regarding livestock systems, the work carried out by the FHRC is a solid base that should be consolidated by addressing the issue of delayed effects related to the loss of animals as it has been integrated through the loss of plant material for crops.

Finally, an important challenge remains to take into account the adaptive capacities of farmers in the long term. Collecting data from agricultural experts who have witnessed flooding on a large number of farms allows us to model a standard behavior. However, we are aware that this average view does not reflect the diversity of individual vulnerability situations at the farm level. Thus, at the individual scale, decisions, especially those concerning long term issues such as replanting, will depend on individual parameters such as investment dynamics, the age of the farm manager, the farm's trajectory... While it would be possible to assess the economic relevance of certain measures in terms of damage avoided using **floodam.agri** (e.g assessment of the damage avoided by establishing a grassland in place of a vineyard), the determinants of these adaptation decisions are much more complex at the level of individuals and in particular farms. Understanding the internal and external determinants of adaptation implementation would require a different approach and investigation at the individual level (Richert et al., 2017).

6 Conclusions

Process-based flood damage assessment models relying on expert knowledge are widely researched and used operationally. However, it is often observed that this work cannot be capitalised on because the models are too attached to their development context. In this paper, we argue that process-based models, based on a rigorous modelling process, can be suitable to be applied in different contexts. We show that following a rigorous modelling process can contribute to their capitalisation and transferability. We propose a framework that improve the development of process-based flood damage models by meeting the properties of assumptions explicitness, validation, updatability and transferability. We show that respecting these properties could help structure a common modeling effort at the international level.

By applying the proposed methodological framework to **floodam.agri**, we show that it is possible to describe explicitly the modeling assumptions. Given the complexity of the phenomena (biophysical and decisional processes), the diversity of the data sources, we argue that the methodological framework is useful to structure and anticipate since the beginning of the development process a spirit of capitalisation in time and space. This rigorous work is a necessary condition to consider the possibility of improvement in the long term and of cooperation around the development on an international scale. The framework proposed here thus opens up prospects for cooperation in improving and transferring existing models, particularly agricultural ones. In terms of research, this work of methodological improvement must be carried out in parallel with the improvement of observation and data collection on the impacts of floods in terms of monetary damage but also to improve the understanding of biophysical damage processes, repair decisions and adaptation on the long term.

Code and data availability. **floodam.agri** has been implemented in R language and will soon be available as a package.

Appendix A: Families and categories of crops considered in floodam.agri

Different typologies had to be used in the development of **floodam.agri**. To work with the experts on the sensitivity of the crops, we used the families (level 1), categories (level 2) and subcategories (level 3) described in the table A1.

The level 1 corresponds to five crop families. It brings together 24 categories of crops usually grouped in agronomy. However, this level is not fine enough to define homogeneous damage processes. The crop category (level 2) is the level where damage process is homogeneous. The crop sub-category (level 3) represents a total of 53 crops that can be related to the second level. For instance, winter wheat, barley, and rye are three types of crops that belong to the winter wheat category and to the grain and oleaginous crops family.

Then, we produced the ready-to-use national damage functions by adjusting the typology to be compatible with the Graphic Plot Register (GPR level, table A2) which is the database for locating agricultural assets based on farmers' declarations to benefit from the European Common Agricultural Policy subsidies.

Table A1. Families and categories of crops considered in **floodam.agri**

Family (level 1)	**Category (level 2)**	**Sub-category (level 3)**
Meadows and feeding crops	Meadow	Meadow
	Recently sowed meadow	Recently sowed meadow
	Alfalfa	Alfalfa
	Recently sowed alfalfa	Recently sowed alfalfa
Grain and oleaginous crops	Corn	Corn
		Non food corn
		Sorghum
		Grain corn
	Silage corn	Silage corn
	Winter wheat	Winter wheat
		Barley
		Non food wheat
		Silage wheat
		Triticale
		Durum wheat
	Spring wheat	Spring wheat
		Spring barley
		Spring durum wheat
		Spring oat
		Grain spring wheat
	Rape	Rape
		Non food rape
		Oleaginous
	Sunflower	Sunflower
		Non food sunflower
		Silage sunflower
Fruit trees	Apple tree	Apple tree
	Pear tree	Pear tree
	Cherry tree	Cherry tree
	Peach tree	Peach tree
	Apricot tree	Apricot tree
	Plum tree	Plum tree
Grape vines	Wine grape	Wine grape
Vegetable crops	Asparagus	Asparagus
	Salad	Salad
	Field tomato	Field tomato
	Greenhouse tomato	Greenhouse tomato
	Various field vegetables	Melon
		Carrot
		Onion
	Tied-in vegetables	Eggplant
		Pepper
	Greenhouse tied-in vegetables	Cucumber

Table A2. Categories of crops in the RPG database, area in flood-prone areas, and maximum damage estimated with **floodam.agri**

GPR level	Area in flood-prone areas (ha)	Maximum damage (Euros/ha)
No information	1 572	-
Soft wheat	5 336 421	2 109
Grain and silage corn	3 067 195	1 897
Barley	1 595 271	1 927
Other cereals	1 119 601	1 658
Rapeseed	1 525 055	2 154
Sunflower	713 633	1 611
Other oleaginous	76 743	1 736
Protein crops	372 320	-
Fibre plants	47 354	-
Seeds	72 248	-
Set-aside lands (without production)	0	-
Industrial set-aside lands	0	-
Other set-aside lands	402 587	-
Rice	25 721	-
Grain legumes	14 770	-
Fodder	176 884	2 544
Pasture	1 888 703	-
Permanent grasslands	6 488 945	2 067
Meadows	3 665 000	2 135
Orchards	87 890	93 549
Vineyards	449 947	50 887
Shell fruits	26 117	-
Olive trees	10 990	-
Other industrial crops	431 726	2 152
Vegetables - Flowers	331 381	20 783
Sugar cane	0	-
Arboriculture	4 204	93 549
Miscellaneous	298 808	-
TOTAL	28 231 555	93 549

The areas in flood-prone areas were estimated using the approximate potential flood extent (EAIP), which was estimated for the whole country within the frame of the first national flood risk assessment between 2011 and 2017. The maximum values of damage are calculated taking into account all possible combinations of flood parameters. The categories in bold are linked to a damage function produced with **floodam.agri**

Appendix B: Resolution of the flood parameters in floodam.agri and catagories chosen for the production of national flood damage functions

The resolution of the model is given in the table B1. For the production of the ready to use national flood damage functions, groupings were made to give duration classes (table B2) and to calibrate the four seasons (table B3.

Table B1. Ranges and resolution of the flood parameters used in **floodam.agri**

Parameter	Categories	Range	Resolution	Unit
water height	-	0 to 250	10	cm
submersion duration	-	0 to 20	1	day
velocity	low, medium, high, very high	0 to 0.5; 0.5 to 1; 1 to 2; > 2	-	m/s
season	crop growth stages	-	-	

Table B2. Categories of flood duration for the French flood damage functions

Category	Minimum (Number of days)	Maximum (Number of days)
low	0	1
medium	2	4
high	5	10
very high	11	20

Table B3. Categories of time of occurrence of the flood for the French flood damage functions

Category	Beginning (week of the year)	End (week of the year)
Spring	14	26
Summer	27	39
Fall	40	52
Winter	1	13

Appendix C: Conceptual comparison of three process-based models to estimate agricultural damage

We present in the table C1 a proposal for using the methodological framework to describe and compare three process-based models for agricultural damage assessment based on existing literature. The table C1 provides an overview of what is and is not included in the models. For example, it allows us to see that the **floodam.agri** and AGDAM models could only be compared on cereal crops.

Table C1. Illustration of the use of the methodological framework to describe and compare three process-based models

Conditions	**floodam.agri**	**FHRC**	**AGDAM**
Axis 1 : Explicit assumptions			
EA1: boundaries	Crop (several types), plant material, soil, equipment	Crop (several types) dairy systems	Crop (cereals)
EA2: biophysical processes	Explicit	Not fully explicit	Not explicit
EA3: decisions	Explicit	Not fully explicit	Not fully explicit
Axis 2 : Validation			
V1: comparison sinistrality data	No	No	No
V2: comparison with other models	No	No	No
V3: meet stakeholders'expectations	Yes	Yes	Yes
V4: application cases	Yes (200)	Yes (unknown)	Yes (unknown)
V5: validation with experts	Yes	Unknown	Unknown
Axis 3 : Updatability			
U1: data explicit	Yes	Yes	Yes
U2: vintage specified	Yes	No	No
U3: data tracked over time	Partially	Unknown	Unknown
Axis 4 : Transferability			
T1: conditions for transfer explicit	Yes	No	No
T2: transferred	Regional flood damage functions (Mao, 2019) Partially in AGRIDE-c (Molinari et al., 2019b; Scorzini et al., 2020)	Unknown	Unknown

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References

Agenais, A.-L., Grelot, F., Brémond, P., and Erdlenbruch, K.: Dommages des inondations au secteur agricole. Guide méthodologique et fonctions nationales, Groupe de travail national acb inondation, IRSTEA, 2013.

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P., Wyser, K., and Feyen, L.: Global projections of river flood risk in a warmer world, Earth's Future, 5, 171–182, https://doi.org/10.1002/2016EF000485, 2017.

Browne, M. J.: The Demand for Flood Insurance: Empirical Evidence, Journal of Risk and Uncertainty, 20, 291–306, https://doi.org/https://doi.org/10.1023/A:1007823631497, 2000.

Brémond, P.: Caractérisation et évaluation économique de la vulnérabilité des exploitations agricoles aux inondations, Thèse de doctorat, spécialité sciences Économiques, Université de Montpellier 1, Montpellier, France, 2011.

Brémond, P. and Grelot, F.: Comparison of a systemic modelling of farm vulnerability and classical methods to appraise flood damage on agricultural activities, in: 11th biennal conference of the International Society for Ecological Economics (ISEE) -Advancing sustainability in a time of crisis, p. 20, 2010.

Brémond, P. and Grelot, F.: Taking into account recovery to assess vulnerability: application to farms exposed to flooding, in: International Congress on Environmental Modelling and Software - Managing Resources of a Limited Planet, edited by Seppelt, R., Voinov, A. A., Lange, S., and Bankamp, D., p. 9, IEMSs, https://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=1803&context=iemssconference, 2012.

Brémond, P., Grelot, F., and Agenais, A. L.: Review Article: Economic evaluation of flood damage to agriculture – review and analysis of existing methods, Nat. Hazards Earth Syst. Sci., 13, 2493–2512, https://doi.org/10.5194/nhess-13-2493-2013, 2013.

Cammerer, H., Thieken, A. H., and Lammel, J.: Adaptability and transferability of flood loss functions in residential areas, Natural Hazards and Earth System Science, 13, 3063–3081, 2013.

Chau, V. N., Cassells, S., and Holland, J.: Economic impact upon agricultural production from extreme flood events in Quang Nam, central Vietnam, Natural Hazards, 75, 1747–1765, https://doi.org/10.1007/s11069-014-1395-x, 2015.

Comiskey, J. J.: Overview of Flood Damages Prevented by U.S. Army Corps of Engineers Flood Control Reduction Programs and Activities, Journal of Contemporary Water Research & Education, 130, 13–19, https://doi.org/https://doi.org/10.1111/j.1936-704X.2005.mp130001003.x, 2005.

Crawford-Brown, D., Syddall, M., Guan, D., Hall, J., Li, J., Jenkins, K., and Beaven, R.: Vulnerability of London's Economy to Climate Change: Sensitivity to Production Loss, Journal of Environmental Protection, 4, 548–563, 2013.

Davis, S. A. and Skaggs, L. L.: Catalog of residential depth-damage functions used by the Army Corps of Engineers in flood damage estimation, Tech. Rep. ADA255462, US Army Corps of Engineers, Institute for Water Resources, https://apps.dtic.mil/sti/pdfs/ADA255462.pdf, 1992.

Dias, P., Arambepola, N., Weerasinghe, K., Weerasinghe, K., Wagenaar, D., Bouwer, L. M., and Gehrels, H.: Development of damage functions for flood risk assessment in the city of Colombo (Sri Lanka), Procedia Engineering, 212, 332–339, https://doi.org/https://doi.org/10.1016/j.proeng.2018.01.043, 7th International Conference on Building Resilience: Using scientific knowledge to inform policy and practice in disaster risk reduction, 2018.

Dottori, F., Figueiredo, R., Martina, M. L. V., Molinari, D., and Scorzini, A. R.: INSYDE: a synthetic, probabilistic flood damage model based on explicit cost analysis, Natural Hazards and Earth System Sciences, 16, 2577–2591, https://doi.org/10.5194/nhess-16-2577-2016, 2016.

Durant, D., Kernéïs, E., Meynard, J.-M., Choisis, J.-P., Chataigner, C., Hillaireau, J.-M., and Rossignol, C.: Impact of storm Xynthia in 2010 on coastal agricultural areas: the Saint Laurent de la Prée research farm's experience, Journal of Coastal Conservation, https://doi.org/10.1007/s11852-018-0627-8, 2018.

Erdlenbruch, K., Thoyer, S., Grelot, F., Kast, R., and Enjolras, G.: Risk-sharing policies in the context of the French Flood Prevention Action Programmes, Journal of Environmental Management, 91, 363–369, 2009.

Forster, S., Kuhlmann, B., Lindenschmidt, K. E., and Bronstert, A.: Assessing flood risk for a rural detention area, Natural Hazards and Earth System Sciences, 8, 311–322, 2008.

Gerl, T., Kreibich, H., Franco, G., Marechal, D., and Schröter, K.: A Review of Flood Loss Models as Basis for Harmonization and Benchmarking, PLOS ONE, 11, 1–22, https://doi.org/10.1371/journal.pone.0159791, 2016.

Grelot, F. and Richert, C.: floodam - Modelling Flood Damage functions of buildings - Manual for floodam v1.0.0, Report, IRSTEA, 2019.

Hallegatte, S.: An Adaptive Regional Input-Output Model and its Application to the Assessment of the Economic Cost of Katrina, Risk Analysis, 28, 779–799, 2008.

Hallegatte, S.: Modeling the Role of Inventories and Heterogeneity in the Assessment of the Economic Costs of Natural Disasters, Risk Analysis, 34, 152–167, 2014.

Hattermann, F. F., Huang, S., Burghoff, O., Hoffmann, P., and Kundzewicz, Z. W.: Brief Communication: An update of the article "Modelling flood damages under climate change conditions – a case study for Germany", Natural Hazards and Earth System Sciences, 16, 1617–1622, https://doi.org/10.5194/nhess-16-1617-2016, 2016.

Hess, T. M. and Morris, J.: Estimating the Value of Flood Alleviation on Agricultural Grassland, Agricultural Water Management, 15, 141–153, 1988.

Jongman, B., Kreibich, H., Apel, H., Barredo, J. I., Bates, P. D., Feyen, L., Gericke, A., Neal, J., Aerts, J. C. J. H., and Ward, P. J.: Comparative flood damage model assessment: towards a European approach, Nat. Hazards Earth Syst. Sci., 12, 3733–3752, https://doi.org/10.5194/nhess-12-3733-2012, 2012.

Jonkman, S. N., Bockarjova, M., Kok, M., and Bernardini, P.: Integrated hydrodynamic and economic modelling of flood damage in the Netherlands, Ecological Economics, 66, 77–90, 2008.

Kelman, I. and Spence, R.: An overview of flood actions on buildings, Engineering Geology, 73, 297–309, https://doi.org/http://dx.doi.org/10.1016/j.enggeo.2004.01.010, 2004.

Kreibich, H., Seifert, I., Merz, B., and Thieken, A. H.: Development of FLEMOcs – a new model for the estimation of flood losses in the commercial sector, Hydrological Sciences Journal, 55, 1302–1314, 2010.

Malgwi, M. B., Schlögl, M., and Keiler, M.: Expert-based versus data-driven flood damage models: A comparative evaluation for data-scarce regions, International Journal of Disaster Risk Reduction, 57, 102 148, https://doi.org/https://doi.org/10.1016/j.ijdrr.2021.102148, 2021.

Mao, G.: Estimation des coûts économiques des inondations par des approches de type physique sur exposition, Phd thesis, École doctorale Sciences économiques et gestion (Lyon), "http://www.theses.fr/2019LYSE1192/document", thèse de doctorat dirigée par Robert, Christian Yann Sciences de gestion Lyon 2019, 2019.

Merz, B., Kreibich, H., Schwarze, R., and Thieken, A. H.: Review article "Assessment of economic flood damage", Natural Hazards and Earth System Sciences, 10, 1697–1724, 2010.

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., Aerts, J. C. J. H., van den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Daniel, V. E., Genovese, E., Green, C. H., Hallegatte, S., Kreibich, H., Lequeux, Q., Lochner, B., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A. H., Thompson, P. M., and Viavattene, C.: Costs of Natural Hazards - A Synthesis, Conhaz - wp09 final report, UFZ, Leipzig, Germany, 2012.

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A. H., and Viavattene, C.: Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps, Nat. Hazards Earth Syst. Sci., 13, 1351–1373, https://doi.org/10.5194/nhess-13-1351-2013, 2013.

Middelmann-Fernandes, M. H.: Flood damage estimation beyond stage-damage functions: an Australian example, Journal of Flood Risk Management, 3, 88–96, http://dx.doi.org/10.1111/j.1753-318X.2009.01058.x, 2010.

Molinari, D., De Bruijn, K. M., Castillo-Rodríguez, J. T., Aronica, G. T., and Bouwer, L. M.: Validation of flood risk models: Current practice and possible improvements, International Journal of Disaster Risk Reduction, 33, 441–448, https://doi.org/https://doi.org/10.1016/j.ijdrr.2018.10.022, 2019a.

Molinari, D., Scorzini, A. R., Gallazzi, A., and Ballio, F.: AGRIDE-c, a conceptual model for the estimation of flood damage to crops: development and implementation, Nat. Hazards Earth Syst. Sci., 19, 2565–2582, https://doi.org/10.5194/nhess-19-2565-2019, 2019b.

Molinari, D., Scorzini, A. R., Arrighi, C., Carisi, F., Castelli, F., Domeneghetti, A., Gallazzi, A., Galliani, M., Grelot, F., Kellermann, P., Kreibich, H., Mohor, G. S., Mosimann, M., Natho, S., Richert, C., Schroeter, K., Thieken, A. H., Zischg, A. P., and Ballio, F.: Are flood damage models converging to reality? Lessons learnt from a blind test, Nat. Hazards Earth Syst. Sci. Discuss., 2020, 1–32, https://doi.org/10.5194/nhess-2020-40, 2020.

Morris, J. and Hess, T. M.: Agricultural flood alleviation benefit assessment: A case study, Journal of Agricultural Economics, 39, 402–412, commandé 2009-09-29 (n° INIST 10533837). Reçu 2009-10-07, 1988.

Morris, J., Tim, H., and Helena, P.: Agriculture's Role in Flood Adaptation and Mitigation, OECD, /content/chapter/9789264083578-9-enhttp://dx.doi.org/10.1787/9789264083578-9-en, 2010.

Nortes Martínez, D.: Prise en compte de la multiscalarité dans la modélisation économique de la vulnérabilité aux inondations : apport d'un modèle multi-agent appliqué aux systèmes coopératifs viticoles, Phd thesis, Montpellier SupAgro, 2019a.

Nortes Martínez, D.: COOPER - Flood impacts over Cooperative Winemaking, Computer program, IRSTEA, https://www.comses.net/codebases/6038/releases/1.0.1/, 2019b.

Nortes Martínez, D., Grelot, F., Brémond, P., Farolfi, S., and Rouchier, J.: Are interactions important in estimating flood damage to economic entities?, Natural Hazards and Earth System Sciences Discussions, 2020, 1–30, https://doi.org/10.5194/nhess-2020-386, 2020.

OCDE: Étude de l'OCDE sur la gestion des risques d'inondation : la Seine en Île-de-France, Tech. rep., OCDE, 2014.

O'Connell, P. E., Ewen, J., O'Donnell, G., and Quinn, P.: Is there a link between agricultural land-use management and flooding?, Hydrol. Earth Syst. Sci., 11, 96–107, https://doi.org/10.5194/hess-11-96-2007, 2007.

Penning-Roswell, E., Johnson, C., Tunstall, S., Tapsell, S., Morris, J., Chatterton, J., and Green, C.: Appraisal of flood risk management for agriculture, pp. 61–70, Flood Hazard Research Centre, Middlesex University Press, UK, 2005.

Penning-Rowsell, E. C. and Chatterton, J. B.: The benefits of flood alleviation: A manual of assessment techniques (The Yellow manual), Saxon House, Farnborough, England, 1977.

Penning-Rowsell, E. C., Green, C. H., Thompson, P. M., Coker, A. M., Tunstall, S. M., Richards, C., and Parker, D. J.: The economics of coastal management: a manual of benefit assessment techniques. (The Blue Manual), Belhaven Press, London, England, 1992.

Penning-Rowsell, E. C., Johnson, C. L., Tunstall, S. M., Tapsell, S., Morris, J., Chatterton, J., and Green, C. H.: The Benefits of Flood and Coastal Risk Management: A Handbook of Assessment Techniques, Flood Hazard Research Centre, Middlesex University Press, 2005.

Penning-Rowsell, E. C., Priest, S. J., Parker, D. J., Morris, J., Tunstall, S. M., Viavattene, C., Chatterton, J., and Owen, D.: Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal, Routledge, 2013.

Posthumus, H. and Morris, J.: Implications of CAP reform for land management and runoff control in England and Wales, Land Use Policy, 27, 42–50, 2010.

Posthumus, H., Hewett, C. J. M., Morris, J., and Quinn, P. F.: Agricultural land use and flood risk management: Engaging with stakeholders in North Yorkshire, Agricultural Water Management, 95, 787–798, 2008.

Posthumus, H., Rouquette, J. R., Morris, J., Gowing, D. J. G., and Hess, T. M.: A framework for the assessment of ecosystem goods and services; a case study on lowland floodplains in England, Ecological Economics, 69, 1510–1523, 2010.

Priest, S., Viavattene, C., Penning-Rowsell, E., Parker, D., Joyce, J., Morris, J., and Chatterton, J.: Appraisal of Flood Risk Management for Agriculture, in: Flood and coastal erosion risk management, p. 12, Flood Hazard Research Centre, Middlesex University, on-line edn., https://www.mcm-online.co.uk/chapter-9/, 2021a.

Priest, S., Viavattene, C., Penning-Rowsell, E., Parker, D., Joyce, J., Morris, J., and Chatterton, J.: Handbook for economic appraisal : Flood and coastal erosion risk management, Flood Hazard Research Centre, Middlesex University, on-line edn., https://www.mcm-online.co.uk, 2021b.

Richert, C., Erdlenbruch, K., and Figuières, C.: The determinants of households' flood mitigation decisions in France - on the possibility of feedback effects from past investments, Ecological Economics, 131, 342–352, https://doi.org/10.1016/j.ecolecon.2016.09.014, 2017.

Rojas, R., Feyen, L., and Watkiss, P.: Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation, Global Environmental Change, 23, 1737–1751, https://doi.org/http://dx.doi.org/10.1016/j.gloenvcha.2013.08.006, 2013.

Rose, A. and Liao, S. Y.: Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions, Journal of Regional Science, 45, 75–112, 2005.

Rouchon, D., Peinturier, C., Christin, N., and Nicklaus, D.: Analyse multicritère des projets de prévention des inondations - Guide méthodologique 2018, Report, MTES, 2018.

Satrapa, L., Fošumpaur, P., Horský, M., Brouček, M., and Nešvarová, P.: Posuzování účinnosti akcí protipovodňové ochrany v rámci činnosti strategického experta programu Prevence před povodněmi v ČR - Assessing the effectiveness of flood protection in the work Expert Strategic Flood Prevention Program in the Czech Republic, Report, Czech Technical University, 2012.

Scorzini, A. R., Di Bacco, M., and Manella, G.: Regional flood risk analysis for agricultural crops: Insights from the implementation of AGRIDE-c in central Italy, International Journal of Disaster Risk Reduction, p. In Press, https://doi.org/https://doi.org/10.1016/j.ijdrr.2020.101999, 2020.

Shabman, L. and Stephenson, K.: Searching for the Correct Benefit Estimate: Empirical Evidence for an Alternative Perspective, Land Economics, 72, 433–449, 1996.

Shrestha, B. B., Kawasaki, A., and Zin, W. W.: Development of flood damage functions for agricultural crops and their applicability in regions of Asia, Journal of Hydrology: Regional Studies, 36, 100 872, https://doi.org/https://doi.org/10.1016/j.ejrh.2021.100872, 2021.

Sébillote, M. and Soler, L. G.: Les processus de décision des agriculteurs, pp. 93–117, INRA, Paris, 1990.

Thieken, A., Olschewski, A., Kreibich, H., Kobsch, S., and Merz, B.: Development and evaluation of FLEMOps - a new Flood Loss Estimation MOdel for the private sector, in: Flood Recovery, Innovation and Response I, edited by Proverbs, D., Brebbia, C. A., and Penning-Rowsell, E., pp. 315–324, WIT Press, 2008a.

Thieken, A., Kreibich, H., Müller, M., and Lamond, J.: Data Collection for a Better Understanding of What Causes Flood Damage–Experiences with Telephone Surveys, chap. 7, pp. 95–106, American Geophysical Union (AGU), https://doi.org/https://doi.org/10.1002/9781119217930.ch7, 2017.

Thieken, A. H., Ackermann, V., Elmer, F., Kreibich, H., Kuhlmann, B., Kunert, U., Maiwald, H., Merz, B., Müller, M., Piroth, K., Schwarz, J., Schwarze, R., Seifert, I., and Seifert, J.: Methods for the evaluation of direct and indirect flood losses, in: RIMAX Contributions at the 4th International Symposium on Flood Defence, Deutsches GeoForschungsZentrum GFZ, 2008b.

USACE: AGDAM, Agricultural Flood Damage Analysis – User's Manual (Provisionnal), Computer Program Documentation CPD-48, US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (HEC), Davis, CA, 1985.

Van der Veen, A., Steenge, A. E., Bockarjova, M., and Logtmeijer, C. J. J.: Structural economic effects of large scale inundation: a simulation of the Krimpen dike breakage, Tech. rep., University of Twente, 2003.

van Loenhout, J., Below, R., and McClean, D.: The human cost of disasters: an overview of the last 20 years (2000-2019), Tech. rep., Centre for Research on the Epidemiology of Disasters (CRED) and United Nations Office for Disaster Risk Reduction (UNISDR), 2020.

Vozinaki, Anthi-Eirini, K., Karatzas, G. P., Sibetheros, I. A., and Varouchakis, E. A.: An agricultural flash flood loss estimation methodology: the case study of the Koiliaris basin (Greece), February 2003 flood, Natural Hazards, 79, 899–920, https://doi.org/10.1007/s11069-015-1882-8, 2015.

Wagenaar, D., Lüdtke, S., Schröter, K., Bouwer, L. M., and Kreibich, H.: Regional and Temporal Transferability of Multivariable Flood Damage Models, Water Resources Research, 54, 3688–3703, https://doi.org/https://doi.org/10.1029/2017WR022233, 2018.

Wagenaar, D., Hermawan, T., van den Homberg, M. J. C., Aerts, J. C. J. H., Kreibich, H., de Moel, H., and Bouwer, L. M.: Improved Transferability of Data-Driven Damage Models Through Sample Selection Bias Correction, Risk Analysis, 41, 37–55, https://doi.org/https://doi.org/10.1111/risa.13575, 2021.

Xie, W., Li, N., Wu, J. D., and Liu, X. Q.: Evaluation of indirect loss from hypothetical catastrophes in two regions with different economic development levels in China, Nat. Hazards Earth Syst. Sci., 12, 3325–3335, 2012.

Xie, W., Li, N., Wu, J. D., and Hao, X. L.: Modeling the economic costs of disasters and recovery: analysis using a dynamic computable general equilibrium model, Nat. Hazards Earth Syst. Sci., 14, 757–772, 2014.

Zandersen, M., Oddershede, J. S., Pedersen, A. B., Nielsen, H. O., and Termansen, M.: Nature Based Solutions for Climate Adaptation - Paying Farmers for Flood Control, Ecological Economics, p. 106705, https://doi.org/https://doi.org/10.1016/j.ecolecon.2020.106705, 2020.