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Point-by-point response to the reviews

Reply to Anonymous Referee #1

We thank the reviewer for taking the time to review the manuscript and for the helpful comments and suggestions. Here we provide answers to the specific comments and indications of how the manuscript could be improved to address the issues raised by the reviewer.

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This paper studies the value of extra information regarding water availability for drought management decisions, focusing on reservoir managers and irrigators. This is an interesting topic and the outputs of the work are relevant to the scientific community. However, there are a few issues in the current version that need to be explained further so the manuscript can be ready for publication.

1) In Section 2.1, when describing your study area, it would be nice to add something related to how droughts have impacted this basin in the past and what were the implications for agriculture in the area.

Three drought events that produced impacts on the agriculture and other sectors have been recorded in the area for the period 2000-2014: a short drought spell in 2002, a multiyear event that lasted from the winter of 2004-2005 to the spring of 2008, and another during the years 2011 and 2012 (Linés et al, 2017). The impacts of the multiyear drought of 2004-2008 in the Ebro basin have been widely studied. The north-eastern part of the basin was the most impacted (Hernández-Mora et al, 2013). Agriculture was the most affected sector, with 540 million of euros of estimated losses in crop production during the hydrological year 2004-2005 and further losses of 272 million in related industries (Perez y Perez & Barreiro-Hurlé, 2009).

Suggested change: We will include this information in the study area section.

References:

Hernández-Mora, N., Gil, M., Garrido, A., & Rodríguez-Casado, R. (2013). *La sequía 2005-2008 en la cuenca del Ebro. Vulnerabilidad, Impactos y Medidas de Gestión* (p. 62). Universidad Politécnica de Madrid - Centro de Estudios e Investigación para la Gestión de Riesgos Agrarios y Medioambientales - CEIGRAM.

Linés, C., Werner, M., & Bastiaanssen, W. (2017). The predictability of reported drought events and impacts in the Ebro Basin using six different remote sensing data sets. *Hydrol. Earth Syst. Sci.*, *21*, 4747–4765.

Perez y Perez, L., & Barreiro-Hurlé, J. (2009). Assessing the socio-economic impacts of drought in the Ebro River Basin. *Spanish Journal of Agricultural Research*, *7*(2), 269–280.

2) In Section 2.2.1, there is hardly any information about how many people do they interview from each group (reservoir operators, irrigators), what type of questionnaire/survey method was used (you mentioned it briefly in the discussion but I think it should be explained here in more detail), etc. I think this is needed to understand a bit better how the assumptions you are making in your model are representing the sector. Authors acknowledged that doing a larger survey would be ideal although out of the scope of the work. But still I think readers need to know more about the survey process. Also, they stated that irrigators are very different in their risk aversion levels and this will affect their decisions during a drought. Without information of the sample, readers might wonder if the participants in the survey are representing that spread.

One interview session was held at each of the locations (the basin authority, the irrigation association and the farm) with two or three people participating in each of them. In the interview that was held at the basin authority, the participants included the head of one of the basin’s management units and two members of the hydrological planning office, both with expertise in drought management in the basin. In the interview at the Irrigation Association, the participants were the head of the Irrigation Association and the engineer in charge of the information service about current and expected water availability. And in the interview at the farm level, two people participated: the head of viticulture and engineer responsible of the information service.

The method used was semi-structured interviews. We had a prepared set of questions to ensure we collected all the details that we needed about their decision processes, the data they use to inform them and the gaps or limitations they identify in the information available to them. These questions were used during the interview as a guide and checklist of the topics of interest that we wanted to cover. As is commonplace in semi-structured interviews, we asked the participants to tell us about their own practices, as well as the practices of the groups they deal with in relation with drought management, letting them tell the story in their own way. We only used the questions to bring out the topics that were not mentioned by the participants to ensure we covered all the topics we intended to cover.

As indicated in section 3.1.3, the information about the practices and attitudes of farmers in the study area was to a great extent obtained from the interview with the Irrigator Association who works in close collaboration with all the farmers in the area and has therefore a wider view than individual farmers. We acknowledge that the sample of interviews is held among a small sample. The objective of these interviews was primarily to build our understanding of how the farmers behave as a function of their expectation of water availability. Although important to the assumptions made in the development of the decision model that we constructed, we would readily agree that our representation of the farmer behavior and the diversity of responses across farmers may be over simplified. A more complete interview would reveal more information, but we feel that is outside the scope of this paper.

Suggested change: We will add this additional detail on the interview of the participants and method to the section 2.2.1. In the revised version we also propose to put less emphasis on the interviews as we acknowledge that the sample of interview is small, and that the representation of the diversity of farmer responses may be simplified.

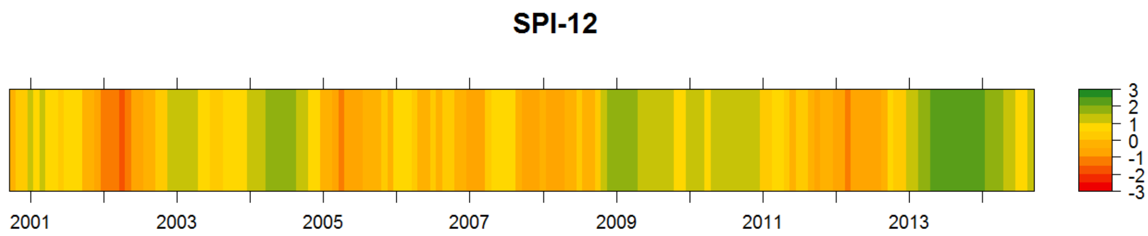
3) In page 13, line 4, you said that you explore different thresholds "keeping the same thresholds at each of the four points where the farmers make decisions during the season". However, in page 16, you give different thresholds for Nov, Feb, April and May. Could you clarify this?

In page 13, line 4. We apologise for the confusion. For each of the four decision moments (Nov, Feb, Apr, May) different thresholds are used, but we meant that the same set of 4 thresholds is kept for all the years analysed.

Suggested change: We agree that is confusing and we will rephrase the sentence in page 13, line 4, to make it clearer.

4) In Table 3, is there any way authors can add some kind of information to show how dry or wet each of the years under study was. From what I understood, 05 and 06 will be drier years as even with high allocation factors the result is not very good...But maybe adding some information (e.g., a standardized precipitation index) could help to interpret the results.

Yes, in 2005 and 2006 there was a drought event, as well as in 2002 and 2012 (see answer to comment 1). This is indeed well represented by the SPI data of the study period (Fig C4).



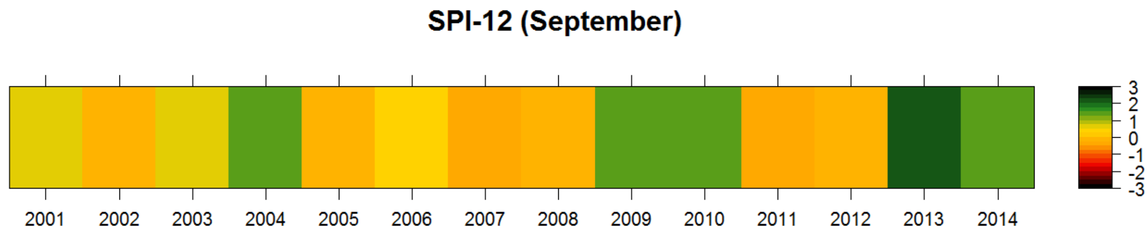


Fig. C4. Monthly SPI-12 (upper plot) and SPI-12 for the month of September (lower plot) for the catchment area of Barasona and Santa Ana reservoirs. Calculated with CHIRPS precipitation data for the period 1981-2015.

Suggested change: We will include the timeline for SPI-12 for September information in the header of table 3 of the manuscript to provide an indication of the dryness of each year.

5) Figure 4, after looking at it a few times, is still a bit confusing to me. Authors could review the explanation of it and/or the presentation of it to make it easier to follow.

We agree that Figure 4 is complex and contains a lot of information. This figure aims to illustrate the optimised thresholds. A threshold is required when taking the decision to choose between two options as a function of a certain indicator. In this case the threshold is the value above which the farmer would consider that the availability of water is good enough to plant the most productive crops (this corresponds to following the paths marked with a blue A in Figure 3). The threshold is perfect if it always makes the farmer take the decision that results in a higher benefit at the end of the season. Using perfect information, we first identified the decisions that result in the highest benefits to the farmers. These decisions are represented in Figure 4 by the coloured points, with the level of the reservoir on the y-axis. If the point is red, then it is best for the farmer to follow the path marked with a red A in Figure 3, while if it is blue then it is best to follow the blue A path. If it is yellow, then it does not matter which of the paths is followed. A perfect threshold for the reservoir level to divide between good and poor water availability would be selected such that all the red points are below and all the blue points above the threshold. As can be seen in Figure 4, it is not possible to select a perfect classification of the reservoir levels with a single threshold. The dashed lines mark the thresholds that maximises the points correctly classified. The fact that the classification cannot be perfect means that the reservoir level alone does not provide enough information on what is the best decision to take. Additional information would be valuable if it contributes to improve the classification and, therefore, results in the decision that maximises the benefits being taken more often. In this case the additional information we consider is the snow coverage data. We show this in the lower part of the figure. Again the figure shows that this information alone does not lead to a perfect classification either (dashed lines).

This is different when the combined information of reservoir level and snow cover extent is used to inform the expectation of water availability. We incorporate this additional information by amending the threshold of the reservoir level. This is the solid line in the figure for the Months Nov, Feb and Apr. Snow cover is not considered in May as that is too late in the season to be of significance.

When snow covers an area larger than the threshold coverage (dashed line in the lower plot), then the original threshold for the reservoir level is used. However, when the snow coverage is smaller than the identified threshold, and therefore the future contribution to the reservoir level from snowmelt is expected to be lower, a second, more conservative threshold for the reservoir level is used. With the second threshold some of the red points incorrectly classified above the original threshold are now classified below the thresholds.

Suggested changes:

- We propose to improve the explanation of figure 4 in the manuscript, describing this step by step to ensure the reader does not get confused.
- We will include the missing label in y axis ("reservoir level") in Figure 4
- We will mention in the caption of Figure 4 that the colours marked in the legend are considered as the "optimal course" and refer to the paths illustrated in Figure 3.

Reply to Anonymous Referee #2

We thank the reviewer for the time and effort to review the manuscript and for providing suggestions to improve it. We include below answers to the specific comments and indications of how the manuscript could be change to address the issues raised by the reviewer.

…………………………………………………………………………………………………….

[Referee] I have approached "Do users benefit from additional information in support of operational drought management decisions in the Ebro basin?" by Clara Linés and co few times by now. The paper touches a very timely topic and (it seems that it) takes an interesting approach to quantify the value of different information attributes on decisions that various stakeholder can take across various spatial scales. The paper demonstrates application of the methodology is Ebro River Basin in northern Spain, which is highly regulated and intervened by socio-economic activities, in particular irrigated agriculture and hydropower generation. As far as the context of the paper is concerned, the paper is certainly inline with aims and scope of HESS and can attract a large portion of the journal's readership. However, at this stage the paper suffers from major issues. In particular, the paper is quite disorganized in terms of sectioning and the sequence of materials provided. Second, it seems that presentation in the paper lacks effective strategy, which hinders the reader to get involved with the paper. Finally, the level of details regarding the data obtained through interviews, methodology used for modeling, experimental setup and investigation made is quite low, in a way that the work is indeed not producible, if some0one wants to apply the same approach in another case study. I do believe the paper should go under major revisions, in terms of the rationale and the content provided and resubmitted for another round of review, this time focusing on the specific results and findings.

Reply: We thank the reviewer for underlining the timeliness of the topic and that its contribution to the readership of HESS. We do apologise though that it appears that the organisation of the paper was not, to the reviewer, as clear as it could be and will endeavour to improve this clarity. We hope and firmly believe that the improvements we propose to the structure will benefit its clarity and remove the confusion.

Below, please see my specific comments

1) The paper is poorly written. The use of English can (and must) be improved in many parts of the paper (e.g. P1, line 8; P2, line 7-9 among others). In addition, it is very hard to read the whole paper in one sitting (at least I was not able to accomplish) due to long sentences and the existence of a lot of text. I strongly suggest a major editorial effort before the paper resubmitted.

Reply: We have carefully analysed the sentences referred to, and can unfortunately not see any grammatical issues with these. However, we do agree that those and other sentences in the manuscript are long, and that such long sentences make reading the text more difficult.

Suggested change: We will review the manuscript and shorten sentences that are unnecessarily long, and summarise the text where possible. Also, the changes of the paper structure suggested as a response to comment 3 will help reduce the length of the paper. We will carefully revise the paper again to ensure correctness of the English grammar used.

2) It seems that the paper has missed positioning itself in the broader context of the current socio-hydrology research. On the one hand, review of previous studies in other parts of the world has been largely ignored. This includes for instance missing previous works on performing semi-structured interviews, developing decision support models through stakeholder engagement, and quantifying the value of information. The paper requires framing itself very clearly in the introduction.

Reply: The intended scope of our paper is to perform a stakeholder oriented analysis of the value of information for drought management decisions. We therefore positioned the paper primarily in the context of research that explores the value of information to decision making. This is the reason why we motivate in the introduction our study from that perspective, primarily providing references that call for this type of research and calling on examples of previous studies that have addressed the quantification of the value of information in support of water management decisions, both from a stakeholder oriented perspective and from a scientific perspective. We do agree that this paper also fits to some extent within the context of the developing field of socio-hydrology in that it explores the co-evolution of the availability of water and the decisions taken by humans (in this case farmer and irrigation operators). While the emerging field of socio-hydrology (Sivapalan, 2002) is a broad field (see also the review of the first biennial of the proclaimed IASH Panta Rhei decade, McMillan et al.,2016), our work is related most to the working group on Drought in the Anthropocene (van Loon et al., 2016), which explicitly addresses the inefficiency of drought management due to poorly understood feedback between people (and the decisions they make) and drought conditions.

As noted in response to the comments of the first reviewer, the objective of the semi-structured interviews was primarily to build our understanding of how the farmers behave as a function of their expectation of water availability, and we do not consider our approach to these interviews as the main contribution of this paper. We have selected this approach as semi-structured interviews are a specific method suited to gather stakeholder input. We agree that its use in hydrological research can be better contextualised by including references to other research that use semi-structured interviews to develop an understanding of stakeholder behaviour.

Suggested changes:

We will extend the introduction to position our research within the context of the emerging field of socio-hydrology, referring in particular to the current poor understanding of how the decisions people make contribute to an efficient management of drought. We will include references (see above) as appropriate. In the methodology section we add the following references about the use of semi-structured interviews:

- Carr et al (2011), that use semi-structured interviews to understand what drives the decision of farmers to reuse wastewater in Jordan.

- O'Keeffe et al (2016), that describe an example of application of semi-structured interviews to gather data on farmer water use practices in two Indian districts.

References:

Carr, G., Potter, R.B., Notclif, S. (2011) Water reuse for irrigation in Jordan: Perceptions of water quality among farmers. Agricultural Water Management 98 (2011) 847–854. doi:

10.1016/j.agwat.2010.12.011

McMillan H., et al. (2016) Panta Rhei 2013–2015: global perspectives on hydrology, society and change, Hydrological Sciences Journal, 61:7, 1174-1191, DOI:10.1080/02626667.2016.1159308

O'Keeffe, J., Buytaert, W., Mijic, A., Brozovi, N., Sinha, R. (2016) The use of semi-structured interviews for the characterisation of farmer irrigation practices, Hydrol. Earth Syst. Sci., 20, 1911–1924. doi:10.5194/hess-20-1911-2016

Van Loon A. et al. 2016. Drought in the Anthropocene. Nature Geoscience 9, 89–91.doi: 10.1038/ngeo2646

Sivapalan M. Savenije H. Blöschl G. 2012. Socio-hydrology: A new science of people and water. Hydrol. Process. 26, 1270–1276. Doi: 10.1002/hyp.8426

3) The paper is extremely disorganized and is poorly sectioned. The section related to Results in particular is very long relative to other sections and is hard to follow. Most importantly, the results section includes even the results of semi-structured interviews that basically provides the data support for developing the decision model. I believe a great portion of what is presented in the results can go under a new section related to the data support and model development.

Reply: We opted to include all results, both from the semi-structured interviews as well as from the model phase, in the result section. Since the model development depends on the results of the survey phase, the drawback of this choice is indeed that a large part of the content of the manuscript needs to be in the results section.

As proposed by the reviewer, an alternative to avoid this would be to include a separate section reporting the results of the semi-structured interviews (including both method and outcomes), followed by another section that discusses the model design and options. In this case the result section would contain only the results of the model runs to quantify the value of information. This alternative structure would also shorten the text by merging the content now divided between the methods and the results section.

Suggested changes: We propose to restructure the article as suggested. The outline for the manuscript following the alternative option mentioned above is included at the end of this document (Annex 1).

4) The way that paper presents the information and findings through text, tables and figures seems not very well thought. For example, a central part of this paper is the decision model, with which the value of new information can be assessed for various stakeholders. After reading the paper this part of the paper quite a few times, I am not still slightly clear about how the model has been developed. A schematic and some formulas would certainly help. To facilitate following the paper, I believe a standalone section is required to discuss the experimental setup and how the results should be viewed. Figures are very hard to understand. Similar to the other reviewer, I do also have problem with understanding Figures 4 (and 5 and 6 and 7). The discussion is also extremely long and rather scrambled. I believe synthesizing information under appropriate subsections would be very helpful.

Reply: The model combines the decision of the farmers of what and when to plant and the decision of the reservoir operators on whether to apply curtailments to the amount of water that can be supplied to farmers. The choices of the farmers are schematically represented in figure 3. The information that drives those decisions and the relations between the parameters as defined in the model are represented in Table 1. We agree that the table can be difficult to follow. In figure 1 (below) we have incorporated the information from Table 1 in a schematic form to make it more visual. We will replace Table 1 with this figure and provide a succinct description in the text to explain the figure.

We also expect that including a standalone section of the model design as also proposed in the answer to comment 3 will help to make it clearer as well. A description of the new outline will be included in the "Approach and data" section (see reply to comment 3 and Annex 1).

Please, see the reply to comment 4 of reviewer 1 for an explanation of figure 4 and the corresponding suggested improvements.

The expected final results of the analysis is the total benefit for the farmers. This benefit depends on the decisions taken during each season, which in turn depend of the information used to inform them. Two information scenarios are tested: one that represents the current use of information (the decisions are informed by the reservoir levels only) and another that represents the use of additional information (the decisions are informed by reservoir levels and snow cover data). *Perfect information* and *No information* scenarios are also used as a reference of the potential value of the information. Figures 5-7 present these results. In Figure 5 the total benefit for the period for each of the scenarios and thresholds is shown. The difference between the perfect information and the no information scenarios shows the potential value of using information, as the use of uncertain information is expected to scale between these two extreme situations. This is shown in the first two columns of the Figure 5. However, as can be seen in the following columns that represent the information scenarios, the use of non-perfect information in this case can result in losses when water availability is overestimated. Figures 6 and 7 show the total relative value of the two information scenarios with respect to the reference scenarios. The relative value is negative, because the losses are higher in these two information scenarios than in the No information scenario, as seen in Figure 5. However, we can see that the losses are lower when using the additional information through the comparison of each pair of columns. The columns on the left show the relative losses when considering only the reservoir levels, while those on the right show the relative losses when also considering the snow cover. These show marginally less losses. Figure 7 has the same structure as Figure 6, and shows the result of lowering the cost of planting, and therefore reducing the losses incurred when the water availability is overestimated. As a result of the reduction in the losses, we can see that the relative value of the information increases with the reduction of the costs.

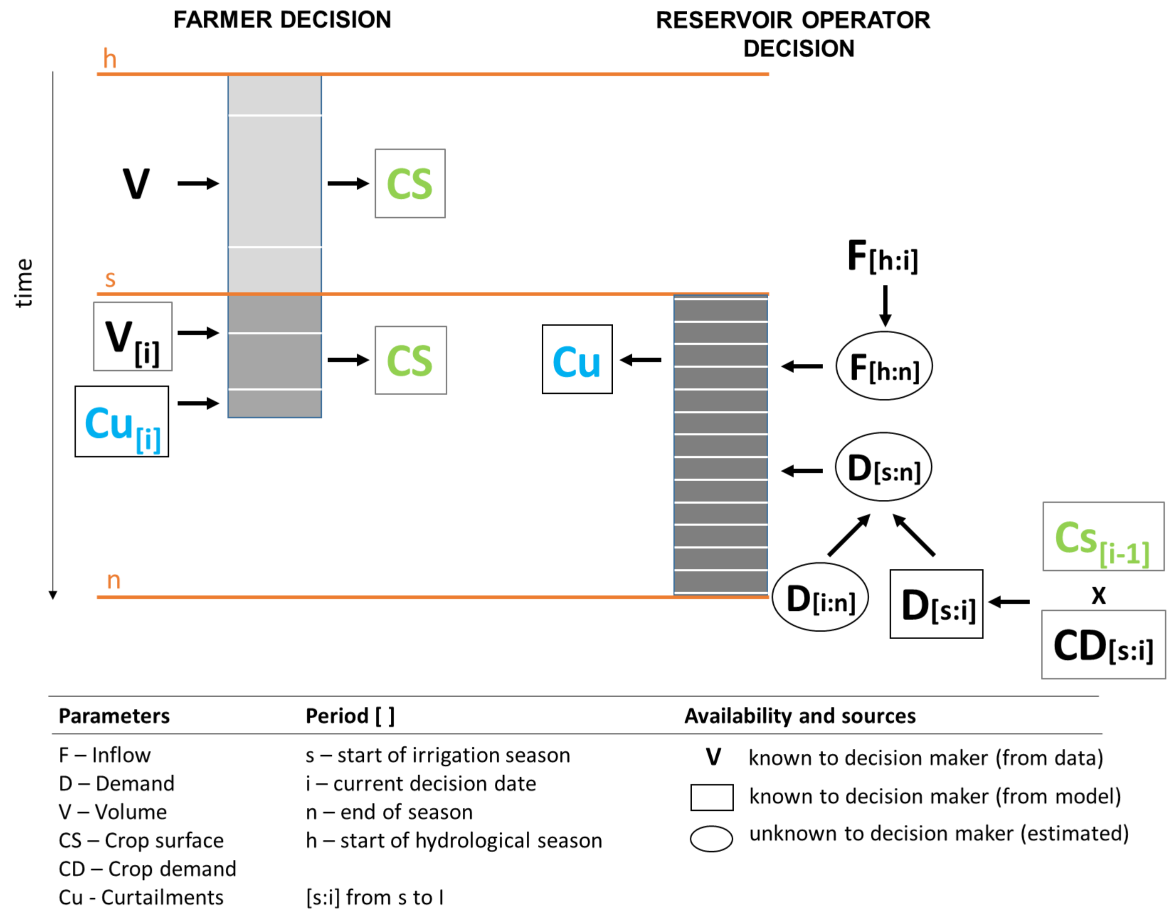


Figure 1. Model decisions and their inputs and outputs.

Suggested changes:

- We will replace Table 1 by Figure 1 (included below), providing also a succinct description of the figure in the text.
- We will change the outline of the paper as outlined in Annex 1 below. The expected results will be explained in the approach section to facilitate following the paper.
- The discussion section will be structured in three subsections to make this clearer (see annex 1)
- We will critically review and improve the supporting texts for figures 5, 6 & 7.

5) While the paper is long, it does not provide information required to reproduce the work or to at least understand the process of data gathering through semi-structured interviews and model development. As noted above, it is not clear how the model has been developed as a result it is not possible to really examine the truthfulness of the results and the relevance of the discussion provided.

Please see our replies to comment 4 above and to comment 2 of reviewer 1 for an explanation about the model development and the data gathering through semi-structured interviews respectively, and the corresponding suggested improvements to the manuscript. In addition to the explanations included in the manuscript, we are happy to share the model code upon request for reproducibility.

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Annex 1 - Alternative outline for the manuscript:

1. Introduction

2. Approach and study area

3. Stakeholders' consultation

3.1. Method

3.2. Responses

3.2.1 Confederación hidrográfica del Ebro

3.2.2 Canal de Aragón y Cataluña (CAyC)

3.2.3 Farmers in the Canal de Aragón y Cataluña irrigated area

4. Decision model

4.1 Farmer Decision: Crop areas

4.2 Reservoir operation decision: Water restrictions

4.3 Crop water demand and benefit

4.4 Model Options

5. Quantifying the effect of additional information

6. Results

6.1 Farmer decisions and curtailments using perfect information

6.2 Value of additional information for the decisions

7. Discussion

7.1. Potential value of additional information

7.2. Effect of the cost of planting on the value of information

7.3. Value of the information for the different types of farmers

List relevant of changes

0. General

The manuscript has been restructured to include a separate section reporting the results of the semi-structured interviews (including both method and outcomes), followed by another section that discusses the model design and options. Previously this content was in the results section. The text has been edited accordingly and the outline suggested in the response to the reviewer has been slightly adjusted in the process [R2 C3].

We have reviewed and edited the manuscript to shorten unnecessarily long sentences and improve the readability [R2 C1].

1. Introduction

An additional paragraph has been added at the end of the introduction to position our research within the context of the field of socio-hydrology [R2 C2].

2. Study area and approach

2.1. The Ebro basin

An additional paragraph has been added to describe how drought has impacted the basin in the past [R1 C1].

2.2. Approach

An explanation of the outline of the article has been added, including the expected results, to facilitate following the paper [R2 C4].

3. Stakeholders consultation

3.1. Method

Additional details on how the interviews were conducted have been added, while the existing text has been shortened to put less emphasis on this part of the study [R1 C2, R2 C5].

Two references about the use of semi-structured interviews have been added [R2 C2]

4. Decision model

4.2. Reservoir operation decision: Water restrictions

Table 1 has been replaced by a figure (Figure 4) and the text has been edited to better describe it [R2 C4, R2 C5].

5. Quantifying the effect of additional information

5.2. Model options

Availability thresholds: The text has been edited to make this section clearer [R1 C3].

Allocation table: The header of table (now table 2) has been updated to provide an indication of the dryness of the years by including the SPI-12 value for the month of September for each of the years [R1 C4].

6. Results

6.1. Selection of optimal thresholds

The text has been rewritten to improve the explanation of the process to select the optimal threshold and the description of the corresponding figure (now Figure 5, Figure 4 in the previous version of the manuscript) [R1 C5: R2 C4].

The missing y-axis label (“reservoir volume”) has been added to Figure 5 [R1 C5].

The caption has been edited to mention that the colours marked in the legend are considered as the “optimal course” and refer to the paths illustrated in Figure 3 [R1 C5].

6.2. Value of additional information for the decisions

The text has been edited to improve the description of the figures [R2 C4].

6.3. Quantifying the effect of additional information

The text has been edited to improve the description of the figure [R2 C4].

7. Discussion

The discussion section has been divided in three subsections to make it clearer [R2 C4].

Do users benefit from additional information in support of operational drought management decisions in the Ebro basin?

C. Linés, A. Iglesias, L. Garrote, V. Sotés, M. Werner

Abstract

We follow a user based approach to examine how information supports operational drought management decisions in the Ebro basin and how ~~the role of~~these can benefit from additional information such as from remote sensing ~~can be assessed~~data. First we consulted decision makers at basin, irrigation district and farmer scale to investigate the drought related decisions they take and the information they use to support their decisions. This allowed us to identify the courses of action available to the farmers and water managers, and to analyse their choices as a function of the information they have available to them. Based on the findings of the consultation, a decision model representing the interrelated decisions of the irrigation association and the farmers was built~~ with ~~. The purpose of the ~~aim~~model is to quantify the effect of additional information on the decisions made. The modelled decisions, which consider the allocation of water, are determined by the expected availability of water during the irrigation season. This is currently informed primarily ~~informed~~ by observed reservoir level data. The decision model was then extended to include additional information on snow cover from remote sensing. The additional information was found to contribute to better decisions in the simulation and ultimately higher benefits for the farmers. However, the ratio between the cost of planting and the market value of the crop proved to be a critical aspect in determining the best course of action to be taken and the value of the (additional) information. Risk averse farmers were found to benefit least from the additional information, while less risk averse farmers ~~can~~stand to benefit most as the additional information helps them take better informed decisions when weighing their options.

1. Introduction

Water managers and farmers regularly take decisions to make the most of the available water resources. Information on the availability and variability of the resource is essential to allow these decision makers to choose among the actions available to them, especially as water becomes scarce, for example during drought events. Improved information on the availability of water can then potentially lead to a more effective management and can therefore contribute to the mitigation of the impacts of drought events.

In situ meteorological and hydrological measurement networks have long served to inform these decisions, often providing accurate water resources observations at high temporal resolution. In addition, the potential of Earth Observation (EO) from satellites to support water management has also been widely recognised (Famiglietti et al. 2015; Fernandez-Prieto et al. 2012). The availability and quality of EO datasets has ~~been~~ continuously ~~improving~~improved during the last decades, providing an increasingly relevant source of globally consistent data that can be used to complement in situ data.

However, the increased quality and availability of information does not necessarily translate directly into benefits due to better decisions. How the information is used and distributed also plays a critical role (Williamson et al. 2002). It is the capacity of the user of information to change the course of action as a result of new information being available to them that largely ~~impacts~~determines the value of that new information (Macauley 2006).

A good understanding of the role that information plays or could play in supporting decisions, as well as the ~~benefits derived from using that information to inform the decision~~resulting benefits, is useful both for the users and the data providers, and helps improve the connection between these two groups. Onoda and Young (2017), ~~in their conclusions established on~~present a series of analyses on the contribution of EO datasets in addressing environmental problems from a policy point of view, ~~recommend~~and conclude recommending more stakeholder oriented studies of the value of these data and the quantification of the benefits of this data through comparisons with current tools. The assessment of the role and impacts of remote sensing products is expected to help in fully achieving the potential of the products, maximising the socioeconomic and environmental benefits and contributing to justify the investment in developing and improving the products.

An example of a stakeholder oriented approach to assess the value of satellite based information in support of water management is presented by Bouma et al. (2009). They develop a framework to measure the benefits of satellite based observations. The framework, which is based on Bayesian decision theory and expert consultation, is applied to water quality management in the North Sea (Bouma et al 2009) and to coral reef protection (Bouma et al 2011).

Macauley (2006) reviews studies on the value of information in Earth science applications, classifying the techniques that are used or that are potentially useful in three groups: studies that measure the value by gains in output or productivity; studies based on hedonic pricing, in which the value is inferred from models based on wages and housing prices; and studies that consider the willingness-to-pay. The main example of the first group of techniques are the studies that relate farm profits and weather information, especially in relation to weather forecasts. Early studies explore simplified cases of decisions such as whether to plant or to leave cultivable land fallow (Brown et al, 1986), or on what crop to plant (Wilks and Murphy, 1986).

From the user's perspectives, the optimal choice for a decision to be made is to take the course of action that results in the highest expected utility, which is defined as the weighted sum of the outcomes of the possible actions and the probability of a given state of nature such as a reduction in the available water resource. Clearly this includes undesirable outcomes, where an action is taken based on an expected state of nature that does not materialise. Additional information is then considered to have value if it can improve the advance knowledge on the probabilities of the different possible states of nature occurring, thus allowing the user to take a better informed decision. A commonly used approach to evaluate the value of advance information, such as information provided through advanced warning, is the cost-loss framework (Zhu et al. 2002; Mylne 2002; Roulin 2006; Verkade and Werner 2011). ~~In~~Often used to evaluate the ~~case~~potential benefit of (flood) warnings~~ for adverse events~~, this is the ratio of the costs of taking protective action to the losses incurred if ~~the~~that action is not taken. This framework has also been extended to water resources management decisions, such as in Quiroga et al. (2011)Quiroga et al. (2011), who analyse the value of climate projections for the water manager decision to applyto decisions on applying measures to reduce the water demand in the Ebro basin. The cost-loss framework does assume a strictly rational behaviour of users in weighing the costs and probability of losses, but has its limitationswhich is a limitation as different users may make different decisions depending on their levels of risk averseness, though this . This can, however, be incorporated through a function of risk aversion (S. Quiroga et al. 2011; Matte et al. 2017)(Matte et al., 2017; Quiroga, et al., 2011).

In this paper we follow a user based approach to examine the operational decisions that stakeholders such as farmers and reservoir operators take within the context of water resources allocation during droughts. The proposed framework first identifies the decisions stakeholders take, and the information they use to inform those decisions, through interviews. A decision model is then established and applied to emulate the decision process using the currently available information, as well as how additional information contributes to improving the decisions made. This study is part of a broader research aimed at assessing the usefulness of global datasets to support decisions at the basin or sub-basin scales.

1. Methods

The aim of our paper is to explore the value of information to drought management decisions through a stakeholder oriented analysis. We examine the operational decisions that stakeholders such as farmers and reservoir operators take within the context of water resources allocation during droughts. The proposed framework first uses interviews to identify the decisions stakeholders take, as well as the information they use to inform those decisions. A decision model is then established and applied to emulate the decision process and how additional information contributes to improving the decisions made. Our work contributes to the developing field of socio-hydrology (Sivapalan et al., 2012) in that it explores the co-evolution of the availability of water and the decisions taken by humans (in this case farmer and irrigation operators). While the emerging field of socio-hydrology is broad (see also the review of the first biennial of the proclaimed IAHS Panta Rhei decade, McMillan et al., 2016), we consider our work to be related most to that of the working group on Drought in the Anthropocene (Van Loon et al., 2016), which explicitly addresses the inefficiency of drought management due to poorly understood feedback between people (and the decisions they make) and drought conditions.

1.2. Study area and approach

2.1. The Ebro basin

We explore the role of information in drought related decisions in the Ebro basin. The Ebro Basin is the largest in Spain (85,600 km^2), and is a highly regulated basin with 125 reservoirs (>1 Mm3) and a total storage capacity of approximately 8,000 Mm^3. These reservoirs are used primarily to supply water to more than 900,000 ha of irrigated agriculture and 360 hydro-electrical plants (CHE, 2015).

The larger irrigation districts are located in the north-east of the basin (Figure 1~~Figure 1~~). We have selected one of these, the irrigation district supplied by the Aragón and Cataluña channel (Canal de Aragón y Cataluña, CAyC) to examine the decisions made at the sub-basin scale.

Over 90% of the water provided by CAyC is used for irrigation. The water it supplies is sourced from three reservoirs (Barasona, San Salvador and Santa Ana), and it is supplied to an irrigated area of around 98,000 ha. Two zones can be distinguished in the irrigated area: an upstream zone that can only be supplied from the Barasona reservoir as well as from the recently inaugurated San Salvador reservoir, and a downstream zone that can be supplied from all three reservoirs. These zones are 54,000 and 44,000 ha in size, respectively. The main crops grown in the area are fruit orchard (apple, pear, peach and nectarine) and extensive herbaceous crops, mainly maize, alfalfa and barley. The area cropped with wine vine surface is increasing, though it is still somewhat localised (CHE, n.d.).

Three drought events that resulted in impacts to agriculture and other sectors have been recorded for the 2000-2014 period: a short drought spell in 2002, a multiyear event that lasted from the winter of 2004-2005 to the spring of 2008, and another during the years 2011 and 2012 (Linés et al, 2017). The impacts of the multiyear drought of 2004-2008 in the Ebro basin have been widely studied. The north-eastern part of the basin was the most impacted (Hernández-Mora et al, 2013) and agriculture was the most affected sector, with 540 million Euros of estimated losses to crop production during the hydrological year 2004-2005 and further losses of 272 million in related industries (Perez y Perez & Barreiro-Hurlé, 2009).

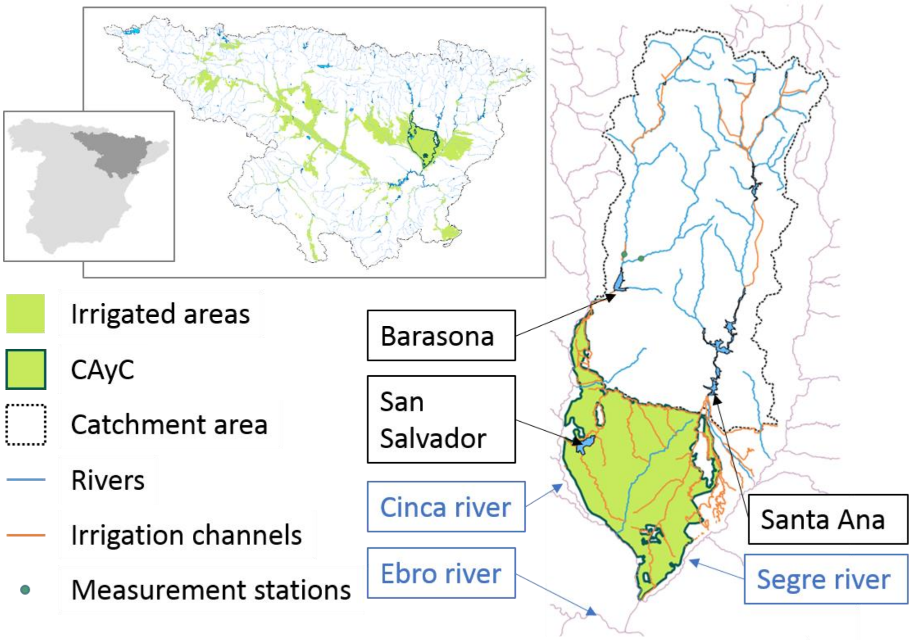

Figure 1. Canal de Aragón y Cataluña: irrigated area and catchment.

~~1.2.~~2.2. Approach

1.2.1. Investigating stakeholders' decisions

As the utility of information strongly depends on the particular details of the decisions and how information is used to support these, we first consulted decision makers at the basin (Confederación Hidrográfica del Ebro, CHE), irrigation district (Comunidad de Regantes del Canal de Aragón y Cataluña), and farmer scale to better understand their decision processes, their information needs, and how they use information to support the decisions they make. For this analysis we focused on decisions regarding the allocation of water resources, in particular during drought, when curtailments may be applied (Figure 2).Figure 2). The methods followed for the consultation and a summary of the outputs of the interviews at each of the locations are provided in section 3.

Several studies have highlighted the significance of taking stakeholders into consideration when implementing a strategy (e.g. Freeman 1984; Eden and Ackermann 1998; Bryson 2004) and this concept has been applied extensively to water resources management (see for example Iglesias & Garrote, 2015). Here we consider as stakeholders the different groups that have the capacity to modify the amount of water to be used for irrigation either by deciding the volume of water to be supplied, or by deciding the area and type of crops planted; thus effectively determining the irrigation demand. Considering this rationale, we included two types of stakeholders: reservoir operators and farmers. We make the assumption that these two groups are uniform within themselves, and that public opinion or interest groups such as environmentalists do not alter the decision. This is clearly a simplification, which could be overcome by carrying a large survey. We consider such a survey as being beyond the scope of this study.

The selection of the participants for the interview is a critical strategic decision (Iglesias et al., 2017). The choice of individuals is guided by the potential unique information that they can provide to the study in relation to water management decisions under drought conditions. The group of farmers has an unequivocal and unanimous interest in avoiding water shortages and ensure irrigation production. All farmers are included in an Irrigation Association that provides them with services of high technical skill and tactical advice on the use of water. The technical advisors at Irrigation Association were selected for an interview as representatives of this position and the collective interests. The basin authority (CHE), responsible for defining measures to be implemented during drought and water shortages, was also interviewed.

Details on water management and possible adjustments of decisions that the stakeholders may take in view of water shortages were collected by means of semi-structured interviews. This is a clear methodological choice to collect additional knowledge not directly articulated in the interview guideline (Harrell and Bradley, 2009). In our case, we wanted to obtain information related to the management choices in drought situations and the barriers and incentives to implement them that are only known in practical terms. The semi-structured interview also gives the possibility to incorporate additional discussion topics, not envisioned by the research team in the guideline.

The findings of the consultation phase were used to build a model of the decisions at irrigation district scale. The design of the model from these findings is described in sections 4.1 (farmer decisions) and 4.2 (reservoir operator decisions). The outputs of these components are the areas of different crops that are planted during the irrigation season and the curtailments applied. The crop yield is then calculated using the area of each crop and observed meteorological data using open source crop models (introduced in section 4.3).

In order to test and quantify the effect that additional information has on the operational drought management decisions analysed, the decision model was run for two scenarios with different input information. The input data and specific parameters used in these two runs are described in section 5.

The expected final results of the analysis are the relative values of information in each of the tested scenarios. We calculate this based on the total net benefit obtained by farmers during the whole period of analysis. This benefit depends on the decisions taken during each season, which in turn depend on the information used to inform them. The results are described in section 6 and followed by discussion and conclusions.

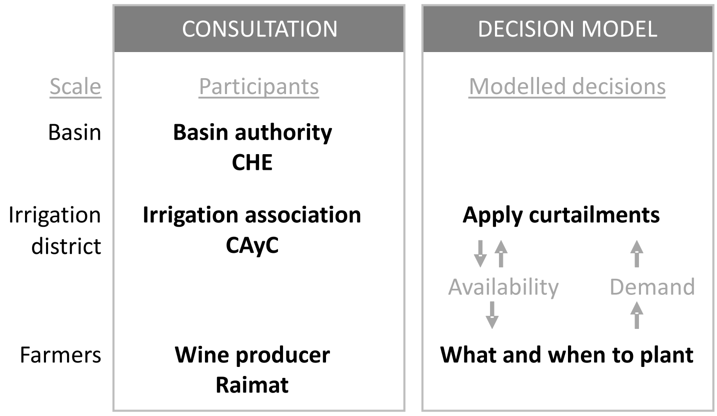

Figure 2. Research phases and spatial scales.

~~1.2.2. Modelling the decision~~

~~The findings of the consultation phase were then used to build a model of the decisions at irrigation district scale, in order to test and quantify the effect that additional information has on the analysed operational drought management decisions. The decision model was built in R (R Core Team, 2016).~~

~~In the year to year planning of water allocation and crops to plant, the basin authority is of lesser relevance in the decision model as they are responsible for the longer term planning through the basin hydrological plan, and for the development of the drought management plan, which though it provides guidelines on measures to be taken during drought, does not go to the detail of the operational decisions to be taken on water allocation. These are taken by the reservoir operators (part of the irrigation association, CAyC), while decisions on what and how much to plant are taken by the farmers. The model represents these two decisions, as well as the interaction between them.~~

~~Expected availability of water during the irrigation season is the main variable used by both the reservoir operators and the farmers to inform their decisions. Information on the availability of water can, however, be obtained from different sources. Currently the main source of information that is used is the volume stored in the reservoirs, obtained through observations of the reservoir levels. Both reservoir operators and farmers indicated that they may also consider the available water resource in the snowpack in the headwaters upstream of the reservoirs, though there are~~

currently no systematic observations of this resource that are formally included in the decision process by either. Satellite images can, however, routinely provide estimates of this resource. Two situations with different input information were therefore simulated: the expected water resource availability as informed by the reservoir levels alone, and the expected availability based on the reservoir levels with the addition of satellite based data on snow cover in the headwaters. In both cases the outputs of the decision model are the areas of different crops that are planted during the irrigation season and the water demand that this cropping schedule results in; the curtailments applied; and the resulting benefit for the farmers in each season. Crop water demand and yield were modelled with AquaCrop-OS (Foster et al. 2017) and CROPWAT 8.0 (2000).

1.4. Quantifying the effect of additional information

Output benefit values using either of the two information scenarios were evaluated against the value (Val) of uninformed decisions and decisions under perfect information following the usual form of skill scores (Stanski, Wilson, and Burrows 1989):

$$RV = \frac{Val_{information} - Val_{uninformed\ decision}}{Val_{perfect\ information} - Val_{uninformed\ decision}}$$

The relative value (RV) is therefore a score between −∞ and 1, with RV=1 meaning that the information is perfect and RV≤0 meaning that the information does not contribute to improving the decisions made.

The value of perfect information was calculated by selecting for each season the best performing course of action given the observed water resource availability, while the value of the uninformed decisions was defined as the result of selecting for all years the course of action that performs best based on the average water resource availability for the whole period.

1.3.5.1. Model input data

Reservoir and meteorological Data

In situ data on reservoir levels was obtained from the automatic measurement stations (SAIH, Automatic Hydrologic Information System). These data are available from http://sig.mapama.es/redes-seguimiento/.

Reservoir volume data for Barasona reservoir and river flow data from the stations at the upstream tributaries (stations located at Graus on the Ésera river, and at Capella on Isábena river, Figure 2) was used to estimate the availability of water during the season. We focus on the Barasona reservoir as it is the levels in this reservoir that triggers the restrictions in the area supplied by CAyC. SAIH provides data for Barasona reservoir from 1931 to September 2014, though there are some data gaps in the first decades. The reservoir was enlarged in 1972 to a capacity of 84.71 hm^3 and we therefore consider only the values after that year.

In addition, daily precipitation and temperature data, and monthly relative humidity data from the meteorological station located just outside the basin at the University of Lleida (station 9771C) was used to provide meteorological inputs to the crop model. Data from this station is available from 1983 through 2014 and can be obtained from https://opendata.aemet.es/centrodedescargas/productosAEMET

Snow Cover Data

MODIS 8-day snow cover 500 m grid data (MOD10A2; Hall, Salomonson, and Riggs 2006) was used to calculate the percentage of snow cover in the headwaters of the reservoirs (Figure 1) as an additional source of water availability information. This dataset covers the period from 26 Feb 2000 to the end of 2016 and was downloaded from the EartH2Observe Water Cycle Integrator (wci.earth2observe.eu).

2. Results

2.1. Investigating stakeholders' decisions

3. Stakeholders consultation

3.1. Method

The stakeholders we consider are the different groups that have the capacity to modify the amount of water to be used for irrigation either by deciding on the volume of water to be supplied, or by deciding on the area and type of crops planted. This decision effectively also determines the irrigation demand. We use semi-structured interviews to develop our understanding of the decisions these stakeholders take in managing water resources and the possible adjustments to those decisions that they may make in view of water shortages. This method gives the possibility to discuss additional topics, not originally envisioned by the research team in the interview guideline (Harrell and Bradley, 2009). O'Keeffe et al. (2016) and Carr et al. (2011) similary apply semi structured interviews to understand water use and management practices. Participants were asked to describe their own practices, as well as the practices of the groups they deal with in relation with drought management. A set of questions had been previously prepared, but was only used to guide the interviews and ensure that topics not mentioned were addressed and that all required details about the decision processes were collected.

One interview session was held at each of the locations (the basin authority, the irrigation association and the farm) with two or three people participating in each. In the interview that was held at the basin authority, the participants included the head of one of the basin's management units and two members of the hydrological planning office, both with expertise in drought management in the basin. In the interview at the Irrigation Association, the participants were the head of the Irrigation Association and the engineer in charge of the information service about current and expected water availability. And in the interview at the farm level, two people participated: the head of viticulture and the engineer responsible for the information service.

The information about the practices and attitudes of farmers in the study area was to a great extent obtained from the interview with the staff at the Irrigation Association who work in close collaboration with all the farmers in the area and therefore have a wider view than individual farmers. We acknowledge that the sample of interviews we held is small. Although important to the assumptions made in the development of the decision model that we constructed, we would readily agree that our representation of the farmer behavior and the diversity of responses across farmers may be over simplified. A larger sample of interviews would reveal more information, but we feel that is outside the scope of this paper.

~~2.1.~~3.2. Confederación ~~hidrográfica~~Hidrográfica del Ebro ~~(CHE)~~

The main operational decisions that the Ebro river basin authority (CHE) takes regarding drought are the declaration of drought conditions and the allocation of water in emergency situations. To guide these decisions, CHE defined a drought management plan in 2007 (CHE, 2007), which was the first of its kind in Europe. It is a very comprehensive plan and links hydro-meteorological indicators to drought severity levels. The decision to declare drought is informed by a set of indicators~~ defined in the plan. These indicators, built~~, derived from measurements from ~~the~~a dense network of in situ automatic stations~~, are used to detect hydrological drought conditions with different levels of severity.~~. The plan establishes the main indicator to be used for each of the areas of the basin. Where ~~possible~~applicable, water stored in the reservoir is used as main indicator, since it is considered the most robust option. Otherwise 3-month ~~water flow~~discharge or groundwater levels are used as indicator.

In their opinion, the declaration of drought is currently well informed and therefore they consider that additional information would be more useful after the declaration, when conditions must be monitored closely and decisions such as selecting the most cost-effective alternative sources of water or how to secure sufficient water to guarantee environmental flows must be taken. For these decisions timing is critical and they point out that information should be available with a maximum delay of one week to be useful for decisions. In addition, they showed particular interest in remote sensing derived snow data to support the quantification of water availability in the basin.

~~2.1.~~3.3. Canal de Aragón y Cataluña (CAyC)

General ~~Irrigator~~Irrigation Associations such as Canal de Aragón y Cataluña (CAyC) are responsible for the distribution of water from the reservoir to the users. In drought situations they can decide to introduce restrictions to irrigation water quotas. The decisions they take on the application of these restrictions are informed by the availability of water in the reservoirs that feed the irrigation canal system.

The main decisions that CAyC take in relation to drought is to apply restrictions (curtailments) to the maximum amount of water that irrigators can request. They take this decision when they consider that the available water resource is insufficient to reach the end of the irrigation season if full irrigation supply to meet demand is maintained. They can also decide to move water among the three reservoirs in the area. When restrictions are necessary, these are applied to all users independently of the reservoirs that they can be supplied from to ensure curtailments are applied equitably across the district. However, when water is scarce, priority is given to ~~the~~perennial crops such as fruit orchards and vines to ensure their survival.

To take their decisions, the reservoir operators need information both on water availability and the expected demand until the end of the season. In the interviews, they indicated that they consider that they are well informed on the availability of water given the levels in the reservoir. However, the information on water demand is limited. The difficulty of knowing the demand is due to the fact that they lack information on what crops farmers are planning on cultivating that year, and especially if the farmers will decide to plant a second crop, thus increasing the demand towards the end of the season. Currently they use historic data to estimate the demand. They are also conducting studies on the feasibility of obtaining this information from remotely sensed NDVI data (described in Casterad Seral 2015; Quintilla~~, Portero, and Casterad~~ et al., 2014), and although this will provide useful information on the current crops, it will not provide information on the future plans of the farmers.

Unlike the managers at the basin scale, CAyC indicated that they consider additional data on the snow cover in the headwaters to be of little use in quantifying the available resource. They argue that they tend to be cautious when accounting for snow in the estimation of total availability, since the reservoir capacity is rather small and therefore the possibility to store snowmelt runoff depends very much on the melt rate.

~~2.1.~~3.4. Farmers in the Canal de Aragón y Cataluña irrigated area

During the consultation, CAyC also provided details on the types of farmers present in their supply area as well as on the decisions these farmers take on what to plant. Typically, the proportion of crops planted is fruit orchards and vines for roughly a third of the area, alfalfa for another third, and ~~variable~~annual crops for the remaining third. These ~~variable~~annual crops are mostly winter cereals and maize. The cropping schedule adopted by farmers is mostly either a single crop of long cycle maize or a winter cereal; or a double crop in which a winter cereal is followed by short cycle maize. The selection of one or the other by the farmers depends on the expected water availability, and is currently mainly informed by the water level in the reservoir. CAyC shares this information with them in the form of biweekly reports. Conversely, the decisions farmers take in terms of what crop to plant, and if they plan to plant a double crop, determines the demand for the season, and will therefore also have an impact on the decision to apply curtailments that are taken by the CAyC.

A prominent farmer in the supply area of CAyC is the Raimat wine producer, who also participated in the consultation process. They provided details of their information use for water resources management. Their parcels extend over 3,200 ha and are highly technified, with extensive use of detailed information. In addition to in-situ measurements and meteorological station data, they use Landsat satellite data and perform flight campaigns to acquire spatial NDVI and thermal data. The thermal data is used to estimate the leaf water potential and, together with temperature data, calculate a crop water stress index. This information on crop condition is used to detect spatial differences in the crops and make the most of the limited water, select the optimal moment for irrigation and prevent plagues; as well as ensuring the production is as uniform and controlled as possible.

The decisions they take are already based on high resolution data, and therefore additional medium resolution global data are not likely to be a valuable contribution to this type of user. However, this extensive use of information is not representative of all the farmers in the basin and other farmers may indeed benefit from additional information.

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2.2. Modelling the decision

4. Decision model

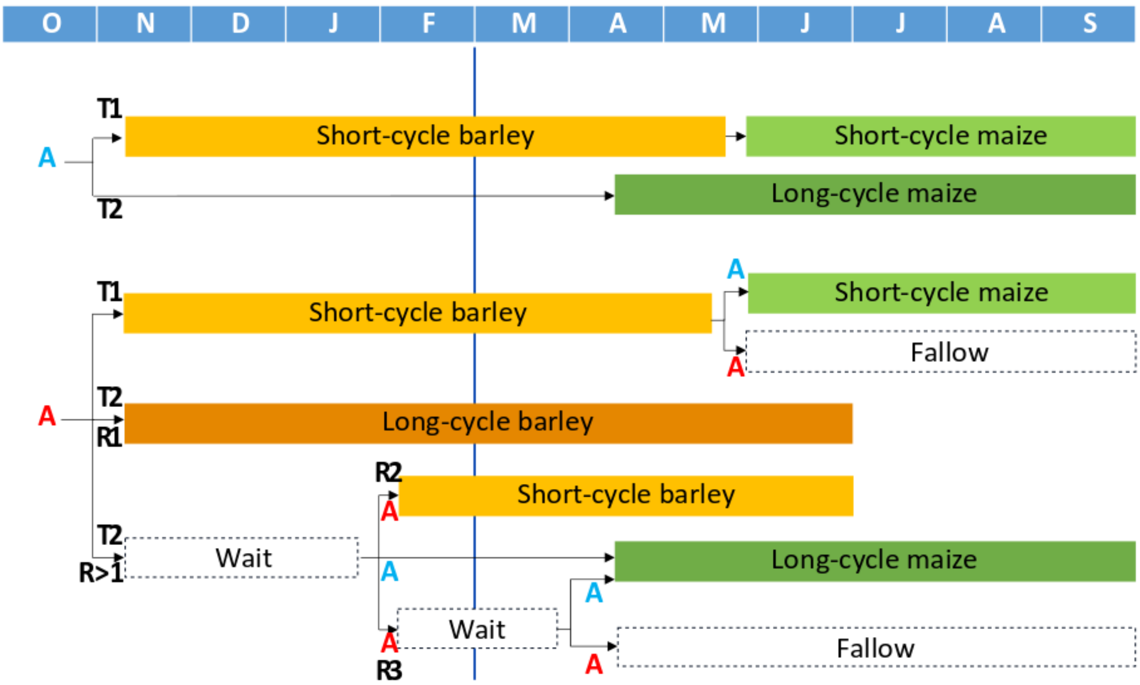
Two of the drought related operational decisions described by the stakeholders were selected to be modelled. These are the decisions of the farmers on what to plant and the decision of the reservoir operators (part of the irrigation association, CAyC) to apply curtailments to the amount of water that farmers can request when this is considered necessary to avoid finishingdepleting the supply before the end of the irrigation season. The model represents both decisions as well as the interaction between the two. In the year to year planning of water allocation and crops to plant, the basin authority is of lesser relevance in the decision model as they are responsible for the longer term planning through the basin hydrological plan. They are also in charge of developing the drought management plan, and although this plan provides guidelines on the measures to be taken during drought, it does not go to the detail of the operational decisions to be taken on water allocation.

The decision model was built in R (R Core Team, 2016).

4.1 Farmer Decision: Crop areas

The farmers have a number of possible crop alternatives for each irrigation season. In this part of the model we simulate the decision of the farmers to follow one of the possible courses of action available to them. The result of the decision is the planted area of the selected crops. Since fruit orchards, vines and alfalfa crops lastare perennial crops and typically are planted for several years, their approximate areal extent is known and is considered as constant in the model. The farmer decision model therefore focuses on determining the variable areal extent of maize and winter cereal, as well as the decision whether to plant a single crop or also a second crop. In the model, barley is selected to represent the winter cereal crop since it is the most common winter cereal crop in the area.

The courses of action represented in the model consist of a series of decisions made during the irrigation season. The possible actions are depicted in Figure 3Figure 3, which shows the choices that can be made at each decision stage in the calendar. At each of these decision pointpoints, the option that farmers would prefer to take if they perceive there are sufficient water resources available is indicated by a blue letter, while the non-A. The preferred decision(s) if there are insufficient resources is marked with a red letterA. The choices and the calendar are based on the information provided by the stakeholders we interviewed, supported by literature sources (Espluga Trenc, 2016; Gil Martínez, 2013; Lloveras, Martínez, & Santiveri, et al., 2014). The model considersWe consider two types of farmers in the model, with different options available to them: ~~technified~~Technified farmers managing large plots and smaller scale farmers. In the model, technified farmers (marked with T1 in Figure 3~~Figure 3~~) can support a double crop, and this is always their preferred option because of its higher productivity. However, in years of low water availability (red A in the figure) they may decide to leave the land fallow instead of planting a second crop. Smaller scale farmers (T2) can only manage a single crop and in this case long cycle maize is the most productive option. In years of low water availability, their decision will depend on the level of risk they are willing to take. We consider three levels of risk aversion (R1, R2 and R3 in the figure). The safest option to secure a crop is to plant long cycle barley at the beginning of the season~~,~~ (R1), but they can also decide to wait for conditions to improve; taking the risk of having to leave the land fallow if there is no improvement~~.~~ (R>1). If, however, water availability increases by February, they can decide to plant long cycle maize. If availability is still low, they can secure a crop by planting a short cycle barley (a less productive option than the long-cycle version) (R2), or they can decide to wait longer~~.~~ (R3). In April, they can still plant a long-cycle maize crop if availability has improved, but, if it has not, then it is too late to plant barley and they have no other option than to leave the land fallow.



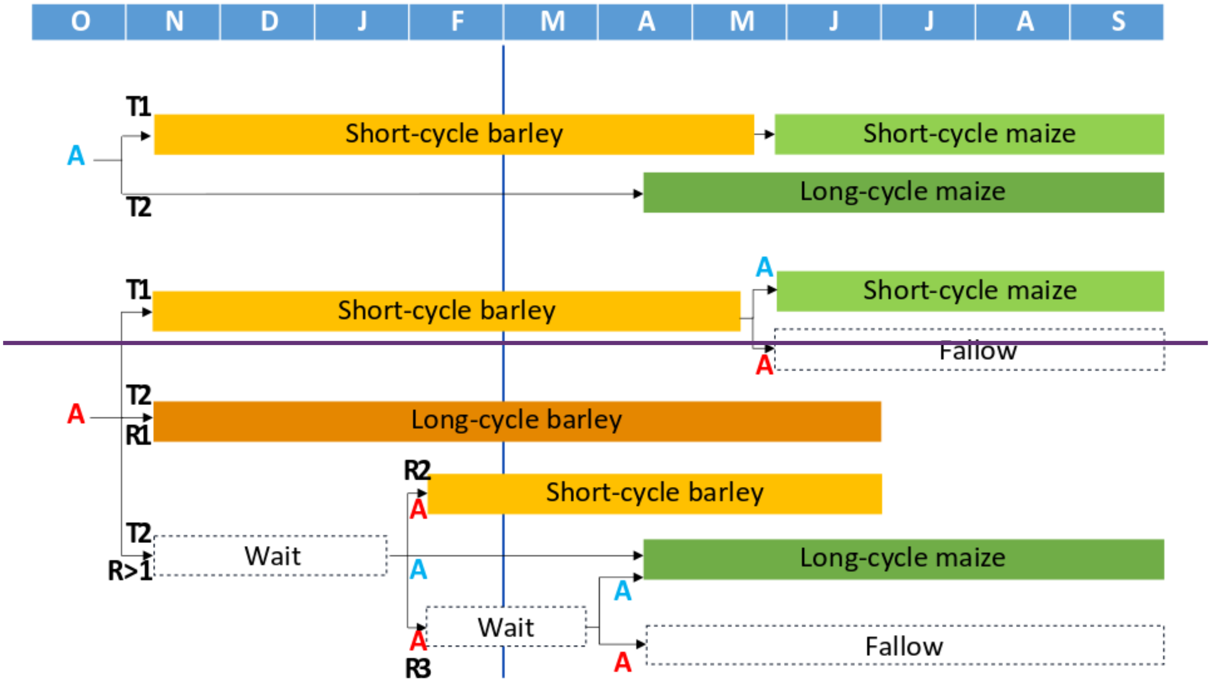


Figure 3. Crop options considered in the model for farmers. Blue and red As represent respectively good and poor water availability at the moment of the decision. R1, R2 and R3 mark the different paths that can be followed depending on the risk the farmers are willing to take, with R1 being the most risk averse and R3 the least risk averse. The blue vertical line marks the start of the irrigation season.

The choice of a particular course of action in the model is based on the water availability at the moment of the decision, and is used as an indicator of the expected availability of water during the remaining season. For the decisions taken before the start of the irrigation season (November and February), the availability is based on the observed volume in the reservoir since these decisions have no influence on the level of the reservoir until the actual start of the irrigation season. For the decisions after the start of the irrigation season (decision points in April and May) a simulated volume is used~~.~~ (Figure 4). The simulated volume is based on the observed volume at the beginning of the irrigation season and the accumulated inflow from the beginning of the irrigation season until the decision date~~ (Table 1).~~. From the start of the irrigation season the decisions taken will have an influence on the level of the reservoir and therefore observed levels are not representative as an input for further decisions. Note that the barley crop is not irrigated, and therefore does not pose a demand on the available water resource. However, as can be seen in Figure 3~~Figure 3~~ the choice for planting a barley crop will have implications for the available options ~~to be made~~ later in the season, and therefore indirectly influences the irrigation demand.

4.2. Reservoir operation decision: ~~water~~Water restrictions

Every two weeks during the irrigation season (March-October), the decision on whether to apply curtailments to the maximum amount of water that irrigators can ~~apply for~~request is re-examined. This decision requires an estimate of the total amount of available water during the season and the total water demand. To estimate the total amount of water that will be available during the season, the inflow into the reservoir from the beginning of the hydrological year in October up to the week of the decision (represented as $F_{[h:i]}$ in Figure 4) is compared with the percentiles of historic data

~~(Table 1).~~. Data of accumulated inflow in the reservoir is preferred to reservoir levels as input information for the reservoir operator decision model to avoid the influence of the actual decisions of the managers and simulate them independently. The percentile curve in which the value of the current year is positioned is then used to sample from the climatological record ~~the~~a projection of the inflow series into the reservoir until the end of the season.

The total water demand for irrigation until the end of the season ($D_{[s:n]}$) is calculated as the sum of the demand until the decision day ($D_{[s:i]}$) and the expected demand from the decision day until the end of the season ~~(Table 1).~~($D_{[i:n]}$). The first is the product of the crop surfaces already planted~~,~~, ($CS_{[i-1]}$), which is the output of the farmer decision model, and the resulting crop demand ($CD_{[s:i]}$) obtained from the crop models using observed meteorological data. The latter ($D_{[i:n]}$) is unknown to the managers. In the model, an average demand per unit area of crop calculated with the crop model data for the period 2000-2014 is used as an estimate to inform their decision. This is a simplification, as the demand to the end of season will depend on the expected climatological conditions and the crop surfaces planted. The actual demand up to the decision day could be used ~~to provide~~as an ~~indication~~estimate of the expected demand until the end of the season. However, while that could provide an indication of the climatological conditions, the decisions taken by farmers on crops to plant at future decision moments are unknown.

When the estimated total amount of available water during the season is insufficient to fulfil the total demand, curtailments are applied. Conversely, if in a later week the expected total available water is found to be enough to fulfil the total demand, restrictions are lifted.

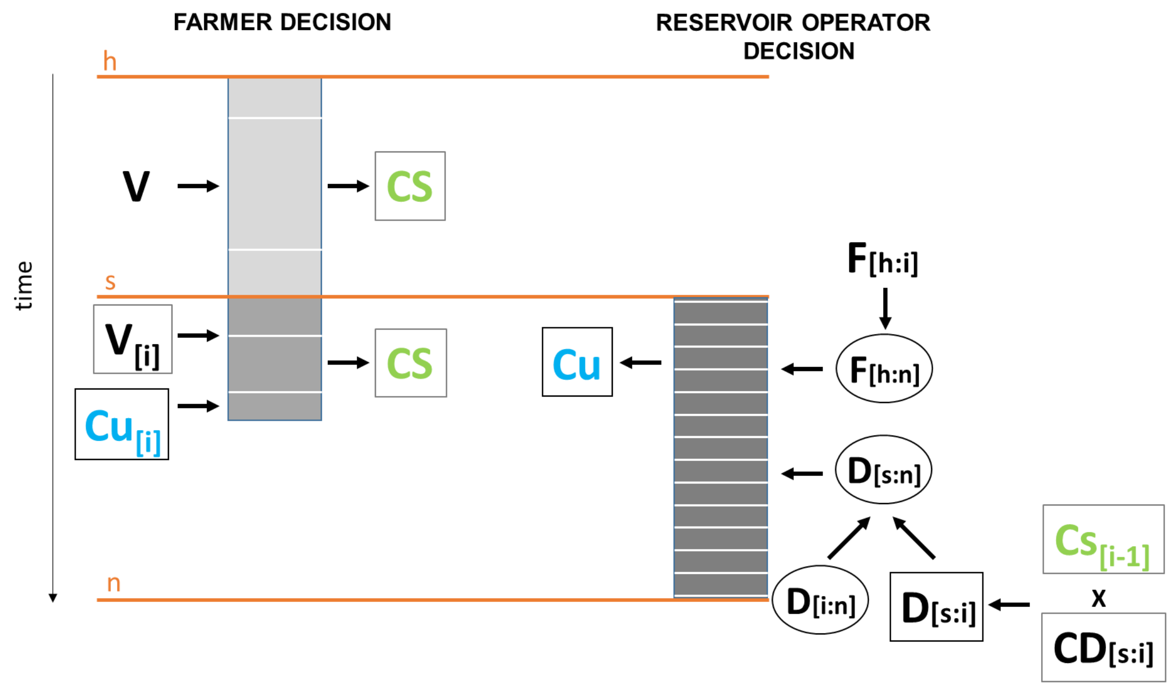
~~*Table 1. Model decisions and parameters that inform them. A description of the abbreviations is included below. The period considered for each parameter is given in between square brackets. The colour indicates the availability and source of the information.*~~

~~**Decision**~~	~~**Informed by**~~	~~**Requires**~~	~~**Output**~~
~~**Farmer decision (FD) [before s]**~~	~~V~~	~~Reservoir level data~~	~~Crops planted [before s]~~
~~**Farmer decision (FD) – [after s]**~~	~~V [i]~~	~~F [h:i], D [s:i]~~ ~~D [s:i] = CS x CD~~ ~~CS ← previous **FDs**~~	~~Crops planted [after s]~~
	~~OD [s:i] (curtailments)~~	~~See **OD** below~~	
~~**Reservoir operator decision (OD) [s:n]**~~	~~F [h:n]~~	~~F [h:i], P_F [i]~~	~~Curtailments~~
	~~D [s:n]~~	~~D [s:i]~~ ~~D [s:i] = CS x CD~~ ~~CS ← **FD**~~ ~~D [i:n] ← average model data (2000-2014)~~	

~~**Abbreviations**~~		
~~**Parameters**~~	~~**Period [ ]**~~	~~**Availability of the information**~~
~~F – Inflow~~ ~~D - Demand~~	~~s - start of irrigation season~~ ~~i – current decision date~~	~~known to the decision maker~~ ~~(from model)~~

~~V - Volume~~ ~~CS - crop surfaces~~ ~~CD - crop demand~~ ~~P – percentile~~	~~n - end of season~~ ~~h – start of hydrological year~~ ~~s:i – from s to i~~	~~known to the decision maker (from data)~~ ~~unknown to the decision maker (estimated)~~

The output of the farmer model ~~is~~are the areas of each of the crops planted each year by the farmers. These crop areas determine the demand in the reservoir operator decision model. The output of the operator decision model on the other hand ~~is~~are the curtailments posed on the water supplied to the farmers to the end of the season, which is determined every two weeks. These curtailments may reduce the yield of the crops if these are already planted and the demand cannot be satisfied, but will also influence the farmer decisions within the irrigation season. If curtailments are in force when the farmers are deciding what to plant (April and May), then the model assumes that the farmers consider water availability as not being good, leading to decisions commensurate with low water availability being taken. These decisions will consequently influence the demand.



Parameters	Period [ ]	Availability and sources
F – Inflow	s – start of irrigation season	V known to decision maker (from data)
D – Demand	i – current decision date	(box) known to decision maker (from model)
V – Volume	n – end of season	(ellipse) unknown to decision maker (estimated)
CS – Crop surface	h – start of hydrological season	
CD – Crop demand		
Cu - Curtailments	[s:i] from s to I	

Figure 4. Model decisions, parameters that inform them and decision outputs. A description of the abbreviations is included below. The period considered for each parameter is given in between square brackets. The shapes indicate the availability and source of the information.

4.3. Crop water demand and benefit

~~AquaCrop-OS~~AquaCrop-OS (Foster et al. 2017) was used to simulate barley and maize yields. These crops are the main focus of the analysis and they require a more detailed and flexible simulation to differentiate the different growing cycles and planting dates. Default parameters for maize and barley were adapted for the diverse cycles using data from Lloveras et al. (2014), Gil-Martínez (2013) and Gutiérrez López (2011).

CropWat 8.0 (FAO, 2000) was used for alfalfa and fruit orchards, the crops that are considered to have a constant crop surface in the analysis. Default parameters were used but were adapted to the cropping calendar in the Ebro basin. Peach tree was selected as the representative fruit orchard crop. An irrigation calendar of 14 days was selected to match the reservoir operators' decision.

The percentage of reduction of crop yield was calculated as the maximum percentage of unsatisfied demand during the season. ~~CropWat was used for alfalfa and fruit orchards, the crops that are considered to have a constant crop surface in the analysis. Default parameters were used but were adapted to the cropping calendar in the Ebro basin. Peach tree was selected as the representative fruit orchard crop. An irrigation calendar of 14 days was selected to match the reservoir operators' decision.~~

~~The percentage of reduction of crop yield was calculated as the maximum percentage of unsatisfied demand during the season.~~ The reason for this is that, when there is insufficient water, farmers prefer to stop watering a part of the area, rather than applying insufficient water to the whole area. These percentages were calculated using the same biweekly time step of the operator decision. The areas in which irrigation was stopped were considered to have no yield and their contribution was subtracted from the full supply yield values derived from the crop models to obtain the final yield for each crop and year. ~~farmers prefer to stop watering a part of the area, rather than applying insufficient water to the whole area. These percentages were calculated using the same biweekly time step of the operator decision. The areas in which irrigation was stopped were considered to have no yield and their contribution was subtracted from the full supply yield values derived from the crop models to obtain the final yield for each crop and year.~~ Priority is given to the ~~multi-annual~~perennial crops, with the curtailments then being applied to the maize crops.

5. Quantifying the effect of additional information

Expected availability of water during the irrigation season is the main variable used by both the reservoir operators and the farmers to inform their decisions. Information on that availability can, however, be obtained from different sources. Currently the main source of information that is used is the volume stored in the reservoirs, obtained through observations of the reservoir levels. Stakeholders indicated that they may also consider the available water resource in the snowpack in the headwaters upstream of the reservoirs, though there are currently no systematic observations of this resource that are formally included in their decision processes. Satellite images can, however, routinely provide estimates of this resource. Two information scenarios were therefore simulated: the expected water resource availability as informed by the reservoir levels alone, and the expected availability based on the reservoir levels with the addition of satellite based data on snow cover in the headwaters.

Output benefit values using either of the two information scenarios were evaluated against the value (Val) of uninformed decisions and decisions under perfect information following the usual form of skill scores (Stanski et al., 1989):

$$\mathrm{RV} = \frac{\mathrm{Val}_{\text{information}} - \mathrm{Val}_{\text{uninformed decision}}}{\mathrm{Val}_{\text{perfect information}} - \mathrm{Val}_{\text{uninformed decision}}}$$

The relative value (RV) is therefore a score between $-\infty$ and 1, with RV=1 meaning that the information is perfect and RV≤0 meaning that the information does not contribute to improving the decisions made.

The value of perfect information and uninformed decisions was calculated by running the model for all possible courses of action represented in Figure 3~~Figure 3~~. The value of perfect information was then obtained by selecting for each season the best performing course of action, while the value of the uninformed decisions was defined as the result of selecting the course of action that performs best on average for all years.

Analysing the pathways in Figure 3 results in seven possible courses of action. These are summarised in Table 1, where the columns represent the four decision points and the colours the course that is followed. Blue and red indicate the good or the poor water availability option is followed, respectively. The points at which no decision is required are marked in yellow. This happens when previous decisions already determine the course of action for later months. Option 7 corresponds to the situation in which the availability of water is good at the beginning of the hydrological year so farmers already select to plant the most productive crops in November and no further decisions are required in the following months. The other six options correspond to situation in which the availability of water is not considered to be good at the beginning of the hydrological year. In options 3 and 6, the situation improves by February, so small scale farmers decide to plant the preferred option (long cycle maize) at this point and do not require further decisions. The difference between these two options results from the decision taken by technified farmers on whether or not to plant a second crop in May. They will do this if they consider the availability of water to be good (option 6), otherwise they will leave the land fallow (option 3).

Table 1. Possible courses of action for farmers. The colours indicate the course that is followed: red – poor availability, blue – good availability, yellow – indifferent.

Path	Nov	Feb	Apr	May
1	red	red	red	red
2	red	red	blue	red
3	red	blue	yellow	red
4	red	red	red	blue
5	red	red	blue	blue
6	red	blue	yellow	blue
7	blue	yellow	yellow	yellow

5.1. Input data

Reservoir and meteorological Data

In situ data on reservoir levels was obtained from the automatic measurement stations (SAIH, Automatic Hydrologic Information System). These data are available from http://sig.mapama.es/redes-seguimiento/.

Reservoir volume data for Barasona reservoir and river flow data from the stations at the upstream tributaries (stations located at Graus on the Ésera river and at Capella on Isábena river, Figure 1) was used to estimate the availability of water during the season. We focus on the Barasona reservoir as it is the levels in this reservoir that triggers the restrictions in the area supplied by CAyC. SAIH provides data for the Barasona reservoir from 1931 to September 2014, though there are some data gaps in the first decades. The reservoir was enlarged in 1972 to a capacity of 84.71 hm^3 and we therefore consider only the values after that year.

In addition, daily precipitation and temperature data, and monthly relative humidity data from the meteorological station located just outside the basin at the University of Lleida (station 9771C) was used to provide meteorological inputs to the crop model. Data from this station is available from 1983 through 2014 and can be obtained from https://opendata.aemet.es/centrodedescargas/productosAEMET

Snow Cover Data

MODIS 8-day snow cover 500 m grid data (MOD10A2; Hall, Salomonson, and Riggs 2006) was used to calculate the percentage of snow cover in the headwaters of the reservoirs (Figure 1~~Figure 1~~) as an additional source of water availability information. This dataset covers the period from 26 Feb 2000 to the end of 2016 and was downloaded from the EartH2Observe Water Cycle Integrator (wci.earth2observe.eu).

~~2.2.~~5.2. Model ~~Options~~options

Availability Thresholds

Thresholds are needed to define at what reservoir level, or at what combination of reservoir level and snow cover, the water availability is regarded by the farmers as good. This judgement is made at each of the decision points. If the availability is above the threshold, then the farmer would follow the decision path associated to good expected availability of water (~~Blue letters~~this corresponds to following the paths marked with a blue A in Figure 3~~Figure 3~~), while if it is below the threshold then the alternative, poor expected availability path will be followed. These thresholds are currently not formally defined, and may also differ between farmers as individual farmers will assess water availability differently, depending on how risk averse they are.

~~Here we~~In a first test we identified the ~~model with a set of~~ thresholds ~~optimised to~~that maximise the sensitivity (rate of true positives) ~~and specificity (rate of true negatives~~for all years analysed and for each of the farmers decisions moments (Nov, Feb, Apr, May). These are measures of the goodness of a binary classification that in this case refers respectively to the points correctly classified either as good or as poor availability of water. To assess the performance of the classification the decisions taken with perfect information are used as a reference. This results in a set of four optimised thresholds, which may be different for each of the decision points. The optimised threshold values at each decision point are kept the same for all years analysed.

~~We explore~~In addition to the ~~effect~~optimised set of ~~different~~ thresholds ~~by testing~~, the model is run with 10 ~~additional~~extra sets of thresholds~~, ranging~~ to explore the sensitivity to these thresholds. In this case, the thresholds are kept the same at each decision point, and the values range from low ~~availability~~(35 hm^3) to almost full capacity (~~35 to~~ 80 hm^3~~), keeping the same thresholds at each of the four points where the farmers make decisions during the season.~~).

The effect of the additional snow cover information on the expected available water resource ~~that is provided by the data on the snow cover~~ is incorporated in the decision model by considering the expected contribution of snowmelt to the available water resource. When the snow cover is below a certain threshold, indicating lower than normal expected runoff from snowmelt, the farmers would require the reservoir level threshold to be higher to regard water availability as being good and thus follow the higher water demanding path. The snow cover thresholds used for this test are ~~determined in an optimisation step, where the reservoir level threshold is maintained at a high level, and the snow cover threshold is~~ again determined using a goodness of fit measure of the binary classification of the decision points correctly identified as having good or poor availability. For the decisions taken in May the snow information was not considered since snow cover is already very limited in that period.

Allocation Factor

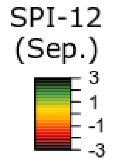
An allocation factor is applied to the accumulated inflow in the reservoir to obtain the proportion of the ~~accumulated water~~available resources that effectively reaches the crops. This factor accounts for water supplied to other uses, water losses due to evaporation, efficiency of the distribution network, and releases from the reservoir to the downstream river. The allocation factor determines the amount of water that is available for irrigation and therefore has significant influence on the decisions taken by the farmers and operators. As the true allocation factor is not known for the area, the sensitivity to this factor is tested by running the model with different allocation factors, considering perfect knowledge on the expected availability of water.

The most profitable choices for farmers were identified for different allocation factors under perfect information, and are shown in Table 2. The first row (AF=1) represents the hypothetical situation in which all the water that enters the reservoir is available to the farmers to irrigate the crops. The following rows represent different levels of allocation of water for irrigation. The results show that when more water is available, farmers already choose to plant the most productive option in November or February (options 7 and 6 respectively). When there is less water they select to plant less maize or nothing at all (option 1). In years of water scarcity, such as 2005, we can see in the table that this is the case even if 80% of the total water is used for irrigation.

Table 2. Most profitable choice for the farmers for each of the years of the period 2001-2014 (represented in the columns) in function of the available water determined by the allocation factor (AF). The numbers of the options refer to the alternatives included in Table 1. The colours for the years represent the SPI-12 for the month of September for the

catchment area of Barasona and Santa Ana reservoirs, calculated with CHIRPS precipitation data for the period 1981-2015.

	Years													
AF	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**
1	7	7	6	6	7	6	7	7	6	7	6	6	7	6
0.8	7	7	6	6	3	6	7	7	6	7	6	6	7	6
0.6	7	6	6	6	1	4	7	7	6	7	6	6	7	6
0.55	7	4	6	6	1	1	7	7	6	7	6	5	7	6
0.5	7	3	6	6	1	1	7	5	6	6	6	3	7	6
0.475	7	2	6	6	1	1	6	4	6	6	4	2	7	6
0.45	7	1	6	6	1	1	4	4	6	4	1	1	7	4
0.425	7	1	6	6	1	1	3	4	6	4	1	1	7	4
0.4	7	1	6	6	1	1	2	4	1	4	1	1	7	4
0.2	4	1	1	1	1	1	1	1	1	1	1	1	1	4



An allocation factor of 0.55 was selected for the following tests, since it is found to be a tipping point between good and poor availability for many of the years in the tested period and therefore allows for a higher range of represented situations. With this level of allocation, the area receives an amount of water that would be able to satisfy the full demand of the most productive alternative of crops in 10 out of the 14 years, with 4 years experiencing water shortages, which reflects the number of drought events in the 2000-2014 period.

To calculate the crop demand an irrigation efficiency of 80% is considered.

Farmer Types

The distribution of the types of farmer was kept constant for all the years and runs. The proportions of technified and smaller scale farmers was established as the mid-range of the yearly ratio between farmers sowing transgenic maize (considered as technified) and farmers sowing conventional maize (considered as small scale farmers) observed in the area for the period 2010-2015 (Espluga Trenc, 2016; Gutiérrez López, 2016). This resulted in 65% of the area being exploited by farmers considered as technified, and 35% by small scale farmers. The proportion of risk aversion used in the model is R1=0.4, R2=0.3, R3=0.3, with R1 being the most risk averse and R3 the most risk acceptant.

Different distributions of farmer types would result in different levels of demand and therefore different optimal paths. The proportion between technified farmers and smaller scale farmers also gives more weight to different decision moments. For example, the decision in May on whether to plant a second crop is only relevant ~~for~~to the technified farmers.

~~-~~**Costs and benefits**

Planting costs and selling prices were used to calculate the value of the yield for the variable crops. The planting costs considered are 496 euro/ha for barley and 1807 euro/ha for maize (MAGRAMA, 2015) and the selling prices are 159 euro/1000 kg for barley and 171.3 euro/1000 kg for maize ~~(n.d.).~~(Aragon Statistics Institute, n.d.). Average yields are 2.349,75 kg/h for rainfed barley and

12.179,34 kg/ha for irrigated maize (MAGRAMA, 2015). No differences in price or cost between the varieties of a same crop type were considered, although the higher productivity of long cycle varieties results in these varieties being more profitable in the model.

2.3.5.1. Quantifying the effect of additional information

To quantify the effect of the additional information, the model was run for the two scenarios with different input information and for two reference scenarios: perfect information and uninformed decisions.

The value of perfect information and uninformed decisions was calculated by running the model for all possible courses of action represented in Figure 3. The seven possible options are summarised in Table 2, where the columns represent the four decision points and the colours the course that is followed. Blue and red indicate, respectively, that the good or poor water availability option is followed. The points at which no decision is required are marked in yellow. This happens when previous decisions already determine the course of action for later months. Option 7 corresponds to the situation in which the availability of water is good at the beginning of the hydrological year so farmers select to plant the most productive crops already in November and no further decisions are required in the following months. The other six options correspond to situations in which the availability of water is not considered to be good at the beginning of the hydrological year. In options 3 and 6, the situation improves by February, so small scale farmers decide to plant the preferred option (long cycle maize) at this point and do not require further decisions. The difference between these two options results from the decision of technified farmers whether or not to plant a second crop in May. They will do this if they consider the availability of water to be good (option 6), otherwise they will leave the land fallow (option 3).

Table 2. Possible courses of action for farmers. The colours indicate the course that is followed: red – poor availability, blue – good availability, yellow – indifferent.

path	Nov	Feb	Apr	May
1	red	red	red	red
2	red	red	blue	red
3	red	blue	yellow	red
4	red	red	red	blue
5	red	red	blue	blue
6	red	blue	yellow	blue
7	blue	yellow	yellow	yellow

Farmer decisions

6. Results

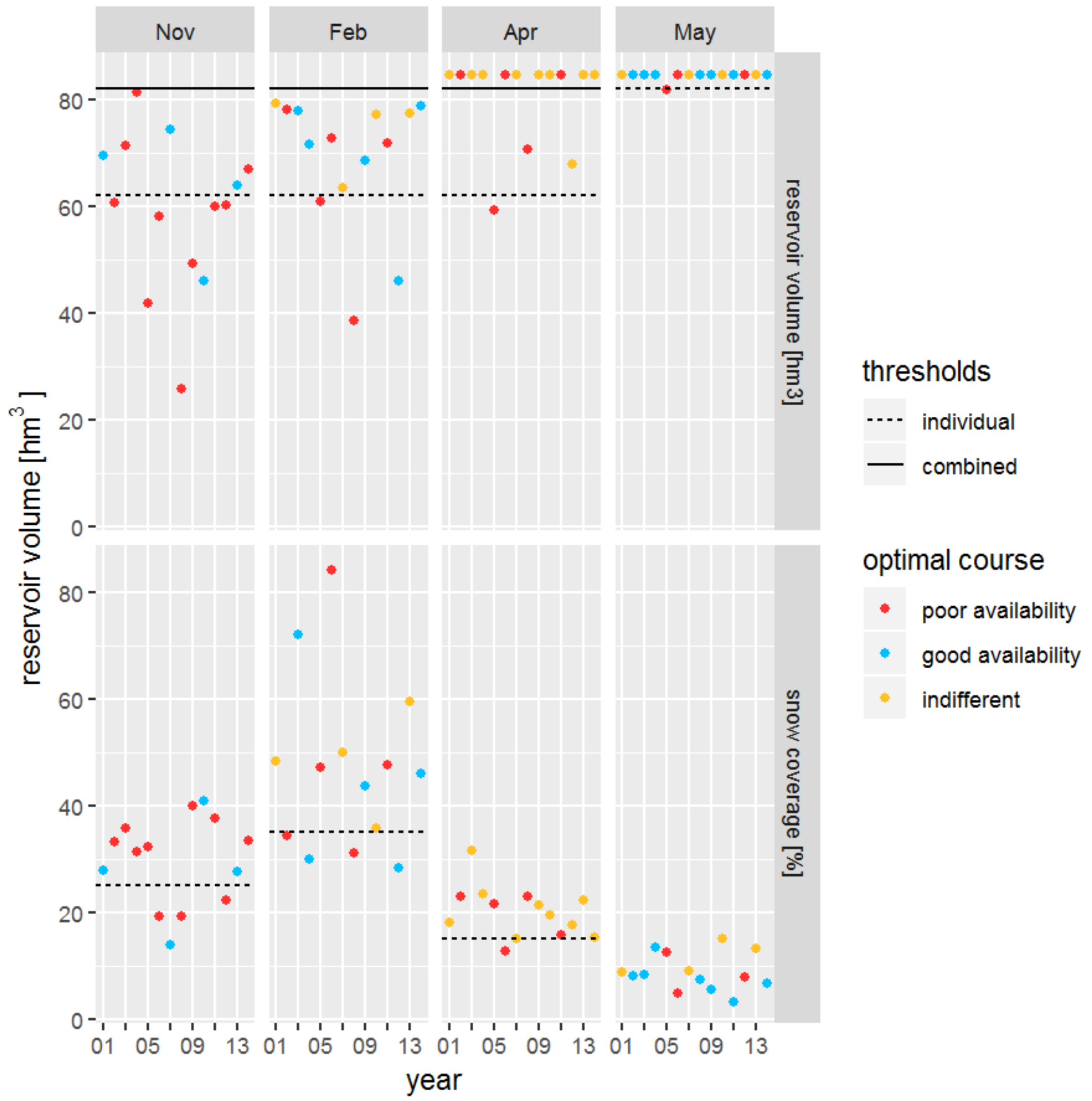
6.1. Selection of optimal thresholds

We first ran all possible decisions paths and identified the decisions that result in the highest benefits to the farmers for each season. These decisions are represented in Figure 5 by the coloured points, with the volume of the reservoir on the y-axis. If the point is red, then the best decision is for the farmer to follow the path marked with a red A in Figure 3. If it is blue, then it is best to follow the blue A path. If the point is yellow, then it does not matter which of the paths is followed.

We use the optimal decisions based on perfect information to establish a threshold for the reservoir level to divide between good and poor water availability. A perfect threshold would be selected such that all the red points are below and all the blue points are above the threshold. This perfect threshold would always allow the farmer to take the decision that results in a higher benefit at the end of the season.

However, as can be seen in Figure 5, it is not possible to obtain a perfect classification of the reservoir levels with a single threshold. The dashed lines mark the thresholds that maximises the points correctly classified. The fact that the classification cannot be perfect means that the reservoir level alone does not provide enough information on what is the best decision to take. Additional information would be valuable if it contributes to improving the classification and, therefore, results in the decision that maximises the benefits being taken more often. In this case the additional information we consider is the snow cover data. This is shown in the lower part of the figure. The coloured points again indicate the decision path that would be taken based on perfect information. Again the figure shows that it is not possible to select a threshold value (dashed lines) where all the red points are below the threshold, and all blue points are above the threshold. This again indicates that this information alone does not lead to a perfect classification either.

This is different when the combined information of reservoir level and snow cover extent is used to inform the expectation of water availability. We incorporate this additional information by amending the threshold of the reservoir level. This is the solid line in the figure for the months November, February and April. Snow cover is not considered in May as that is too late in the season for snow to be of significance. When snow covers an area larger than the threshold coverage (dashed line in the lower plot), then the original threshold for the reservoir level is used. However, when the snow cover is smaller than the identified threshold, and therefore the future contribution to the reservoir volume from snowmelt is expected to be low, a second, more conservative threshold for the reservoir level is used (solid line). With the second threshold some of the red points incorrectly classified above the original threshold are now classified below the threshold.



~~2.3.1.~~ Figure 5. The position of the points represents reservoir levels (upper plot) and ~~curtailments using perfect information~~

~~The selection of choices that can be made by a farmer that result in the highest benefits given perfect knowledge on the expected availability of water were identified for different water availability scenarios as a function of the proportion of the allocation factor. This factor determines the fraction of the total available water that reaches the irrigation area. The results are included in Table 3. The first row (AF=1) represents the hypothetical situation in which all the water that enters the reservoir is available to the farmers to irrigate the crops. The following rows represent different levels of allocation of water for irrigation. The results show that when more water is available, farmers choose to plant the most productive option already in November or February (options 7 and 6 respectively). When there is less water they select to plant less maize or nothing at all (option 1). In years of water scarcity, such as 2005, we can see in the table that this is the case even if 80% of the total water is used for irrigation.~~

~~Table 3. Option selected by the farmers for each of the years of~~snow cover (lower plot) for the period 2001-2014 ~~(represented in the columns) in function of the available water determined by the allocation factor (AF). The numbers of the options refer to the alternatives included in Table 2.~~

~~AF~~	~~2001~~	~~02~~	~~03~~	~~04~~	~~05~~	~~06~~	~~07~~	~~08~~	~~09~~	~~10~~	~~11~~	~~12~~	~~13~~	~~14~~
~~1~~	~~7~~	~~7~~	~~6~~	~~6~~	~~7~~	~~6~~	~~7~~	~~7~~	~~6~~	~~7~~	~~6~~	~~6~~	~~7~~	~~6~~
~~0.8~~	~~7~~	~~7~~	~~6~~	~~6~~	~~3~~	~~6~~	~~7~~	~~7~~	~~6~~	~~7~~	~~6~~	~~6~~	~~7~~	~~6~~
~~0.6~~	~~7~~	~~6~~	~~6~~	~~6~~	~~1~~	~~4~~	~~7~~	~~7~~	~~6~~	~~7~~	~~6~~	~~6~~	~~7~~	~~6~~
~~0.55~~	~~7~~	~~4~~	~~6~~	~~6~~	~~1~~	~~1~~	~~7~~	~~7~~	~~6~~	~~7~~	~~6~~	~~5~~	~~7~~	~~6~~
~~0.5~~	~~7~~	~~3~~	~~6~~	~~6~~	~~1~~	~~1~~	~~7~~	~~5~~	~~6~~	~~6~~	~~6~~	~~3~~	~~7~~	~~6~~
~~0.475~~	~~7~~	~~2~~	~~6~~	~~6~~	~~1~~	~~1~~	~~6~~	~~4~~	~~6~~	~~6~~	~~4~~	~~2~~	~~7~~	~~6~~
~~0.45~~	~~7~~	~~1~~	~~6~~	~~6~~	~~1~~	~~1~~	~~4~~	~~4~~	~~6~~	~~4~~	~~1~~	~~1~~	~~7~~	~~4~~
~~0.425~~	~~7~~	~~1~~	~~6~~	~~6~~	~~1~~	~~1~~	~~3~~	~~4~~	~~6~~	~~4~~	~~1~~	~~1~~	~~7~~	~~4~~
~~0.40~~	~~7~~	~~1~~	~~6~~	~~6~~	~~1~~	~~1~~	~~2~~	~~4~~	~~1~~	~~4~~	~~1~~	~~1~~	~~7~~	~~4~~
~~0.20~~	~~4~~	~~1~~	~~1~~	~~1~~	~~1~~	~~1~~	~~1~~	~~1~~	~~1~~	~~1~~	~~1~~	~~1~~	~~1~~	~~4~~

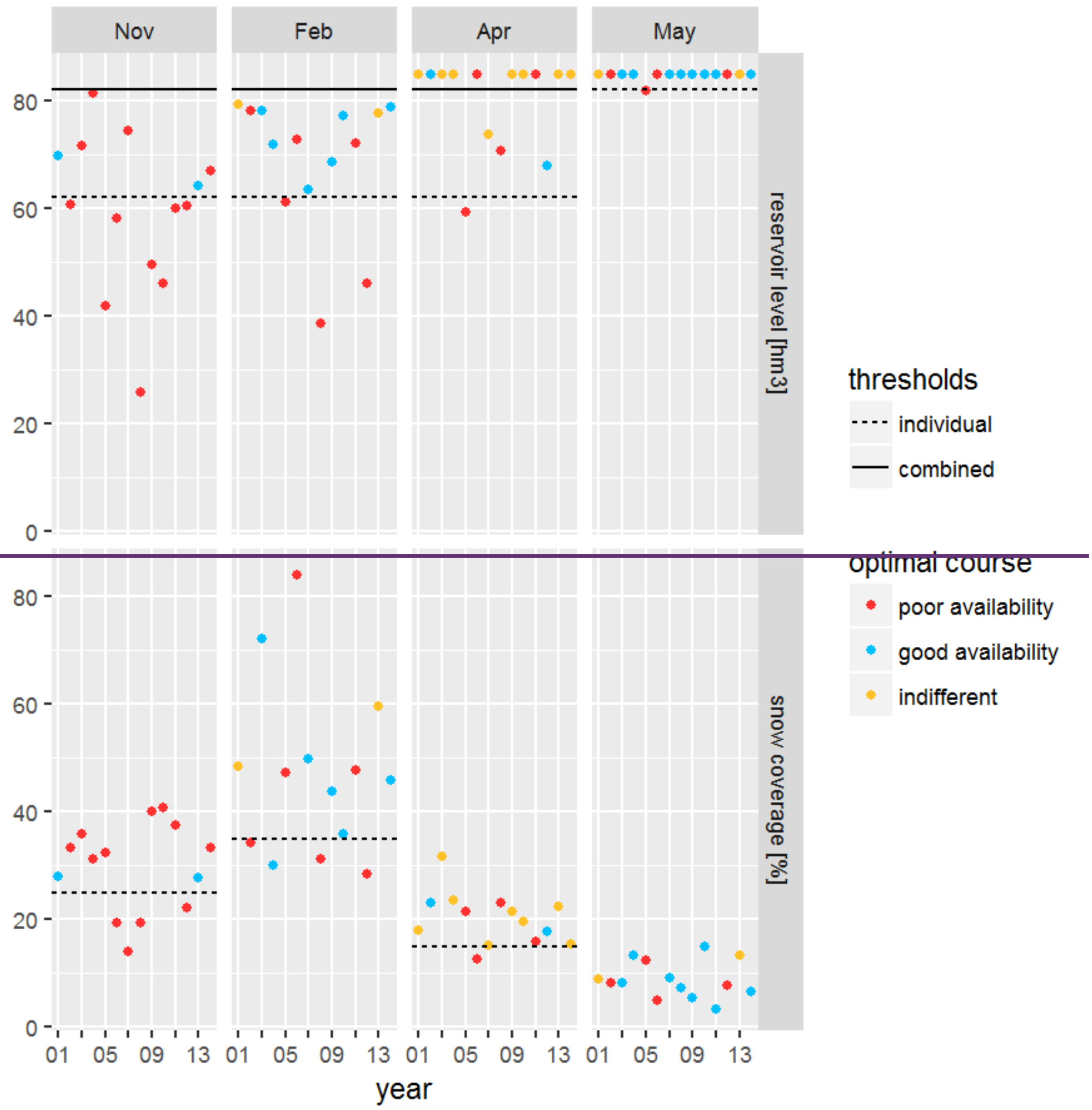
~~An allocation factor of 0.55 was selected for the following tests, since it is found to be a tipping point between good and poor availability for many of the years in the tested period and therefore allows for a higher range of represented situations. With this level of allocation, the area receives an amount of water that would be able to satisfy the full demand of the most productive alternative of crops in 10 out of the 14 years, with 4 years experiencing water shortages, reflecting the number of drought events in the 2000-2014 period.~~

~~2.3.5.1. Value of additional information for the decisions~~

~~The model was run with the optimised thresholds as well as with the 10 additional sets of thresholds. The optimised thresholds together with the reservoir levels and snow cover values from which they are derived are shown in Figure 4.~~. The points are coloured according to the decisions taken with perfect information at ~~each of the~~those decision points~~. The objective of this step is~~, which are considered as the "optimal course", and refer to ~~identify a set of~~the paths illustrated in Figure 3.The individual thresholds ~~that maximises the number of points that are correctly classified according to~~mark the ~~optimal path. The perfect classification~~threshold for reservoir level or snow cover when ~~using only reservoir level data would have all the years in which the good availability path should be followed (coloured in blue) above the dashed threshold and the years in which the poor availability path should be followed (coloured in red) below it. The additional dataset, if useful, should then help to improve the classification with a second threshold. In this case, the years in which the snow cover is above a certain threshold (dashed line in the lower plot) are classified with the same threshold used when no additional information is considered~~considered independently, while the ~~years that have snow cover below~~combined thresholds are the ~~threshold require a higher~~modified thresholds for reservoir level for years in ~~order to classify~~which the ~~availability as good.~~ snow cover threshold is not reached.

The optimised thresholds for the reservoir level were established at 62 hm^3 for November, February and April, and 82 hm^3 for May; the thresholds for snow cover were set at 25%, 35% and 15% for November, February and April respectively, while the increase in the reservoir level threshold for the years that are below the snow threshold was set at 20 hm^3.

6.2. Value of additional information for the decisions



~~Figure 4.~~ The ~~points represent reservoir levels (upper plot) and snow cover (lower plot) for the period 2001-2014. The points are coloured according to the decisions taken with perfect information at those decision points. The individual thresholds mark the threshold for reservoir level or snow cover when considered independently, while the combined thresholds are the modified thresholds for reservoir level for years~~value of information is assessed here in ~~which the snow cover threshold is not reached.~~

~~Figure 5 shows~~terms of the total and relative benefit ~~obtained~~ for the farmers during the ~~period tested using reservoir level data only and using both the reservoir level data and the snow cover data~~whole period of analysis in each of the information scenarios. **Error! Reference source not found.** shows the total benefits obtained considering the two information scenarios with each of the 10 sets of thresholds~~and with~~. The benefits obtained using the optimised set identified in the previous step is also included (labelled as 62 in the figure). ~~For each threshold, two columns are shown. The column on the left provides the gains and losses when considering only the reservoir levels, while the column on the right shows the benefits and losses when both snow cover and reservoir levels are considered. The length of the columns is determined by the accumulated years with net gains (above zero), and the accumulated years with net losses (below zero). The black dot represents the net benefit for the whole period. The gains and losses obtained using perfect~~

information (right column) and no information are included in the first two columns as reference, and are independent of the thresholds. The columns are coloured to show the net benefit in terms of total gain (above 0) or loss (below 0) of each of the years in the period. The black dot represents the net benefit taken over the whole period.

The two reference scenarios are included in the first two columns. These show the net benefits using the uninformed decision and decisions made using perfect information, which are independent of the thresholds.

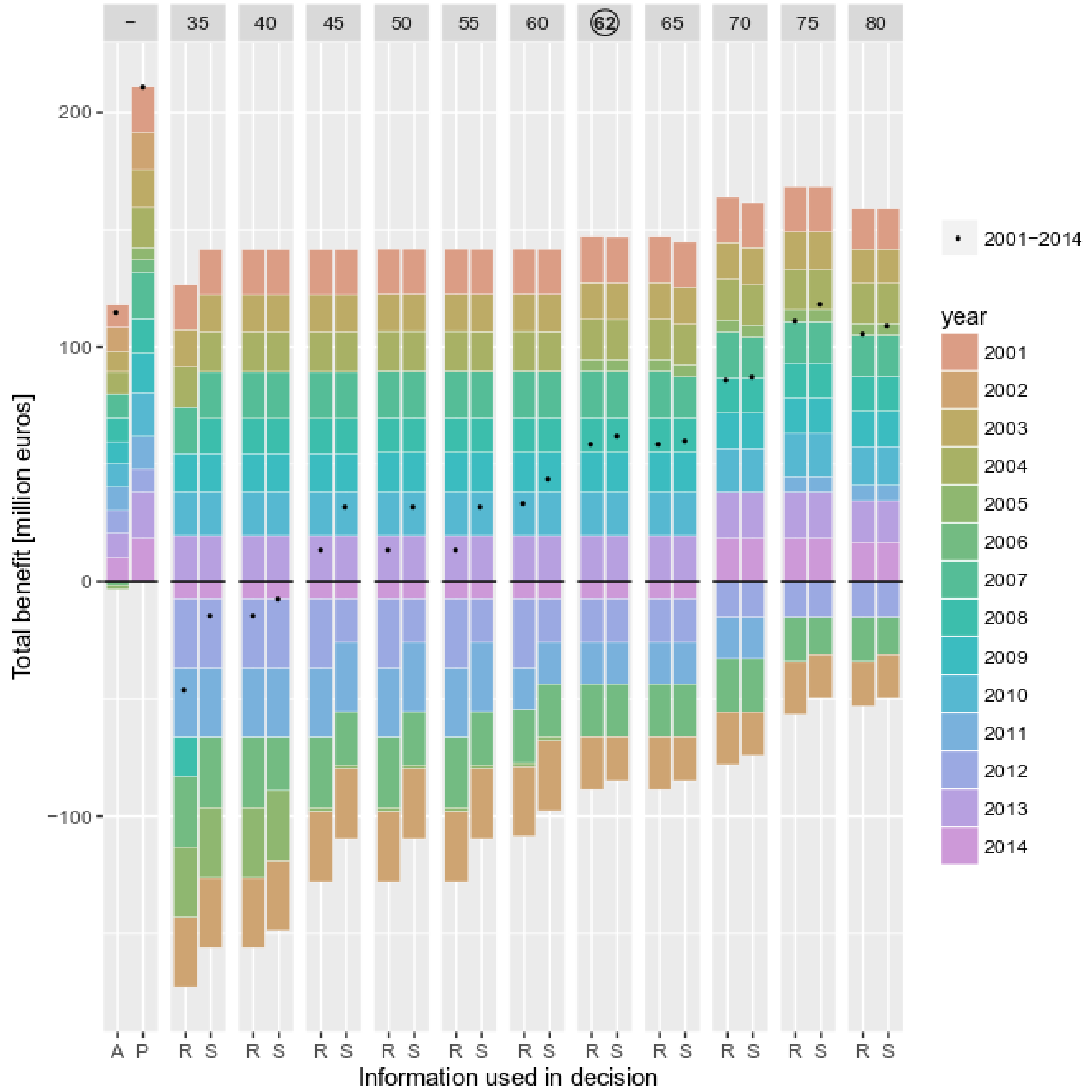


Figure 6. Total benefit for decisions informed by reservoir level alone (R) and with the addition of snow information (S) for the 10 sets of thresholds and the optimized thresholds (labelled as 62). The total benefit for uninformed decisions (A) and perfect information (P) is included as a reference. The colours indicate the yearly benefit while the points represent the total benefit for the period (total gainsFigure 6 - total losses).

The difference between the perfect information (column labelled P) and the no information (labelled A) reference scenarios shows the potential value of using information, as the use of uncertain information is expected to scale between these two extreme situations. However, as can be seen in the following columns that represent the net benefits of the informed scenarios as a function of the threshold (labelled R for information from reservoir levels only and S for information from both reservoir levels and snow cover), the use of non-perfect information in this case results in losses for some of the years. This is particularly so for the lower thresholds, as water availability is often judged to be good when in fact it is poor.

Error! Reference source not found. presents the Relative Value (RV) of the decisions using each of the two tested sources of information with respect to the decisions informed by perfect information and the uninformed decisions. This shows that the relative values for the total benefits are negative for almost all thresholds, both when using only reservoir levels as well as when also using additional information ofon snow cover. This means that, for the period as a whole, selecting a course of action based on the expected availability informed by these datasets does not result in higher benefits than when following the path that performs best on average every year. The reason for this lies in the large losses incurred when failing to recognise a poor availability year and as a consequence planting more than what can be irrigated. This is the case for the years with a negative benefit represented in Figure 5.Figure 6. These high losses also result in higher thresholds showing a better relative value, since these thresholds lead to more years being regarded as poor availability years, thus leading to lower areas being planted.

Still, the results show that the additional information does help to reduce the losses in some of the years and for all thresholds a better relative value is obtained when using the additional dataset on snow cover. The totalThis can be seen by the net benefit for the period 2001-2014 (represented by a black dotdots in Figure 5) is **Error! Reference source not found.**Figure 7) being higher for all thresholds when the snow-cover information is used.

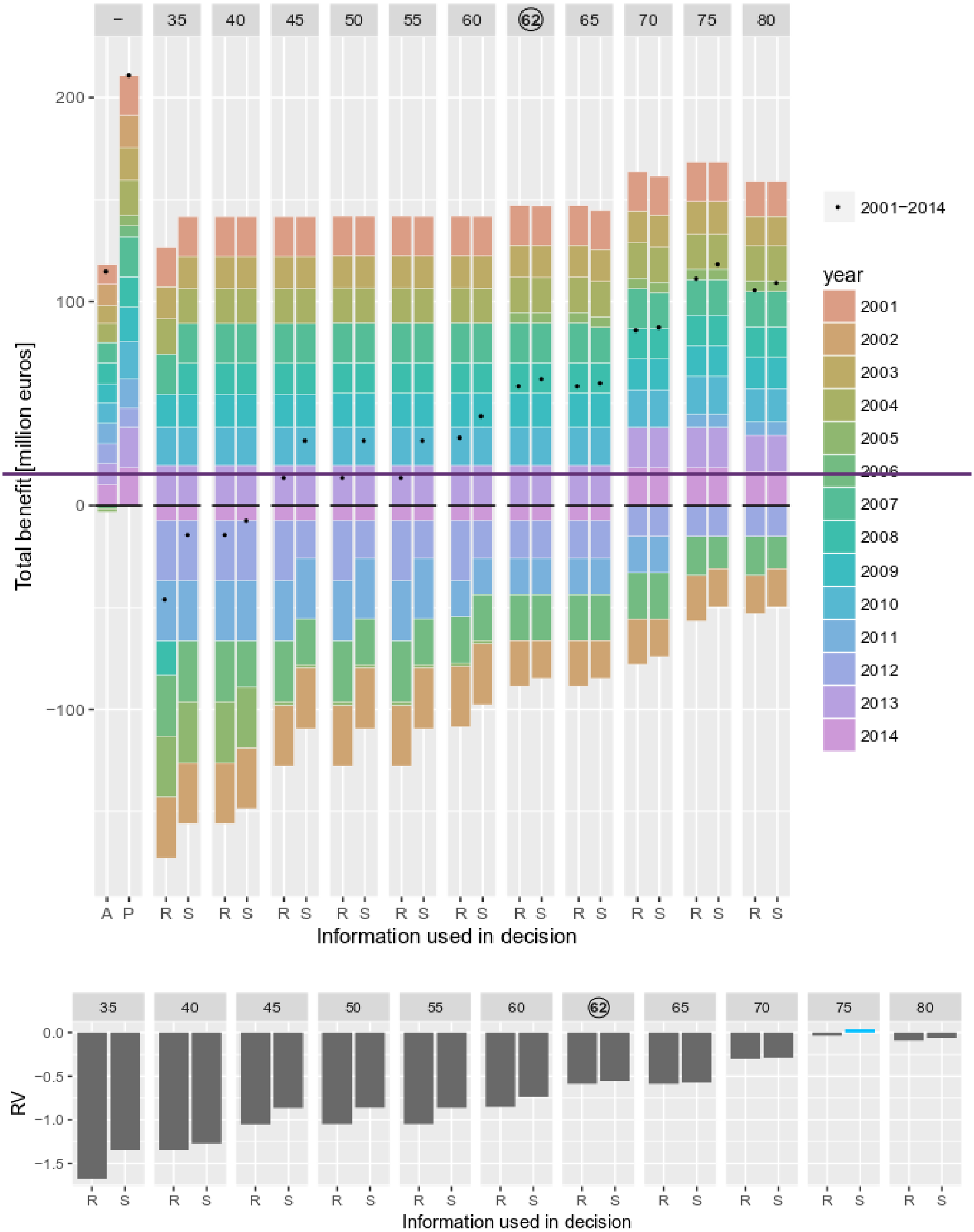
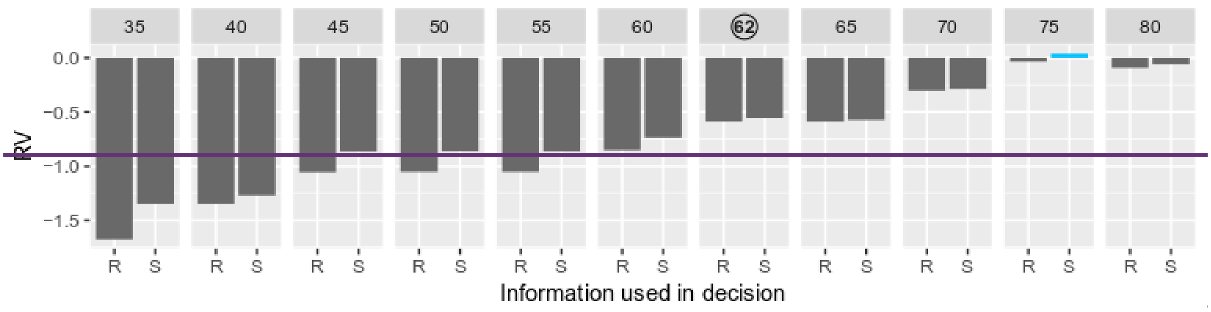


Figure 75. ~~Total benefit for decisions informed by reservoir level alone (R) and with the addition of snow information (S) for the 10 sets of thresholds and the optimized thresholds (labelled as 62). The total benefit for uninformed decisions (A) and perfect information (P) is included as a reference. The colours indicate the yearly benefit while the points represent the total benefit for the period (total gains-total losses).~~



~~Figure 6.~~ Total Relative Value for the period 2001-2014 for decisions informed by reservoir level alone (R) and with the addition of snow information (S) for the 10 sets of thresholds and the optimized thresholds (labelled as 62).

6.3. Quantifying the effect of additional information

The high losses in some of the years are the result of the limited profit margin between the cost of planting and the selling price of the products. To illustrate further the effect of the profit margin in the decision and the value of information, we have run a series of additional simulations where the costs of planting is reduced by 50%, 75% and 100% (~~or~~which is the same as zero cost). The relative value of information for these simulations (shown in ~~Figure 7~~Figure 8) indicates there is a gradual increase in the relative value of the informed decisions as the ratio of the benefits from the crop yield to the cost of planting increases. The fully detailed gains and losses for these simulations can be found in the supplementary material (S1). Relative values are still low, however, even when there is no cost for planting. This is because the uninformed decision used as a reference also improves with the reduction of the cost of planting. The course of action that performs better on average, in which the uninformed decision is based, is path 3 for the full reported cost, path 4 for the reduced costs and path 5 when no cost is considered. This means that with lower or no investment ~~cost in terms of~~costs for planting it is better on average to plant the more water demanding crops. ~~This reduces~~These results also show that as the ratio between the profit made from the crop yield and the costs of planting increases, the relative value of the informed decisions for the years in which the optimal path is followed is also reduced.

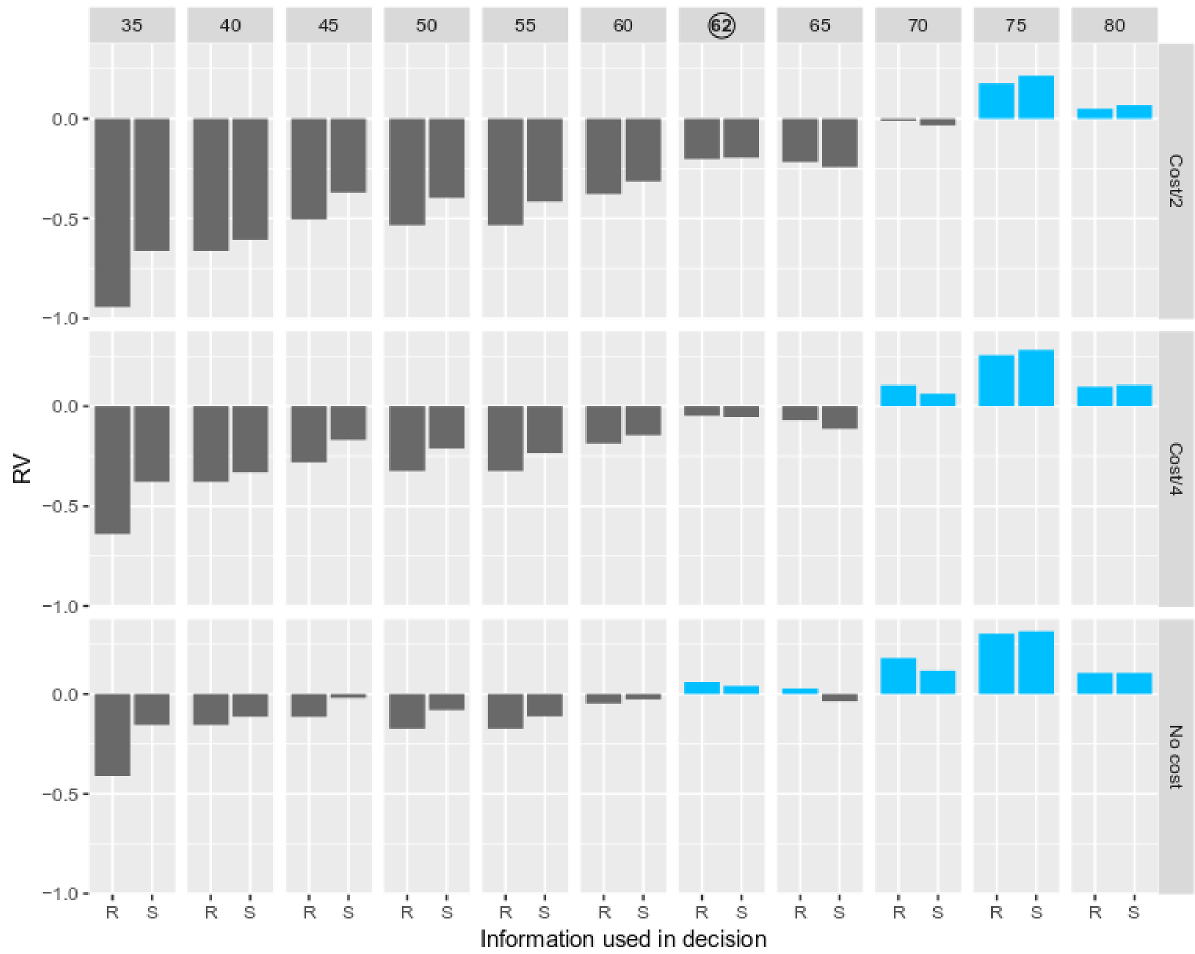
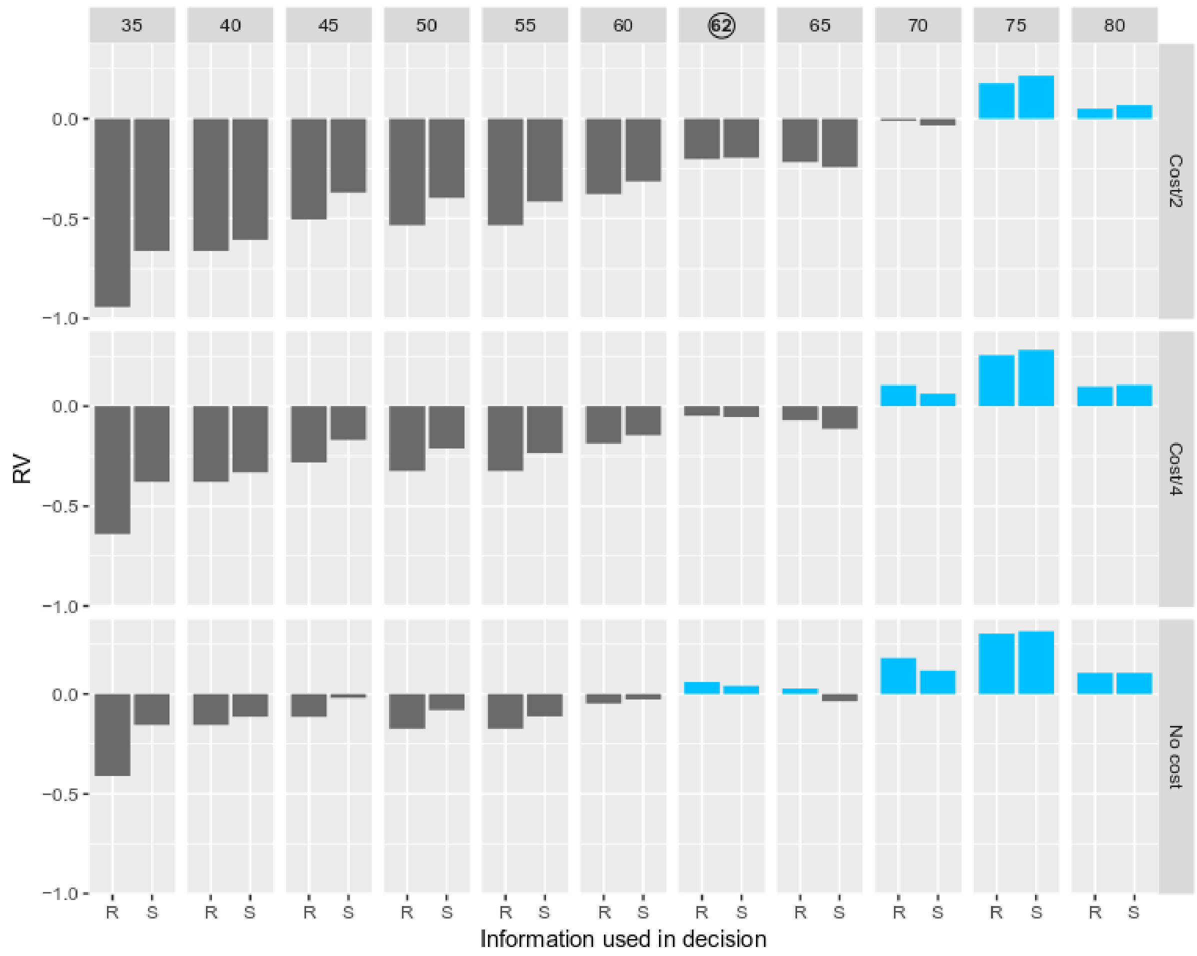


Figure 8. Relative value with different levels of cost for planting.

At the reduced costs it also appears that the added value of the information from snow cover reduces, and in some cases is even detrimental, particularly at the higher reservoir level thresholds. This is likely caused by the uncertainty in ~~of~~ the relationship between snow cover and available water resource, which will be elaborated ~~on~~further in the discussion.



~~*Figure 7. Relative value with different levels of cost for planting.*~~

~~5.~~7. Discussion

To answer the question posed in the title ~~if~~on whether users ~~can~~would benefit from additional information ~~to support operational~~on available water resources in drought ~~management decisions~~conditions, we ~~follow~~adopt an approach that ~~combines~~starts with a stakeholder consultation to be able to understand the decisions users make and how they use information to support those decisions~~, and decision modelling to explore~~. This is followed by a model of the decisions to quantify how additional information can be used to inform and influence the decision process. ~~As stated by Iglesias et al. (2017), the main advantage of the~~

The consultation was performed by semi-~~-~~structured interviews to key stakeholders. The advantage of this method is ~~these encourage~~that it encourages discussion~~, while~~ (Iglesias et al. 2017), although the main limitations are ~~related to~~ the small sample size, which means that only a partial view is obtained of the plurality of the stakeholders that make these decisions. Despite ~~the limitations~~this limitation, the responses of the interviews provided a detailed description of the possible choices to deal with water shortages in the Ebro basin, and the interaction and feedbacks between water management strategies at basin, irrigation district and local farmer scales ~~by providing increased~~

~~comprehension of the stakeholders' views.~~. This knowledge was ~~then~~ used to ~~explore the value of data products that the users can benefit from.~~

~~Based on these findings,~~build a model of the interrelated decisions of farmers and water managers at the irrigation district scale ~~was built. The objective was to quantitatively assess the effect of information on the decisions.~~. The decisions modelled are informed by the expected water availability during the irrigation season, which is currently derived mainly from the reservoir levels. ~~The model can, however, be used to test any dataset that can inform the represented decisions.~~ In this case we test the use of additional information of remotely sensed snow cover, as this is information users currently may consider, but further research on the value of different datasets that inform the expectation of the available water resource could be conducted using the model.

7.1. ~~The~~ Potential value of additional information

Decisions taken with perfect or no information were used as reference cases. The difference in the net benefit between these two cases reveals the potential improvements that information can bring with respect to the uninformed decisions. With perfect information, losses can be avoided in seasons of water scarcity and benefits maximised when enough water is available. It should be noted that the paths for perfect information as included in the model maximise the benefit of the whole group of farmers, rather than that of individual farmers. In reality, the benefits and losses are not shared by the group and individual farmers would try to optimise their individual benefit instead, though community collaboration in the form of the established user associations in the basin ensure that to an extent farmers do take decisions that contribute to a common good and the tragedy of the commons does not arise.

The uninformed case follows a conservative approach considering that for every year the available water will be limited. Although this results in high losses being avoided, the benefits are well below the potential. Using additional information to inform decisions is expected to help the decision makers in characterising each season in terms of the water availability and selecting what and when to plant, and accordingly increasing their benefits. As additional information we test a medium resolution snow cover product ~~tested is a medium resolution global~~derived through remote sensing ~~product~~. Gascoin et al. ~~(2015) showed~~(2015) show the value of this product to provide snow cover information at the Pyrenees range scale. ~~In our~~Our analysis ~~we used~~shows that the information from this product also has value at the basin headwater scale ~~and the results show~~, showing improvements in the decisions ~~with respect~~made when compared to ~~using the~~decisions informed by reservoir levels alone. ~~These improvements in the relative value, although small, correspond to significant reductions of losses. These losses~~

Detailed analysis of the years where there is benefit of using the additional information shows that this arises mainly from the reduction of the losses in those years in which the optimal decision to take is more uncertain. In these the years the classification of the water resource as being good or bad is difficult, and the additional information on the snow cover adds value by making it more difficult for a bad year to look good. Losses occur in 2002, 2006, 2011 and 2012~~,~~ (see supplementary material S2 for yearly relative value plots), which match the years for which drought impacts ~~on~~in irrigation agriculture have been reported ~~(Linés, Werner, and Bastiaanssen 2017), and are the result~~(Linés et al., 2017). They are the consequence of an inappropriate course of action being chosen, as a result of the expected availability of water being too high, compounded by the high cost of planting relative to the return on investment of the crops planted.

To test the robustness of the observed effect of the additional information, the model was run 10 times with ~~random~~randomly sampled values of snow cover~~.~~ at each of the decision points. The results of these runs (included in the supplementary material, S3) show that the improvement then also follows a more random pattern and in some cases are detrimental, thus supporting the hypothesis that the improvements in the decisions are indeed caused by the additional information on snow cover.

~~Decisions taken with perfect or no information were used as reference cases. The difference in benefit between these two cases reveals the potential improvements that information can bring with respect to the uninformed decisions. With perfect information, losses can be avoided in seasons of water scarcity and benefits maximised when enough water is available. It should be noted that the paths for perfect information as included in the model maximise the benefit of the whole group of farmers, rather than that of individual farmers. In reality, however, benefits and losses are not shared by the group and individual farmers would try to optimise their individual benefit instead, though community collaboration in the form of the established user associations in the basin ensure that a tragedy of the commons does not arise.~~

~~The uninformed case follows a conservative approach considering every year that water will be limited. In this way high losses are avoided, but the benefits are well below the potential. In this scenario, information is expected to help the decision makers in characterising each season in terms of the water availability and selecting what and when to plant accordingly, increasing their benefits.~~ However, the results of the model indicate that selecting the option that performs better on average, as ~~it~~ is done in the uninformed case, leads to higher benefits than when using the information on reservoir levels (either alone or supported by the MODIS snow cover information~~) to decide what the best option for that particular year is.~~). This is in contradiction with the current practice, in which the reservoir level information is used to support the decision and different choices are taken each year. ~~The~~One reason ~~for these differences~~that farmers do not follow this strategy may lie in the fact that not all the losses are assumed by the farmers, since there are subsidies for certain crops or for losses incurred in disastrous years~~, and these~~. These subsidies are often based on planted surface~~,~~ and ~~will~~ influence the ratio between the return from the crop yield and the investment costs incurred when planting. ~~In addition~~Additionally, the actual farmer decision on what to plant is influenced not only by water availability, but also by the market prices of the crops ~~and these and other subsidies.~~. Maize has a high cost of production and therefore, when its selling price is low, farmers tend to select other crops with lower production cost ~~(Espluga Trenc 2016).~~(Espluga Trenc, 2016). In the model, however, the planting costs and selling prices were kept constant for all the years to better observe the effect of information in the selection of the crops.

7.2. Effect of the cost of planting on the value of information

The effect of the cost of planting and the profit margins on the usefulness of the information was explored by running the model for different planting costs. Changing the cost of planting modified the course of action both for the informed and uninformed decisions. The reduction of the costs results in higher relative values for the informed decisions for the period as a whole caused again by the reduction of the net losses. The ratio between the cost of planting and the return on investment on the crop is similar to the cost-loss ratio used in evaluating the benefit of flood warnings ~~(Verkade and Werner 2011).~~(Verkade and Werner, 2011). Where the cost-loss ratio is high, the cost of taking an action in vain (false alarm) is also high, and significant losses may be incurred. This may even result in the information~~, which~~ to be detrimental, since it does contain uncertainty and may therefore lead to wrong choices being made~~, to be detrimental~~. Larger losses than if that information is simply ignored and the business as usual action is taken may then be ~~made~~incurred. For users with a lower cost-loss ratio, explored here by lowering the cost of planting, additional (uncertain) information becomes increasingly valuable as these users become more tolerant to taking a wrong decision. The role of uncertainty in the link between the information used (reservoirs levels and snow) and the realisation of the available water resource is not ~~explicitly~~directly explored in this study through for example a hydrological model, though explicitly considering the uncertainty can add further value to the information. Several authors (Roulin, ~~2007,~~2006; Verkade ~~&~~and Werner, 2011) have shown that the value of information from forecasts is always higher when these are probabilistic. In the application presented here, the relation between the reservoir levels and the available water resources is more certain than the relation between the snow cover and the available water. This may also explain the poorer performance when using snow cover information than when using only reservoir levels such as occurs in 2006. In this year the snow cover at the start of the year (February) was exceptionally high, leading to an expectation of good water resource conditions. However, this was due to~~ a~~ widespread snowfall at the end of January just before the decision point in February. This snow melted rapidly and the snow cover in April was anomalously low, with low water resource availability for the rest of the season.

7.3. ~~Detailed analysis of the years where the benefit of using the additional information shows that this arises mainly from the reduction of the losses in those years in which the optimal decision to take is more uncertain. These are the years when the classification of the water resource as being good or bad is difficult, and the added value of the additional information on the snow cover is in that it makes it more difficult for a bad year to look good. However, the~~Value of the information for the different types of farmers

The value of the additional information is not equal to each of the different types of farmers identified. The additional information on the expected water resource provided by the snow cover is found to be relevant only to the decisions that are made in February. For the technified farmers the information is therefore of little value, as the main decisions made by them fall in November and in May, respectively before the snow accumulation period~~,~~ and after the snowmelt period.

For the small scale farmers, the additional information can be relevant for the decisions that are made when there is snow cover, primarily those made in February, but also those made in April. These small scale farmers have only one crop. Once a decision is made to plant a crop, there is no further value to information as there is no further decision to be made. However, the benefit is again not evenly distributed. ~~These small~~Small scale farmers were divided here into three groups of decreasing risk averseness (R1, R2 and R3). We find that the additional information benefits the group of farmers that is willing to take more risk most. These are the farmers that decide to take the risk to wait for a possible improvement when the water availability is classified as not being good at the decision ~~moment~~point, instead of taking the safe bet and securing a crop by planting a barley crop, which does not depend on irrigation and possible curtailments. The most risk averse small scale farmers (R1), do not even wait for any information on water availability, and already plant barley in November. For them there is no value in the additional information. For the slightly less risk averse farmers (R2) there is limited value in the additional information. If in January the water resource situation is expected to be good, then they will choose to plant maize, but at the first sign of it being bad they will forfeit the possible higher profits from maize and opt to take the safe bet by planting barley. The most risk acceptant small scale farmers benefit the most from the additional information, as it will help them make the choice between taking the gamble of waiting for the water resource availability become better so that they can plant maize, or ~~if it does not run~~plant a cereal to avoid the risk of having to leave the land fallow~~. These small scale farmers have only one crop, so once the decisions is made there is no further value to information.~~

~~This is an important result as it demonstrates how the value of information depends on how it can improve advanced insight into the probable state of nature, which is important to the expected utility of the decision. However, it also depends on the level of risk aversion of the user. For users that are very averse to risk, there is no added value to using the information in this case on the snow-cover as they will take the safe bet and plant barley at the first sign of poor availability in November. The added value is the highest to those small scale farmers (R3) willing to take the risk of waiting for water resources improving before taking action~~ if it does not. In this case these results show that the additional information may be beneficial to improved equity across the farmers in the irrigation district as it is most beneficial to small-scale farmers, provided they are willing to take a gamble to improve their benefits. ~~In this paper we model the distribution of risk averseness using only a simple percentile distribution. A more realistic distribution of risk averseness can be developed using for example the Constant Absolute Risk Aversion Utility Function (Matte et al., 2017; Quiroga et al., 2011), though this will require extensive survey data to determine how risk averseness is distributed among farmers.~~

In this paper we model the distribution of risk averseness using only a simple percentile distribution. A more realistic distribution of risk averseness can be developed using for example the Constant Absolute Risk Aversion Utility Function (Matte et al., 2017; Quiroga et al., 2011), though this will require extensive survey data to determine how risk averseness is distributed among farmers.

~~6.~~8. Conclusions

~~Operational drought management decisions were examined with the aim to assess the role of information in these decisions, following an~~An approach that combines stakeholder consultation and decision modelling was followed, allowing a comprehensive analysis of the role of information on drought management decisions in the area. Consultation with the different decision makers in the Ebro basin provided useful insight into the operational decisions they take in managing water resources when scarce, and their information needs and use. This allowed us to identify the courses of action available to the farmers and water managers, and to analyse their choices as a function of the information they have available to them. Feedbacks between the decisions made by farmers and the reservoir operators at irrigation district level were identified: ~~Curtailments~~curtailments imposed at irrigation district level as a result of water scarcity influences the decision farmers make on the planting of crops, which in turn influence demand and consequently water scarcity.

Based on the findings of the consultation, a decision model representing these interrelated decisions was built with the aim to quantify the effect of additional information on the decisions. The modelled decisions, which consider the allocation of water, are taken based on the expected availability of water during the irrigation season. This is currently informed primarily by observed reservoir level data. When levels are above a defined threshold at the time of the decision, water resources availability is classified as good, whereas when levels are below the threshold and expected demand is high it is classified as poor and curtailments to water allocations applied. Farmers decide on the crop to be planted based on their expectation of water resources availability, and whether curtailments are in force. The decision model was then extended from considering only reservoir levels to include additional information on snow cover in the basin headwaters obtained from MODIS remote sensing data to inform the expectation of water resources availability.

Our simulations with the decision model show the additional information can contribute to better decisions and ultimately to higher benefits for the farmers. However, the ratio between the cost of planting and the market value of the crop proved to be a critical aspect in determining the best course of action to be taken and the value of the (additional) information. When there is little room for error due to small margins, then any information used to inform the decision may even be detrimental to any benefits being made. However, even in this case the additional information on snow cover can provide benefit over using the reservoir levels alone. Tests with reduced planting costs, thus increasing margins, does lead to ~~additional~~a higher benefit when using the additional information from snow cover~~, although~~. Nevertheless uncertainty in the relationship between good snow cover and water resource availability may lead to overestimation of the expected resource~~,~~ and consequent losses.

A key finding of our research is that farmers can benefit when the operational decisions they make consider the additional information. To what extent they benefit does, however, depend to a great extent to their level of risk averseness. Risk-averse farmers will decide to take the safe option early on, with information on the available water resource then having no value. Farmers that are less risk averse do benefit as the information helps them weigh the options between planting a crop with a higher return~~,~~ or having to leave the land fallow.

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