First of all the authors want to thank the Editor for his comments which are contributing, with no doubt, to the improvement of the manuscript. In the following we address the comments.

Editor Comment:
EC1: In addition to the comments from the reviewers, I kindly ask you to add "Author contribution" and "Data availability" sections to the manuscript, as indicated in the guidance for authors (see https://www.hydrology-and-earth-system-sciences.net/for_authors/manuscript_preparation.html).

AC1: We are sorry for not considering those sections before. These two sections were included in the new version of the manuscript.

Answers to Reviewer 1 comments

General comments: The paper “Land cover effects on hydrologic services under a precipitation gradient” describes an exhaustive statistical analysis to evaluate the role of vegetation on the hydrology of a large region with a precipitation gradient in Northern Spain. The authors utilized a large amount of data to test the impacts of forest (native and exotic), as well as pastureland on hydrological variables. The manuscript reads well, is well organized, the objectives are clearly defined, the authors were supported by a good choice of bibliography in the field. It is an interesting paper, however, there are some aspects that require improvement before being considered for publication. In particular, the use of the term “hydrological services” that was not matured enough through the text, and the use of so many tables and appendixes. Specific comments and suggestions are included bellow. I believe they can be addressed with additional, descriptive text, and no additional analysis are needed.

Specific comments:
RC 1: Page 2, lines 15-20: The title expresses the concept of hydrological services, a term used to specifically relate the benefits people obtain from ecosystems related to water. These include, not only water quantity and regulation but also the dimension of quality. It is well recognized the role of forest on reducing diffuse water pollution. Since the manuscript only focus on the flows of water and their relations to land-use/cover, but never gets the human dimension of the hydrological services, why to use the term hydrological services and not simply water flows. My feeling is that the term “hydrological services” is not sufficiently polished in the Introduction section and throughout the manuscript to be used in the title. I suggest to revise the title accordingly, or to emphasize the concept of hydrological services, not only in the Introduction but throughout the text.

AC 1: All the text, specially the results and discussion section and the conclusions were reviewed in this sense.
Water flows were linked to hydrological services more clearly. In this sense, terms as water provisioning, flood protection or conservation of ecological status, have been used when referring to average, high or low flows along the text. Additionally, as later suggested by this reviewer, a new subsection was included at the end the results section, highlighting this dimension of the work.

P11; L18: "As Ellison et al. (2017) stated, the impact of land management politics on hydrological services is not usually considered, however, taking into account local findings on the relationship between land cover and water-related ecosystem services is necessary for an adequate integrated catchment management. Results observed in Table 4 and Figures 2 and 3, are in this sense useful to be considered when planning land management, in order to have some knowledge on different trends on hydrologic services that can be derived from different decisions under areas with different precipitation amounts. There is no unique "best combination" for all locations and all services, water provision, flood risk protection, ecological status conservation…."

RC 2: Page 4, line 1-2: Were the oak forests removed for plantations of pinus radiata? 39-48% of the area refers to total area or to forest area?

AC 2: In some cases the introduction of exotic species occurred directly removing broad-leaved forest to plant *Pinus radia*. In other cases, the native forest was first removed to create spaces for pasture, that later, were abandoned to plant exotic species.
39- 48% of the area refers to the potential oak forest area.

The orginal text at this point:
"These exotic species were introduced in the second half of the twentieth century as a result of government support for afforestation policies and currently cover 39–48 % of the area that could sustain oak forests (Garmendia et al., 2012).
The abandonment of traditional cattle and sheep farming practices has also contributed to the conversion of pastureland and rangelands to fast-growth exotic plantations (Ruiz Urrestarazu, 1999)."

was modified as follows trying to clarify these points:
P4; L1: "These exotic species were introduced in the second half of the twentieth century as a result of government support for afforestation policies. The abandonment of traditional cattle and sheep farming practices has also contributed to the conversion of pastureland and rangelands, most of them previously converted from broad-leaved forests, to fast-growth exotic plantations (Ruiz Urrestarazu, 1999). As a result, those exotic species currently cover 39–48 % of the potential oak forests (Garmendia et al., 2012)."

RC 3: It is not clear in section 3.4, at what scale were the statistical analysis performed? I supposed for the entire 20 catchments, but then the aggregated value for the entire region masks geographical asymmetries.

AC 3: As the referee comments the statistical analysis was performed for the 20 catchments. We are not sure of which is the referees concern about geographical asymmetry In fact, precipitation is the variable that shows a higher variability in the area, and that is the reason why we considered it necessary to be included in the analysis.

In order to clarify this point in the manuscript, the original text:
"As a first step, the influence of precipitation on different hydrological indices was analysed using the following simple linear regression, Eq. (1)"

Was modified as follows:
P6; L11: "As a first step, the influence of precipitation on different hydrological indices was analysed using the following simple linear regression that included the 20 catchment, Eq. (1):"

RC 4: The combinations used do not differ substantially from each other, why not to reduce for 3 combinations. Perhaps instead of number, the combinations should have a name, e.g. more exotic, more pasture, in order to better guide the reader in the further tables of results. It was not clear where do these combinations applied? To the entire catchment. Why to call realistic. They seem to be scenarios of land cover? I recommend to clarify better these methodology for the readers understand results.

AC 4: With the six combinations included, apart from considering maximum of one or of other land use, different average values of exotic, native and pasturelands are considered. In our opinion this helps understanding what may happen, not only when land cover is very different, but how smaller differences can affect to hydrological services. In that sense, we consider that none of the combinations should be remover. However, and following the recommendation of this reviewer we added in the manuscript a description and an acronym for each of the combinations. These acronyms are also included in table 3 and have been used when describing results. In our opinion, as the referee says, this will better guide the reader through the manuscript.

The combinations were considered for the entire catchment and we call them realistic because they are built using real data obtained from table 3 (this point was also clarified in the manuscript). We decided to call them combinations instead of scenarios to avoid confusion with other studies based on hydrological modelling, and because land cover alternatives are not considered, as in modelling, for certain areas in the catchment but globally in the regression equation.

In order to include the reviewer proposals on this topic in the manuscript, the original text:
"The different land cover combinations shown in Table 3 were explored under low and high precipitation conditions, and compared to a "base" land cover combination (combination 0) of 76 % exotic, 18 % pastureland, and 6 % native. Land cover combination 0 was defined as a combination with a maximum area of exotic plantations, minimum area of native forests, and a low percentage of pasturelands (calculated as the remaining percentage to cover 100 % of the area). Combinations from 1 to 5 were defined as realistic alternative patterns to combination 0. Differences between these patterns and combination 0 were calculated for each hydrological index under low and high precipitation conditions (Tables 4, 5 and 6). These combinations were defined considering real data (e.g., maximum, minimum, or mean percentages of native forests, exotic plantations, and pasturelands). Defined in this way, each combination was used to examine interactions between realistic data; results for scenarios that might be very different from the existing ones were not extrapolated."

Was modified as follows:
P7; L3: "The different land cover combinations shown in Table 3 were explored for the catchments, under low and high precipitation conditions, and compared to a "base" land cover combination (combination EXO) of 76 % exotic, 18 % pastureland, and 6 % native. Land cover combination EXO was defined as a combination with a maximum area of exotic plantations, minimum area of

native forests, and a low percentage of pasturelands (calculated as the remaining percentage to cover 100 % of the area). Other 5 combinations were defined as realistic alternative patterns to combination EXO as they were calculated considering real data (e.g., maximum, minimum, or mean percentages of native forests (NAT), exotic plantations (EXO), and pasturelands (PAST) (see Table 2)) and considering the sum of the three as 100 %. Following this approach combination EXO + PAST represents high percentages of exotic plantations and pastureland, combination EXO + NAT high percentage of forest, combination NAT high percentage of native forest, combination NAT + PAST is mostly native forests and pasturelands and combination EXO + NAT + PAST a mixture of average percentages of exotic plantations, native forests and pasturelands. Differences between these patterns and combination EXO were calculated for each hydrological index under low and high precipitation conditions (Table 4). Defined in this way, each combination was used to examine interactions between realistic data; results for combinations that might be very different from the existing ones were not extrapolated."

RC 5: Page 6: in which software were the statistical analysis carried out?

AC 5: All the statistical analysis was programmed and performed using the free software R in its version 3.1.2 in the R studio interface.

The following text was included in point 3.4 of the manuscript: P6; L27: *"All the statistical analysis were programmed and performed using the free software R in its version 3.1.2 in the R studio interface."*

RC 6: Page 8, lines 7-10: This discussion is well organized and results are well-thought-out in perspective against work done by others. However, please consider that sometimes the growth of forest can have only a slight effect, depending of course on other environmental factors, such as depth of soil, precipitation episodes, etc. Please consider to take a look on this publication: (Hawtree et al., 2015)

AC 6: This reference was considered in the new version of the manuscript as follows:
P10; L32: "No statistically significant influences were observed on median, high, or low autumn and summer flows or on other hydrological indices related to the timing of low flows or other changes to the hydrograph; however, this does not rule out the possibility of relationships between land cover and the hydrological indices. As shown in Appendix C, precipitation (volume and distribution) is the main driver of the system, and thus the influence of other drivers, such as land cover, may fail to emerge as statistically significant. Additionally, there may be other environmental factors, such as soil depth, as Hawtree et al., (2015) found in a catchment of north-central Portugal."

RC 7: I would like to suggest a table with major findings of the study, a kind of summary to guide the reader. And also add a paragraph on this in the discussion. I think this table will summarize the work and can maybe substitute Table 5 and 6.

AC 7: Following the suggestions of reviewer 1 all results included in previous table 4, 5 and 6 were merged in one table that includes all findings (Table 4 in the reviewed version of the manuscript). And a global discussion, previously included in conclusions, is now included in the results section as follows:

P11; L6: "Clear conclusions about the effect of each land cover combination on hydrological services cannot be drawn without considering the amount of precipitation. However, results show that in the Bay of Biscay area, the presence of any kind of forest decreases water provisioning service (Y50m), and this effect is more evident with exotic plantations as the annual precipitation increases. Additionally, similar to other studies (Robinson et al., 2003; Carrick et al., 2017), this study indicates that the potential for forests to reduce flooding risk is low; however, the effect of land cover on high flows also changes with precipitation. For low precipitation amounts, forests, especially exotic plantations, show greater potential to reduce annual and wintertime high flows than pasturelands, but this potential decreases as annual or seasonal precipitation increases. Moreover, when high annual precipitation is considered, the potential of exotic plantations to reduce flood magnitude is lower than that of native forests or pasturelands. Further, the results also show that exotic plantations have a slight positive effect on annual low flows under low annual precipitation conditions; however, low flows increase as annual precipitation increases and when exotic forests are replaced by pasturelands. This effect is most evident in winter and spring, and when the combination of pasturelands and native forests account for most of the catchment area."

RC 8: Are forest fires a threat in this region? Are there any other possible factor that may influence discharge, e.g. forest management that is worthy to discuss? If yes for fire or other factors please add a paragraph in the discussion section around these topics.

AC 8: Forest fires are not a main threat in this region, at least not as in other regions of the Iberian Peninsula. Forest management is an important issue, specially that related to exotic species. In fact, a text was already included explaining the specificity of those plantations in the study area. However, those are the current practices, and there are not, at least at significant spatial scales, other type of managements that could imply hydrological differences between catchments with exotic plantation. The text we refer to says as follows:

P11; L28: "Further study is needed in the Bay of Biscay area to determine how the characteristics of specific tree species (e.g., their phenology and physiology) affect various components of the hydrological cycle. Analyses are also needed to establish the relationship between forest types, land management issues and soil development. For instance, clearcutting of exotic species in the study area is usually accompanied by harvesting with chainsaws, skidding, and mechanical site preparation (prior to replanting) such as scarification and ripping (Gartzia-Bengoetexea et al., 2009). These logging operations alter the physical properties of soil, affecting processes such as infiltration, evapotranspiration, percolation, and lateral flow, and in turn, catchment water balance and temporal distribution river discharge. A deepened understanding of those relationships will help achieve a solid understanding of how trees characteristics, forest types and management strategies, and soil properties influence water flows."

RC 9: Tables 4 to 6 – Did you dived results from catchments with high and low precipitation? Why not the same amount of precipitation in all analysis? Seeing Figures 2 and 3 I got the meaning of this precipitation division. I recommend this to be explained in the captions of the

tables and in the methods section. In addition, please put what does each acronym in the table means, at least in the caption, otherwise it is difficult to follow.

RC 9: As the referee already guessed, there is no catchment division in the analysis, but the same analysis was repeated with low and high precipitation amounts. As it is already explained in the methodology section, *P6; L29: "The objective of this study was to compare predicted hydrological indices for various land cover combinations under different precipitation amounts. To avoid biased results affected by considering extreme values, the 1st and 3rd quartiles of the precipitation data series were calculated for the selected period (annual or seasonal) and defined as the low and high precipitation conditions." ..... P7; L3: "The different land cover combinations shown in Table 3 were explored for the catchments, under low and high precipitation conditions, and compared to a "base" land cover combination".*
However, and reading the question of the referee, we realize that this idea needs to be reinforced and, following the suggestion of the referee we include some explanation in the caption of table 4.

The original caption:
"Table 4. Results obtained, from multiple regression models, in the variation in percentage with respect to the base land cover combination (EXO) in the annual median, high and low flows with land cover for low and high precipitation amounts."

Was modified as follows (table 4 as example):
"Table 4. Results obtained, from multiple regression models, for base land cover combination (EXO) and for alternative combinations defined in Table 3 expressed as the difference (in %) with respect to EXO combination. Results for annual, winter and spring median, high and low flows are included, for low (1st quartile) and high (3rd quartile) precipitation amounts (see Figs. 2 and 3). Y50m, Y90m and Y10m refer to median, high and low flows of the annual discharge series; W90m and W10m refer to high and low flows of the winter discharge series; and Sp50m and Sp10m refer to median and low flows of the spring discharge series."

RC 10: I was missing a discussion around the practicability of these findings. Are they useful for policy makers? In which way?

RC 10: A text on this was included in the new subsection of the manuscript: *"4.4 Land cover effects on hydrological services. Implications."*

P11; L18: "As Ellison et al. (2017) stated, the impact of land management politics on hydrological services is not usually considered, however, taking into account local findings on the relationship between land cover and water-related ecosystem services is necessary for an adequate integrated catchment management. Results observed in Table 4 and Figures 2 and 3, are in this sense useful to be considered when planning land management, in order to have some knowledge on different trends on hydrologic services that can be derived from different decisions under areas with different precipitation amounts. There is no unique "best combination" for all locations and all services, water provision, flood risk protection, ecological status conservation. However, the effect of different land cover combinations, apart from those analysed in this paper, and always inside the limits those included in the multiple regression models proposed, on different hydrological services may be applied. Results obtained, should be in the range of those shown in figures 2 and

3, and could be used to compare the benefits and disadvantages in each of the commented services.”

RC 11: Page 11, Lines 10 to 20: For me these sentences are more a part of discussion. You could create an extra section in the discussion section with major findings and policy implications. I would like to see a conclusion more summarized and without comparing the work with others.

RC 11: These finding were moved to the new subsection of the manuscript: *“4.5 Land cover effects on hydrological services. Implications.”*

Technical corrections:
RC 12: Page 2, line 18: Keestra et al., 2018, appears “Keesstra” in the References, which one is correct?

AC 12: We are sorry for the mistake. Keestra is the correct form. It has been corrected in the reference list of the new version of the manuscript

RC 13: Figure 1: The figure is very informative. However, in figure 1 a) it was difficult to understand the border of the catchments, it is difficult to read what are the dashed lines for and the bold lines for. Maybe to delete the dashed lines since they are not informative and highlight the border of the region and dashed lines the border of the catchments. Update legend accordingly. In the legend, please mention the spatial resolution and source of land cover maps.

AC 13: Figure 1 was modified following the recommendations of this reviewer and trying to make it clearer (see new figure in the reviewed version of the manuscript). Legend was updated and spatial resolution and source of maps were included in the figure caption.

The original caption:
“Figure 1. a) Location and digital terrain model of the study area with the main drainage network, location of gauging stations, catchments, and average precipitation values. b) Land cover map of the study area in 2002 and 2009.”

Was modified as follows:
“Figure 1. a) Location and digital terrain model (5x5 m of resolution) of the study area with the main drainage network, location of gauging stations, catchments, and average precipitation values. b) Land cover map of the study area in 2002 (IFN3, 2005) and 2009 (IFN4, 2011) at the 1:25000 scale.”

RC 14: Table 1: Please detail where are land cover maps 2002 and 2009 coming from, spatial resolution, source.

AC 14: Spatial resolution and source of maps were included in the table caption. Some more information was also included in the caption.

The original caption:
"Table 1. Catchment descriptions."
Was modified as follows:
"Table 1. Catchment descriptions. Code of the gauging station, catchment name, catchment area, primary land cover types percentages for 2002 (IFN3, 2005) and 2009 (IFN4, 2011) at the 1:25000 scale."

RC 15: Table 2: I would like to suggest the meaning of the abbreviations described in the table, otherwise the reader has to look for these different meanings spread all over the text. The table as it is not informative. Please also put native and exotic 2 or 3 spaces right, because they are inside of forest section.

AC 15: A footnote was included in the table with abbreviation meaning. Table caption was modified in accordance with this change.

The original caption:
"Table 2. Statistics of hydrological indices, land cover types, and precipitation amounts used in this study. See the text for abbreviation meaning."

Was modified as follows:
"Table 2. Statistics of hydrological indices, land cover types, and precipitation amounts used in this study."

Add footnote was included:
" YR: annual runoff; Y10m, A10m, W10m, Sp10m and Su10m: 10th percentile for annual, autumn, winter, spring and summer discharge series; Y50m, A50m, W50m, Sp50m and Su50m: 50th percentile for annual, autumn, winter, spring and summer discharge series; Y90m, A90m, W90m, Sp90m and Su90m: 90th percentile for annual, autumn, winter, spring and summer discharge series; CVY, CVA, CVW, CVSp and CVSu: coefficient of variation for annual, autumn, winter, spring and summer discharge series; skn: skewnwss of the annual discharge series; JY10m: Julian day of the beginning of the low flow period. YP: annual precipitation amount for the catchment; AP + SuP: summer plus previous autumn precipitation amount for the catchment; WP + AP: winter plus previous autumn precipitation amount for the catchment; SpP + WP: spring plus previous winter precipitation amount for the catchment; SuP + SpP: summer plus previous spring precipitation amount for the catchment. See the text for more information."*

RC 16: Page 5, line 11: where is Fig A1? Please cite Appendix A1.

AC 16: The text was reviewed accordingly.

Where it said:
"(Fig. A1)"

Now it says:
“(Appendix A)”

RC 17: Page 7, line 11: Fig. C1 is Appendix C? Please use the term Appendix, otherwise people will not understand.

AC 17: The text was reviewed accordingly.

Where it said:
“(Fig. C1)”

Now it says:
“(Appendix C)”

RC 18: If figures in the Appendixes are so important for the study, why not to introduce them in the body of the text? Readers will need to have extra work downloading appendix to fully understand the paper. This is a suggestion, please consider if you feel that all the figures are important.

AC 18: In our opinion appendixes help going further in the context of the paper, however, they are not very necessary to understand the main findings of the paper. Introducing them in the text would mean too many figures and tables and as HESS gives authors the chance to include some extra material as appendices we thought to take advantage of it, in order to extend information for those readers more interested in the hydro-meteorological context or the more specifically statistical results.

RC 19: Please mention the periods of analysis, either in the captions (as Appendix A has), as well in the text (e.g. page 7 line 12 is missing the period of analysis).

AC 19: Periods of analysis were included in the text and in the caption of table 2.

Original text in the manuscript:
“The regression includes all data collected during the study period …”

Was modified as follows:
P7; L21: “The regression includes all data collected during the study period (from 2000–2001 to 2004–2005 and from 2007–2008 to 2011–2012)”

RC 20: Page 7, line 24. Please use “from” instead of “of”. Figure 2a shows results “from” the multiple regression

Suggested change was made.

RC 21: Page 8, line 23: where are the performance statistics shown?

All the performance statistics are included in Appendix D. The text was modified for clarification at this point. However, Figures 2 and 3 were also modified in order to include some statistics and make the understanding of the text easier. See modified figure in the new version of the manuscript.

The original text:
"Regression results shown in Fig. 3b indicate that native forests, pasturelands, and precipitation in interactions with both types of land cover are significant (p values <0.05). The percentage of exotic plantations in the catchment significantly influences the median discharge in the spring. The coefficient of determination for this graph is 0.63, indicating a good fit."

Was modified as follows:
P8; L33: "Regression in Fig. 2b show significant effect of native forests, pasturelands, and precipitation in interactions with both types of land cover (p values <0.05) on Sp50m. The percentage of exotic plantations in the catchment significantly influences the median discharge in the spring. The coefficient of determination for this graph is 0.63, indicating a good fit."

RC 22: Page 8, line 26: in which way increases discharge? Values, Table??

AC 22: The text was slightly modified at this point to include some data and table reference.

The original text:
"Decreasing the percentage of exotic plantations (by increasing pasturelands or native forests) increases spring discharge under high precipitation amounts (Sp50m). The magnitude of this increase is larger when the extension of pasturelands is larger (combinations 1 (EXO) and 4 (NAT+PAST)). At low precipitation rates, the positive effect of pasturelands on Sp50m remains, while increasing native forest (combinations 2 (EXO+NAT) and 3 (NAT)) has a negative effect on median discharge."

Was modified as follows:
P8; L3: "Decreasing the percentage of exotic plantations (by increasing pasturelands or native forests) increases spring average discharge (Sp50m), up to a 76 %, under high precipitation amounts (852 mm) (Table 4). The magnitude of this increase is larger when the extension of pasturelands is larger (combinations EXO and NAT+PAST). At low precipitation rates (646 mm), the positive effect of pasturelands on Sp50m remains, while increasing native forest (combinations EXO+NAT and NAT) has a negative effect on median discharge."

RC 23: Page 8, line 35: which land cover? Please refine the sentence.

AC 23: Authors do not understand this question.
Is the referee referring to next sentences? *P9; L11: "Conversely, land cover combinations 3 and 4 (with the highest percentage of native forests and pasturelands, respectively, and lowest percentage*

of exotic plantations) show the highest variation in Y50m and Sp50m in the precipitation gradient existing in the study area. Consequently, the land cover combination that gives the highest or lowest median discharge values changes with annual and seasonal precipitation amounts."

RC 24: Page 9, line 15: Please consider this article on these matters: (Carrick et al., 2018)Carrick, J., Bin Abdul Rahim, M.S.A., Adjei, C., Ashraa Kalee, H.H.H., Banks, S.J., Bolam, F.C., Campos Luna, I.M., Clark, B., Cowton, J., Domingos, I.F.N., Golicha, D.D., Gupta, G., Grainger, M., Hasanaliyeva, G., Hodgson, D.J., Lopez-Capel, E., Magistrali, A.J., Merrell, I.G., Oikeh, I., Othman, M.S., Ranathunga Mudiyanselage, T.K.R., Samuel, C.W.C., Sufar, E.K., Watson, P.A., Zakaria, N.N.A.B., Stewart, G., 2018. Is Planting Trees the Solution to Reducing Flood Risks? J. Flood Risk Manag. 1–10. https://doi.org/10.1111/jfr3.12484

AC 24: A reference to this paper was included in the results section of the new version of the manuscript.

P10; L5: "In this sense Carrick et al., (2017) after a met-analysis of 156 papers, concluded that a weak direct evidence of the effects of tree cover on flood risk, due to the high uncertainty found in results."

RC 25: Page 11, line 23. Please remove "in" in the beginning of the sentence.

AC 25: Sorry for this error. "in" was removed from the sentence.

RC 26: Page 11, line 27: There simply is no unique "best combination. Please remove "simply".

AC 26: Suggested change was made.

Answers to Reviewer 2 comments

Anonymous Referee #2

This paper, discussing the influence of precipitation and land cover on hydrological indicators, is well-written and fits well within the scope of HESS. There are a few things to clarify though before publication, as listed below.

RC 1: The main things I would like to see more clarified are how the base and 5 other land cover combinations are created

AC 1: Land cover combination 0 was defined as a combination with a maximum area of exotic plantations, minimum area of native forests, and a low percentage of pasturelands (calculated as the remaining percentage to cover 100 % of the area). Combinations from 1 to 5 were calculated considering real data (e.g., maximum, minimum, or mean percentages of native forests, exotic plantations, and pasturelands (see Table 2)) and considering the sum of the three as 100 %.

Following the recommendation of both reviewers we better explained this part of the methodology, and the original text:
"The different land cover combinations shown in Table 3 were explored under low and high precipitation conditions, and compared to a "base" land cover combination (combination 0) of 76 % exotic, 18 % pastureland, and 6 % native. Land cover combination 0 was defined as a combination with a maximum area of exotic plantations, minimum area of native forests, and a low percentage of pasturelands (calculated as the remaining percentage to cover 100 % of the area). Combinations from 1 to 5 were defined as realistic alternative patterns to combination 0. Differences between these patterns and combination 0 were calculated for each hydrological index under low and high precipitation conditions (Tables 4, 5 and 6). These combinations were defined considering real data (e.g., maximum, minimum, or mean percentages of native forests, exotic plantations, and pasturelands). Defined in this way, each combination was used to examine interactions between realistic data; results for scenarios that might be very different from the existing ones were not extrapolated."

was modified as follows:
P7; L2: "The different land cover combinations shown in Table 3 were explored for the catchments, under low and high precipitation conditions, and compared to a "base" land cover combination (combination EXO) of 76 % exotic, 18 % pastureland, and 6 % native. Land cover combination EXO was defined as a combination with a maximum area of exotic plantations, minimum area of native forests, and a low percentage of pasturelands (calculated as the remaining percentage to cover 100 % of the area). Other 5 combinations were defined as realistic alternative patterns to combination EXO as they were calculated considering real data (e.g., maximum, minimum, or mean percentages of native forests (NAT), exotic plantations (EXO), and pasturelands (PAST) (see Table 2)) and considering the sum of the three as 100 %. Following this approach combination EXO + PAST represents high percentages of exotic plantations and pastureland, combination EXO + NAT high percentage of forest, combination NAT high percentage of native forest, combination NAT + PAST is mostly native forests and pasturelands and combination EXO + NAT + PAST a mixture of average percentages of exotic plantations, native forests and pasturelands. Differences between these patterns and combination EXO were calculated for each hydrological index under low and high precipitation conditions (Table 4). Defined in this way, each combination was used to examine interactions between realistic data; results for combinations that might be very different from the existing ones were not extrapolated."

RC 2: and how dependent your conclusions are on changes in your assumptions (for instance a slight change in those combinations, or using only seasonal instead of 6 month precipitation, etc).

AC 2: Figures 2 and 3 show the effect of different land cover combinations in hydrological indices considering a precipitation gradient. In this sense, it could be considered that slight changes in those land cover combinations, inside the limits of maximum and minimum cover percentage considered for each of them, should give results inside the range of the obtained lines.

However, changing land cover percentages out of the real limits could lead to erroneous extrapolation of results. In any case, this type of analysis should be more considered to obtain trends of changes than to obtain numerical absolute results.

Some new text explaining this was included in the new 4.5 subsection:
P11; L24: "…the effect of different land cover combinations, apart from those analysed in this paper, and always inside the limits those included in the multiple regression models proposed, on different hydrological services may be applied. Results obtained, should be in the range of those shown in figures 2 and 3, and could be used to compare the benefits and disadvantages in each of the commented services."

Including precipitation of only one season in the analysis does not give significant statistical results.
in order to clarify this, in the original text:
"…, while for seasonal scale, precipitation of the season studied plus that of the previous season (6 months total) were considered."

The following was added:
P6; L33: "…, while for seasonal scale, precipitation of the season studied plus that of the previous season (6 months total) were considered. The statistical analysis was also carried out considering precipitation of the studied season (3 months), however, no statistically significant results were found."

Introduction:

RC 3: P2, line 8-10: what is the deforestation in hectares and /or the afforestation in %?

AC 3: Deforestation between 1990 and 2015 reported in the Global Forest Resources Assessment published by FAO in 2016 was about 129 millions of hectares (FAO, 2016).

This data was included in the original text, where it said:
"Worldwide, deforestation rates outstrip afforestation by several million hectares per year. Overall global forest cover declined by 3.25% between 1990 and 2015 (FAO, 2016)"

Now it says:
P2; L8: "Worldwide, deforestation rates outstrip afforestation by several million hectares per year. Overall global forest cover declined by 3.25% (129 million ha) between 1990 and 2015 (FAO, 2016)"

FAO: Global Forest Resources Assessment 2015: How Are the World's Forests Changing? 2nd Ed., Food and Agriculture Organization of the United Nations, Rome, Italy, 2016.

Study area:

RC 4: P3: is the study area a closed drainage network (I assume so) or is there inflow from other / higher regions?

The study area are 20 catchments located in the Gipuzkoa province with no inflow from other areas. In the manuscript, a first general description of the province is included in order to give some general geo-environmental characterization of the area and after, specific land cover characteristics of the 20 catchments are resumed in Table 1 and Figure 1.

The text in the manuscript was slightly modified in order to clarify this point:
Where it said:
"The study area is in Gipuzkoa Province (1980 km2) in the Basque Country…"
Now it says:
P3; L14: "The studied catchments are located in Gipuzkoa Province (1980 km2), in the Basque Country…"

And where it said:
P4; L10: "The study catchments exhibit a diverse mix of land cover types…"
Now it says:
"The catchments studied in this area exhibit a diverse mix of land cover types…"

Methodology:

RC 5: P4, line 26-30: for clarity you could already indicate here that the land cover for 2002 and 2009 is very similar, to support the 'merging' of the two 5-year periods of hydrologic observations

AC 5: In fact, the authors created a unique database that includes both five-year periods, hydrological data are not merged considering one unique land cover distribution. However, land cover data corresponding to hydrological data from 2000-2001 to 2004-2005 is that from the 2002 inventory, and land cover data from the 2009 corresponds to hydrological data from 2007-2008 to 2011-2012.

Original text in the manuscript:
"To maintain coherence with land cover data obtained from forest inventories carried out during 2002 and 2009, discharge data was considered for two five-hydrological-year periods. The first period, from 2000–2001 to 2004–2005, was compared with land cover data obtained during 2002 (IFN3, 2005). The second period, from 2007–2008 to 2011–2012, was compared with land cover data from 2009 (IFN4, 2011). In this way, two sets of discharge series, accounting for a total of 10 hydrological-years, were selected for each gauging station. To facilitate comparison among catchment responses, all discharge data, including those for hydrological indicators, are referred to as specific discharges (L s^{-1} km^{-2}*)."*

Was slightly modified in order to clarify this point:
P4; L28: "To maintain coherence with land cover data obtained from forest inventories carried out during 2002 and 2009, discharge data was considered for two five-hydrological-year periods. Data from the first period, from 2000–2001 to 2004–2005, was compared with land cover data obtained during 2002 (IFN3, 2005). Data from the second period, from 2007–2008 to 2011–2012, was compared with land cover data from 2009 (IFN4, 2011). In this way, hydrological data accounting for 10 hydrological-years were considered for each gauging

station. To facilitate comparison among catchment responses, all discharge data, including those for hydrological indicators, are referred to as specific discharges (L s–1 km–2).”

RC 6: P4: line 31: in specific discharge unit L/s/km^2 what is L? The letter would indicate a length but specific discharge = discharge / area so L would be a volume?

AC 6: In this case, L refers to a volume, litre, allowed in the SI (international system) and in the manuscript preparation guidelines of HESS. It could lead to confusion in a context in which dimensions are expressed, however, in this case, units are expressed for all dimensions (seconds for time or km^2 for area) so that, we do not think it need any clarification in the text.

RC 7: P5, line 29-20: ‘Seasonal precipitation amounts : : : were also computed’, are they also based on estimates from the Environment and Hydraulic Works Department like annual precipitation or do you yourself compute them from the annual precipitation?

AC 7: Seasonal precipitation amounts were computed based on these annual precipitation amounts provided by the Environment and Hydraulic Works Department for each catchment and the seasonal distribution of precipitation in the hydro-meteorological stations listed in Table 1.

In order to clarify this in the manuscript, the original text:
“Seasonal precipitation amounts for autumn (AP, mm), winter (WP, mm), spring (SpP, mm) and summer (SuP, mm) were also computed.”

Was modified as follows:
P5; L31: “Seasonal precipitation amounts for autumn (AP, mm), winter (WP, mm), spring (SpP, mm) and summer (SuP, mm) were computed based on the annual precipitation amounts for each catchment and the seasonal distribution of precipitation in the hydro-meteorological station listed in Table 1 for each catchment”.

RC 8: P6, line 21-34: this section would be a bit more clear if you switch the paragraph starting in line 30 with that starting in line 25, since the “real values of explanatory variables” in line 23 are the land cover combinations explained starting from line 30 if I understand correctly?

AC 8: In this case, variables are precipitation and land cover types, and the next two paragraphs are explaining how those variables (precipitation first and land cover later) are considered. As in the first equation only precipitation is considered and in the second the equation is extended to land cover, the order selected was the one in the manuscript.

However, in order to clarify this, in the original text:
“This allowed for a simple and direct interpretation of the influence of all variables.”

The following was added:

P6; L26: "This allowed for a simple and direct interpretation of the influence of all variables (precipitation and land cover types)".

RC 9: P6 line 25-29: How sensitive are your results to the choice to exclude outliers and to add precipitation of the previous study? i.e. are your conclusions different if you do not exclude outliers and / or only include precipitation of the 3-month season?

AC 9: The objective of the paper was to study the influence of land cover in a natural precipitation gradient. Including extreme values, would give us the response of catchments to extreme, very particular conditions, which, each of them, should be analyzed very carefully and deeply. Moreover, the inclusion of so particular values could bias the relationship between precipitation, land cover and hydrological services.

in order to clarify this, the original text:
"To avoid considering outliers, the 1st and 3rd quartiles of the precipitation data series were calculated for the selected period (annual or seasonal) and defined as the low and high precipitation conditions."

Was slightly modified as follows:
P6; L30: "To avoid biased results affected by considering extreme values, the 1st and 3rd quartiles of the precipitation data series were calculated for the selected period (annual or seasonal) and defined as the low and high precipitation conditions."

The authors do not know what the referee refers to when talking about precipitation of the previous study.

Including precipitation of only one season in the analysis does not give significant statistical results.
in order to clarify this, in the original text:
"…, while for seasonal scale, precipitation of the season studied plus that of the previous season (6 months total) were considered."

The following was added:
P6; L32: "…, while for seasonal scale, precipitation of the season studied plus that of the previous season (6 months total) were considered. The statistical analysis was also carried out considering precipitation of the studied season (3 months), however, no statistically significant results were found."

RC 10: P6 line 30 – P7 line 5: are your 6 land cover combinations the most common ones in the region? If so how much of the area do they represent?

AC 10: The 6 land cover combinations created are based on real data, so that even if the combination itself may not exactly exist in any of the catchments as is, catchments with high percentage of exotic plantations (76 % in Aixola, Table 1); of native forests (66% in Añarbe, Table1); of paturelands (42 % in Urkulu, Table 1) exist. Table 1 shows the real combinations existing in the studied catchments and Table 2 shows the statistics for those land cover types. Additionally, in the study area section some general data for land cover in Gipuzkoa province are also included.

In this sense, the original text in the study area section:
"... Forests are the main land use (73 % in 2011) (MAGRAMA, 2013). The original broad-leaved forests (oak–Quercus robur, and beech–Fagus sylvatica), presently reduced to 15 % of their original area, share space with tree plantations of rapid-growth exotic species such as Pinus radiata. These exotic species were introduced in the second half of the twentieth century as a result of government support for afforestation policies."

Was slightly modified as follows:
P3; L30: "... Forests are the main land use (63 % in 2011) (MAGRAMA, 2013). The original broad-leaved forests (oak–Quercus robur, and beech–Fagus sylvatica), presently reduced to 15 % of their original area, account for 28 % of the province and share space with tree plantations of rapid-growth exotic species such as Pinus radiata. These exotic species were introduced in the second half of the twentieth century as a result of government support for afforestation policies."

*Note that a correction was also done in the forest type percentage due to incorrect data included in the previous version of the manuscript.

Results and discussion:
RC 11: P8 line 20: Table 6 is mentioned before Table 5. Furthermore, you could mention in the table captions that you do not show insignificant results (now I wondered for instance why Table 6 did not include Sp90m – that results for Sp90m are insignificant is only mentioned in later sections).

AC 11: In the new version of the manuscript, and following recomentations of reviewer 1, tables 4, 5 and 6 were merged in one unique table.

About insignificant results not included, a footnote in tables 4, 5 and 6 was already included to mention not significant results are not included in those tables.

RC 12: P8 line 21: I think you refer to figure 2b (Sp50m) instead if 3b (Sp10m)

AC 12: We are very sorry for the mistake, the referee is wright, so that we changed the reference to the figure in the text

Where it said:
"Regression results shown in Fig. 3b indicate that native forests, pasturelands,…"

Now it says:
P8; L33: "Regression results shown in Fig. 2b indicate that native forests, pasturelands,…"

RC 13: P9 line 14-16: what potentials are usually claimed?

AC 13: A potential of reducing high flows has for a long time been attributed to forests in the literature, and some governments have somehow applied this findings. In fact, as literally mentioned in the referenced paper (Robinson et al., 2003) *“In February 1995, the Environment Ministers of France, Germany, Luxembourg and the Netherlands adopted the “Declaration of Arles” to take measures to reduce future flood risks, which include land management and forestry (WMO, 1995)”*.

First version of the manuscript

Land cover effects on hydrologic services under a precipitation gradient

Ane Zabaleta[1], Eneko Garmendia[2, 3], Petr Mariel[4], Ibon Tamayo[5], Iñaki Antigüedad[1]

[1]Hidro-Environmental Processes Group, Science and Technology Faculty, University of the Basque Country UPV/EHU, Leioa, 48940, Basque Country, Spain
[2]Department of Applied Economics I, University of the Basque Country UPV/EHU, Vitoria-Gasteiz, 01006, Spain
[3]Basque Centre for Climate Change (BC3), Parque Científico de UPV/EHU, Leioa, 48940, Spain
[4]Department of Applied Economics III (Econometrics and Statistics), University of the Basque Country UPV/EHU, Bilbao, 48015, Spain
[2]Department of Statistics, Harvard University, Cambridge, 02140, US

Correspondence to: Ane Zabaleta (ane.zabaleta@ehu.eus)

Abstract. Climate change impacts on the hydrological cycle are altering the quantity, quality, and temporal distribution of riverine discharge, necessitating a more rigorous consideration of changes in land cover and land use. This study establishes relationships between different land cover combinations (e.g., percentages of forest – both native and exotic – and pastureland) and hydrological services, using hydrological indices estimated at annual and seasonal time scales in an area with a steep precipitation gradient (900–2600 mm y^{-1}). Using discharge data from 20 catchments in the Bay of Biscay, a climate transition zone, the study applied multiple regression models to better understand how the interaction between precipitation and land cover combinations influence hydrological services. Findings showed the relationship between land cover combinations and hydrological services is highly dependent on the amount of precipitation, even in a climatically homogeneous and relatively small area. In general, in the Bay of Biscay area, the greater presence of any type of forests is associated with lower annual water resources, especially with greater percentages of exotic plantations and high annual precipitation. Where precipitation is low, forests show more potential to reduce annual and winter high flows than pasturelands, but this potential decreases as annual or seasonal precipitation increases. As annual precipitation increases, low flows increase as the percentage of exotic plantations decreases and pasturelands increase. Results obtained in this study improve understanding of the multiple effects of land cover on hydrological services, and illustrate the relevance of land planning to the management of water resources, especially under a climate change scenario.

1 Introduction

The potential impacts of land cover on the hydrological cycle should be considered during land use policy-making (Fidelis and Roebeling, 2014; Ellison et al., 2017), including by integrating mitigation and adaptation strategies (Locatelli et al., 2016). Climate change impacts on the hydrological cycle are altering the quantity, quality, and temporal distribution of discharge in rivers (Bates et al., 2008); however, climate change alone is insufficient to explain observed trends in streamflow (Schilling

and Libra, 2003; Gallart and Llorens, 2003; Tomer and Schilling, 2009; López-Moreno et al., 2011). To fully understand these trends, changes in land cover and land use must be also considered (Garmendia et al., 2012, Liu et al., 2013; Brogna et al., 2017). Bauman et al. (2007) noted that vegetation is often the main driving force in ecosystem effects that influence hydrological service provision. For example, in areas such as the Pyrenean region, observed decreases in streamflow have been related primarily to changes in land cover, rather than to climate change (Gallart and Llorens, 2004; López-Moreno et al., 2011; Morán-Tejeda et al., 2012).

Worldwide, deforestation rates outstrip afforestation by several million hectares per year. Overall global forest cover declined by 3.25% between 1990 and 2015 (FAO, 2016). During this same period, plantations increased globally by over 105 million hectares; by 2015, about 31 % of the world's forests were designated primarily as production forests. This expansion is actively supported by governments (Enters and Durst, 2004; Schirmer and Bull, 2014), which assume that plantation forests can provide a range of economic, social, and environmental benefits. However, the impact of afforestation on water-related ecological services is not usually considered (Ellison et al., 2017).

Research suggests that forests play important roles in regulating fresh water flows (van Dijk and Keenan, 2007). Trees may enhance soil infiltration and, under suitable conditions, improve groundwater recharge, delivering purified ground and surface water (Calder, 2005; Neary et al., 2009). Yet, the interpretation of the relationship between forests and hydrological services remains controversial (Bosch and Hewlett, 1982; Calder et al., 1997; Iroumé and Huber, 2002; Brown et al., 2005; Little et al., 2009; Keestra et al., 2018). Results vary among geographical latitudes and can be influenced by factors such as forest characteristics, changes in the seasonal structure, bio-geographical characteristics of catchments, soil types, and spatial scales. Typically, however, streamflow decreases substantially following afforestation and reforestation, and increases after deforestation or forest clearing (Bosch and Hewlett, 1982; Andréassian, 2004; Farley et al., 2005, Li et al., 2017).

Streamflow changes are influenced by characteristics such as forest tree species, age, and density. A change from coniferous to deciduous forest cover can improve catchment water yield (Hirsch et al., 2011), presumably due to the longer rotation times. Young, fast-growing forests typically consume more water than old-growth forests (Kuczera, 1987; Vertessy et al., 2001; Delzon and Loustau, 2005). Hence, though the impact of tree cover on water provision service tends to be negative in the short term, it may become neutral over the long term (Scott and Prinsloo, 2008). In the appropriate spatial settings, afforestation can improve water availability; however, plantation forests and the use of exotic species can disturb the hydrological balance with possible negative impacts (Trabucco et al., 2008 Huber et al., 2008; Lara et al., 2009, Little et al, 2009). Additionally, recent studies show that land management practices on tree plantations may promote rather than prevent soil erosion (Banfield et al., 2018). This effect has been observed in the Bay of Biscay region (Zabaleta et al., 2016).

In the context of rising temperatures associated with climate change, afforestation may lead to additional decreases in available water resources (Rind et al., 1990; Liu et al., 2016). Thus, climate change mitigation policies focused on carbon sequestration could negatively affect water provision service (Jackson et al., 2005). These observations highlight the importance of placing water-related ecosystem services at the centre of reforestation and forest-based mitigation strategies, while considering carbon

storage and timber/non-timber forest products as co-benefits of strategies designed to protect the hydrological cycle (Locatelli et al. 2015; Ellison et al., 2017).

Efforts to prioritise hydrological services in mitigation and adaptation strategies, and, hence, in land use policy, should be supported by a solid understanding of how trees, forest characteristics, and forest management strategies influence water flows in areas with different climatic, geographical, geological, and biological characteristics. Toward this end, this study analysed the effect of alternative land cover types (i.e., pastureland, native forests, and exotic plantations) on hydrological services in the Bay of Biscay using hydrological indicators obtained from the discharge series of 20 catchments during the periods 2000–2004 and 2007–2011. The specific objectives of this research were: i) to analyse the relationship between precipitation and several hydrological indicators at annual and seasonal time scales in an area with a steep precipitation gradient (Bay of Biscay); (ii) to assess the relationships between different alternative land covers in use and hydrological indicators considering the existing precipitation gradient; and (iii) to detect patterns in the study area that should be considered in devising adaptation strategies and land use management policies.

2 Study area

The study area is in Gipuzkoa Province (1980 km^2) in the Basque Country of southwestern Europe (average latitude 43 °N and average longitude 1 °W; Fig. 1). The latitude of the province and its geographical situation near the Bay of Biscay favour high mean annual precipitation (1500 mm with no dry season) and a mild climate (mean annual temperature of 13 °C) that varies little between winter (8–10 °C, on average) and summer (18–20 °C, on average). A spatial gradient is observed in annual precipitation, with maximum values in the eastern part of the province (up to 2500 mm) and decreasing precipitation towards the west and south (to about 1000 mm). The altitude ranges from sea level to a maximum of 1554 m; steep slopes, exceed 25 % throughout most of the province with mean values between 40 % and 50 % for most of the catchments.

The drainage network in the area is dense and can be described as dendritic and rectangular. The main rivers flow generally south to north, perpendicular to the coast line. Tributaries are frequently perpendicular to main rivers, influenced by the geological structure of the region, resulting in very narrow water courses that are typically short and steep. Gipuzkoa is located at the western end of the Pyrenees; the region is structurally complex and lithologically diverse, with materials from Palaeozoic plutonic rocks to Quaternary sediments (EVE, 1990). Most of the materials in this region (>70 %) are of low or very low permeability. Sandstones, shales, limestones, and marls are dominant in most of the region, except in the east, where slates prevail (Zabaleta et al., 2016).

The mean soil depth in the study area is about 1 m, but highly variable. Cambisol is the prevailing soil type (FAO, 1977), generally characterised by a loam texture. Forests are the main land use (73 % in 2011) (MAGRAMA, 2013). The original broad-leaved forests (oak–*Quercus robur*, and beech–*Fagus sylvatica*), presently reduced to 15 % of their original area, share space with tree plantations of rapid-growth exotic species such as *Pinus radiata*. These exotic species were introduced in the second half of the twentieth century as a result of government support for afforestation policies and currently cover 39–48 % of the area that could sustain oak forests (Garmendia et al., 2012).

The abandonment of traditional cattle and sheep farming practices has also contributed to the conversion of pastureland and rangelands to fast-growth exotic plantations (Ruiz Urrestarazu, 1999). *Pinus radiata* stands in Gipuzkoa are well adapted to the environment and provide good support for the rapid development of forest communities (Carrascal, 1986; Ainz, 2008). Nevertheless, the expansion of these plantations results in substantial changes not only in the landscape, but also in forest management that affects the hydrological cycle (Garmendia et al., 2012) and sediment delivery (Zabaleta et al., 2016).

The study catchments exhibit a diverse mix of land cover types within a small geographical area that has similar climatic, geological, and topographical characteristics. This provides a good empirical basis for analysing how different land cover types affect median, low, and high flows. More precisely, the 20 selected catchments (some of which are nested catchments; see Fig. 1 and Table 1) include pasturelands (herbaceous vegetation), native forests (oak and beech), and exotic plantations (*Pinus radiata* plantations), as well as small areas of other cover types (e.g., urban land, roads, bare rock, water bodies, etc.). Discharge and precipitation are routinely measured for all the catchments as they are part of the hydro-meteorological monitoring network of Gipuzkoa Provincial Council (http://www.gipuzkoahidraulikoak.eus/es/).

3 Methodology

The methodology employed to assess the impacts of alternative combinations of different land cover types on selected hydrological indicators can be summarised in four steps: 1) extraction of hydrological indicators from discharge data series; 2) measurement of alternative land covers for each catchment; 3) assessment of the extent to which annual and seasonal precipitation control the hydrological indicators; and 4) analysis of the relationship between hydrological indicators, precipitation, and alternative land covers.

3.1 Hydrological data

Gauging stations included in the hydro-meteorological network of the Basque Country are located at each outlet of the 20 studied catchments (Fig. 1, Table 1). Water depth (m) is measured every 10 minutes and discharge ($m^3 s^{-1}$) is estimated through calibration conducted by the water services of the province (Environment and Hydraulic Works Department of Gipuzkoa Provincial Council) (Zabaleta et al., 2016).

To maintain coherence with land cover data obtained from forest inventories carried out during 2002 and 2009, discharge data was considered for two five-hydrological-year periods. The first period, from 2000–2001 to 2004–2005, was compared with land cover data obtained during 2002 (IFN3, 2005). The second period, from 2007–2008 to 2011–2012, was compared with land cover data from 2009 (IFN4, 2011). In this way, two sets of discharge series, accounting for a total of 10 hydrological-years, were selected for each gauging station. To facilitate comparison among catchment responses, all discharge data, including those for hydrological indicators, are referred to as specific discharges ($L s^{-1} km^{-2}$).

A comparison of the daily hydrographs obtained for the outlets of the 20 catchments shows the homogeneity in the timing of the discharge (Appendix A) and its relationship to the prevalence of Atlantic storms approaching from the northwest (Nadal-Romero et al., 2015). These storms influence the entire study area and are the main sources of precipitation. For this reason, even if there are important differences in total amounts of precipitation from east (higher) to west (lower), the distribution of precipitation over time is very similar in all the catchments analysed, which translates to similar patterns in the annual hydrographs.

Hydrological indicators related to different hydrological services were calculated considering fundamental characteristics of streamflow: magnitude, frequency, variability, and timing (Ritcher et al., 1996; Olden and Poff, 2003). As a first step, seven hydrological indicators were calculated from the discharge series for each hydrological year. At annual and seasonal time scales, the 10th (10m), 50th (50m), and 90th (90m) percentiles (L s^{-1} km^{-2}) were analysed as indicators of discharge magnitude (Fig. A1). The coefficient of variation (CV) was used as a measure of the variability of the discharge series analysed. At the annual scale, the following were also calculated: runoff (R, mm), timing of low flows expressed as the first Julian day of the low flow period (J10), and skewness (skn), as a measure of the asymmetry of the hydrograph related to the frequency of discharge data, of each of the series. As a result, the annual value (Y) and the values for autumn (A), winter (W), spring (Sp) and summer (Su) were obtained for each hydrological year for the different indicators. All calculated indicators are listed in Table 2.

3.2 Land cover data

In 2005 and 2011, the Basque Government published detailed forest inventories. These forestry maps of the Basque Country were created by on-screen photo-interpretation, based on colour orthophotos generated by the SIGPAC project (http://www.mapama.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/), with a minimum pixel size of 25 cm. For this study, geographic information systems were used to reclassify the land cover types into four main types: native forest, exotic plantations, pasturelands, and others. The areas corresponding to each type in each of the catchments were estimated using Environmental Systems Research Institute (ESRI) software (ArcGIS 10.1). The resulting data are listed in Table 1, which shows the percentage of each land cover type in the 20 catchments for both 5-year periods. Note that variations in land cover between the two periods are small.

3.3 Precipitation data

Annual precipitation (YP, mm) estimates for each of the 20 catchments were provided by the Environment and Hydraulic Works Department of the Gipuzkoa Provincial Council. These estimates were calculated by interpolation, based on a universal isotropic kriging method, using data obtained from the rain gauge network. Seasonal precipitation amounts for autumn (AP, mm), winter (WP, mm), spring (SpP, mm) and summer (SuP, mm) were also computed. These values were used to describe the overall precipitation regime for the 10 hydrological years under study and to assess the extent to which precipitation controlled the hydrological variables considered.

The annual and seasonal distribution of precipitation across catchments over the period studied is shown in Appendix B. In the catchments studied, annual precipitation varied from minimums of 958 mm for the 2001/2002 hydrological year in the C1Z2 catchment and 1581 mm for 2008/2009 in the C1P3 catchment to maximums that range from 1664 mm in D2W1 for 2001/2002 to 2611 mm in F1W1 for 2008/2009 (Fig. B1). On a seasonal basis (Fig. B2), autumn is usually the rainiest season with a mean precipitation of 551 mm, followed by winter and spring with means of 425 mm and 343 mm respectively; summer is the season with the least precipitation (mean of 216 mm).

3.4 Statistical analysis

As a first step, the influence of precipitation on different hydrological indices was analysed using the following simple linear regression, Eq. (1):

$$H_{it} = \gamma_1 + (\gamma_2 \times P_{it}) + \varepsilon_{it} \qquad (1)$$

where H_{it} represents one of the hydrological indices in Table 2; γ_1 and γ_2 are parameters to be estimated; P_{it} is the total precipitation amount considered; and ε_{it} is a regression error satisfying the standard basic assumptions for each of the $i = 1,\ldots,$ 20 catchments and $t = 1,\ldots,$ 10 hydrological years.

Equation (1) was extended to include different land covers to study their possible influence on the hydrological indices, taking into account their interactions with precipitation. Thus, Eq. (1) was extended to Eq. (2):

$$H_{it} = \beta_1 + (\beta_2 \times P_{it}) + (\beta_3 \times Nat_{it}) + (\beta_4 \times Exo_{it}) + (\beta_5 \times Past_{it}) + (\beta_6 \times Nat_{it} \times P_{it}) + (\beta_7 \times Exo_{it} \times P_{it}) + (\beta_8 \times Past_{it} \times P_{it}) + \mu_{it} \qquad (2)$$

where β_1 to β_8 are parameters to be estimated; Nat_{it}, Exo_{it}, and $Past_{it}$ are the percentages of native forest, exotic forest, and pastureland, respectively; and μ_{it} is a regression error satisfying the standard basic assumptions for each of the $i = 1,\ldots,$ 20 catchments and $t = 1,\ldots,$ 10 hydrological years.

Because Eq. (2) includes interactions of explanatory variables, the interpretation of results can be difficult. For this reason, different representative combinations were defined based on real values of explanatory variables and the corresponding predictions of hydrological indices were computed. This allowed for a simple and direct interpretation of the influence of all variables.

The objective of this study was to compare predicted hydrological indices for various land cover combinations under different precipitation amounts. To avoid considering outliers, the 1st and 3rd quartiles of the precipitation data series were calculated for the selected period (annual or seasonal) and defined as the low and high precipitation conditions. For annual scale data, annual precipitation was considered, while for seasonal scale, precipitation of the season studied plus that of the previous season (6 months total) were considered.

The different land cover combinations shown in Table 3 were explored under low and high precipitation conditions, and compared to a "base" land cover combination (combination 0) of 76 % exotic, 18 % pastureland, and 6 % native. Land cover combination 0 was defined as a combination with a maximum area of exotic plantations, minimum area of native forests, and a low percentage of pasturelands (calculated as the remaining percentage to cover 100 % of the area). Combinations from 1 to

5 were defined as realistic alternative patterns to combination 0. Differences between these patterns and combination 0 were calculated for each hydrological index under low and high precipitation conditions (Tables 4, 5 and 6). These combinations were defined considering real data (e.g., maximum, minimum, or mean percentages of native forests, exotic plantations, and pasturelands). Defined in this way, each combination was used to examine interactions between realistic data; results for scenarios that might be very different from the existing ones were not extrapolated.

4 Results and discussion

4.1 Effect of precipitation on hydrological indicators

Precipitation is generally agreed to be the main driver of large-scale variability in monthly, seasonal, and annual streamflows (Ward and Trimble, 2004). In the study area a certain spatial homogeneity in the precipitation-runoff ratio at an annual scale can be deduced from the high value of the coefficient of determination ($R^2 = 0.8$; p value < 0.001) obtained in the linear regression (Eq. (1)) between annual precipitation (YP, mm) and annual runoff (YR, mm) (Fig. C1). The regression includes all data collected during the study period in the 20 catchments listed in Table 1, which constitutes 182 pairs of data (some pairs are not included in the analysis due to missing data) and has a high level of significance. Thus, precipitation explains a high percentage of the variability in annual runoff (80 %). There is also a significant correlation between annual precipitation and median, high, and low flows, with coefficients of determination of 0.75, 0.62 and 0.54 (p values <0.001), respectively.

Conversely, the relationships between precipitation and hydrological indicators related to variability (CV, at all time-scales), timing (JY of the beginning of low flows, JY10m), and frequency (skn) show very low coefficients of determination (<0.25) at an annual scale, and less than 0.1 at the seasonal scale in the case of the coefficient of variation. The significance of the relationship between seasonal precipitation and seasonal median, high, and low flows is lower than that at the annual scale: the coefficient of determination is greater than 0.5 (p values <0.001) for median flows in spring and summer (Sp50m and Su50m; $R^2 = 0.58$ and 0.56, respectively), high flows in autumn and winter (A90m and W90m; $R^2 = 0.50$ and 0.55, respectively), and low flows in spring and summer (Sp10m and Su10m; $R^2 = 0.5$ and 0.51, respectively) (Figs. C2, C3, C4).

4.2 Effect of land cover on median discharge

Figure 2a shows results of the multiple regression, defined in Eq. (2), between alternative land covers, annual precipitation amounts, and median annual discharge as a hydrological index. The three land cover types are significant (p values < 0.05) and precipitation is significant in interactions with all land covers (p values < 0.1). This indicates that the degree of influence of precipitation is contingent on the specific land cover. The coefficient of determination is 0.78, indicating that the model fits the data well.

The results shown in Table 4 are expressed as the percentage change in the hydrological index with respect to the results obtained for the base land cover (combination 0) for low and high YP. The variations are highly conditioned by annual precipitation, both in terms of the percentage change and whether the change was positive or negative. Median annual discharge

(Y50m) increases when a decrease in exotic plantations is accompanied by an increase in pasturelands (combinations 1 and 4), by as much as 44 % and 67 % for low and high annual precipitation amounts, respectively. Conversely, replacing exotic plantations with native forests (combinations 2 and 3) has a slightly negative impact on median discharge for low precipitation amounts (up to 18 %) while for higher precipitation amounts median discharge increases (up to 24 %). Further, increases in median discharge are higher with higher annual precipitation amounts. The magnitude of the observed change is similar to that reported by Farley et al. (2005) for catchments located in northern Europe and higher than those obtained from hydrological modelling by Carvalho-Santos et al. (2016) and Morán-Tejeda et al. (2014) for catchments in the Iberian Peninsula.

Hence in the study area, greater forest cover may result in lower annual water yields. Similarly, numerous studies have shown that replacement of forest by grasslands leads to increased annual water yields, while afforestation processes can decrease annual yields (e.g., Bosch and Hewlett, 1982; Brown et al., 2005; Brogna et al, 2017). Additionally, as annual precipitation amounts increase, this effect becomes clearer in the case of exotic plantations (Fig. 2). Forest plantation species have been selected for rapid early growth, which has high associated water consumption (Farley et al., 2005); maximizing timber production generally involves harvesting trees before their growth slows, that is, before their water consumption starts to decrease. Current forest management of cultivated plantations in the study area involves clearcutting with rotations of around 30 years. Conversely, native forests, established for other purposes, may be left to mature and hence will tend to exhibit lower water consumption (van Dijk and Keenan, 2007) and have reduced interception losses during the leafless period (autumn-winter).

Alternative land covers seem to have little significant effect on median discharge during autumn, winter, and summer, as the coefficients for land covers obtained in the multiple regressions are not significant (not shown). Nevertheless, the inclusion of land cover is important for median spring discharge (Table 6), with effects similar to those observed for median annual discharge (Y50m). Regression results shown in Fig. 3b indicate that native forests, pasturelands, and precipitation in interactions with both types of land cover are significant (p values <0.05). The percentage of exotic plantations in the catchment significantly influences the median discharge in the spring. The coefficient of determination for this graph is 0.63, indicating a good fit.

Decreasing the percentage of exotic plantations (by increasing pasturelands or native forests) increases spring discharge under high precipitation amounts (Sp50m). The magnitude of this increase is larger when the extension of pasturelands is larger (combinations 1 and 4). At low precipitation rates, the positive effect of pasturelands on Sp50m remains, while increasing native forest (combinations 2 and 3) has a negative effect on median discharge.

The base land cover combination used in Table 3 (with the highest percentage of exotic plantations) is associated with the least change in median discharge indices across the precipitation gradient (combination 0, Fig. 2): Y50m and Sp50m vary from about 2–3 L s^{-1} km^{-2} for annual and seasonal precipitation amounts around 1000 and 400 mm, respectively, to about 20 L s^{-1} km^{-2} for precipitations around 2000 and 1000 mm, respectively. Conversely, land cover combinations 3 and 4 (with the highest percentage of native forests and pasturelands, respectively, and lowest percentage of exotic plantations) show the highest variation in Y50m and Sp50m in the precipitation gradient existing in the study area. Consequently, the land cover combination that gives the highest or lowest median discharge values changes with annual and seasonal precipitation amounts. This fact must be kept in mind in an area with a steep precipitation gradient under current and future climate change scenarios.

4.3 Effect of land cover on high flows

As shown in Table 4, an increase in high flows (Y90m) can be observed at low precipitation amounts, as the percentage of exotic plantations decreases and native forests (combination 3) or pasturelands (mainly, combination 4) increases. The increase in Y90m seems to be similar to the increase in native forest or in pastureland. For higher precipitation amounts, Y90m changes little with land cover, with the observed changes being negative in all cases. Considering changes in Y90m across the precipitation gradient for different land cover combinations (Fig. 3a), the base land cover combination (the one with the highest percentage of exotic plantations) exhibits the lowest Y90m for low annual precipitation, but it is also the one with the steepest slope; hence, it is the combination that yields the highest Y90m results for higher precipitation. Conversely, combination 4, with the lowest percentage of exotic plantations considered (10 %), a moderate percentage of native forest (31 %), and high percentage of pastureland (59 %) exhibits the highest Y90m for low precipitation amounts and the lowest Y90m for higher ones. This indicates that the potential of forests to reduce high flows decreases as annual precipitation increases (Fig 3a), and therefore, in the area studied, when high annual precipitation is considered, this potential is quite low. Robinson et al., 2003 found that, under realistic forest management procedures, the potential for forests to reduce peak flows in Europe was lower than usually claimed.

Similar conclusions can be reached from seasonal data analysis. Land cover coefficients are significant only for the winter period; during autumn, spring, and summer, land cover does not appear as a significant variable influencing the magnitude of high flows. For winter (W90m), results differ depending on precipitation (in this case considered as the sum of winter and previous autumn precipitation). Under low precipitation amounts, W90m increases (up to 31 %) in combinations (e.g., cases 3 and 2) where the decrease in exotic plantations is compensated for mainly by an increase in native forests (Table 5). This implies that high flows are attenuated under land cover combinations with high percentages of exotic plantations, which is favourable for flood regulation (Carvalho-Santos et al., 2016). Under high precipitation amounts, the situation remains practically unchanged for all land cover combinations.

4.4 Effect of land cover on low flows

With regard to satisfying aquatic ecosystem or socio-economic water demands, and, in turn, the ecological status of water bodies (European Commission, 2000), it is important to consider low flow values. For annual low flows, a small variation in Y10m (Table 4) was observed when the percentage of pasturelands increases at the expense of exotic plantations (combination 1), and a decrease in Y10m (up to 50 %) in combination 3 with 66 % of native forests under the lowest annual precipitation amount. In contrast, for higher YP values, the land cover combination with the higher percentage of exotic plantations (combination 0) is one of the combinations with the lowest Y10m. Under high precipitation amounts (Table 4), low flows exhibit least change when decreases in exotics are compensated for by increases in native forests (combinations 2, 3, 5) and

Y10m increases when exotic plantations decrease and pasturelands increase (combinations 1, 4). Therefore, in line with the findings of Brogna et al., (2017), this study shows exotic plantations have a slightly positive effect on low flows under low annual precipitation amounts; with annual precipitation of less than 700 mm, other land covers provide smaller values of Y10m than the base combination. These positive effects disappear, however, under higher annual precipitation regimes. The positive effects of forests on base flow, strongly related to annual low flows, have been associated with better infiltration of forested soils (Price, 2011), while negative effects have been linked to higher evapotranspiration rates (Hicks et al., 1991).

During winter, low flows (W10m) increase as exotic forests decrease in all land cover combinations and as native forests (combination 3) or pasturelands (combination 4) increase; the increase for W10m is greater with higher precipitation amounts (Table 5). During spring, native forests (combinations 2, 3) seem to have a negative effect (up to 87 %) on Sp10m when precipitation is low, but this negative effect disappears in areas with higher precipitation (Table 6). Greater pastureland (combinations 1 and 4) positively affects springtime low flows under low and high precipitation rates by as much as 90 %. Land cover combination 3, which has the highest percentage of native forests (66 %) shows the greatest change in Y10m across the precipitation gradient of the study area (Table 4, Fig. 3b), while catchments with high percentages of exotic plantations (combination 0), show the least change in low flows across the precipitation gradient.

No statistically significant influences were observed on median, high, or low autumn and summer flows or on other hydrological indices related to the timing of low flows or other changes to the hydrograph; however, this does not rule out the possibility of relationships between land cover and the hydrological indices. As shown in Appendix C, precipitation (volume and distribution) is the main driver of the system, and thus the influence of other drivers, such as land cover, may fail to emerge as statistically significant.

Further study is needed in the Bay of Biscay area to determine how the characteristics of specific tree species (e.g., their phenology and physiology) affect various components of the hydrological cycle. Analyses are also needed to establish the relationship between forest types, land management issues and soil development. For instance, clearcutting of exotic species in the study area is usually accompanied by harvesting with chainsaws, skidding, and mechanical site preparation (prior to replanting) such as scarification and ripping (Gartzia-Bengoetexea et al., 2009). These logging operations alter the physical properties of soil, affecting processes such as infiltration, evapotranspiration, percolation, and lateral flow, and in turn, catchment water balance and temporal distribution river discharge. A deepened understanding of those relationships will help achieve a solid understanding of how trees characteristics, forest types and management strategies, and soil properties influence water flows.

5 Conclusions

This study identifies the relationships among different land cover combinations (forests–native and exotic–and pasturelands) and hydrological services in an area with a steep precipitation gradient (900–2600 mm yr^{-1}). Annual and seasonal hydrological indices were estimated using discharge data from 20 catchments in the Bay of Biscay area. Results indicate that precipitation has a significant positive impact on median, high, and low flows and is the main driver of annual and seasonal discharge. That strong influence may obscure the relationship between land cover and the hydrological responses of catchments in high precipitation gradient areas. From a policy-making perspective, it is important to assess how land cover changes affect streamflows, as these changes are strongly influenced by human intervention (e.g., through land use planning or public policies to enhance certain land uses and constrain damaging practices, etc.).

Unravelling the effects of land cover on hydrological services is especially important in a climatic transition zone like the Bay of Biscay (Meaurio et al., 2017), which is characterised by a steep precipitation gradient and is subject to the uncertain effects of climate change in terms of magnitude and temporal distribution of precipitation projections. In this regard, the methodology developed in this study to deal with the interactions between the two drivers (i.e., precipitation and land cover) increases the understanding of how various land cover combinations affect hydrological services across an entire precipitation gradient.

Conclusions about the effect of each land cover combination cannot be drawn without considering the amount of precipitation. However, results show that in the Bay of Biscay area, the presence of any kind of forest decreases annual water resources (Y50m), and this effect is more evident with exotic plantations as the annual precipitation increases. Similar to studies by Robinson et al. (2003), this study indicates that the potential for forests to reduce peak flows is lower than usually claimed; however, the effect of land cover on high flows also changes with precipitation. For low precipitation amounts, forests, especially exotic plantations, show greater potential to reduce annual and wintertime high flows than pasturelands, but this potential decreases as annual or seasonal precipitation increases. Moreover, when high annual precipitation is considered, the potential of exotic plantations to reduce high flows is lower than that of native forests or pasturelands. The results also show that exotic plantations have a slight positive effect on annual low flows under low annual precipitation conditions; however, low flows increase as annual precipitation increases and when exotic forests are replaced by pasturelands. This effect is most evident in winter and spring, and when the combination of pasturelands and native forests account for most of the catchment area.

Results from in this study show that a trade-off among the different hydrological services may emerge as a result of changes in land cover, and that such services are highly dependent on the amount of precipitation. Hence, to design appropriate water management policies (e.g., to ensure the provision of water resources or to avoid the impact of extreme events), policy-makers need to focus on catchment-scale measures that consider the effect of land cover on hydrological services across a precipitation gradient. There simply is no unique “best combination” for all locations and all services. This is especially relevant under a climate change scenario, as precipitation projections remain largely uncertain both in magnitude and direction (e.g., positive or negative changes). It is time for land planning and forest policies to place water at the centre of the decision-making agenda.

ACKNOWLEDGEMENTS

This research was supported by the Basque Government (Consolidated Groups IT1029/16, IT-642-13) and the Spanish Ministry of Economy and Competitiveness (ECO2017-82111-R). Eneko Garmendia acknowledges financial support from

SOSTEPASTOS project (MIMECO AGL2013-48361-C2-1-R). The authors would like to thank Iñaki Aizpuru for his help with land cover data and the Environment and Hydraulic Work Department of the Gipuzkoa Provincial Council for providing hydrologic data series.

References

Ainz Ibarrondo, M. J.: The monoculture of radiata pine in the Basque Country: origin and keys of the survival of a system of exploitation in opposite with sustainable development, Estudios Geográficos, 265, 335–356, doi:10.3989/estgeogr.0426, 2008.

Andréassian, V.: Waters and forests: from historical controversy to scientific debate, J. Hydrol., 291, 1–27, doi:10.1016/j.jhydrol.2003.12.015, 2004.

Banfield, C. C., Braun, A. C., Barra, R., Castillo, A., and Vogt, J.: Erosion proxies in an exotic tree plantation question the appropriate land use in Central Chile, Catena, 161, 77–84. doi:10.1016/j.catena.2017.10.017, 2018

Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P. Eds.: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp, 2008.

Bauman, K. A., Gretchen, C. D., Duarte, T. K., and Mooney, H. A.: The nature and value of ecosystem services: an overview highlighting hydrologic services, Annu. Rev. Environ. Resour., 32, 6.1–6.32, doi:10.1146/annurev.energy.32.031306.102758, 2007.

Bosch, J. M., and Hewlett, J. D.: A review of catchment experiment to determine the effect of vegetation changes on water yield and evapotranspiration, J. Hydrol., 55, 3–23, doi:10.1016/0022-1694(82)90117-2, 1982.

Brogna, D., Vincke, C., Brostaux, Y., Soyeurt, H., Dufrêne, M., and Dendoncker, N.: How does forest cover impact water flows and ecosystem services? Insights from "real-life" catchments in Wallonia (Belgium), Ecol. Indic., 72, 675–685, doi:10.1016/j.ecolind.2016.08.011, 2017.

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., and Vertessy, R. A.: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, J. Hydrol., 310, 28–61, doi:10.1016/j.jhydrol.2004.12.010, 2005.

Calder, I. R.: Blue Revolution: Integrated Land and Water Resource Management, 2nd edition Earthscan, London, 382 pp., 2005.

Calder, I. R., Rosier, P. T. W., Prasanna, K. T., and Parameswarappa, S.: Eucalyptus water use greater than rainfall input a possible explanation from southern India, Hydrol. Earth Syst. Sci., 1, 249–256, doi:10.5194/hess-1-249-1997, 1997.

Carrascal, M.: Estructura de las comunidades de aves de las repoblaciones de Pinus radiata del País Vasco, Munibe (Ciencias Naturales), 38, 3–8, 1986.

Carvalho-Santos, C., Nunes, J. P., Monteiro, A. T., Hein, L., and Honrado, J. P.: Assessing the effects of land cover and future climate conditions on the provision of hydrological services in a medium-sized watershed of Portugal, Hydrol. Process., 30, 720–738, doi:10.1002/hyp.10621, 2016.

Delzon, S., and Loustau, D.: Age-related decline in stand water use: sap flow and transpiration in a pine forest chronosequence, Agric. For. Meteorol., 129, 105–119, doi:10.1016/j.agrformet.2005.01.002, 2005.

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., van Noordwijk, M., Creed, I. F., Pokorny, J., Gaveau, D., Spracklen, D. V., Bargués Tobella, A., Ilstedt, U., Teuling, A. J., Gebreyohannis Gebrehiwot, S., Sands, D. C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., and Sullivan, C. A.: Trees, forests and water: Cool insights for a hot world, Global Environ. Change., 43, 51–61, doi:10.1016/j.gloenvcha.2017.01.002, 2017.

Enters, T., and Durst, P.(Eds.): What Does It Take? The Role of Incentives in Forest Plantation Development in the Asia-Pacific Region. FAO RAP Publication 2004/27, FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, 2004.

European Commission: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy, Off. J. Eur. Communities, 2000.

EVE (Ente Vasco de la Energía) [BasqueEnergy Agency]. 1990. Mapa geológico simplificado del País Vasco. Escala 1:40000. EVE: Bilbao.

FAO: Guidelines for Soil Profile Description. Food and Agriculture Organization of the United Nations, Rome, Italy, 1977.

FAO: Global Forest Resources Assessment 2015: How Are the World's Forests Changing? 2nd Ed., Food and Agriculture Organization of the United Nations, Rome, Italy, 2016.

Farley, K. A., Jobbágy, E. G., and Jackson, R. B.: Effect of afforestation on water yield: a global synthesis with implications for policy, Global Change Biol., 11, 1565–1576, doi:10.1111/j.1365-2486.2005.01011.x, 2005.

Fidelis, T., and Roebeling, P.: Water resources and land use planning systems in Portugal—Exploring better synergies through Ria de Aveiro, Land Use Policy, 39, 84–95, doi:10.1016/j.landusepol.2014.03.010, 2014.

Gallart, F., and Llorens, P.: Catchment management under environmental change: Impact of land cover change on water resources, Water Int., 28 (3), 334–340, doi:10.1080/02508060308691707, 2003.

Gallart, F., and Llorens, P.: Observations on land cover changes and water resources in the headwaters of the Ebro catchment, Iberian Peninsula, Phys. Chem. Earth, 29, 769–773, doi:10.1016/j.pce.2004.05.004, 2004.

Garmendia, E., Mariel, P., Tamayo, I., Aizpuru, I., and Zabaleta, A.: Assessing the effect of alternative land uses in the provision of water resources: evidence and policy implications from southern Europe, Land Use Policy, 29(4), 761–770, doi:10.1016/j.landusepol.2011.12.001, 2012.

Gartzia-Bengoetxea, N., Gonzalez-Arias, A., Kandeler, E., and Martínez de Arano, I.: Potential indicators of soil quality in temperate forest ecosystems: a case study in the Basque Country, Ann. For. Sci., 66, 303, doi:010.1051/forest/2009008, 2009.

Hicks, B.J., Beschta, R.L., and Harr, R.D.: Long-term changes in streamflow following logging in western oregon and associated fisheries implications, J. Am. Water Resour. Assoc., 27, 217–226, doi:10.1111/j.1752-1688.1991.tb03126.x, 1991.

Hirsch, F., Clark, D., and Vihervaara, P.: Payments for Forest related Ecosystem Services: What Role for a Green Economy? Background Paper for the Workshop on Payments for Ecosystem Services, UNECE/FAO Forestry and Timber Section, Geneva, 2011.

http://www.mapama.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/, last access: 18 January 2018.

Huber, A., Iroumé, A., and Bathurst, J.: Effect of *Pinus radiata* plantation on water balance in Chile, Hydrol. Process., 22, 142–148, doi:10.1002/hyp.6582, 2008.

IFN3, 2005. www.euskadi.eus/inventario-forestal-cae-2005/web01-a3estbin/es/, last access: 29 November 2017.

IFN4, 2011. http://www.euskadi.eus/inventario-forestal-2011/web01-a3estbin/es/, last access: 29 November 2017.

Iroumé, A., and Huber, A.: Comparison of interception losses in a broadleaved native forest and a *Pseudotsuga menziesii* (Douglas fir) plantation in the Andes mountains of southern Chile, Hydrol. Process., 16 (12), 2347–2361, doi:10.1002/hyp.1007, 2002.

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., Maitre, B. A., le McCarl, D. C., Murray, B. A., and Murray, B. C.: Trading water for carbon with biological carbon sequestration, Science, 310, 1944–1947, doi:10.1126/science.1119282, 2005.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., and Cerdà, A.: The superior effect of nature based solutions in land management for enhancing ecosystem services, Sci. Total Environ., 610–611, 997–1009, doi:10.1016/j.scitotenv.2017.08.077, 2018.

Kuczera, G.: Prediction of water yield reductions following a bushfire in ash mixed species eucalypt forest, J. Hydrol., 94, 215–236, doi:10.1016/0022-1694(87)90054-0, 1987.

Lara, A., Little, C., Urrutia, R., McPhee, J., Álvarez-Garretón, C., Oyarzún, C., Soto, D., Donoso, P., Nahuelhual, L., Pino, M., and Arismendi, I.: Assessment of ecosystem services as an opportunity for the conservation and management of native forest in Chile, For. Ecol. Manage., 258, 415–424, doi:10.1016/j.foreco.2009.01.004, 2009.

Little, C., Lara, A., McPhee, J., and Urrutia, R.: Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile, J. Hydrol., 374, 162–170, doi:10.1016/j.jhydrol.2009.06.011, 2009.

Li, Q., Wei, X., Zhang, M., Liu, W., Fan, H., Zhou, G., Giles-Hansen, K., Liu, S., and Wang, Y.: Forest cover change and water yield in large forested watersheds: A global synthetic assessment, Ecohydrology. doi:10.1002/eco.1838, 2017.

Liu, H. L., Bao, A. M., Pan, X. L., and Chen, X.: Effect of land-use change and artificial recharge on the groundwater in an arid inland river basin, Water Resour. Manage., 27, 3775–3790. doi:10.1007/s11269-013-0380-6, 2013.

Liu, Y., Xiao, J., Ju, W., Xu, K., Zhou, Y., and Zhao, Y.: Recent trends in vegetation greenness in China significantly altered annual evapotranspiration and water yield, Environ. Res. Lett., 11, 094010, doi:10.1088/1748-9326/11/9/094010, 2016.

Locatelli, B., Catterall, C. P., Imbach, P., Kumar, C., Lasco, R., Marín-Spiotta, E., Mercer, B., Powers, J. S., Schwartz, N., and Uriarte, M.: Tropical reforestation and climate change: beyond carbon., Restor. Ecol., 23, 337–343, doi:10.1111/rec.12209, 2015.

Locatelli, B., Fedele, G., Fayolle, V., and Baglee, A.: Synergies between adaptation and mitigation in climate change finance, Int. J. Clim. Change Strategies Manage., 8, 112–128, doi:10.1108/IJCCSM-07-2014-0088, 2016.

López-Moreno, J. I., Vicente-Serrano, S. M., Morán-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., and García-Ruíz, J. M.: Impact of climate evolution and land-use changes on water yield in the Ebro basin, Hydrol. Earth Syst. Sci., 15, 311–322, doi:10.5194/hess-15-311-2011, 2011.

MAGRAMA: Cuarto Inventario Forestal Nacional. Comunidad Autónoma del País Vasco / Euskadi. Ed.: Ministerio de Agricultura, Alimentación y Medio Ambiente, Secretaría General Técnica, Centro de Publicaciones, Madrid. 59 pp. ISBN: 978-84-491-1293-5, 2013.

Meaurio, M., Zabaleta, A., Boithias, L., Epelde, A. M., Sauvage, S., Sanchez-Perez, J. M., Srinivasan, R., and Antiguedad, I.: Assessing the hydrological response from an ensemble of CMIP5 climate projections in the transition zone of the Atlantic region (Bay of Biscay), J. Hydrol., 548, 46–62, doi:10.1016/j.jhydrol.2017.02.029, 2017.

Morán-Tejeda, E., Ceballos-Barbancho, A., Llorente-Pinto, J.M., and López-Moreno, J.I.: Land-cover changes and recent hydrological evolution in the Duero Basin (Spain), Reg. Environ. Change, 12, 17–33, 2012.

Morán-Tejeda, E., Zabalza., J, Rahman, K., Gago-Silva, A., Ignacio López-Moreno, J., Vicente-Serrano, S., Lehmann, A., Tague, C. L., and Beniston, M.: Hydrological impacts of climate and land use changes in a mountain watershed: uncertainty estimation based on model comparison, Ecohydrology, doi:10.1002/eco1590, 2014.

Nadal-Romero, E., González-Hidalgo, J. C., Cortesi, N., Desir, G., Gómez, J. A., Lasanta, T., Lucía, A., Marín, C., Martínez-Murillo, J. F., Pacheco, E., Rodríguez-Blanco, M. L., Romero Díaz, A., Ruiz-Sinoga, J. D., Taguas, E. V., Taboada-Castro, M. M., Taboada-Castro, M. T., Úbeda, X., and Zabaleta, A.: Relationship of runoff, erosion and sediment yield to weather types in the Iberian Peninsula. Geomorphology, 228, 372–381, doi:10.1016/j.geomorph.2014.09.011, 2015.

Neary, D. G., Ice, G. G., and Jackson, C. R.: Linkages between forest soils and water quality and quantity, For. Ecol. Manage., 258, 2269–2281, doi:10.1016/j.foreco.2009.05.027, 2009.

Olden, J. D., and Poff, N. L.: Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Res. Appl., 19 (2), 1535–1467, doi:10.1002/rra.700, 2003.

Price, K.: Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review, Prog. Phys. Geogr. 35, 465–492, doi:10.1177/0309133311402714, 2011.

Rind, D., Goldberg, R., Hansen, J., Rosenzweig, C., and Ruedy, R.: Potential evapotranspiration and the likelihood of future drought., J. Geophys. Res. Atmos., 95, 9983–10004, doi:10.1029/JD095iD07p09983, 1990.

Ritcher, B. D., Baumgartner, J. V., Powell, J., and Braun, D. P.: A method for assessing hydrologic alteration within ecosystem, Conserv. Biol., 10, 1163–1174, doi.org/10.1046/j.1523-1739.1996.10041163.x, 1996.

Robinson, M., Cognard-Plancq, A. -L., Cosandey, C., David, J., Durand, P., Führer, H. -W., Hall, R., Hendriques, M. O., Marc, V., McCarthy, R., McDonnell, M., Martin, C., Nisbet, T., O'Dea, P., Rodgers, M., and Zollner, A.: Studies of the impact of forests on peak flows and baseflows: a European perspective, Forest Ecol. Manage., 186 (1–3), 85–97, doi:10.1016/S0378-1127(03)00238-X, 2003.

Ruiz Urrestarazu, E.: Adaptación y gestión de las medidas agroambientales y de forestación en el País Vasco in Corbera, M. (Ed.) Cambios en los espacios rurales cantábricos tras la integración de España en la UE, Santander, Universidad de Cantabria, 1999.

Schilling, K. E., and Libra, R. D.: Increased baseflow in Iowa over the second half of the 20th century, J. Am. Water Resour. Assoc., 39, 851–860, doi:10.1111/j.1752-1688.2003.tb04410.x, 2003.

Schirmer, J., and Bull, L.: Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects, Global Environ. Change., 24, 306–320, doi:10.1016/j.gloenvcha.2013.11.009, 2014.

Scott, D. F., and Prinsloo, F. W.: Longer-term effects of pine and eucalypt plantations on streamflow, Water Resour. Res., 44, W00A08, doi:10.1029/ 2007wr006781, 2008.

Tomer, M. D., and Schilling, K. E.: A simple approach to distinguish land-use and climate change effects on watershed hydrology, J. Hydrol., 376, 24–33, doi:10.1016/j.jhydrol.2009.07.029, 2009.

Trabucco, A., Zomer, R. J., Bossio, D. A., van Straaten, O., and Verchot, L. V.: Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies, Int. Agric. Ecosyst. Environ., 126, 81–97, doi:10.1016/j.agee.2008.01.015, 2008.

van Dijk, A. I. J. M., and Keenan, R. J.: Planted forests and water in perspective, Forest Ecol. Manage., 251 (1–2), 1–9, doi:10.1016/j.foreco.2007.06.010, 2007.

Vertessy, R. A., Watson, F.G.R., and O'Sullivan, S. K.: Factors determining relations between stand age and catchment water balance in mountain ash forests. Forest Ecol. Manage., 143, 13–26, doi:10.1016/S0378-1127(00)00501-6, 2001.

Ward, A. D., and Trimble, S. W.: Environmental Hydrology, 2nd ed., Lewis Publishers/CRC Press Company, London/New York, p. 472, 2004.

Zabaleta, A., Antiguedad, I., Barrio, I., and Probst, J. -L.: Suspended sediment delivery from small catchments to the Bay of Biscay. What are the controlling factors?, Earth Surf. Process. Landforms, 41, 1894–1910, doi: 10.1002/esp.3957, 2016.

Tables

Table 1. Catchment descriptions.

Code	Catchment	Catchment area (km^2)	Primary Cover Types (%)							
			2002				2009			
			Forest Cover			Pasture Cover	Forest Cover			Pasture Cover
			Native	Exotic	**Total**		Native	Exotic	**Total**	
A1Z1	San Prudentzio	121.78	21	49	**70**	24	21	46	**67**	26
A1Z2	Oñati	105.78	27	46	**73**	25	27	45	**72**	26
A1Z3	Urkulu	9	43	14	**57**	42	47	10	**57**	42
A2Z1	Aixola	5.03	6	76	**82**	12	7	73	**80**	15
A3Z1	Altzola	464.25	19	52	**71**	23	20	50	**70**	24
B1T1	Barrendiola	3.8	48	18	**66**	0	48	18	**66**	0
B1Z1	Aitzu	56.13	19	56	**75**	18	19	55	**74**	19
B1Z2	Ibai-Eder	62.73	25	53	**78**	20	25	53	**78**	20
B2Z1	Aizarnazabal	269.77	19	50	**69**	26	20	49	**69**	26
C1P3	Arriaran	2.77	24	62	**86**	12	24	62	**86**	12
C1Z2	Estanda	55.02	16	54	**70**	23	17	52	**69**	24
C2Z1	Agauntza	69.64	57	24	**81**	18	57	23	**80**	18
C5Z1	Alegia	333.34	30	39	**69**	27	30	36	**66**	29
C7Z1	Berastegi	33.34	25	35	**60**	38	25	34	**59**	37
C8Z1	Leitzaran	110.01	39	39	**78**	20	46	33	**79**	20
C9Z1	Lasarte	796.5	32	34	**66**	30	33	31	**64**	31
D1W1	Añarbe	47.69	66	19	**85**	15	66	19	**85**	15
D2W1	Ereñozu	218.42	48	30	**78**	21	50	27	**77**	21
E1W1	Oiartzun	56.6	26	33	**59**	35	31	28	**59**	35
F1W1	Endara	6.19	15	53	**68**	32	15	53	**68**	32

Note: Only forest (native and exotic) or pasture land covers are shown. Other types of land cover are not shown as they are usually less than 10 %, except for Barrendiola catchment where about 30 % of the catchment is bare rock.

Table 2. Statistics of hydrological indices, land cover types, and precipitation amounts used in this study. See the text for abbreviation meaning.

	Index	Mean	s.d.	Min	Max
Hydrologic indices	YR, mm	839	320	246	1873
	Y10m, L s^{-1} km^{-2}	4.93	4.40	0.14	28.22
	A10m, L s^{-1} km^{-2}	6.90	7.75	0.28	67.48
	W10m, L s^{-1} km^{-2}	13.55	10.31	1.91	90.89
	Sp10m, L s^{-1} km^{-2}	8.42	6.63	0.34	36.18
	Su10m, L s^{-1} km^{-2}	4.41	4.42	0.02	36.22
	Y50m, L s^{-1} km^{-2}	14.68	9.72	2.71	58.98
	A50m, L s^{-1} km^{-2}	18.94	16.63	2.18	118.74
	W50m, L s^{-1} km^{-2}	27.22	15.63	5.59	125.77
	Sp50m, L s^{-1} km^{-2}	17.50	12.29	2.85	66.43
	Su50m, L s^{-1} km^{-2}	6.22	6.26	0.21	49.69
	Y90m, L s^{-1} km^{-2}	59.81	24.62	15.27	153.27
	A90m, L s^{-1} km^{-2}	74.40	45.14	7.22	217.21
	W90m, L s^{-1} km^{-2}	87.18	34.28	17.38	190.39
	Sp90m, L s^{-1} km^{-2}	49.17	24.24	7.61	113.48
	Su90m, L s^{-1} km^{-2}	12.54	16.09	0.8	120.83
	CVY	1.54	0.42	0.63	3.02
	CVA	1.40	0.59	0.17	3.08
	CVW	1.11	0.41	0.15	2.44
	CVSp	1.17	0.53	0.36	3.54
	CVSu	0.79	0.60	0.1	3.95
	skn	4.57	2.00	0.92	12.43
	JY10m	251	46	52	343
Land cover	Forest, %	72	8	56	85
	Native, %	31	15	6	66
	Exotic, %	41	16	10	76
	Pasturelands, %	23	9	0	42
	Others, %	5	7	0	34
Precipitation	YP, mm	1538	345	958	2611
	AP + SuP, mm	776	228	323	1681
	WP + AP, mm	975	253	441	1874
	SpP + WP, mm	767	171	402	1406
	SuP + SpP, mm	560	179	285	1146

Table 3. Percentage of different land cover types for each land cover combination. Note that base land cover combination in the text refers to combination (0).

Land use combination	0	1	2	3	4	5
Exotic (%)	76	40.8	40.8	10	10	40.8
Native (%)	6	6	41.2	66	30.84	30.84
Pasture (%)	18	53.2	18	24	59.16	28.36

Table 4. Results obtained, from multiple regression models, in the variation in percentage with respect to the base land cover combination (0) in the annual median, high and low flows with land cover for low and high precipitation amounts.

		Result for base land cover (L s^{-1} km^{-2})	Differences from base land cover					Result for base land cover (L s^{-1} km^{-2})	Differences from base land cover				
		Low Annual Precipitation (1279 mm)						High Annual Precipitation (1719 mm)					
	Combination	0	1	2	3	4	5	0	1	2	3	4	5
Hydrologic differences	Y50m	7.81	44 %	–15 %	–18 %	41 %	2 %	14.59	52 %	9 %	24 %	67 %	22 %
	Y90m	39.1	23 %	17 %	33 %	39 %	19 %	70.87	–11 %	–2 %	–5 %	–10 %	–3 %
	Y10m	2.93	–4 %	–31 %	–53 %	–27 %	–22 %	6.25	45 %	–9 %	–8 %	46 %	7 %

Note: Only results for regression with statistically significant coefficients for land cover variables and determination coefficient higher than 0.5 are included. Precipitation considered (1st and the 3rd quartiles of annual and seasonal) in each case is also included.

Table 5. Results obtained, from multiple regression models, in the variation in percentage with respect to the base land cover combination (0) in the winter high and low flows with land cover for low and high precipitation amounts.

		Result for base land cover (L s^{-1} km^{-2})	Differences from base land cover					Result for base land cover (L s^{-1} km^{-2})	Differences from base land cover				
		Precipitation = 814 mm (Winter + previous Autumn)						Precipitation = 1147 mm (Winter + previous Autumn)					
	Combination	0	1	2	3	4	5	0	1	2	3	4	5
Hydrologic differences	W90m	67.7	–5 %	18 %	31 %	8 %	12 %	106.34	–7 %	2 %	3 %	–6 %	–0.4 %
	W10m	8.5	19 %	21 %	39 %	37 %	21 %	10.94	42 %	40 %	75 %	77 %	41 %

Note: Only results for regression with statistically significant coefficients for land cover variables and determination coefficient higher than 0.5 are included. Precipitation considered (1st and the 3rd quartiles of annual and seasonal) in each case is also included.

Table 6. Results obtained, from multiple regression models, in the variation in percentage with respect to the base land cover combination (0) in the spring median and low flows with land cover for low and high precipitation amounts.

		Result for base land cover (L s^{-1} km^{-2})	Differences from base land cover					Result for base land cover (L s^{-1} km^{-2})	Differences from base land cover				
		Precipitation = 646 mm (Spring + previous Winter)						Precipitation = 852 mm (Spring + previous Winter)					
	Combination	0	1	2	3	4	5	0	1	2	3	4	5
Hydrologic differences	Sp50m	9.95	55 %	–32 %	–45 %	42 %	–6 %	15.6	56 %	15 %	35 %	76 %	27 %
	Sp10m	4.98	69 %	–58 %	–87 %	40 %	–20 %	8.12	77 %	0 %	13 %	90 %	22 %

Note: Only results for regression with statistically significant coefficients for land cover variables and determination coefficient higher than 0.5 are included. Precipitation considered (1st and the 3rd quartiles of annual and seasonal) in each case is also included.

Figure Captions

Figure 1. a) Location and digital terrain model of the study area with the main drainage network, location of gauging stations, catchments, and average precipitation values. b) Land cover map of the study area in 2002 and 2009.

Figure 2. Expected values of a) annual average flows (Y50m, L s^{-1} km^{-2}) and b) average discharge for spring (Sp50m, L s^{-1} km^{-2}) for the land cover combinations described in Table 3 and a gradient of precipitation, as a result of the multiple regression models shown in Appendix D (tables D1 and D2, respectively).

Figure 3. Expected values of a) annual high flows (Y90m, L s^{-1} km^{-2}) and b) low flows for spring (Sp10m, L s^{-1} km^{-2}) for the land cover combinations described in Table 3 and a gradient of precipitation, as a result of the multiple regression models shown in Appendix D (tables D3 and D4, respectively).

Appendix

Appendix A: Hydrographs for the 20 catchments in Table 1 for the hydrological year 2000–2001. The meaning of some of the calculated hydrological indicators is also indicated in the figure.

Appendix B: Boxplots representing the statistics of a) annual and b) seasonal precipitation for the 20 studied catchments during the hydrological years considered. A = Autumn, W = Winter, Sp = Spring and Sm = Summer.

Appendix C: Linear regressions obtained between a) annual precipitation (YP, mm) and runoff (YR, mm) b) precipitation from spring and winter (SpP + WP) and average discharge in spring (Sp50m) c) precipitation from winter and autumn (WP + AP) and wintertime high flows (W90m) and d) precipitation from spring and winter (SpP + WP) and low flows in spring (Sp10m).

Appendix D: Multiple regression models. a) Multiple regression model for annual average flows (Y50m) considering alternative land cover and its interaction with annual precipitation (YP). b) Multiple regression model for average discharge for spring (Sp50m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt). c) Multiple regression model for annual high flows (Y90m) considering alternative land cover and its interaction with annual precipitation (YP). d) Multiple regression model for low flows for spring (Sp10m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt).

Figure 1.

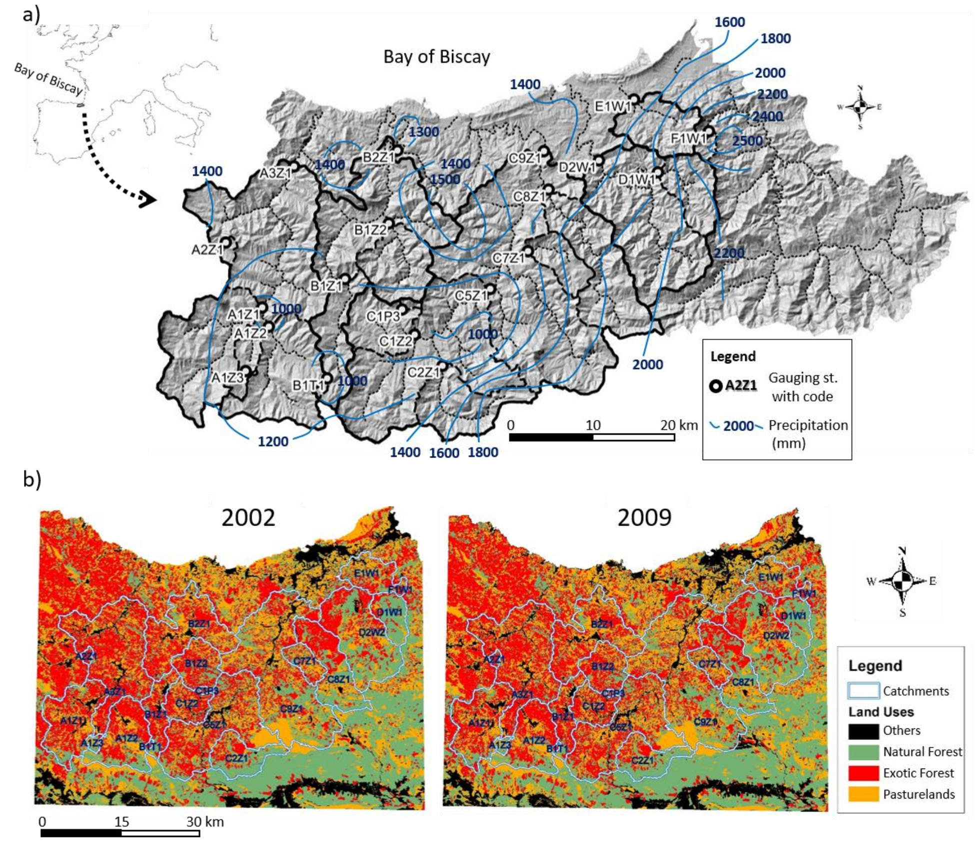

a)
Bay of Biscay
Bay of Biscay
1600
1800
2000
2200
2400
2500
1400
1300
1400
1400
1500
1400
1000
1000
1000
1200
1400
1600
1800
2000
2200
E1W1
F1W1
D2W1
D1W1
C9Z1
C8Z1
C7Z1
C5Z1
C1P3
C1Z2
C2Z1
B2Z1
B1Z2
B1Z1
B1T1
A3Z1
A2Z1
A1Z1
A1Z2
A1Z3
Legend
A2Z1 Gauging st. with code
2000 Precipitation (mm)
0
10
20 km
N
W
E
S
b)
2002
2009
Legend
Catchments
Land Uses
Others
Natural Forest
Exotic Forest
Pasturelands
0
15
30 km
N
W
E
S

Figure 2.

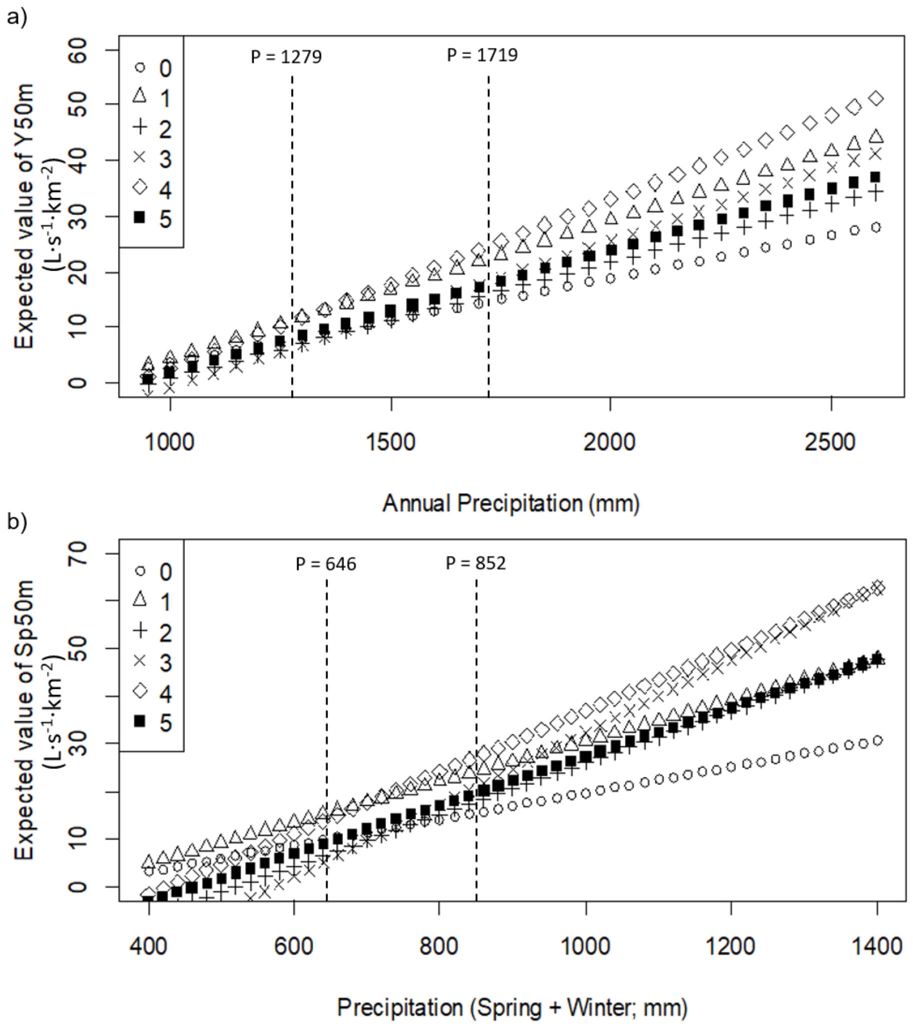
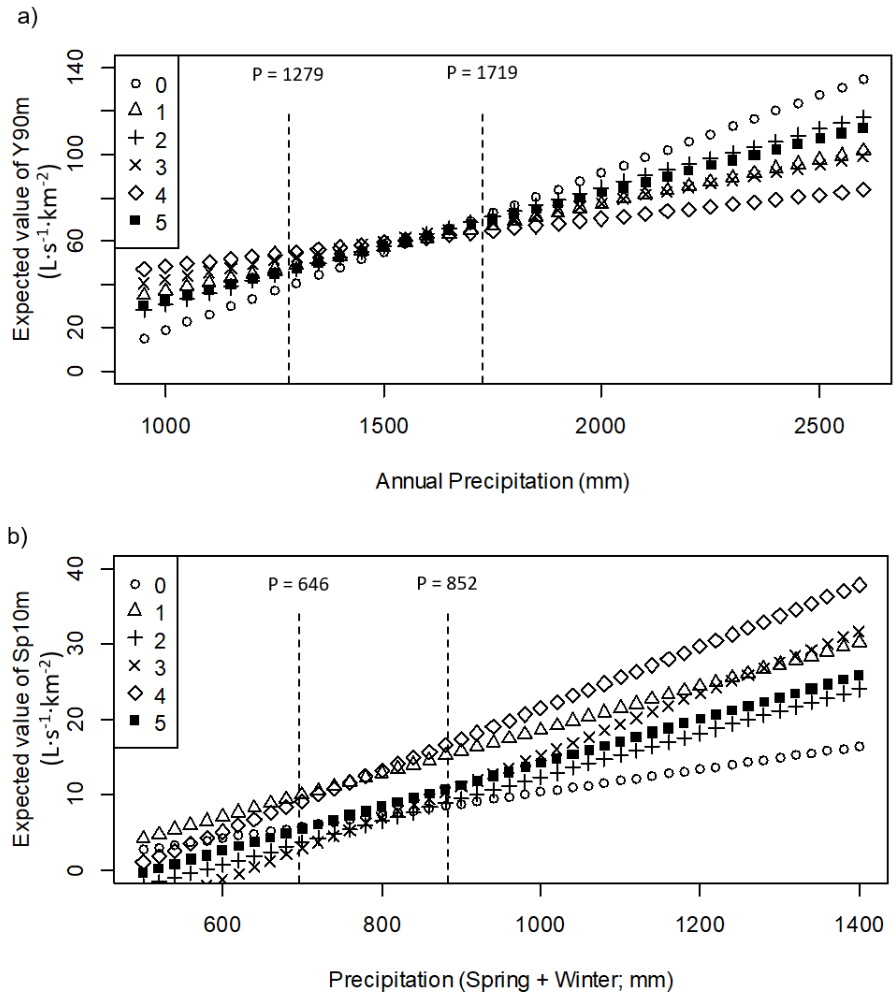
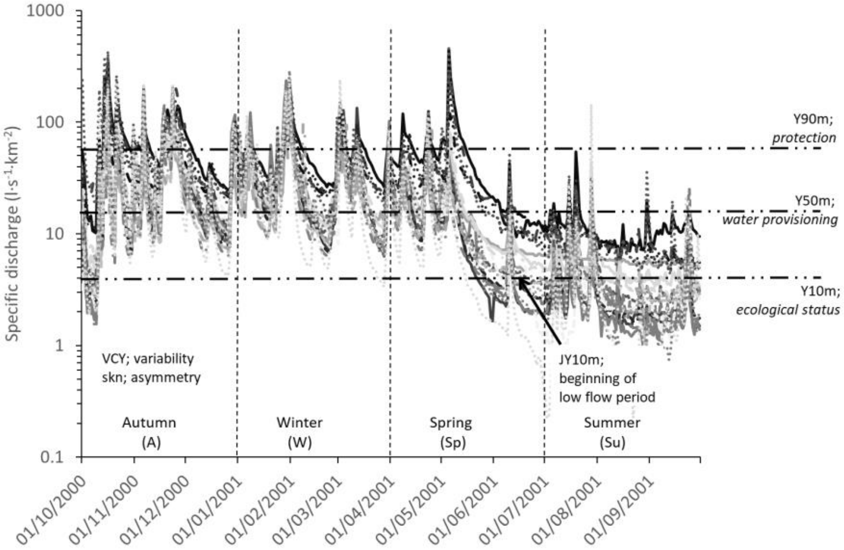

a)
Expected value of Y50m
(L·s⁻¹·km⁻²)
0
10
20
30
40
50
60
0
1
2
3
4
5
P = 1279
P = 1719
1000
1500
2000
2500
Annual Precipitation (mm)
b)
Expected value of Sp50m
(L·s⁻¹·km⁻²)
0
10
30
50
70
0
1
2
3
4
5
P = 646
P = 852
400
600
800
1000
1200
1400
Precipitation (Spring + Winter; mm)

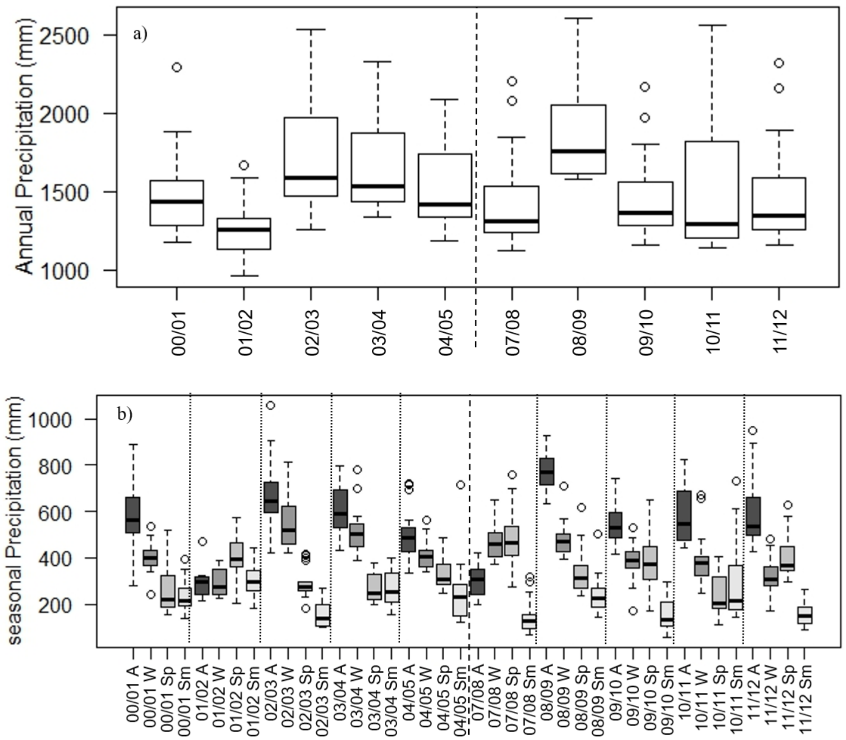
Figure 3.


a)
Expected value of Y90m
(L·s-1·km-2)
0
20
60
100
140
0
1
2
3
4
5
P = 1279
P = 1719
1000
1500
2000
2500
Annual Precipitation (mm)
b)
Expected value of Sp10m
(L·s-1·km-2)
0
10
20
30
40
0
1
2
3
4
5
P = 646
P = 852
600
800
1000
1200
1400
Precipitation (Spring + Winter; mm)

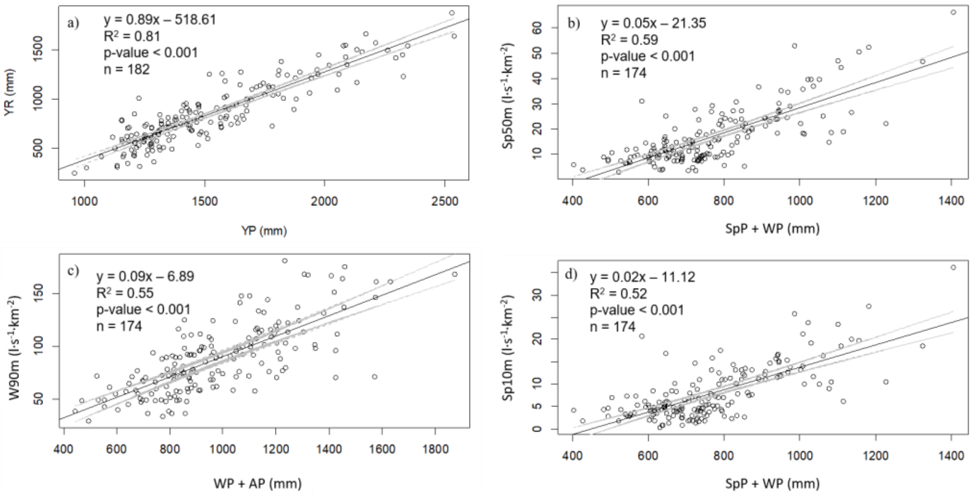
Appendix A:


1000
100
10
1
0.1
Specific discharge (l·s-1·km-2)
Y90m;
protection
Y50m;
water provisioning
Y10m;
ecological status
JY10m;
beginning of
low flow period
VCY; variability
skn; asymmetry
Autumn
(A)
Winter
(W)
Spring
(Sp)
Summer
(Su)
01/10/2000
01/11/2000
01/12/2000
01/01/2001
01/02/2001
01/03/2001
01/04/2001
01/05/2001
01/06/2001
01/07/2001
01/08/2001
01/09/2001

Appendix B:


a)
Annual Precipitation (mm)
1000
1500
2000
2500
00/01
01/02
02/03
03/04
04/05
07/08
08/09
09/10
10/11
11/12
b)
seasonal Precipitation (mm)
200
400
600
800
1000
00/01 A
00/01 W
00/01 Sp
00/01 Sm
01/02 A
01/02 W
01/02 Sp
01/02 Sm
02/03 A
02/03 W
02/03 Sp
02/03 Sm
03/04 A
03/04 W
03/04 Sp
03/04 Sm
04/05 A
04/05 W
04/05 Sp
04/05 Sm
07/08 A
07/08 W
07/08 Sp
07/08 Sm
08/09 A
08/09 W
08/09 Sp
08/09 Sm
09/10 A
09/10 W
09/10 Sp
09/10 Sm
10/11 A
10/11 W
10/11 Sp
10/11 Sm
11/12 A
11/12 W
11/12 Sp
11/12 Sm

Appendix C:


a)
y = 0.89x – 518.61
R² = 0.81
p-value < 0.001
n = 182
YR (mm)
500
1000
1500
1000
1500
2000
2500
YP (mm)
b)
y = 0.05x – 21.35
R² = 0.59
p-value < 0.001
n = 174
Sp50m (l·s⁻¹·km⁻²)
10
20
30
40
50
60
400
600
800
1000
1200
1400
SpP + WP (mm)
c)
y = 0.09x – 6.89
R² = 0.55
p-value < 0.001
n = 174
W90m (l·s⁻¹·km⁻²)
50
100
150
400
600
800
1000
1200
1400
1600
1800
WP + AP (mm)
d)
y = 0.02x – 11.12
R² = 0.52
p-value < 0.001
n = 174
Sp10m (l·s⁻¹·km⁻²)
0
5
10
20
30
400
600
800
1000
1200
1400
SpP + WP (mm)

Appendix D.

a) Multiple regression model for annual average flows (Y50m) considering alternative land cover and its interaction with annual precipitation (YP).

D1	Estimate	Std. Error	t value	p value	Significance
(Intercept)	50.67649	21.3388	2.3749	0.01862	*
YP	-0.02049	0.0150	-1.3635	0.17446	
Native	-0.80268	0.2677	-2.9985	0.00310	**
Exotic	-0.56718	0.2329	-2.4354	0.01586	*
Pasturelands	-0.81356	0.2181	-3.7296	0.00026	***
I(Native * YP)	0.00046	0.0002	2.6403	0.00902	**
I(Exotic *YP)	0.00030	0.0002	1.8558	0.06513	.
I(Pasturelands * YP)	0.00057	0.0002	3.4285	0.00075	***

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 3.96 on 178 degrees of freedom
Multiple R-squared: 0.7791, Adjusted R-squared: 0.7704
F-statistic: 89.69 on 7 and 178 DF, p-value: < 2.2e-16

b) Multiple regression model for average discharge for spring (Sp50m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt).

	Estimate	Std. Error	t value	p value	Significance
(Intercept)	84.01452	43.1914	1.9452	0.05345	.
SpPt (SpP+WP)	-0.06791	0.0586	-1.1585	0.24833	
Native	-1.44268	0.5367	-2.6879	0.00792	**
Exotic	-0.86076	0.5230	-1.6457	0.10172	
Pasturelands	-0.98659	0.3952	-2.4965	0.01352	*
I(Native * SpPt)	0.00159	0.0007	2.3249	0.02129	*
I(Exotic *SpPt)	0.00083	0.0007	1.1590	0.24811	
I(Pasturelands * SpPt)	0.00127	0.0006	2.2893	0.02332	*

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 6.784 on 166 degrees of freedom
Multiple R-squared: 0.6407, Adjusted R-squared: 0.6256
F-statistic: 42.29 on 7 and 166 DF, p-value: < 2.2e-16

c) Multiple regression model for annual high flows (Y90m) considering alternative land cover and its interaction with annual precipitation (YP).

	Estimate	Std. Error	t value	p value	Significance
(Intercept)	-2.86E+02	1.06E+02	-2.707	0.007451	**
YP	2.46E-01	7.31E-02	3.364	0.000941	***
Native	2.88E+00	1.14E+00	2.5281	0.01234	*
Exotic	2.02E+00	1.14E+00	1.766	0.079105	.
Pasturelands	3.44E+00	1.19E+00	2.8874	0.004367	**
I(Native * YP)	-2.07E-03	7.54E-04	-2.7403	0.006764	**
I(Exotic *YP)	-1.54E-03	7.85E-04	-1.9637	0.051117	.
I(Pasturelands * YP)	-2.45E-03	8.50E-04	-2.8772	0.004503	**

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 13.5 on 178 degrees of freedom
Multiple R-squared: 0.6837, Adjusted R-squared: 0.6713
F-statistic: 54.97 on 7 and 178 DF, p-value: < 2.2e-16

d) Multiple regression model for low flows for spring (Sp10m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt).

	Estimate	Std. Error	t value	p value	Significance
(Intercept)	65.57420	33.1084	1.9806	0.04929	*
SpPt (SpP+WP)	-0.06361	0.0458	-1.3876	0.16712	
Native	-0.99263	0.3915	-2.5358	0.01214	*
Exotic	-0.65681	0.3678	-1.7858	0.07596	.
Pasturelands	-0.80725	0.3327	-2.4266	0.01631	*
I(Native * SpPt)	0.00109	0.0005	2.1315	0.03452	*
I(Exotic *SpPt)	0.00070	0.0005	1.3761	0.17065	
I(Pasturelands * SpPt)	0.00108	0.0005	2.2733	0.02429	*

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 3.955 on 166 degrees of freedom
Multiple R-squared: 0.5759, Adjusted R-squared: 0.558
F-statistic: 32.2 on 7 and 166 DF, p-value: < 2.2e-16

Manuscript with track changes

Land cover effects on hydrologic services under a precipitation gradient

Ane Zabaleta[1], Eneko Garmendia[2, 3], Petr Mariel[4], Ibon Tamayo[5], Iñaki Antigüedad[1]

[1]Hidro-Environmental Processes Group, Science and Technology Faculty, University of the Basque Country UPV/EHU, Leioa, 48940, Basque Country, Spain
[2]Department of Applied Economics I, University of the Basque Country UPV/EHU, Vitoria-Gasteiz, 01006, Spain
[3]Basque Centre for Climate Change (BC3), Parque Científico de UPV/EHU, Leioa, 48940, Spain
[4]Department of Applied Economics III (Econometrics and Statistics), University of the Basque Country UPV/EHU, Bilbao, 48015, Spain
[2]Department of Statistics, Harvard University, Cambridge, 02140, US

Correspondence to: Ane Zabaleta (ane.zabaleta@ehu.eus)

Abstract. Climate change impacts on the hydrological cycle are altering the quantity, quality, and temporal distribution of riverine discharge, necessitating a more rigorous consideration of changes in land cover and land use. This study establishes relationships between different land cover combinations (e.g., percentages of forest – both native and exotic – and pastureland) and hydrological services, using hydrological indices estimated at annual and seasonal time scales in an area with a steep precipitation gradient (900–2600 mm y^{-1}). Using discharge data from 20 catchments in the Bay of Biscay, a climate transition zone, the study applied multiple regression models to better understand how the interaction between precipitation and land cover combinations influence hydrological services. Findings showed the relationship between land cover combinations and hydrological services is highly dependent on the amount of precipitation, even in a climatically homogeneous and relatively small area. In general, in the Bay of Biscay area, the greater presence of any type of forests is associated with lower annual water resources, especially with greater percentages of exotic plantations and high annual precipitation. Where precipitation is low, forests show more potential to reduce annual and winter high flows than pasturelands, but this potential decreases as annual or seasonal precipitation increases. As annual precipitation increases, low flows increase as the percentage of exotic plantations decreases and pasturelands increase. Results obtained in this study improve understanding of the multiple effects of land cover on hydrological services, and illustrate the relevance of land planning to the management of water resources, especially under a climate change scenario.

1 Introduction

The potential impacts of land cover on the hydrological cycle should be considered during land use policy-making (Fidelis and Roebeling, 2014; Ellison et al., 2017), including by integrating mitigation and adaptation strategies (Locatelli et al., 2016). Climate change impacts on the hydrological cycle are altering the quantity, quality, and temporal distribution of discharge in rivers (Bates et al., 2008); however, climate change alone is insufficient to explain observed trends in streamflow (Schilling

and Libra, 2003; Gallart and Llorens, 2003; Tomer and Schilling, 2009; López-Moreno et al., 2011). To fully understand these trends, changes in land cover and land use must be also considered (Garmendia et al., 2012, Liu et al., 2013; Brogna et al., 2017). Bauman et al. (2007) noted that vegetation is often the main driving force in ecosystem effects that influence hydrological service provision. For example, in areas such as the Pyrenean region, observed decreases in streamflow have been related primarily to changes in land cover, rather than to climate change (Gallart and Llorens, 2004; López-Moreno et al., 2011; Morán-Tejeda et al., 2012).

Worldwide, deforestation rates outstrip afforestation by several million hectares per year. Overall global forest cover declined by 3.25% (129 million ha) between 1990 and 2015 (FAO, 2016). During this same period, plantations increased globally by over 105 million hectares; by 2015, about 31 % of the world's forests were designated primarily as production forests. This expansion is actively supported by governments (Enters and Durst, 2004; Schirmer and Bull, 2014), which assume that plantation forests can provide a range of economic, social, and environmental benefits. However, the impact of afforestation on water-related ecological services is not usually considered (Ellison et al., 2017).

Research suggests that forests play important roles in regulating fresh water flows (van Dijk and Keenan, 2007). Trees may enhance soil infiltration and, under suitable conditions, improve groundwater recharge, delivering purified ground and surface water (Calder, 2005; Neary et al., 2009). Yet, the interpretation of the relationship between forests and hydrological services remains controversial (Bosch and Hewlett, 1982; Calder et al., 1997; Iroumé and Huber, 2002; Brown et al., 2005; Little et al., 2009; Keestra et al., 2018). Results vary among geographical latitudes and can be influenced by factors such as forest characteristics, changes in the seasonal structure, bio-geographical characteristics of catchments, soil types, and spatial scales. Typically, however, streamflow decreases substantially following afforestation and reforestation, and increases after deforestation or forest clearing (Bosch and Hewlett, 1982; Andréassian, 2004; Farley et al., 2005, Li et al., 2017).

Streamflow changes are influenced by characteristics such as forest tree species, age, and density. A change from coniferous to deciduous forest cover can improve catchment water yield (Hirsch et al., 2011), presumably due to the longer rotation times. Young, fast-growing forests typically consume more water than old-growth forests (Kuczera, 1987; Vertessy et al., 2001; Delzon and Loustau, 2005). Hence, though the impact of tree cover on water provision service tends to be negative in the short term, it may become neutral over the long term (Scott and Prinsloo, 2008). In the appropriate spatial settings, afforestation can improve water availability; however, plantation forests and the use of exotic species can disturb the hydrological balance with possible negative impacts (Trabucco et al., 2008 Huber et al., 2008; Lara et al., 2009, Little et al, 2009). Additionally, recent studies show that land management practices on tree plantations may promote rather than prevent soil erosion (Banfield et al., 2018). This effect has been observed in the Bay of Biscay region (Zabaleta et al., 2016).

In the context of rising temperatures associated with climate change, afforestation may lead to additional decreases in available water resources (Rind et al., 1990; Liu et al., 2016). Thus, climate change mitigation policies focused on carbon sequestration could negatively affect water provision service (Jackson et al., 2005). These observations highlight the importance of placing water-related ecosystem services at the centre of reforestation and forest-based mitigation strategies, while considering carbon

storage and timber/non-timber forest products as co-benefits of strategies designed to protect the hydrological cycle (Locatelli et al. 2015; Ellison et al., 2017).

Efforts to prioritise hydrological services in mitigation and adaptation strategies, and, hence, in land use policy, should be supported by a solid understanding of how trees, forest characteristics, and forest management strategies influence water flows in areas with different climatic, geographical, geological, and biological characteristics. Toward this end, this study analysed the effect of alternative land cover types (i.e., pastureland, native forests, and exotic plantations) on hydrological services in the Bay of Biscay using hydrological indicators obtained from the discharge series of 20 catchments during the periods 2000–2004 and 2007–2011. The specific objectives of this research were: i) to analyse the relationship between precipitation and several hydrological indicators at annual and seasonal time scales in an area with a steep precipitation gradient (Bay of Biscay); (ii) to assess the relationships between different alternative land covers in use and hydrological indicators considering the existing precipitation gradient; and (iii) to detect patterns in the study area that should be considered in devising adaptation strategies and land use management policies.

2 Study area

The ~~study~~studied catchments are located in~~ area is in~~ Gipuzkoa Province (1980 km^2), in the Basque Country of southwestern Europe (average latitude 43 °N and average longitude 1 °W; Fig. 1). The latitude of the province and its geographical situation near the Bay of Biscay favour high mean annual precipitation (1500 mm with no dry season) and a mild climate (mean annual temperature of 13 °C) that varies little between winter (8–10 °C, on average) and summer (18–20 °C, on average). A spatial gradient is observed in annual precipitation, with maximum values in the eastern part of the province (up to 2500 mm) and decreasing precipitation towards the west and south (to about 1000 mm). The altitude ranges from sea level to a maximum of 1554 m; steep slopes, exceed 25 % throughout most of the province with mean values between 40 % and 50 % for most of the catchments.

The drainage network in the area is dense and can be described as dendritic and rectangular. The main rivers flow generally south to north, perpendicular to the coast line. Tributaries are frequently perpendicular to main rivers, influenced by the geological structure of the region, resulting in very narrow water courses that are typically short and steep. Gipuzkoa is located at the western end of the Pyrenees; the region is structurally complex and lithologically diverse, with materials from Palaeozoic plutonic rocks to Quaternary sediments (EVE, 1990). Most of the materials in this region (>70 %) are of low or very low permeability. Sandstones, shales, limestones, and marls are dominant in most of the region, except in the east, where slates prevail (Zabaleta et al., 2016).

The mean soil depth in the study area is about 1 m, but highly variable. Cambisol is the prevailing soil type (FAO, 1977), generally characterised by a loam texture. Forests are the main land use (~~73~~ 63 % in 2011) (MAGRAMA, 2013). The original broad-leaved forests (oak–*Quercus robur*, and beech–*Fagus sylvatica*), presently reduced to 15 % of their original area, account for 28 % of the province and share space with tree plantations of rapid-growth exotic species such as *Pinus radiata*.

These exotic species were introduced in the second half of the twentieth century as a result of government support for afforestation policies. ~~and currently cover 39–48 % of the area that could sustain oak forests (Garmendia et al., 2012).~~

The abandonment of traditional cattle and sheep farming practices has also contributed to the conversion of pastureland and rangelands, most of them previously converted from broad-leaved forests, to fast-growth exotic plantations (Ruiz Urrestarazu, 1999). As a result, those exotic species currently cover 39–48 % of the potential oak forests (Garmendia et al., 2012).

Pinus radiata stands in Gipuzkoa are well adapted to the environment and provide good support for the rapid development of forest communities (Carrascal, 1986; Ainz, 2008). Nevertheless, the expansion of these plantations results in substantial changes not only in the landscape, but also in forest management that affects the hydrological cycle (Garmendia et al., 2012) and sediment delivery (Zabaleta et al., 2016).

The ~~study~~ catchments studied in this area exhibit a diverse mix of land cover types within a small geographical area that has similar climatic, geological, and topographical characteristics. This provides a good empirical basis for analysing how different land cover types affect median, low, and high flows. More precisely, the 20 selected catchments (some of which are nested catchments; see Fig. 1 and Table 1) include pasturelands (herbaceous vegetation), native forests (oak and beech), and exotic plantations (*Pinus radiata* plantations), as well as small areas of other cover types (e.g., urban land, roads, bare rock, water bodies, etc.). Discharge and precipitation are routinely measured for all the catchments as they are part of the hydro-meteorological monitoring network of Gipuzkoa Provincial Council (http://www.gipuzkoahidraulikoak.eus/es/).

3 Methodology

The methodology employed to assess the impacts of alternative combinations of different land cover types on selected hydrological indicators can be summarised in four steps: 1) extraction of hydrological indicators from discharge data series; 2) measurement of alternative land covers for each catchment; 3) assessment of the extent to which annual and seasonal precipitation control the hydrological indicators; and 4) analysis of the relationship between hydrological indicators, precipitation, and alternative land covers.

3.1 Hydrological data

Gauging stations included in the hydro-meteorological network of the Basque Country are located at each outlet of the 20 studied catchments (Fig. 1, Table 1). Water depth (m) is measured every 10 minutes and discharge ($m^3\ s^{-1}$) is estimated through calibration conducted by the water services of the province (Environment and Hydraulic Works Department of Gipuzkoa Provincial Council) (Zabaleta et al., 2016).

To maintain coherence with land cover data obtained from forest inventories carried out during 2002 and 2009, discharge data was considered for two five-hydrological-year periods. ~~The~~Data from the first period, from 2000–2001 to 2004–2005, was compared with land cover data obtained during 2002 (IFN3, 2005). Data from the ~~The~~ second period, from 2007–2008 to 2011–2012, was compared with land cover data from 2009 (IFN4, 2011). In this way, ~~two sets of discharge series,~~hydrological data accounting for ~~a total of 10~~10 hydrological~~-years,~~years were ~~selected~~ considered for each gauging station. To facilitate comparison among catchment responses, all discharge data, including those for hydrological indicators, are referred to as specific discharges (L s^{-1} km^{-2}).

A comparison of the daily hydrographs obtained for the outlets of the 20 catchments shows the homogeneity in the timing of the discharge (Appendix A) and its relationship to the prevalence of Atlantic storms approaching from the northwest (Nadal-Romero et al., 2015). These storms influence the entire study area and are the main sources of precipitation. For this reason, even if there are important differences in total amounts of precipitation from east (higher) to west (lower), the distribution of precipitation over time is very similar in all the catchments analysed, which translates to similar patterns in the annual hydrographs.

Hydrological indicators related to different hydrological services were calculated considering fundamental characteristics of streamflow: magnitude, frequency, variability, and timing (Ritcher et al., 1996; Olden and Poff, 2003). As a first step, seven hydrological indicators were calculated from the discharge series for each hydrological year. At annual and seasonal time scales, the 10th (10m), 50th (50m), and 90th (90m) percentiles (L s^{-1} km^{-2}) were analysed as indicators of discharge magnitude (~~Fig.~~Appendix A~~1~~). The coefficient of variation (CV) was used as a measure of the variability of the discharge series analysed. At the annual scale, the following were also calculated: runoff (R, mm), timing of low flows expressed as the first Julian day of the low flow period (J10), and skewness (skn), as a measure of the asymmetry of the hydrograph related to the frequency of discharge data, of each of the series. As a result, the annual value (Y) and the values for autumn (A), winter (W), spring (Sp) and summer (Su) were obtained for each hydrological year for the different indicators. All calculated indicators are listed in Table 2.

3.2 Land cover data

In 2005 and 2011, the Basque Government published detailed forest inventories. These forestry maps of the Basque Country were created by on-screen photo-interpretation, based on colour orthophotos generated by the SIGPAC project (http://www.mapama.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/), with a minimum pixel size of 25 cm. For this study, geographic information systems were used to reclassify the land cover types into four main types: native forest, exotic plantations, pasturelands, and others. The areas corresponding to each type in each of the catchments were estimated using Environmental Systems Research Institute (ESRI) software (ArcGIS 10.1). The resulting data are listed in Table 1, which shows the percentage of each land cover type in the 20 catchments for both 5-year periods. Note that variations in land cover between the two periods are small.

3.3 Precipitation data

Annual precipitation (YP, mm) estimates for each of the 20 catchments were provided by the Environment and Hydraulic Works Department of the Gipuzkoa Provincial Council. These estimates were calculated by interpolation, based on a universal isotropic kriging method, using data obtained from the rain gauge network. Seasonal precipitation amounts for autumn (AP, mm), winter (WP, mm), spring (SpP, mm) and summer (SuP, mm) were ~~also~~ computed based on the annual precipitation amounts for each catchment and the seasonal distribution of precipitation in the hydro-meteorological station listed in Table 1 for each catchment. These values were used to describe the overall precipitation regime for the 10 hydrological years under study and to assess the extent to which precipitation controlled the hydrological variables considered.

The annual and seasonal distribution of precipitation across catchments over the period studied is shown in Appendix B. In the catchments studied, annual precipitation varied from minimums of 958 mm for the 2001/2002 hydrological year in the C1Z2 catchment and 1581 mm for 2008/2009 in the C1P3 catchment to maximums that range from 1664 mm in D2W1 for 2001/2002 to 2611 mm in F1W1 for 2008/2009 (~~Fig~~Appendix~~.~~ B a)~~1~~). On a seasonal basis (Appendix B b)~~Fig. B2~~), autumn is usually the rainiest season with a mean precipitation of 551 mm, followed by winter and spring with means of 425 mm and 343 mm respectively; summer is the season with the least precipitation (mean of 216 mm).

3.4 Statistical analysis

As a first step, the influence of precipitation on different hydrological indices was analysed using the following simple linear regression that included the 20 catchment, Eq. (1):

$$H_{it} = \gamma_1 + (\gamma_2 \times P_{it}) + \varepsilon_{it} \qquad (1)$$

where H_{it} represents one of the hydrological indices in Table 2; γ_1 and γ_2 are parameters to be estimated; P_{it} is the total precipitation amount considered; and ε_{it} is a regression error satisfying the standard basic assumptions for each of the $i = 1,\ldots, 20$ catchments and $t = 1,\ldots, 10$ hydrological years.

Equation (1) was extended to include different land covers to study their possible influence on the hydrological indices, taking into account their interactions with precipitation. Thus, Eq. (1) was extended to Eq. (2):

$$H_{it} = \beta_1 + (\beta_2 \times P_{it}) + (\beta_3 \times Nat_{it}) + (\beta_4 \times Exo_{it}) + (\beta_5 \times Past_{it}) + (\beta_6 \times Nat_{it} \times P_{it}) + (\beta_7 \times Exo_{it} \times P_{it}) + (\beta_8 \times Past_{it} \times P_{it}) + \mu_{it} \qquad (2)$$

where β_1 to β_8 are parameters to be estimated; Nat_{it}, Exo_{it}, and $Past_{it}$ are the percentages of native forest, exotic forest, and pastureland, respectively; and μ_{it} is a regression error satisfying the standard basic assumptions for each of the $i = 1,\ldots, 20$ catchments and $t = 1,\ldots, 10$ hydrological years.

Because Eq. (2) includes interactions of explanatory variables, the interpretation of results can be difficult. For this reason, different representative combinations were defined based on real values of explanatory variables and the corresponding predictions of hydrological indices were computed. This allowed for a simple and direct interpretation of the influence of all variables (precipitation and land cover types). All the statistical analysis were programmed and performed using the free software R in its version 3.1.2 in the R studio interface.

The objective of this study was to compare predicted hydrological indices for various land cover combinations under different precipitation amounts. To avoid biased results affected by considering extreme values~~outliers~~, the 1st and 3rd quartiles of the precipitation data series were calculated for the selected period (annual or seasonal) and defined as the low and high precipitation conditions. For annual scale data, annual precipitation was considered, while for seasonal scale, precipitation of the season studied plus that of the previous season (6 months total) were considered. The statistical analysis was also carried out considering precipitation of the studied season (3 months), however, no statistically significant results were found.

The different land cover combinations shown in Table 3 were explored for the catchments, under low and high precipitation conditions, and compared to a “base” land cover combination (combination ~~0~~EXO) of 76 % exotic, 18 % pastureland, and 6 % native. Land cover combination ~~0~~ EXO was defined as a combination with a maximum area of exotic plantations, minimum area of native forests, and a low percentage of pasturelands (calculated as the remaining percentage to cover 100 % of the area). ~~Combinations~~ Other 5 combinations~~from 1 to 5~~ were defined as realistic alternative patterns to combination ~~0~~EXO as they were ~~These combinations were defined~~calculated considering real data (e.g., maximum, minimum, or mean percentages of native forests (NAT), exotic plantations (EXO), and pasturelands (PAST) (see Table 2)) and considering the sum of the three as 100 %~~)~~. Following this approach combination EXO + PAST represents high percentages of exotic plantations and pastureland, combination EXO + NAT high percentage of forest, combination NAT high percentage of native forest, combination NAT + PAST is mostly native forests and pasturelands and combination EXO + NAT + PAST a mixture of average percentages of exotic plantations, native forests and pasturelands. Differences between these patterns and combination ~~0~~ EXO were calculated for each hydrological index under low and high precipitation conditions (Table~~s~~ 4~~, 5 and 6~~)~~. These combinations were defined considering real data (e.g., maximum, minimum, or mean percentages of native forests, exotic plantations, and pasturelands)~~. Defined in this way, each combination was used to examine interactions between realistic data; results for ~~scenarios~~ combinations that might be very different from the existing ones were not extrapolated.

4 Results and discussion

4.1 Effect of precipitation on hydrological indicators

Precipitation is generally agreed to be the main driver of large-scale variability in monthly, seasonal, and annual streamflows (Ward and Trimble, 2004). In the study area a certain spatial homogeneity in the precipitation-runoff ratio at an annual scale can be deduced from the high value of the coefficient of determination ($R^2 = 0.8$; p value < 0.001) obtained in the linear regression (Eq. (1)) between annual precipitation (YP, mm) and annual runoff (YR, mm) (~~Fig.~~Appendix C a)~~1~~). The regression includes all data collected during the study period (from 2000–2001 to 2004–2005 and from 2007–2008 to 2011–2012) in the 20 catchments listed in Table 1, which constitutes 182 pairs of data (some pairs are not included in the analysis due to missing data) and has a high level of significance. Thus, precipitation explains a high percentage of the variability in ~~annual runoff~~ water provisioning (80 %). There is also a significant correlation between annual precipitation and magnitude indices of streamflow as median, high, and low flows, with coefficients of determination of 0.75, 0.62 and 0.54 (p values <0.001), respectively.

Conversely, the relationships between precipitation and hydrological indicators related to variability (CV, at all time-scales), timing (JY of the beginning of low flows, JY10m), and frequency (skn) show very low coefficients of determination (<0.25) at an annual scale, and less than 0.1 at the seasonal scale in the case of the coefficient of variation. The significance of the relationship between seasonal precipitation and seasonal median, high, and low flows is lower than that at the annual scale: the coefficient of determination is greater than 0.5 (p values <0.001) for median flows in spring and summer (Sp50m and Su50m; R^2 = 0.58 and 0.56, respectively), high flows in autumn and winter (A90m and W90m; R^2 = 0.50 and 0.55, respectively), and low flows in spring and summer (Sp10m and Su10m; R^2 = 0.5 and 0.51, respectively) (~~Figs~~Appendix C b), c), d)~~. C2, C3, C4~~).

4.2 Effect of land cover on median discharge

Figure 2a shows results ~~of~~ from the multiple regression analyses, defined in Eq. (2), between alternative land covers, annual precipitation amounts, and median annual discharge as a hydrological index. The three land cover types are significant (p values < 0.05) and precipitation is significant in interactions with all land covers (p values < 0.1). This indicates that the degree of influence of precipitation is contingent on the specific land cover. The coefficient of determination is 0.78, indicating that the model fits the data well.

The results shown in Table 4 are expressed as the percentage change in the hydrological index with respect to the results obtained for the base land cover (combination ~~0~~EXO) for low and high ~~YP~~precipitation amounts. The variations are highly conditioned by annual precipitation, both in terms of the percentage change and whether the change was positive or negative. Median annual discharge (Y50m) increases when a decrease in exotic plantations is accompanied by an increase in pasturelands (combinations ~~1~~ EXO+PAST and ~~4~~NAT+PAST), by as much as 44 % and 67 % for low and high annual precipitation amounts, respectively. Conversely, replacing exotic plantations with native forests (combinations ~~2~~ EXO+NAT and ~~3~~NAT) has a slightly negative impact on median discharge (up to 18 %) for low precipitation amounts (1279 mm)~~(up to 18 %)~~ while for higher precipitation amounts (1719 mm) median discharge increases (up to 24 %). Further, increases in median discharge are higher with higher annual precipitation amounts. The magnitude of the observed change is similar to that reported by Farley et al. (2005) for catchments located in northern Europe and higher than those obtained from hydrological modelling by Carvalho-Santos et al. (2016) and Morán-Tejeda et al. (2014) for catchments in the Iberian Peninsula.

Hence, in the study area, greater forest cover may result in lower water provision capability ~~annual water yields~~of catchments. Similarly, numerous studies have shown that replacement of forest by grasslands leads to increased annual water yields, while afforestation processes can decrease annual yields (e.g., Bosch and Hewlett, 1982; Brown et al., 2005; Brogna et al, 2017). Additionally, as annual precipitation amounts increase, this effect becomes clearer in the case of exotic plantations (Fig. 2). Forest plantation species have been selected for rapid early growth, which has high associated water consumption (Farley et al., 2005); maximizing timber production generally involves harvesting trees before their growth slows, that is, before their water consumption starts to decrease. Current forest management of cultivated plantations in the study area involves clearcutting with rotations of around 30 years. Conversely, native forests, established for other purposes, may be left to mature and hence will tend to exhibit lower water consumption (van Dijk and Keenan, 2007) and have reduced interception losses during the leafless period (autumn-winter).

Alternative land covers seem to have little significant effect on median discharge during autumn, winter, and summer, as the coefficients for land covers obtained in the multiple regressions are not significant (not shown). Nevertheless, the inclusion of land cover is important for median spring discharge (Table ~~6~~4), with effects similar to those observed for median annual discharge (Y50m). Regression ~~results shown~~ in Fig. 2~~3~~b show significant effect of ~~indicate that~~ native forests, pasturelands, and precipitation in interactions with both types of land cover (*p* values <0.05) ~~are significant~~on Sp50m ~~(*p* values <0.05)~~. The percentage of exotic plantations in the catchment significantly influences the median discharge in the spring. The coefficient of determination for this graph is 0.63, indicating a good fit.

Decreasing the percentage of exotic plantations (by increasing pasturelands or native forests) increases spring average discharge (Sp50m), up to a 76 %, under high precipitation amounts ~~-~~(852 mm) (Table 4)~~(Sp50m)~~. The magnitude of this increase is larger when the extension of pasturelands is larger (combinations ~~1~~ EXO and ~~4~~NAT+PAST). At low precipitation rates (646 mm), the positive effect of pasturelands on Sp50m remains, while increasing native forest (combinations ~~2~~ EXO+NAT and ~~3~~NAT) has a negative effect on median discharge.

The base land cover combination used in Table 3 (with the highest percentage of exotic plantations) is associated with the least change in median discharge indices across the precipitation gradient (combination ~~0~~EXO), Fig. 2): Y50m and Sp50m vary from about 2–3 L s^{-1} km^{-2} for annual and seasonal precipitation amounts around 1000 and 400 mm, respectively, to about 20 L s^{-1} km^{-2} for precipitations around 2000 and 1000 mm, respectively. Conversely, land cover combinations ~~3~~ NAT and 4 NAT+PAST (with the highest percentage of native forests and pasturelands, respectively, and lowest percentage of exotic plantations) show the highest variation in Y50m and Sp50m in the precipitation gradient existing in the study area. Consequently, the land cover combination that gives the highest or lowest median discharge values changes with annual and seasonal precipitation amounts. This fact must be kept in mind from the water provision perspective in an area with a steep precipitation gradient, under current and future climate change scenarios.

4.3 Effect of land cover on high flows

As shown in Table 4, an increase in high flows (Y90m) can be observed at low precipitation amounts, as the percentage of exotic plantations decreases and native forests (combination ~~3~~NAT) or pasturelands (mainly, combination ~~4~~NAT+PAST) increases. The increase in Y90m seems to be similar to the increase in native forest or in pastureland. For higher precipitation amounts, Y90m changes little with land cover, with the observed changes being negative in all cases. Considering changes in Y90m across the precipitation gradient for different land cover combinations (Fig. 3a), the base land cover combination (~~the one with the highest percentage of exotic plantations~~EXO) exhibits the lowest Y90m for low annual precipitation, but it is also the one with the steepest slope; hence, it is the combination that yields the highest Y90m results for higher precipitation. Conversely, combination ~~4~~NAT+PAST, with the lowest percentage of exotic plantations considered (10 %), a moderate percentage of native forest (31 %), and high percentage of pastureland (59 %) exhibits the highest Y90m for low precipitation amounts and the lowest Y90m for higher ones. This indicates that the potential of forests to reduce high flows decreases as annual precipitation increases (Fig 3a), and therefore, in the area studied, when high annual precipitation is considered, this potential is quite low. Robinson et al., 2003 found that, under realistic forest management procedures, the potential for forests to reduce peak flows in North Western Europe was lower than usually claimed.

Similar conclusions can be reached from seasonal data analysis. Land cover coefficients are significant only for the winter period; during autumn, spring, and summer, land cover does not appear as a significant variable influencing the magnitude of high flows. For winter (W90m), results differ depending on precipitation (in this case considered as the sum of winter and previous autumn precipitation). Under low precipitation amounts, W90m increases (up to 31 %) in combinations (e.g., cases ~~3~~ NAT and ~~2~~EXO+NAT) where the decrease in exotic plantations is compensated for mainly by an increase in native forests (Table ~~5~~4). This implies that high flows are attenuated under land cover combinations with high percentages of exotic plantations, which is favourable for flood regulation (Carvalho-Santos et al., 2016). Under high precipitation amounts, the situation remains practically unchanged for all land cover combinations. In this sense Carrick et al., (2017) after a met-analysis of 156 papers, concluded that a weak direct evidence of the effects of tree cover on flood risk, due to the high uncertainty found in results.

4.4 Effect of land cover on low flows

With regard to satisfying aquatic ecosystem or socio-economic water demands, and, in turn, the ecological status of water bodies (European Commission, 2000), it is important to consider low flow values. For annual low flows, a small variation in Y10m (Table 4) was observed when the percentage of pasturelands increases at the expense of exotic plantations (combination ~~1~~EXO+PAST), and a decrease in Y10m (up to 50 %) in combination ~~3~~ NAT with 66 % of native forests under the lowest annual precipitation amount. In contrast, for higher YP values, the land cover combination with the higher percentage of exotic plantations (~~combination 0~~EXO) is one of the combinations with the lowest Y10m. Under high precipitation amounts (Table 4), low flows exhibit least change when decreases in exotics are compensated for by increases in native forests (combinations ~~2~~EXO+NAT, ~~3~~NAT, ~~5~~EXO+NAT+PAST) and Y10m increases when exotic plantations decrease and pasturelands increase (combinations ~~1~~EXO+PAST, ~~4~~NAT+PAST). Therefore, in line with the findings of Brogna et al., (2017), this study shows exotic plantations have a slightly positive effect on low flows under low annual precipitation amounts; with annual precipitation of less than 700 mm, other land covers provide smaller values of Y10m than the base combination (EXO). These positive effects disappear, however, under higher annual precipitation regimes. The positive effects of forests on base flow, strongly related to annual low flows, have been associated with better infiltration of forested soils (Price, 2011), while negative effects have been linked to higher evapotranspiration rates (Hicks et al., 1991).

During winter, low flows (W10m) increase as exotic forests decrease in all land cover combinations and as native forests (combination ~~3~~ NAT) or pasturelands (combination ~~4~~NAT+PAST) increase; the increase for W10m is greater with higher precipitation amounts (Table ~~5~~4). During spring, native forests (combinations ~~2~~EXO+NAT, ~~3~~NAT) seem to have a negative effect (up to 87 %) on Sp10m when precipitation is low, but this negative effect disappears in areas with higher precipitation (Table ~~6~~4). Greater pastureland (combinations ~~1~~ EXO+PAST and ~~4~~NAT+PAST) positively affects springtime low flows under low and high precipitation rates by as much as 90 %. Land cover combination ~~3~~ NAT, which has the highest percentage of native forests (66 %) shows the greatest change in Y10m across the precipitation gradient of the study area (Table 4, Fig. 3b), while catchments with high percentages of exotic plantations (~~combination 0~~EXO), show the least change in low flows across the precipitation gradient.

No statistically significant influences were observed on median, high, or low autumn and summer flows or on other hydrological indices related to the timing of low flows or other changes to the hydrograph; however, this does not rule out the possibility of relationships between land cover and the hydrological indices. As shown in Appendix C, precipitation (volume and distribution) is the main driver of the system, and thus the influence of other drivers, such as land cover, may fail to emerge as statistically significant. Additionally, there may be other environmental factors, such as soil depth, as Hawtree et al., (2015) found in a catchment of north-central Portugal.

4.5 Land cover effects on hydrological services. Implications.

Clear ~~C~~conclusions about the effect of each land cover combination on hydrological services cannot be drawn without considering the amount of precipitation. However, results show that in the Bay of Biscay area, the presence of any kind of forest decreases ~~annual water resources~~water provisioning service (Y50m), and this effect is more evident with exotic plantations as the annual precipitation increases. Additionally, ~~S~~similar to other studies ~~studies by~~ (Robinson et al., ~~(~~2003~~)~~; Carrick et al., 2017), this study indicates that the potential for forests to reduce ~~peak flows~~flooding risk is low~~er than usually claimed~~; however, the effect of land cover on high flows also changes with precipitation. For low precipitation amounts, forests, especially exotic plantations, show greater potential to reduce annual and wintertime high flows than pasturelands, but this potential decreases as annual or seasonal precipitation increases. Moreover, when high annual precipitation is considered, the potential of exotic plantations to reduce ~~high flows~~flood magnitude is lower than that of native forests or pasturelands. Further, ~~T~~the results also show that exotic plantations have a slight positive effect on annual low flows under low annual precipitation conditions; however, low flows increase as annual precipitation increases and when exotic forests are replaced by pasturelands. This effect is most evident in winter and spring, and when the combination of pasturelands and native forests account for most of the catchment area.

As Ellison et al. (2017) stated, the impact of land management politics on hydrological services is not usually considered, however, taking into account local findings on the relationship between land cover and water-related ecosystem services is necessary for an adequate integrated catchment management. Results observed in Table 4 and Figures 2 and 3, are in this sense useful to be considered when planning land management, in order to have some knowledge on different trends on hydrologic services that can be derived from different decisions under areas with different precipitation amounts. There is no unique “best combination” for all locations and all services, water provision, flood risk protection, ecological status conservation. However, the effect of different land cover combinations, apart from those analysed in this paper, and always inside the limits those included in the multiple regression models proposed, on different hydrological services may be applied. Results obtained, should be in the range of those shown in figures 2 and 3, and could be used to compare the benefits and disadvantages in each of the commented services.

Further study is needed in the Bay of Biscay area to determine how the characteristics of specific tree species (e.g., their phenology and physiology) affect various components of the hydrological cycle. Analyses are also needed to establish the relationship between forest types, land management issues and soil development. For instance, clearcutting of exotic species in the study area is usually accompanied by harvesting with chainsaws, skidding, and mechanical site preparation (prior to replanting) such as scarification and ripping (Gartzia-Bengoetexea et al., 2009). These logging operations alter the physical properties of soil, affecting processes such as infiltration, evapotranspiration, percolation, and lateral flow, and in turn, catchment water balance and temporal distribution river discharge. A deepened understanding of those relationships will help achieve a solid understanding of how trees characteristics, forest types and related management strategies, and soil properties influence water flows.

5 Conclusions

This study identifies the relationships among different land cover combinations (forests–native and exotic–and pasturelands) and hydrological services in an area with a steep precipitation gradient (900–2600 mm yr^{-1}). Annual and seasonal hydrological indices were estimated using discharge data from 20 catchments in the Bay of Biscay area. Results indicate that precipitation has a significant positive impact on median, high, and low flows and is the main driver of annual and seasonal discharge. That strong influence may obscure the relationship between land cover and the hydrological responses of catchments in high precipitation gradient areas. From a policy-making perspective, it is important to assess how land cover changes affect streamflows, as these changes are strongly influenced by human intervention (e.g., through land use planning or public policies to enhance certain land uses and constrain damaging practices, etc.).

Unravelling the effects of land cover on hydrological services is especially important in a climatic transition zone like the Bay of Biscay (Meaurio et al., 2017), which is characterised by a steep precipitation gradient and is subject to the uncertain effects of climate change in terms of magnitude and temporal distribution of precipitation projections. In this regard, the methodology developed in this study to deal with the interactions between the two drivers (i.e., precipitation and land cover) increases the understanding of how various land cover combinations affect hydrological services across an entire precipitation gradient.

The consideration of precipitation amounts turns necessary in order to draw some conclusion about the effect of each land cover combination on hydrological services. Results show that:

- in the study area, forest decreases annual water provisioning, with a higher effect when exotic plantations and high precipitation amounts come together.
- the potential for forests to reduce annual and wintertime flooding risk is low, being higher for low precipitation amounts, especially with a high presence of exotic plantations. For high precipitation amounts, native forest or pasturelands show higher flood reduction potential.

- exotic plantations have a slight positive effect on annual low flows under low annual precipitation conditions; conversely, for high precipitation amounts, low flows increase (especially during winter and spring) when the combination of pasturelands and native forests account for most of the catchment area.

~~Conclusions about the effect of each land cover combination cannot be drawn without considering the amount of precipitation. However, results show that in the Bay of Biscay area, the presence of any kind of forest decreases annual water resources (Y50m), and this effect is more evident with exotic plantations as the annual precipitation increases. Similar to studies by Robinson et al. (2003), this study indicates that the potential for forests to reduce peak flows is lower than usually claimed; however, the effect of land cover on high flows also changes with precipitation. For low precipitation amounts, forests, especially exotic plantations, show greater potential to reduce annual and wintertime high flows than pasturelands, but this potential decreases as annual or seasonal precipitation increases. Moreover, when high annual precipitation is considered, the potential of exotic plantations to reduce high flows is lower than that of native forests or pasturelands. The results also show that exotic plantations have a slight positive effect on annual low flows under low annual precipitation conditions; however, low flows increase as annual precipitation increases and when exotic forests are replaced by pasturelands. This effect is most evident in winter and spring, and when the combination of pasturelands and native forests account for most of the catchment area.~~

Results from ~~in~~ this study show that a trade-off among the different hydrological services may emerge as a result of changes in land cover, and that such services are highly dependent on the amount of precipitation. Hence, to design appropriate water management policies (e.g., to ensure the provision of water resources or to avoid the impact of extreme events), policy-makers need to focus on catchment-scale measures that consider the effect of land cover on hydrological services across a precipitation gradient. There ~~simply~~ is no unique “best combination” for all locations and all services. This is especially relevant under a climate change scenario, as precipitation projections remain largely uncertain both in magnitude and direction (e.g., positive or negative changes). It is time for land planning and forest policies to place water at the centre of the decision-making agenda.

Data availability: All original data are publicly available. Discharge and precipitation data for gauging stations can be obtained in the Environment and Hydraulic Works Department of Gipuzkoa Provincial Council website (https://www.gipuzkoa.eus/es/web/obrahidraulikoak/hidrologia-y-calidad/datos-en-tiempo-real) and original landuse data for the study area can be found in the forest inventories of 2005 (IFN3, 2005) and (2011).

Con formato: Fuente: Negrita

Author contribution: Ane Zabaleta, Eneko Garmendia and Ibon Tamayo worked on the conceptualization of the research. Ibon Tamayo made the data curation (obtained all the hydrological indices, calculated the land cover percentages for each catchment from the original data) and prepared the land cover maps. Petr Mariel prepared the formal analysis, designing and writing the scripts for carrying out the statistics and Ane Zabaleta run the statistics and obtained the results. Iñaki Antiguedad

Con formato: Fuente: Negrita

supervised the design of the work. Eneko Garmendia, Iñaki Antiguedad and Ane Zabaleta discussed the results. Ane Zabaleta prepared the manuscript with contributions of all the authors.

ACKNOWLEDGEMENTS

This research was supported by the Basque Government (Consolidated Groups IT1029/16, IT-642-13) and the Spanish Ministry of Economy and Competitiveness (ECO2017-82111-R). Eneko Garmendia acknowledges financial support from SOSTEPASTOS project (MIMECO AGL2013-48361-C2-1-R). The authors would like to thank Iñaki Aizpuru for his help with land cover data and the Environment and Hydraulic Work Department of the Gipuzkoa Provincial Council for providing hydrologic data series.

References

Ainz Ibarrondo, M. J.: The monoculture of radiata pine in the Basque Country: origin and keys of the survival of a system of exploitation in opposite with sustainable development, Estudios Geográficos, 265, 335–356, doi:10.3989/estgeogr.0426, 2008.

Andréassian, V.: Waters and forests: from historical controversy to scientific debate, J. Hydrol., 291, 1–27, doi:10.1016/j.jhydrol.2003.12.015, 2004.

Banfield, C. C., Braun, A. C., Barra, R., Castillo, A., and Vogt, J.: Erosion proxies in an exotic tree plantation question the appropriate land use in Central Chile, Catena, 161, 77–84. doi:10.1016/j.catena.2017.10.017, 2018

Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P. Eds.: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp, 2008.

Bauman, K. A., Gretchen, C. D., Duarte, T. K., and Mooney, H. A.: The nature and value of ecosystem services: an overview highlighting hydrologic services, Annu. Rev. Environ. Resour., 32, 6.1–6.32, doi:10.1146/annurev.energy.32.031306.102758, 2007.

Bosch, J. M., and Hewlett, J. D.: A review of catchment experiment to determine the effect of vegetation changes on water yield and evapotranspiration, J. Hydrol., 55, 3–23, doi:10.1016/0022-1694(82)90117-2, 1982.

Brogna, D., Vincke, C., Brostaux, Y., Soyeurt, H., Dufrêne, M., and Dendoncker, N.: How does forest cover impact water flows and ecosystem services? Insights from "real-life" catchments in Wallonia (Belgium), Ecol. Indic., 72, 675–685, doi:10.1016/j.ecolind.2016.08.011, 2017.

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., and Vertessy, R. A.: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, J. Hydrol., 310, 28–61, doi:10.1016/j.jhydrol.2004.12.010, 2005.

Calder, I. R.: Blue Revolution: Integrated Land and Water Resource Management, 2nd edition Earthscan, London, 382 pp., 2005.

Calder, I. R., Rosier, P. T. W., Prasanna, K. T., and Parameswarappa, S.: Eucalyptus water use greater than rainfall input a possible explanation from southern India, Hydrol. Earth Syst. Sci., 1, 249–256, doi:10.5194/hess-1-249-1997, 1997.

Carrascal, M.: Estructura de las comunidades de aves de las repoblaciones de Pinus radiata del País Vasco, Munibe (Ciencias Naturales), 38, 3–8, 1986.

Carrick, J., Bin Abdul Rahim, M. S. A., Adjei, C., Ashraa Kalee, H. H. H., Banks, S. J., Bolam, F. C., Campos Luna, I. M., Clark, B., Cowton, J., Domingos, I. F. N., Golicha, D. D., Gupta, G., Grainger, M., Hasanaliyeva, G., Hodgson, D.J., Lopez-Capel, E., Magistrali, A. J., Merrell, I. G., Oikeh, I., Othman, M. S., Ranathunga Mudiyanselage, T. K. R., Samuel, C. W. C., Sufar, E. K., Watson, P. A., Zakaria, N. N. A. B., Stewart, G.: Is Planting Trees the Solution to Reducing Flood Risks? J. Flood Risk Manag. 1–10, https://doi.org/10.1111/jfr3.12484, 2018.

Carvalho-Santos, C., Nunes, J. P., Monteiro, A. T., Hein, L., and Honrado, J. P.: Assessing the effects of land cover and future climate conditions on the provision of hydrological services in a medium-sized watershed of Portugal, Hydrol. Process., 30, 720–738, doi:10.1002/hyp.10621, 2016.

Delzon, S., and Loustau, D.: Age-related decline in stand water use: sap flow and transpiration in a pine forest chronosequence, Agric. For. Meteorol., 129, 105–119, doi:10.1016/j.agrformet.2005.01.002, 2005.

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., van Noordwijk, M., Creed, I. F., Pokorny, J., Gaveau, D., Spracklen, D. V., Bargués Tobella, A., Ilstedt, U., Teuling, A. J., Gebreyohannis Gebrehiwot, S., Sands, D. C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., and Sullivan, C. A.: Trees, forests and water: Cool insights for a hot world, Global Environ. Change., 43, 51–61, doi:10.1016/j.gloenvcha.2017.01.002, 2017.

Enters, T., and Durst, P.(Eds.): What Does It Take? The Role of Incentives in Forest Plantation Development in the Asia-Pacific Region. FAO RAP Publication 2004/27, FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, 2004.

European Commission: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy, Off. J. Eur. Communities, 2000.

EVE (Ente Vasco de la Energía) [BasqueEnergy Agency]. 1990. Mapa geológico simplificado del País Vasco. Escala 1:40000. EVE: Bilbao.

FAO: Guidelines for Soil Profile Description. Food and Agriculture Organization of the United Nations, Rome, Italy, 1977.

FAO: Global Forest Resources Assessment 2015: How Are the World's Forests Changing? 2nd Ed., Food and Agriculture Organization of the United Nations, Rome, Italy, 2016.

Farley, K. A., Jobbágy, E. G., and Jackson, R. B.: Effect of afforestation on water yield: a global synthesis with implications for policy, Global Change Biol., 11, 1565–1576, doi:10.1111/j.1365-2486.2005.01011.x, 2005.

Fidelis, T., and Roebeling, P.: Water resources and land use planning systems in Portugal—Exploring better synergies through Ria de Aveiro, Land Use Policy, 39, 84–95, doi:10.1016/j.landusepol.2014.03.010, 2014.

Gallart, F., and Llorens, P.: Catchment management under environmental change: Impact of land cover change on water resources, Water Int., 28 (3), 334–340, doi:10.1080/02508060308691707, 2003.

Con formato: Inglés (Estados Unidos)

Código de campo cambiado

Con formato: Inglés (Estados Unidos)

Con formato: Inglés (Estados Unidos)

Gallart, F., and Llorens, P.: Observations on land cover changes and water resources in the headwaters of the Ebro catchment, Iberian Peninsula, Phys. Chem. Earth, 29, 769–773, doi:10.1016/j.pce.2004.05.004, 2004.

Garmendia, E., Mariel, P., Tamayo, I., Aizpuru, I., and Zabaleta, A.: Assessing the effect of alternative land uses in the provision of water resources: evidence and policy implications from southern Europe, Land Use Policy, 29(4), 761–770, doi:10.1016/j.landusepol.2011.12.001, 2012.

Gartzia-Bengoetxea, N., Gonzalez-Arias, A., Kandeler, E., and Martínez de Arano, I.: Potential indicators of soil quality in temperate forest ecosystems: a case study in the Basque Country, Ann. For. Sci., 66, 303, doi:010.1051/forest/2009008, 2009.

Hawtree, D., Nunes, J. P., Keizer, J. J., Jacinto, R., Santos, J., Rial-Rivas, M. E., Boulet, A.-K., Tavares-Wahren, F., and Feger, K.-H.: Time series analysis of the long-term hydrologic impacts of afforestation in the Águeda watershed of north-central Portugal, Hydrol. Earth Syst. Sci., 19, 3033-3045, https://doi.org/10.5194/hess-19-3033-2015, 2015.

Hicks, B.J., Beschta, R.L., and Harr, R.D.: Long-term changes in streamflow following logging in western oregon and associated fisheries implications, J. Am. Water Resour. Assoc., 27, 217–226, doi:10.1111/j.1752-1688.1991.tb03126.x, 1991.

Hirsch, F., Clark, D., and Vihervaara, P.: Payments for Forest related Ecosystem Services: What Role for a Green Economy? Background Paper for the Workshop on Payments for Ecosystem Services, UNECE/FAO Forestry and Timber Section, Geneva, 2011.

http://www.mapama.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/, last access: 18 January 2018.

Huber, A., Iroumé, A., and Bathurst, J.: Effect of *Pinus radiata* plantation on water balance in Chile, Hydrol. Process., 22, 142–148, doi:10.1002/hyp.6582, 2008.

IFN3, 2005. www.euskadi.eus/inventario-forestal-cae-2005/web01-a3estbin/es/, last access: 29 November 2017.

IFN4, 2011. http://www.euskadi.eus/inventario-forestal-2011/web01-a3estbin/es/, last access: 29 November 2017.

Iroumé, A., and Huber, A.: Comparison of interception losses in a broadleaved native forest and a *Pseudotsuga menziesii* (Douglas fir) plantation in the Andes mountains of southern Chile, Hydrol. Process., 16 (12), 2347–2361, doi:10.1002/hyp.1007, 2002.

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., Maitre, B. A., le McCarl, D. C., Murray, B. A., and Murray, B. C.: Trading water for carbon with biological carbon sequestration, Science, 310, 1944–1947, doi:10.1126/science.1119282, 2005.

Kees~~s~~tra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., and Cerdà, A.: The superior effect of nature based solutions in land management for enhancing ecosystem services, Sci. Total Environ., 610–611, 997–1009, doi:10.1016/j.scitotenv.2017.08.077, 2018.

Kuczera, G.: Prediction of water yield reductions following a bushfire in ash mixed species eucalypt forest, J. Hydrol., 94, 215–236, doi:10.1016/0022-1694(87)90054-0, 1987.

Lara, A., Little, C., Urrutia, R., McPhee, J., Álvarez-Garretón, C., Oyarzún, C., Soto, D., Donoso, P., Nahuelhual, L., Pino, M., and Arismendi, I.: Assessment of ecosystem services as an opportunity for the conservation and management of native forest in Chile, For. Ecol. Manage., 258, 415–424, doi:10.1016/j.foreco.2009.01.004, 2009.

Little, C., Lara, A., McPhee, J., and Urrutia, R.: Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile, J. Hydrol., 374, 162–170, doi:10.1016/j.jhydrol.2009.06.011, 2009.

Li, Q., Wei, X., Zhang, M., Liu, W., Fan, H., Zhou, G., Giles-Hansen, K., Liu, S., and Wang, Y.: Forest cover change and water yield in large forested watersheds: A global synthetic assessment, Ecohydrology. doi:10.1002/eco.1838, 2017.

Liu, H. L., Bao, A. M., Pan, X. L., and Chen, X.: Effect of land-use change and artificial recharge on the groundwater in an arid inland river basin, Water Resour. Manage., 27, 3775–3790. doi:10.1007/s11269-013-0380-6, 2013.

Liu, Y., Xiao, J., Ju, W., Xu, K., Zhou, Y., and Zhao, Y.: Recent trends in vegetation greenness in China significantly altered annual evapotranspiration and water yield, Environ. Res. Lett., 11, 094010, doi:10.1088/1748-9326/11/9/094010, 2016.

Locatelli, B., Catterall, C. P., Imbach, P., Kumar, C., Lasco, R., Marín-Spiotta, E., Mercer, B., Powers, J. S., Schwartz, N., and Uriarte, M.: Tropical reforestation and climate change: beyond carbon., Restor. Ecol., 23, 337–343, doi:10.1111/rec.12209, 2015.

Locatelli, B., Fedele, G., Fayolle, V., and Baglee, A.: Synergies between adaptation and mitigation in climate change finance, Int. J. Clim. Change Strategies Manage., 8, 112–128, doi:10.1108/IJCCSM-07-2014-0088, 2016.

López-Moreno, J. I., Vicente-Serrano, S. M., Morán-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., and García-Ruíz, J. M.: Impact of climate evolution and land-use changes on water yield in the Ebro basin, Hydrol. Earth Syst. Sci., 15, 311–322, doi:10.5194/hess-15-311-2011, 2011.

MAGRAMA: Cuarto Inventario Forestal Nacional. Comunidad Autónoma del País Vasco / Euskadi. Ed.: Ministerio de Agricultura, Alimentación y Medio Ambiente, Secretaría General Técnica, Centro de Publicaciones, Madrid. 59 pp. ISBN: 978-84-491-1293-5, 2013.

Meaurio, M., Zabaleta, A., Boithias, L., Epelde, A. M., Sauvage, S., Sanchez-Perez, J. M., Srinivasan, R., and Antiguedad, I.: Assessing the hydrological response from an ensemble of CMIP5 climate projections in the transition zone of the Atlantic region (Bay of Biscay), J. Hydrol., 548, 46–62, doi:10.1016/j.jhydrol.2017.02.029, 2017.

Morán-Tejeda, E., Ceballos-Barbancho, A., Llorente-Pinto, J.M., and López-Moreno, J.I.: Land-cover changes and recent hydrological evolution in the Duero Basin (Spain), Reg. Environ. Change, 12, 17–33, 2012.

Morán-Tejeda, E., Zabalza., J, Rahman, K., Gago-Silva, A., Ignacio López-Moreno, J., Vicente-Serrano, S., Lehmann, A., Tague, C. L., and Beniston, M.: Hydrological impacts of climate and land use changes in a mountain watershed: uncertainty estimation based on model comparison, Ecohydrology, doi:10.1002/eco1590, 2014.

Nadal-Romero, E., González-Hidalgo, J. C., Cortesi, N., Desir, G., Gómez, J. A., Lasanta, T., Lucía, A., Marín, C., Martínez-Murillo, J. F., Pacheco, E., Rodríguez-Blanco, M. L., Romero Díaz, A., Ruiz-Sinoga, J. D., Taguas, E. V., Taboada-Castro, M. M., Taboada-Castro, M. T., Úbeda, X., and Zabaleta, A.: Relationship of runoff, erosion and sediment yield to weather types in the Iberian Peninsula. Geomorphology, 228, 372–381, doi:10.1016/j.geomorph.2014.09.011, 2015.

Neary, D. G., Ice, G. G., and Jackson, C. R.: Linkages between forest soils and water quality and quantity, For. Ecol. Manage., 258, 2269–2281, doi:10.1016/j.foreco.2009.05.027, 2009.

Olden, J. D., and Poff, N. L.: Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Res. Appl., 19 (2), 1535–1467, doi:10.1002/rra.700, 2003.

Price, K.: Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review, Prog. Phys. Geogr. 35, 465–492, doi:10.1177/0309133311402714, 2011.

Rind, D., Goldberg, R., Hansen, J., Rosenzweig, C., and Ruedy, R.: Potential evapotranspiration and the likelihood of future drought., J. Geophys. Res. Atmos., 95, 9983–10004, doi:10.1029/JD095iD07p09983, 1990.

Ritcher, B. D., Baumgartner, J. V., Powell, J., and Braun, D. P.: A method for assessing hydrologic alteration within ecosystem, Conserv. Biol., 10, 1163–1174, doi.org/10.1046/j.1523-1739.1996.10041163.x, 1996.

Robinson, M., Cognard-Plancq, A. -L., Cosandey, C., David, J., Durand, P., Führer, H. -W., Hall, R., Hendriques, M. O., Marc, V., McCarthy, R., McDonnell, M., Martin, C., Nisbet, T., O'Dea, P., Rodgers, M., and Zollner, A.: Studies of the impact of forests on peak flows and baseflows: a European perspective, Forest Ecol. Manage., 186 (1–3), 85–97, doi:10.1016/S0378-1127(03)00238-X, 2003.

Ruiz Urrestarazu, E.: Adaptación y gestión de las medidas agroambientales y de forestación en el País Vasco in Corbera, M. (Ed.) Cambios en los espacios rurales cantábricos tras la integración de España en la UE, Santander, Universidad de Cantabria, 1999.

Schilling, K. E., and Libra, R. D.: Increased baseflow in Iowa over the second half of the 20th century, J. Am. Water Resour. Assoc., 39, 851–860, doi:10.1111/j.1752-1688.2003.tb04410.x, 2003.

Schirmer, J., and Bull, L.: Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects, Global Environ. Change., 24, 306–320, doi:10.1016/j.gloenvcha.2013.11.009, 2014.

Scott, D. F., and Prinsloo, F. W.: Longer-term effects of pine and eucalypt plantations on streamflow, Water Resour. Res., 44, W00A08, doi:10.1029/ 2007wr006781, 2008.

Tomer, M. D., and Schilling, K. E.: A simple approach to distinguish land-use and climate change effects on watershed hydrology, J. Hydrol., 376, 24–33, doi:10.1016/j.jhydrol.2009.07.029, 2009.

Trabucco, A., Zomer, R. J., Bossio, D. A., van Straaten, O., and Verchot, L. V.: Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies, Int. Agric. Ecosyst. Environ., 126, 81–97, doi:10.1016/j.agee.2008.01.015, 2008.

van Dijk, A. I. J. M., and Keenan, R. J.: Planted forests and water in perspective, Forest Ecol. Manage., 251 (1–2), 1–9, doi:10.1016/j.foreco.2007.06.010, 2007.

Vertessy, R. A., Watson, F.G.R., and O'Sullivan, S. K.: Factors determining relations between stand age and catchment water balance in mountain ash forests. Forest Ecol. Manage., 143, 13–26, doi:10.1016/S0378-1127(00)00501-6, 2001.

Ward, A. D., and Trimble, S. W.: Environmental Hydrology, 2nd ed., Lewis Publishers/CRC Press Company, London/New York, p. 472, 2004.

Zabaleta, A., Antiguedad, I., Barrio, I., and Probst, J. -L.: Suspended sediment delivery from small catchments to the Bay of Biscay. What are the controlling factors?, Earth Surf. Process. Landforms, 41, 1894–1910, doi: 10.1002/esp.3957, 2016.

Tables

Table 1. Catchment descriptions. Code of the gauging station, catchment name, catchment area, primary land cover types percentages for 2002 (IFN3, 2005) and 2009 (IFN4, 2011) at the 1:25000 scale.

			Primary Cover Types (%)							
		Catchment area (km^2)	2002				2009			
			Forest Cover			Pasture Cover	Forest Cover			Pasture Cover
Code	Catchment		Native	Exotic	**Total**		Native	Exotic	**Total**	
A1Z1	San Prudentzio	121.78	21	49	**70**	24	21	46	**67**	26
A1Z2	Oñati	105.78	27	46	**73**	25	27	45	**72**	26
A1Z3	Urkulu	9	43	14	**57**	42	47	10	**57**	42
A2Z1	Aixola	5.03	6	76	**82**	12	7	73	**80**	15
A3Z1	Altzola	464.25	19	52	**71**	23	20	50	**70**	24
B1T1	Barrendiola	3.8	48	18	**66**	0	48	18	**66**	0
B1Z1	Aitzu	56.13	19	56	**75**	18	19	55	**74**	19
B1Z2	Ibai-Eder	62.73	25	53	**78**	20	25	53	**78**	20
B2Z1	Aizarnazabal	269.77	19	50	**69**	26	20	49	**69**	26
C1P3	Arriaran	2.77	24	62	**86**	12	24	62	**86**	12
C1Z2	Estanda	55.02	16	54	**70**	23	17	52	**69**	24
C2Z1	Agauntza	69.64	57	24	**81**	18	57	23	**80**	18
C5Z1	Alegia	333.34	30	39	**69**	27	30	36	**66**	29
C7Z1	Berastegi	33.34	25	35	**60**	38	25	34	**59**	37
C8Z1	Leitzaran	110.01	39	39	**78**	20	46	33	**79**	20
C9Z1	Lasarte	796.5	32	34	**66**	30	33	31	**64**	31
D1W1	Añarbe	47.69	66	19	**85**	15	66	19	**85**	15
D2W1	Ereñozu	218.42	48	30	**78**	21	50	27	**77**	21
E1W1	Oiartzun	56.6	26	33	**59**	35	31	28	**59**	35
F1W1	Endara	6.19	15	53	**68**	32	15	53	**68**	32

Note: Only forest (native and exotic) or pasture land covers are shown. Other types of land cover are not shown as they are usually less than 10 %, except for Barrendiola catchment where about 30 % of the catchment is bare rock.

Table 2. Statistics of hydrological indices, land cover types, and precipitation amounts used in this study. Statistics of hydrological indices and precipitation amounts were calculated for the entire study period (from 2000–2001 to 2004–2005 and from 2007–2008 to 2011–2012).

	Index	Mean	s.d.	Min	Max
Hydrologic indices	YR, mm	839	320	246	1873
	Y10m, L s^{-1} km^{-2}	4.93	4.40	0.14	28.22
	A10m, L s^{-1} km^{-2}	6.90	7.75	0.28	67.48
	W10m, L s^{-1} km^{-2}	13.55	10.31	1.91	90.89
	Sp10m, L s^{-1} km^{-2}	8.42	6.63	0.34	36.18
	Su10m, L s^{-1} km^{-2}	4.41	4.42	0.02	36.22
	Y50m, L s^{-1} km^{-2}	14.68	9.72	2.71	58.98
	A50m, L s^{-1} km^{-2}	18.94	16.63	2.18	118.74
	W50m, L s^{-1} km^{-2}	27.22	15.63	5.59	125.77
	Sp50m, L s^{-1} km^{-2}	17.50	12.29	2.85	66.43
	Su50m, L s^{-1} km^{-2}	6.22	6.26	0.21	49.69
	Y90m, L s^{-1} km^{-2}	59.81	24.62	15.27	153.27
	A90m, L s^{-1} km^{-2}	74.40	45.14	7.22	217.21
	W90m, L s^{-1} km^{-2}	87.18	34.28	17.38	190.39
	Sp90m, L s^{-1} km^{-2}	49.17	24.24	7.61	113.48
	Su90m, L s^{-1} km^{-2}	12.54	16.09	0.8	120.83
	CVY	1.54	0.42	0.63	3.02
	CVA	1.40	0.59	0.17	3.08
	CVW	1.11	0.41	0.15	2.44
	CVSp	1.17	0.53	0.36	3.54
	CVSu	0.79	0.60	0.1	3.95
	skn	4.57	2.00	0.92	12.43
	JY10m	251	46	52	343
Land cover	Forest, %	72	8	56	85
	Native (NAT), %	31	15	6	66
	Exotic (EXO), %	41	16	10	76
	Pasturelands (PAST), %	23	9	0	42
	Others, %	5	7	0	34
Precipitation	YP, mm	1538	345	958	2611
	AP + SuP, mm	776	228	323	1681
	WP + AP, mm	975	253	441	1874
	SpP + WP, mm	767	171	402	1406

SuP + SpP, mm	560	179	285	1146

Abreviation description: YR: annual runoff; Y10m, A10m, W10m, Sp10m and Su10m: 10th percentile for annual, autumn, winter, spring and summer discharge series; Y50m, A50m, W50m, Sp50m and Su50m: 50th percentile for annual, autumn, winter, spring and summer discharge series; Y90m, A90m, W90m, Sp90m and Su90m: 90th percentile for annual, autumn, winter, spring and summer discharge series; CVY, CVA, CVW, CVSp and CVSu: coefficient of variation for annual, autumn, winter, spring and summer discharge series; skn: skewnwss of the annual discharge series; JY10m: Julian day of the beginning of the low flow period. YP: annual precipitation amount for the catchment; AP + SuP: summer plus previous autumn precipitation amount for the catchment; WP + AP: winter plus previous autumn precipitation amount for the catchment; SpP + WP: spring plus previous winter precipitation amount for the catchment; SuP + SpP: summer plus previous spring precipitation amount for the catchment. See the text for more information.

Con formato: Fuente: Sin Negrita

Table 3. Percentage of different land cover types for each land cover combination. Note that base land cover combination in the text refers to combination ~~(0)~~EXO. The name given to each combination refers to the main land use types considered. EXO = exotic plantation; NAT = native forests; PAST = pasturelands.

Land use combination	EXO	EXO+ PAST	EXO+ NAT	NAT	NAT+ PAST	EXO+ NAT+PAST
Exotic (%)	76	40.8	40.8	10	10	40.8
Native (%)	6	6	41.2	66	30.84	30.84
Pasturelands (%)	18	53.2	18	24	59.16	28.36

Table 4. Results obtained, from multiple regression models, for alternative land cover combinations in the variation in percentage with respect to the base land cover combination (EXO) in the annual median, high and low flows for low (1st quartile) and high (3rd quartile) precipitation amounts (see Fig. 2 and Fig. 3).

			Low Precipitation (1st quartile)						High Precipitation (3rd quartile)					
			Result for base land cover (L s^{-1} km^{-2})	Differences from base land cover (%)					Result for base land cover (L s^{-1} km^{-2})	Differences from base land cover (%)				
		Combination	EXO	EXO+ PAST	EXO+ NAT	NAT	NAT+ PAST	EXO+ NAT+PAST	EXO	EXO+ PAST	EXO+ NAT	NAT	NAT+ PAST	EXO+ NAT+PAST
Hydrologic differences	Annual	Y50m	7.81	44 %	–15 %	–18 %	41 %	2 %	14.59	52 %	9 %	24 %	67 %	22 %
		Y90m	39.1	23 %	17 %	33 %	39 %	19 %	70.87	–11 %	–2 %	–5 %	–10 %	–3 %
		Y10m	2.93	–4 %	–31 %	–53 %	–27 %	–22 %	6.25	45 %	–9 %	–8 %	46 %	7 %
	Winter	W90m	67.7	–5 %	18 %	31 %	8 %	12 %	106.34	–7 %	2 %	3 %	–6 %	–0.4 %
		W10m	8.5	19 %	21 %	39 %	37 %	21 %	10.94	42 %	40 %	75 %	77 %	41 %
	Spring	Sp50m	9.95	55 %	–32 %	–45 %	42 %	–6 %	15.6	56 %	15 %	35 %	76 %	27 %
		Sp10m	4.98	69 %	–58 %	–87 %	40 %	–20 %	8.12	77 %	0 %	13 %	90 %	22 %

Note: Only results for regression with statistically significant coefficients for land cover variables and determination coefficient higher than 0.5 are included. Precipitations considered in each case are: 1279 and 1719 for annual low and high precipitations, respectively; 814 and 1147 for winter low and high precipitations, respectively; 646 and 852 for winter low and high precipitations, respectively.

~~**Table 4.** Results obtained, from multiple regression models, in the variation in percentage with respect to the base land cover combination (EXO) in the annual median, high and low flows with land cover for low and high precipitation amounts.~~

		~~Result for base land cover (L s^{-1} km^{-2})~~	~~Differences from base land cover~~					~~Result for base land cover (L s^{-1} km^{-2})~~	~~Differences from base land cover~~				
		~~Low Annual Precipitation (1279 mm)~~						~~High Annual Precipitation (1719 mm)~~					
	~~Combination~~	~~EXO~~	~~EXO+ PAST~~	~~EXO+ NAT~~	~~NAT~~	~~NAT+ PAST~~	~~EXO+ NAT+PAST~~	~~EXO~~	~~EXO+ PAST~~	~~EXO+ NAT~~	~~NAT~~	~~NAT+ PAST~~	~~EXO+ NAT+PAST~~
~~Hydrologic differences~~	~~Y50m~~	~~7.81~~	~~44 %~~	~~−15 %~~	~~−18 %~~	~~41 %~~	~~2 %~~	~~14.59~~	~~52 %~~	~~9 %~~	~~24 %~~	~~67 %~~	~~22 %~~
	~~Y90m~~	~~39.1~~	~~23 %~~	~~17 %~~	~~33 %~~	~~39 %~~	~~19 %~~	~~70.87~~	~~−11 %~~	~~−2 %~~	~~−5 %~~	~~−10 %~~	~~−3 %~~
	~~Y10m~~	~~2.93~~	~~−4 %~~	~~−31 %~~	~~−53 %~~	~~−27 %~~	~~−22 %~~	~~6.25~~	~~45 %~~	~~−9 %~~	~~−8 %~~	~~46 %~~	~~7 %~~

~~Note: Only results for regression with statistically significant coefficients for land cover variables and determination coefficient higher than 0.5 are included. Precipitation considered (1st and the 3rd quartiles of annual and seasonal) in each case is also included.~~

~~**Table 5.** Results obtained, from multiple regression models, in the variation in percentage with respect to the base land cover combination (EXO) in the winter high and low flows with land cover for low and high precipitation amounts.~~

		~~Result for base land cover (L s^{-1} km^{-2})~~	~~Differences from base land cover~~					~~Result for base land cover (L s^{-1} km^{-2})~~	~~Differences from base land cover~~				
		~~Precipitation = 814 mm (Winter + previous Autumn)~~						~~Precipitation = 1147 mm (Winter + previous Autumn)~~					
	~~Combination~~	~~EXO~~	~~EXO+ PAST~~	~~EXO+ NAT~~	~~NAT~~	~~NAT+ PAST~~	~~EXO+ NAT+PAST~~	~~EXO~~	~~EXO+ PAST~~	~~EXO+ NAT~~	~~NAT~~	~~NAT+ PAST~~	~~EXO+ NAT+PAST~~
~~Hydrologic differences~~	~~W90m~~	~~67.7~~	~~−5 %~~	~~18 %~~	~~31 %~~	~~8 %~~	~~12 %~~	~~106.34~~	~~−7 %~~	~~2 %~~	~~3 %~~	~~−6 %~~	~~−0.4 %~~
	~~W10m~~	~~8.5~~	~~19 %~~	~~21 %~~	~~39 %~~	~~37 %~~	~~21 %~~	~~10.94~~	~~42 %~~	~~40 %~~	~~75 %~~	~~77 %~~	~~41 %~~

~~Note: Only results for regression with statistically significant coefficients for land cover variables and determination coefficient higher than 0.5 are included. Precipitation considered (1st and the 3rd quartiles of annual and seasonal) in each case is also included.~~

~~**Table 6.** Results obtained, from multiple regression models, in the variation in percentage with respect to the base land cover combination (EXO) in the spring median and low flows with land cover for low and high precipitation amounts.~~

		~~Result for base land cover (L s^{-1} km^{-2})~~	~~Differences from base land cover~~					~~Result for base land cover (L s^{-1} km^{-2})~~	~~Differences from base land cover~~				
		~~Precipitation = 646 mm (Spring + previous Winter)~~						~~Precipitation = 852 mm (Spring + previous Winter)~~					
	~~Combination~~	~~EXO~~	~~EXO+ PAST~~	~~EXO+ NAT~~	~~NAT~~	~~NAT+ PAST~~	~~EXO+ NAT+PAST~~	~~EXO~~	~~EXO+ PAST~~	~~EXO+ NAT~~	~~NAT~~	~~NAT+ PAST~~	~~EXO+ NAT+PAST~~
~~Hydrologic differences~~	~~Sp50m~~	~~9.95~~	~~55 %~~	~~−32 %~~	~~−45 %~~	~~42 %~~	~~−6 %~~	~~15.6~~	~~56 %~~	~~15 %~~	~~35 %~~	~~76 %~~	~~27 %~~
	~~Sp10m~~	~~4.98~~	~~69 %~~	~~−58 %~~	~~−87 %~~	~~40 %~~	~~−20 %~~	~~8.12~~	~~77 %~~	~~0 %~~	~~13 %~~	~~90 %~~	~~22 %~~

~~Note: Only results for regression with statistically significant coefficients for land cover variables and determination coefficient higher than 0.5 are included. Precipitation considered (1st and the 3rd quartiles of annual and seasonal) in each case is also included.~~

Figure Captions

Figure 1. a) Location and digital terrain model (5x5 m of resolution) of the study area with the main drainage network, location of gauging stations, catchments, and average precipitation values. b) Land cover map of the study area in 2002 (IFN3, 2005) and 2009(IFN4, 2011) at the 1:25000 scale.

Figure 2. Expected values of a) annual average flows (Y50m, L s^{-1} km^{-2}) and b) average discharge for spring (Sp50m, L s^{-1} km^{-2}) for the land cover combinations described in Table 3 and a gradient of precipitation, as a result of the multiple regression models shown in Appendix D (~~tables D1 and D2~~a) and b), respectively). Statistics of the regression model are included. Significance of variables in the model are shown: *** means significant at the 0.001 level, ** at the 0.01, * at the 0.05 and ¨ at the 0.1 level.

Figure 3. Expected values of a) annual high flows (Y90m, L s^{-1} km^{-2}) and b) low flows for spring (Sp10m, L s^{-1} km^{-2}) for the land cover combinations described in Table 3 and a gradient of precipitation, as a result of the multiple regression models shown in Appendix D (~~tables D3and D4~~c) and d), respectively). Statistics of the regression model are included. Significance of variables in the model are shown: *** means significant at the 0.001 level, ** at the 0.01, * at the 0.05 and ¨ at the 0.1 level.

Appendix

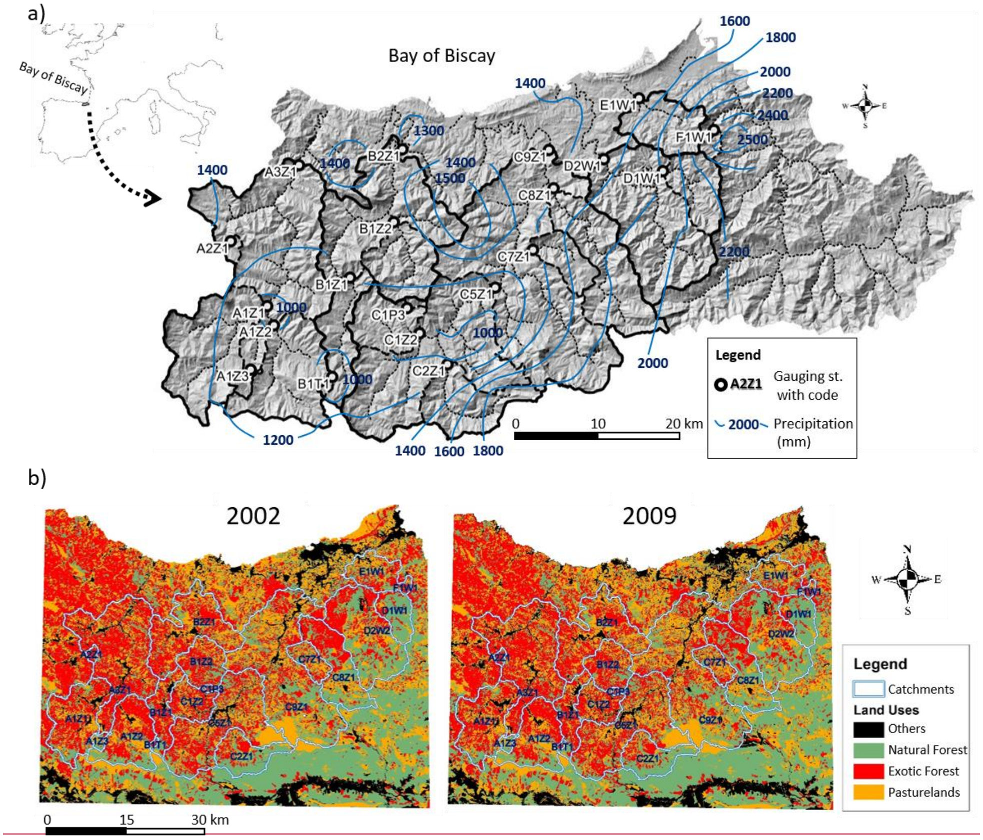
Appendix A: Hydrographs for the 20 catchments in Table 1 for the hydrological year 2000–2001. The meaning of some of the calculated hydrological indicators is also indicated in the figure.

Appendix B: Boxplots representing the statistics of a) annual and b) seasonal precipitation for the 20 studied catchments during the hydrological years considered. A = Autumn, W = Winter, Sp = Spring and Sm = Summer.

Appendix C: Linear regressions obtained between a) annual precipitation (YP, mm) and runoff (YR, mm) b) precipitation from spring and winter (SpP + WP) and average discharge in spring (Sp50m) c) precipitation from winter and autumn (WP + AP) and wintertime high flows (W90m) and d) precipitation from spring and winter (SpP + WP) and low flows in spring (Sp10m).

Appendix D: Multiple regression models. a) Multiple regression model for annual average flows (Y50m) considering alternative land cover and its interaction with annual precipitation (YP). b) Multiple regression model for average discharge for spring (Sp50m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt). c) Multiple regression model for annual high flows (Y90m) considering alternative land cover and its interaction with annual precipitation (YP). d) Multiple regression model for low flows for spring (Sp10m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt).

Figure 1.


a)
Bay of Biscay
Bay of Biscay
1600
1800
2000
2200
2400
2500
1400
1300
1500
1000
1200
A3Z1
A2Z1
A1Z1
A1Z2
A1Z3
B1T1
B1Z1
B1Z2
B2Z1
C1P3
C1Z2
C2Z1
C5Z1
C7Z1
C8Z1
C9Z1
D2W1
D1W1
E1W1
F1W1
0
10
20 km
Legend
A2Z1 Gauging st. with code
2000 Precipitation (mm)
N
W
E
S
b)
2002
2009
Legend
Catchments
Land Uses
Others
Natural Forest
Exotic Forest
Pasturelands
0
15
30 km

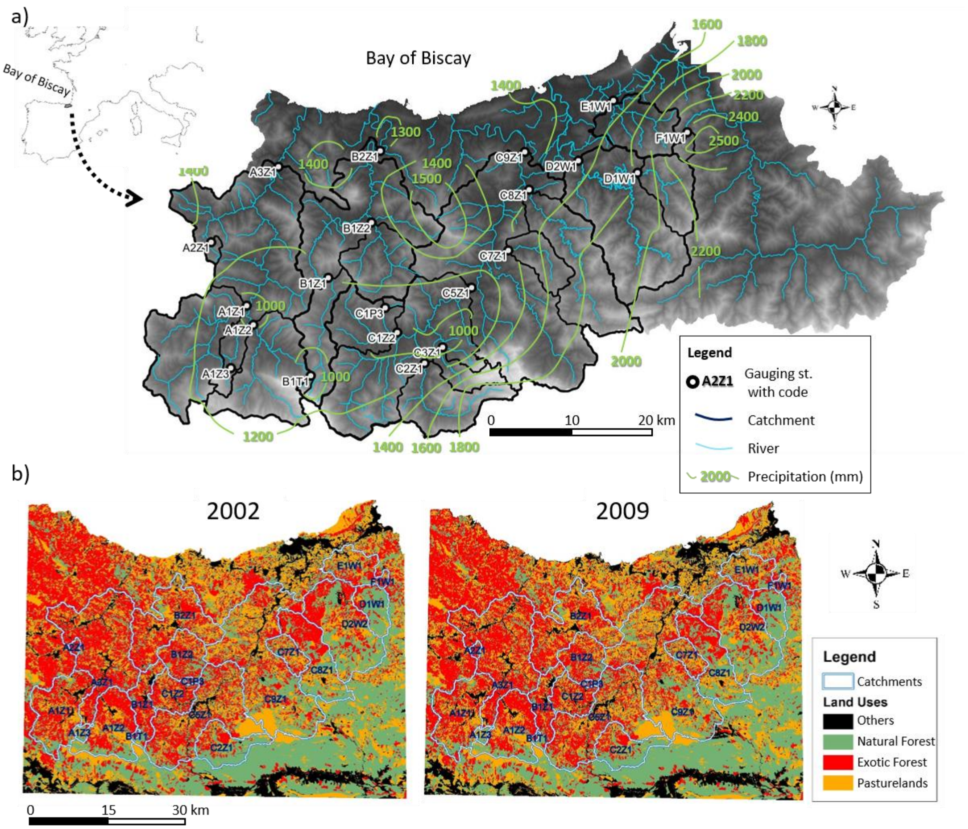
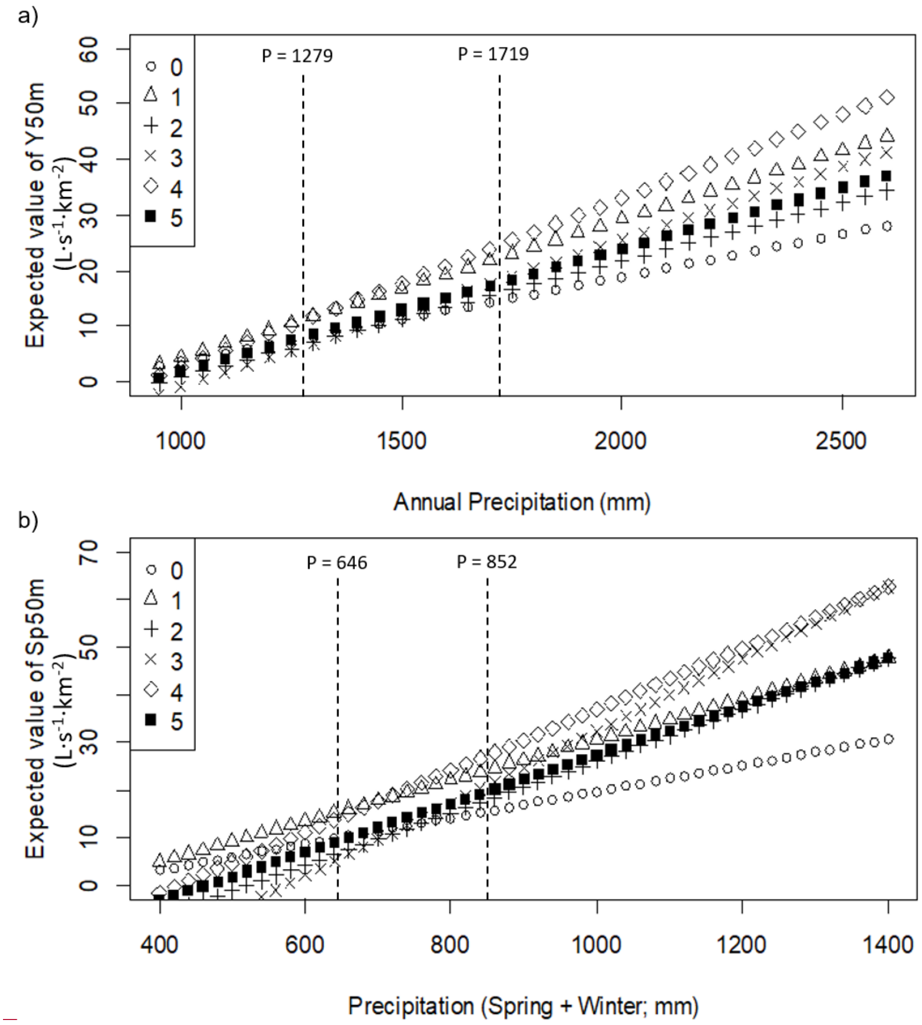
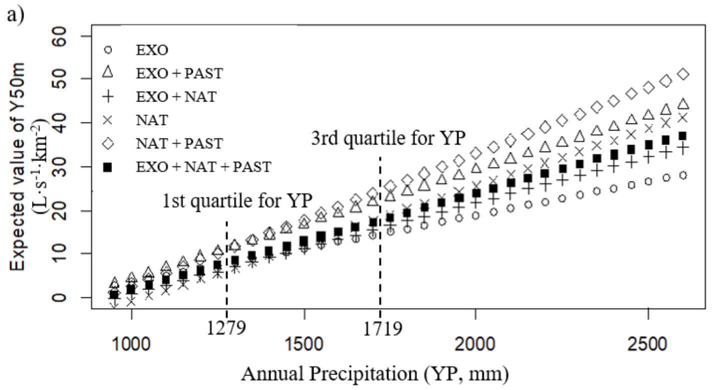

a)
Bay of Biscay
Bay of Biscay
A1Z1
A1Z2
A1Z3
A2Z1
A3Z1
B1T1
B1Z1
B1Z2
B2Z1
C1P3
C1Z2
C2Z1
C3Z1
C5Z1
C7Z1
C8Z1
C9Z1
D1W1
D2W1
E1W1
F1W1
1000
1200
1300
1400
1500
1600
1800
2000
2200
2400
2500
N
S
W
E
0
10
20 km
Legend
A2Z1 Gauging st. with code
Catchment
River
2000 Precipitation (mm)
b)
2002
2009
D2W2
C6Z1
Legend
Catchments
Land Uses
Others
Natural Forest
Exotic Forest
Pasturelands
0
15
30 km

Figure 2.

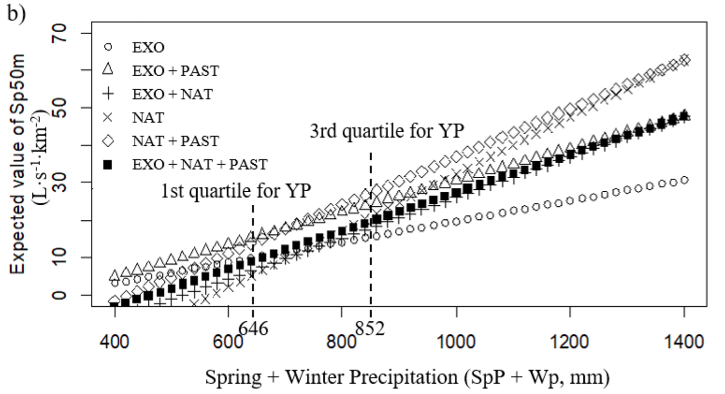

a)
Expected value of Y50m
(L·s⁻¹·km⁻²)
0
10
20
30
40
50
60
P = 1279
P = 1719
0
1
2
3
4
5
1000
1500
2000
2500
Annual Precipitation (mm)
b)
Expected value of Sp50m
(L·s⁻¹·km⁻²)
0
10
30
50
70
P = 646
P = 852
0
1
2
3
4
5
400
600
800
1000
1200
1400
Precipitation (Spring + Winter; mm)



Adjusted R-squared: 0.7704

F-statistic: 89.69 on 7 and 178 DF, p-value: < 2.2e-16

NAT**; EXO*; PAST***; I(NAT * YP)**; I(EXO * YP)¨; I(PAST * YP)***

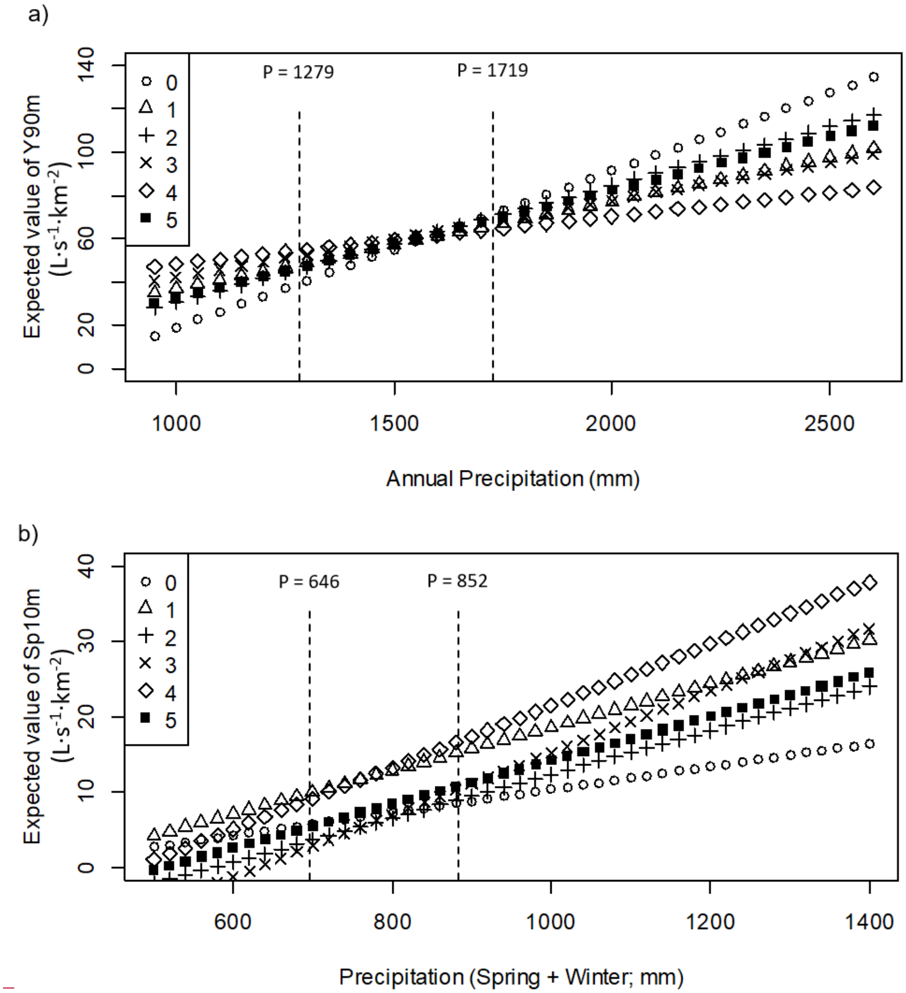


Adjusted R-squared: 0.4936

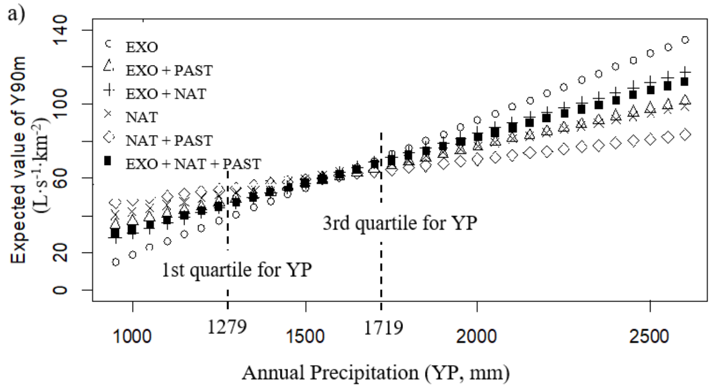
F-statistic: 25.09 on 7 and 166 DF, p-value: < 2.2e-16

YP¨; NAT¨; PAST**; I(NAT * YP)*; I(EXO * YP)¨; I(Pasturelands * YP)**

Figure 3.



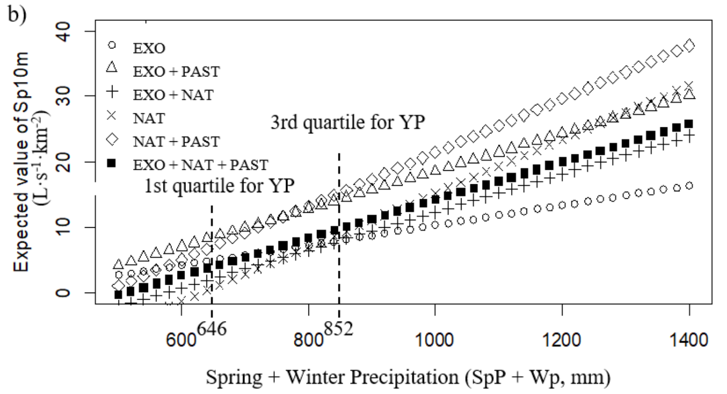
a)
Expected value of Y90m (L·s^{-1}·km^{-2})
0
20
60
100
140
0
1
2
3
4
5
P = 1279
P = 1719
1000
1500
2000
2500
Annual Precipitation (mm)
b)
Expected value of Sp10m (L·s^{-1}·km^{-2})
0
10
20
30
40
0
1
2
3
4
5
P = 646
P = 852
600
800
1000
1200
1400
Precipitation (Spring + Winter; mm)



Adjusted R-squared: 0.6713

F-statistic: 54.97 on 7 and 178 DF, p-value: < 2.2e-16

YP***; NAT*; EXO¨; PAST**; I(NAT * YP)**; I(EXO * YP)¨; I(PAST * YP)**

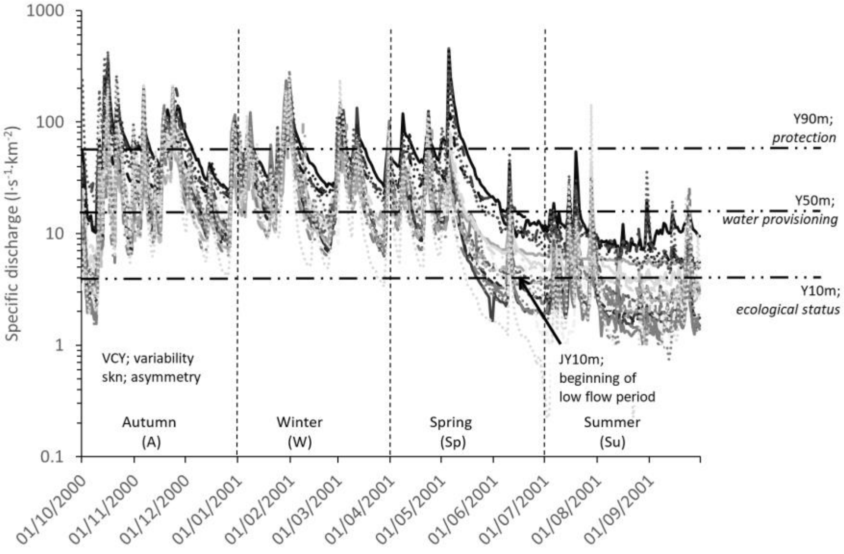


Adjusted R-squared: 0.558

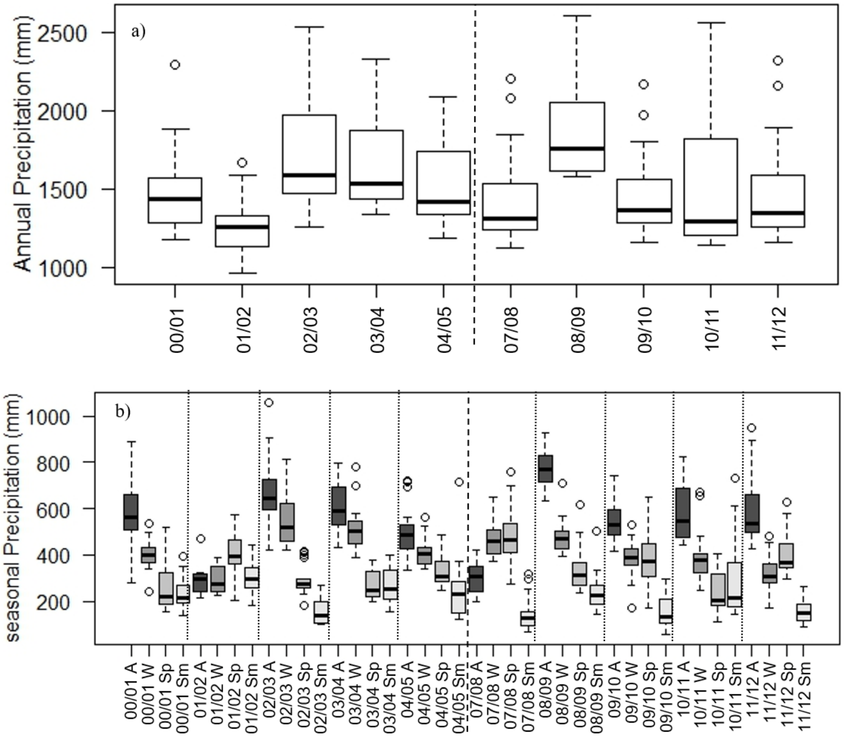
F-statistic: 32.2 on 7 and 166 DF, p-value: < 2.2e-16

NAT*; EXO¨; PAST*; I(NAT x (SpP+WP))*; I(Pasturelands x (SpP+WP))*

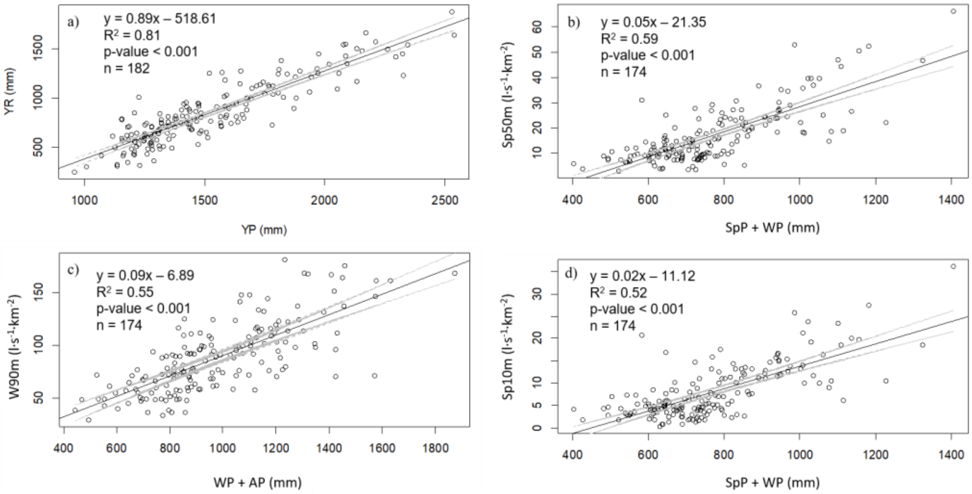
Appendix A:


1000
100
10
1
0.1
Specific discharge (l·s⁻¹·km⁻²)
Y90m;
protection
Y50m;
water provisioning
Y10m;
ecological status
VCY; variability
skn; asymmetry
JY10m;
beginning of
low flow period
Autumn
(A)
Winter
(W)
Spring
(Sp)
Summer
(Su)
01/10/2000
01/11/2000
01/12/2000
01/01/2001
01/02/2001
01/03/2001
01/04/2001
01/05/2001
01/06/2001
01/07/2001
01/08/2001
01/09/2001

Appendix B:


a)
Annual Precipitation (mm)
1000
1500
2000
2500
00/01
01/02
02/03
03/04
04/05
07/08
08/09
09/10
10/11
11/12
b)
seasonal Precipitation (mm)
200
400
600
800
1000
00/01 A
00/01 W
00/01 Sp
00/01 Sm
01/02 A
01/02 W
01/02 Sp
01/02 Sm
02/03 A
02/03 W
02/03 Sp
02/03 Sm
03/04 A
03/04 W
03/04 Sp
03/04 Sm
04/05 A
04/05 W
04/05 Sp
04/05 Sm
07/08 A
07/08 W
07/08 Sp
07/08 Sm
08/09 A
08/09 W
08/09 Sp
08/09 Sm
09/10 A
09/10 W
09/10 Sp
09/10 Sm
10/11 A
10/11 W
10/11 Sp
10/11 Sm
11/12 A
11/12 W
11/12 Sp
11/12 Sm

Appendix C:


a)
y = 0.89x – 518.61
R² = 0.81
p-value < 0.001
n = 182
YR (mm)
YP (mm)
b)
y = 0.05x – 21.35
R² = 0.59
p-value < 0.001
n = 174
Sp50m (l·s⁻¹·km⁻²)
SpP + WP (mm)
c)
y = 0.09x – 6.89
R² = 0.55
p-value < 0.001
n = 174
W90m (l·s⁻¹·km⁻²)
WP + AP (mm)
d)
y = 0.02x – 11.12
R² = 0.52
p-value < 0.001
n = 174
Sp10m (l·s⁻¹·km⁻²)
SpP + WP (mm)

Appendix D.

a) Multiple regression model for annual average flows (Y50m) considering alternative land cover and its interaction with annual precipitation (YP).

D1	Estimate	Std. Error	t value	p value	Significance
(Intercept)	50.67649	21.3388	2.3749	0.01862	*
YP	-0.02049	0.0150	-1.3635	0.17446	
Native	-0.80268	0.2677	-2.9985	0.00310	**
Exotic	-0.56718	0.2329	-2.4354	0.01586	*
Pasturelands	-0.81356	0.2181	-3.7296	0.00026	***
I(Native * YP)	0.00046	0.0002	2.6403	0.00902	**
I(Exotic *YP)	0.00030	0.0002	1.8558	0.06513	.
I(Pasturelands * YP)	0.00057	0.0002	3.4285	0.00075	***

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 3.96 on 178 degrees of freedom

Multiple R-squared: 0.7791, Adjusted R-squared: 0.7704

F-statistic: 89.69 on 7 and 178 DF, p-value: < 2.2e-16

b) Multiple regression model for average discharge for spring (Sp50m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt).

	Estimate	Std. Error	t value	p value	Significance
(Intercept)	84.01452	43.1914	1.9452	0.05345	.
SpPt (SpP+WP)	-0.06791	0.0586	-1.1585	0.24833	
Native	-1.44268	0.5367	-2.6879	0.00792	**
Exotic	-0.86076	0.5230	-1.6457	0.10172	
Pasturelands	-0.98659	0.3952	-2.4965	0.01352	*
I(Native * SpPt)	0.00159	0.0007	2.3249	0.02129	*
I(Exotic *SpPt)	0.00083	0.0007	1.1590	0.24811	
I(Pasturelands * SpPt)	0.00127	0.0006	2.2893	0.02332	*

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 6.784 on 166 degrees of freedom

Multiple R-squared: 0.6407, Adjusted R-squared: 0.6256

F-statistic: 42.29 on 7 and 166 DF, p-value: < 2.2e-16

c) Multiple regression model for annual high flows (Y90m) considering alternative land cover and its interaction with annual precipitation (YP).

	Estimate	Std. Error	t value	p value	Significance
(Intercept)	-2.86E+02	1.06E+02	-2.707	0.007451	**
YP	2.46E-01	7.31E-02	3.364	0.000941	***
Native	2.88E+00	1.14E+00	2.5281	0.01234	*
Exotic	2.02E+00	1.14E+00	1.766	0.079105	.
Pasturelands	3.44E+00	1.19E+00	2.8874	0.004367	**
I(Native * YP)	-2.07E-03	7.54E-04	-2.7403	0.006764	**
I(Exotic *YP)	-1.54E-03	7.85E-04	-1.9637	0.051117	.
I(Pasturelands * YP)	-2.45E-03	8.50E-04	-2.8772	0.004503	**

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 13.5 on 178 degrees of freedom
Multiple R-squared: 0.6837, Adjusted R-squared: 0.6713
F-statistic: 54.97 on 7 and 178 DF, p-value: < 2.2e-16

d) Multiple regression model for low flows for spring (Sp10m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt).

	Estimate	Std. Error	t value	p value	Significance
(Intercept)	65.57420	33.1084	1.9806	0.04929	*
SpPt (SpP+WP)	-0.06361	0.0458	-1.3876	0.16712	
Native	-0.99263	0.3915	-2.5358	0.01214	*
Exotic	-0.65681	0.3678	-1.7858	0.07596	.
Pasturelands	-0.80725	0.3327	-2.4266	0.01631	*
I(Native * SpPt)	0.00109	0.0005	2.1315	0.03452	*
I(Exotic *SpPt)	0.00070	0.0005	1.3761	0.17065	
I(Pasturelands * SpPt)	0.00108	0.0005	2.2733	0.02429	*

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 3.955 on 166 degrees of freedom
Multiple R-squared: 0.5759, Adjusted R-squared: 0.558
F-statistic: 32.2 on 7 and 166 DF, p-value: < 2.2e-16

Reviewed manuscript

Land cover effects on hydrologic services under a precipitation gradient

Ane Zabaleta[1], Eneko Garmendia[2, 3], Petr Mariel[4], Ibon Tamayo[5], Iñaki Antigüedad[1]

[1]Hidro-Environmental Processes Group, Science and Technology Faculty, University of the Basque Country UPV/EHU, Leioa, 48940, Basque Country, Spain
[2]Department of Applied Economics I, University of the Basque Country UPV/EHU, Vitoria-Gasteiz, 01006, Spain
[3]Basque Centre for Climate Change (BC3), Parque Científico de UPV/EHU, Leioa, 48940, Spain
[4]Department of Applied Economics III (Econometrics and Statistics), University of the Basque Country UPV/EHU, Bilbao, 48015, Spain
[2]Department of Statistics, Harvard University, Cambridge, 02140, US

Correspondence to: Ane Zabaleta (ane.zabaleta@ehu.eus)

Abstract. Climate change impacts on the hydrological cycle are altering the quantity, quality, and temporal distribution of riverine discharge, necessitating a more rigorous consideration of changes in land cover and land use. This study establishes relationships between different land cover combinations (e.g., percentages of forest – both native and exotic – and pastureland) and hydrological services, using hydrological indices estimated at annual and seasonal time scales in an area with a steep precipitation gradient (900–2600 mm y^{-1}). Using discharge data from 20 catchments in the Bay of Biscay, a climate transition zone, the study applied multiple regression models to better understand how the interaction between precipitation and land cover combinations influence hydrological services. Findings showed the relationship between land cover combinations and hydrological services is highly dependent on the amount of precipitation, even in a climatically homogeneous and relatively small area. In general, in the Bay of Biscay area, the greater presence of any type of forests is associated with lower annual water resources, especially with greater percentages of exotic plantations and high annual precipitation. Where precipitation is low, forests show more potential to reduce annual and winter high flows than pasturelands, but this potential decreases as annual or seasonal precipitation increases. As annual precipitation increases, low flows increase as the percentage of exotic plantations decreases and pasturelands increase. Results obtained in this study improve understanding of the multiple effects of land cover on hydrological services, and illustrate the relevance of land planning to the management of water resources, especially under a climate change scenario.

1 Introduction

The potential impacts of land cover on the hydrological cycle should be considered during land use policy-making (Fidelis and Roebeling, 2014; Ellison et al., 2017), including by integrating mitigation and adaptation strategies (Locatelli et al., 2016). Climate change impacts on the hydrological cycle are altering the quantity, quality, and temporal distribution of discharge in rivers (Bates et al., 2008); however, climate change alone is insufficient to explain observed trends in streamflow (Schilling

and Libra, 2003; Gallart and Llorens, 2003; Tomer and Schilling, 2009; López-Moreno et al., 2011). To fully understand these trends, changes in land cover and land use must be also considered (Garmendia et al., 2012, Liu et al., 2013; Brogna et al., 2017). Bauman et al. (2007) noted that vegetation is often the main driving force in ecosystem effects that influence hydrological service provision. For example, in areas such as the Pyrenean region, observed decreases in streamflow have been related primarily to changes in land cover, rather than to climate change (Gallart and Llorens, 2004; López-Moreno et al., 2011; Morán-Tejeda et al., 2012).

Worldwide, deforestation rates outstrip afforestation by several million hectares per year. Overall global forest cover declined by 3.25% (129 million ha) between 1990 and 2015 (FAO, 2016). During this same period, plantations increased globally by over 105 million hectares; by 2015, about 31 % of the world's forests were designated primarily as production forests. This expansion is actively supported by governments (Enters and Durst, 2004; Schirmer and Bull, 2014), which assume that plantation forests can provide a range of economic, social, and environmental benefits. However, the impact of afforestation on water-related ecological services is not usually considered (Ellison et al., 2017).

Research suggests that forests play important roles in regulating fresh water flows (van Dijk and Keenan, 2007). Trees may enhance soil infiltration and, under suitable conditions, improve groundwater recharge, delivering purified ground and surface water (Calder, 2005; Neary et al., 2009). Yet, the interpretation of the relationship between forests and hydrological services remains controversial (Bosch and Hewlett, 1982; Calder et al., 1997; Iroumé and Huber, 2002; Brown et al., 2005; Little et al., 2009; Keestra et al., 2018). Results vary among geographical latitudes and can be influenced by factors such as forest characteristics, changes in the seasonal structure, bio-geographical characteristics of catchments, soil types, and spatial scales. Typically, however, streamflow decreases substantially following afforestation and reforestation, and increases after deforestation or forest clearing (Bosch and Hewlett, 1982; Andréassian, 2004; Farley et al., 2005, Li et al., 2017).

Streamflow changes are influenced by characteristics such as forest tree species, age, and density. A change from coniferous to deciduous forest cover can improve catchment water yield (Hirsch et al., 2011), presumably due to the longer rotation times. Young, fast-growing forests typically consume more water than old-growth forests (Kuczera, 1987; Vertessy et al., 2001; Delzon and Loustau, 2005). Hence, though the impact of tree cover on water provision service tends to be negative in the short term, it may become neutral over the long term (Scott and Prinsloo, 2008). In the appropriate spatial settings, afforestation can improve water availability; however, plantation forests and the use of exotic species can disturb the hydrological balance with possible negative impacts (Trabucco et al., 2008 Huber et al., 2008; Lara et al., 2009, Little et al, 2009). Additionally, recent studies show that land management practices on tree plantations may promote rather than prevent soil erosion (Banfield et al., 2018). This effect has been observed in the Bay of Biscay region (Zabaleta et al., 2016).

In the context of rising temperatures associated with climate change, afforestation may lead to additional decreases in available water resources (Rind et al., 1990; Liu et al., 2016). Thus, climate change mitigation policies focused on carbon sequestration could negatively affect water provision service (Jackson et al., 2005). These observations highlight the importance of placing water-related ecosystem services at the centre of reforestation and forest-based mitigation strategies, while considering carbon

storage and timber/non-timber forest products as co-benefits of strategies designed to protect the hydrological cycle (Locatelli et al. 2015; Ellison et al., 2017).

Efforts to prioritise hydrological services in mitigation and adaptation strategies, and, hence, in land use policy, should be supported by a solid understanding of how trees, forest characteristics, and forest management strategies influence water flows in areas with different climatic, geographical, geological, and biological characteristics. Toward this end, this study analysed the effect of alternative land cover types (i.e., pastureland, native forests, and exotic plantations) on hydrological services in the Bay of Biscay using hydrological indicators obtained from the discharge series of 20 catchments during the periods 2000–2004 and 2007–2011. The specific objectives of this research were: i) to analyse the relationship between precipitation and several hydrological indicators at annual and seasonal time scales in an area with a steep precipitation gradient (Bay of Biscay); (ii) to assess the relationships between different alternative land covers in use and hydrological indicators considering the existing precipitation gradient; and (iii) to detect patterns in the study area that should be considered in devising adaptation strategies and land use management policies.

2 Study area

The studied catchments are located in Gipuzkoa Province (1980 km^2), in the Basque Country of southwestern Europe (average latitude 43 °N and average longitude 1 °W; Fig. 1). The latitude of the province and its geographical situation near the Bay of Biscay favour high mean annual precipitation (1500 mm with no dry season) and a mild climate (mean annual temperature of 13 °C) that varies little between winter (8–10 °C, on average) and summer (18–20 °C, on average). A spatial gradient is observed in annual precipitation, with maximum values in the eastern part of the province (up to 2500 mm) and decreasing precipitation towards the west and south (to about 1000 mm). The altitude ranges from sea level to a maximum of 1554 m; steep slopes, exceed 25 % throughout most of the province with mean values between 40 % and 50 % for most of the catchments.

The drainage network in the area is dense and can be described as dendritic and rectangular. The main rivers flow generally south to north, perpendicular to the coast line. Tributaries are frequently perpendicular to main rivers, influenced by the geological structure of the region, resulting in very narrow water courses that are typically short and steep. Gipuzkoa is located at the western end of the Pyrenees; the region is structurally complex and lithologically diverse, with materials from Palaeozoic plutonic rocks to Quaternary sediments (EVE, 1990). Most of the materials in this region (>70 %) are of low or very low permeability. Sandstones, shales, limestones, and marls are dominant in most of the region, except in the east, where slates prevail (Zabaleta et al., 2016).

The mean soil depth in the study area is about 1 m, but highly variable. Cambisol is the prevailing soil type (FAO, 1977), generally characterised by a loam texture. Forests are the main land use (63 % in 2011) (MAGRAMA, 2013). The original broad-leaved forests (oak–*Quercus robur*, and beech–*Fagus sylvatica*), presently reduced to 15 % of their original area, account for 28 % of the province and share space with tree plantations of rapid-growth exotic species such as *Pinus radiata*.

These exotic species were introduced in the second half of the twentieth century as a result of government support for afforestation policies. The abandonment of traditional cattle and sheep farming practices has also contributed to the conversion of pastureland and rangelands, most of them previously converted from broad-leaved forests, to fast-growth exotic plantations (Ruiz Urrestarazu, 1999). As a result, those exotic species currently cover 39–48 % of the potential oak forests (Garmendia et al., 2012).

Pinus radiata stands in Gipuzkoa are well adapted to the environment and provide good support for the rapid development of forest communities (Carrascal, 1986; Ainz, 2008). Nevertheless, the expansion of these plantations results in substantial changes not only in the landscape, but also in forest management that affects the hydrological cycle (Garmendia et al., 2012) and sediment delivery (Zabaleta et al., 2016).

The catchments studied in this area exhibit a diverse mix of land cover types within a small geographical area that has similar climatic, geological, and topographical characteristics. This provides a good empirical basis for analysing how different land cover types affect median, low, and high flows. More precisely, the 20 selected catchments (some of which are nested catchments; see Fig. 1 and Table 1) include pasturelands (herbaceous vegetation), native forests (oak and beech), and exotic plantations (*Pinus radiata* plantations), as well as small areas of other cover types (e.g., urban land, roads, bare rock, water bodies, etc.). Discharge and precipitation are routinely measured for all the catchments as they are part of the hydro-meteorological monitoring network of Gipuzkoa Provincial Council (http://www.gipuzkoahidraulikoak.eus/es/).

3 Methodology

The methodology employed to assess the impacts of alternative combinations of different land cover types on selected hydrological indicators can be summarised in four steps: 1) extraction of hydrological indicators from discharge data series; 2) measurement of alternative land covers for each catchment; 3) assessment of the extent to which annual and seasonal precipitation control the hydrological indicators; and 4) analysis of the relationship between hydrological indicators, precipitation, and alternative land covers.

3.1 Hydrological data

Gauging stations included in the hydro-meteorological network of the Basque Country are located at each outlet of the 20 studied catchments (Fig. 1, Table 1). Water depth (m) is measured every 10 minutes and discharge ($m^3 s^{-1}$) is estimated through calibration conducted by the water services of the province (Environment and Hydraulic Works Department of Gipuzkoa Provincial Council) (Zabaleta et al., 2016).

To maintain coherence with land cover data obtained from forest inventories carried out during 2002 and 2009, discharge data was considered for two five-hydrological-year periods. Data from the first period, from 2000–2001 to 2004–2005, was compared with land cover data obtained during 2002 (IFN3, 2005). Data from the second period, from 2007–2008 to 2011–2012, was compared with land cover data from 2009 (IFN4, 2011). In this way, hydrological data accounting for 10 hydrological-years were considered for each gauging station. To facilitate comparison among catchment responses, all discharge data, including those for hydrological indicators, are referred to as specific discharges (L s^{-1} km^{-2}).

A comparison of the daily hydrographs obtained for the outlets of the 20 catchments shows the homogeneity in the timing of the discharge (Appendix A) and its relationship to the prevalence of Atlantic storms approaching from the northwest (Nadal-Romero et al., 2015). These storms influence the entire study area and are the main sources of precipitation. For this reason, even if there are important differences in total amounts of precipitation from east (higher) to west (lower), the distribution of precipitation over time is very similar in all the catchments analysed, which translates to similar patterns in the annual hydrographs.

Hydrological indicators related to different hydrological services were calculated considering fundamental characteristics of streamflow: magnitude, frequency, variability, and timing (Ritcher et al., 1996; Olden and Poff, 2003). As a first step, seven hydrological indicators were calculated from the discharge series for each hydrological year. At annual and seasonal time scales, the 10th (10m), 50th (50m), and 90th (90m) percentiles (L s^{-1} km^{-2}) were analysed as indicators of discharge magnitude (Appendix A). The coefficient of variation (CV) was used as a measure of the variability of the discharge series analysed. At the annual scale, the following were also calculated: runoff (R, mm), timing of low flows expressed as the first Julian day of the low flow period (J10), and skewness (skn), as a measure of the asymmetry of the hydrograph related to the frequency of discharge data, of each of the series. As a result, the annual value (Y) and the values for autumn (A), winter (W), spring (Sp) and summer (Su) were obtained for each hydrological year for the different indicators. All calculated indicators are listed in Table 2.

3.2 Land cover data

In 2005 and 2011, the Basque Government published detailed forest inventories. These forestry maps of the Basque Country were created by on-screen photo-interpretation, based on colour orthophotos generated by the SIGPAC project (http://www.mapama.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/), with a minimum pixel size of 25 cm. For this study, geographic information systems were used to reclassify the land cover types into four main types: native forest, exotic plantations, pasturelands, and others. The areas corresponding to each type in each of the catchments were estimated using Environmental Systems Research Institute (ESRI) software (ArcGIS 10.1). The resulting data are listed in Table 1, which shows the percentage of each land cover type in the 20 catchments for both 5-year periods. Note that variations in land cover between the two periods are small.

3.3 Precipitation data

Annual precipitation (YP, mm) estimates for each of the 20 catchments were provided by the Environment and Hydraulic Works Department of the Gipuzkoa Provincial Council. These estimates were calculated by interpolation, based on a universal isotropic kriging method, using data obtained from the rain gauge network. Seasonal precipitation amounts for autumn (AP, mm), winter (WP, mm), spring (SpP, mm) and summer (SuP, mm) were computed based on the annual precipitation amounts for each catchment and the seasonal distribution of precipitation in the hydro-meteorological station listed in Table 1 for each catchment. These values were used to describe the overall precipitation regime for the 10 hydrological years under study and to assess the extent to which precipitation controlled the hydrological variables considered.

The annual and seasonal distribution of precipitation across catchments over the period studied is shown in Appendix B. In the catchments studied, annual precipitation varied from minimums of 958 mm for the 2001/2002 hydrological year in the C1Z2 catchment and 1581 mm for 2008/2009 in the C1P3 catchment to maximums that range from 1664 mm in D2W1 for 2001/2002 to 2611 mm in F1W1 for 2008/2009 (Appendix B a)). On a seasonal basis (Appendix B b)), autumn is usually the rainiest season with a mean precipitation of 551 mm, followed by winter and spring with means of 425 mm and 343 mm respectively; summer is the season with the least precipitation (mean of 216 mm).

3.4 Statistical analysis

As a first step, the influence of precipitation on different hydrological indices was analysed using the following simple linear regression that included the 20 catchment, Eq. (1):

$$H_{it} = \gamma_1 + (\gamma_2 \times P_{it}) + \varepsilon_{it} \qquad (1)$$

where H_{it} represents one of the hydrological indices in Table 2; γ_1 and γ_2 are parameters to be estimated; P_{it} is the total precipitation amount considered; and ε_{it} is a regression error satisfying the standard basic assumptions for each of the $i = 1,\ldots,$ 20 catchments and $t = 1,\ldots,$ 10 hydrological years.

Equation (1) was extended to include different land covers to study their possible influence on the hydrological indices, taking into account their interactions with precipitation. Thus, Eq. (1) was extended to Eq. (2):

$$H_{it} = \beta_1 + (\beta_2 \times P_{it}) + (\beta_3 \times Nat_{it}) + (\beta_4 \times Exo_{it}) + (\beta_5 \times Past_{it}) + (\beta_6 \times Nat_{it} \times P_{it}) + (\beta_7 \times Exo_{it} \times P_{it}) + (\beta_8 \times Past_{it} \times P_{it}) + \mu_{it} \qquad (2)$$

where β_1 to β_8 are parameters to be estimated; Nat_{it}, Exo_{it}, and $Past_{it}$ are the percentages of native forest, exotic forest, and pastureland, respectively; and μ_{it} is a regression error satisfying the standard basic assumptions for each of the $i = 1,\ldots,$ 20 catchments and $t = 1,\ldots,$ 10 hydrological years.

Because Eq. (2) includes interactions of explanatory variables, the interpretation of results can be difficult. For this reason, different representative combinations were defined based on real values of explanatory variables and the corresponding predictions of hydrological indices were computed. This allowed for a simple and direct interpretation of the influence of all variables (precipitation and land cover types). All the statistical analysis were programmed and performed using the free software R in its version 3.1.2 in the R studio interface.

The objective of this study was to compare predicted hydrological indices for various land cover combinations under different precipitation amounts. To avoid biased results affected by considering extreme values, the 1st and 3rd quartiles of the precipitation data series were calculated for the selected period (annual or seasonal) and defined as the low and high precipitation conditions. For annual scale data, annual precipitation was considered, while for seasonal scale, precipitation of the season studied plus that of the previous season (6 months total) were considered. The statistical analysis was also carried out considering precipitation of the studied season (3 months), however, no statistically significant results were found.

The different land cover combinations shown in Table 3 were explored for the catchments, under low and high precipitation conditions, and compared to a "base" land cover combination (combination EXO) of 76 % exotic, 18 % pastureland, and 6 % native. Land cover combination EXO was defined as a combination with a maximum area of exotic plantations, minimum area of native forests, and a low percentage of pasturelands (calculated as the remaining percentage to cover 100 % of the area). Other 5 combinations were defined as realistic alternative patterns to combination EXO as they were calculated considering real data (e.g., maximum, minimum, or mean percentages of native forests (NAT), exotic plantations (EXO), and pasturelands (PAST) (see Table 2)) and considering the sum of the three as 100 %. Following this approach combination EXO + PAST represents high percentages of exotic plantations and pastureland, combination EXO + NAT high percentage of forest, combination NAT high percentage of native forest, combination NAT + PAST is mostly native forests and pasturelands and combination EXO + NAT + PAST a mixture of average percentages of exotic plantations, native forests and pasturelands. Differences between these patterns and combination EXO were calculated for each hydrological index under low and high precipitation conditions (Table 4). Defined in this way, each combination was used to examine interactions between realistic data; results for combinations that might be very different from the existing ones were not extrapolated.

4 Results and discussion

4.1 Effect of precipitation on hydrological indicators

Precipitation is generally agreed to be the main driver of large-scale variability in monthly, seasonal, and annual streamflows (Ward and Trimble, 2004). In the study area a certain spatial homogeneity in the precipitation-runoff ratio at an annual scale can be deduced from the high value of the coefficient of determination ($R^2 = 0.8$; p value < 0.001) obtained in the linear regression (Eq. (1)) between annual precipitation (YP, mm) and annual runoff (YR, mm) (Appendix C a)). The regression includes all data collected during the study period (from 2000–2001 to 2004–2005 and from 2007–2008 to 2011–2012) in the 20 catchments listed in Table 1, which constitutes 182 pairs of data (some pairs are not included in the analysis due to missing data) and has a high level of significance. Thus, precipitation explains a high percentage of the variability in water provisioning (80 %). There is also a significant correlation between annual precipitation and magnitude indices of streamflow as median, high, and low flows, with coefficients of determination of 0.75, 0.62 and 0.54 (p values <0.001), respectively.

Conversely, the relationships between precipitation and hydrological indicators related to variability (CV, at all time-scales), timing (JY of the beginning of low flows, JY10m), and frequency (skn) show very low coefficients of determination (<0.25) at an annual scale, and less than 0.1 at the seasonal scale in the case of the coefficient of variation. The significance of the relationship between seasonal precipitation and seasonal median, high, and low flows is lower than that at the annual scale: the coefficient of determination is greater than 0.5 (p values <0.001) for median flows in spring and summer (Sp50m and Su50m; $R^2 = 0.58$ and 0.56, respectively), high flows in autumn and winter (A90m and W90m; $R^2 = 0.50$ and 0.55, respectively), and low flows in spring and summer (Sp10m and Su10m; $R^2 = 0.5$ and 0.51, respectively) (Appendix C b), c), d)).

4.2 Effect of land cover on median discharge

Figure 2a shows results from the multiple regression analyses, defined in Eq. (2), between alternative land covers, annual precipitation amounts, and median annual discharge as a hydrological index. The three land cover types are significant (p values < 0.05) and precipitation is significant in interactions with all land covers (p values < 0.1). This indicates that the degree of influence of precipitation is contingent on the specific land cover. The coefficient of determination is 0.78, indicating that the model fits the data well.

The results shown in Table 4 are expressed as the percentage change in the hydrological index with respect to the results obtained for the base land cover (combination EXO) for low and high precipitation amounts. The variations are highly conditioned by annual precipitation, both in terms of the percentage change and whether the change was positive or negative. Median annual discharge (Y50m) increases when a decrease in exotic plantations is accompanied by an increase in pasturelands (combinations EXO+PAST and NAT+PAST), by as much as 44 % and 67 % for low and high annual precipitation amounts, respectively. Conversely, replacing exotic plantations with native forests (combinations EXO+NAT and NAT) has a slightly negative impact on median discharge (up to 18 %) for low precipitation amounts (1279 mm) while for higher precipitation amounts (1719 mm) median discharge increases (up to 24 %). Further, increases in median discharge are higher with higher annual precipitation amounts. The magnitude of the observed change is similar to that reported by Farley et al. (2005) for catchments located in northern Europe and higher than those obtained from hydrological modelling by Carvalho-Santos et al. (2016) and Morán-Tejeda et al. (2014) for catchments in the Iberian Peninsula.

Hence, in the study area, greater forest cover may result in lower water provision capability of catchments. Similarly, numerous studies have shown that replacement of forest by grasslands leads to increased annual water yields, while afforestation processes can decrease annual yields (e.g., Bosch and Hewlett, 1982; Brown et al., 2005; Brogna et al, 2017). Additionally, as annual precipitation amounts increase, this effect becomes clearer in the case of exotic plantations (Fig. 2). Forest plantation species have been selected for rapid early growth, which has high associated water consumption (Farley et al., 2005); maximizing timber production generally involves harvesting trees before their growth slows, that is, before their water consumption starts to decrease. Current forest management of cultivated plantations in the study area involves clearcutting with rotations of around 30 years. Conversely, native forests, established for other purposes, may be left to mature and hence will tend to exhibit lower water consumption (van Dijk and Keenan, 2007) and have reduced interception losses during the leafless period (autumn-winter).

Alternative land covers seem to have little significant effect on median discharge during autumn, winter, and summer, as the coefficients for land covers obtained in the multiple regressions are not significant (not shown). Nevertheless, the inclusion of land cover is important for median spring discharge (Table 4), with effects similar to those observed for median annual discharge (Y50m). Regression in Fig. 2b show significant effect of native forests, pasturelands, and precipitation in interactions with both types of land cover (p values <0.05) on Sp50m. The percentage of exotic plantations in the catchment significantly influences the median discharge in the spring. The coefficient of determination for this graph is 0.63, indicating a good fit.

Decreasing the percentage of exotic plantations (by increasing pasturelands or native forests) increases spring average discharge (Sp50m), up to a 76 %, under high precipitation amounts (852 mm) (Table 4). The magnitude of this increase is larger when the extension of pasturelands is larger (combinations EXO and NAT+PAST). At low precipitation rates (646 mm), the positive effect of pasturelands on Sp50m remains, while increasing native forest (combinations EXO+NAT and NAT) has a negative effect on median discharge.

The base land cover combination used in Table 3 (with the highest percentage of exotic plantations) is associated with the least change in median discharge indices across the precipitation gradient (combination EXO), Fig. 2): Y50m and Sp50m vary from about 2–3 L s^{-1} km^{-2} for annual and seasonal precipitation amounts around 1000 and 400 mm, respectively, to about 20 L s^{-1} km^{-2} for precipitations around 2000 and 1000 mm, respectively. Conversely, land cover combinations NAT and NAT+PAST (with the highest percentage of native forests and pasturelands, respectively, and lowest percentage of exotic plantations) show the highest variation in Y50m and Sp50m in the precipitation gradient existing in the study area. Consequently, the land cover combination that gives the highest or lowest median discharge values changes with annual and seasonal precipitation amounts. This fact must be kept in mind from the water provision perspective in an area with a steep precipitation gradient, under current and future climate change scenarios.

4.3 Effect of land cover on high flows

As shown in Table 4, an increase in high flows (Y90m) can be observed at low precipitation amounts, as the percentage of exotic plantations decreases and native forests (combination NAT) or pasturelands (mainly, combination NAT+PAST) increases. The increase in Y90m seems to be similar to the increase in native forest or in pastureland. For higher precipitation amounts, Y90m changes little with land cover, with the observed changes being negative in all cases. Considering changes in Y90m across the precipitation gradient for different land cover combinations (Fig. 3a), the base land cover combination (EXO) exhibits the lowest Y90m for low annual precipitation, but it is also the one with the steepest slope; hence, it is the combination that yields the highest Y90m results for higher precipitation. Conversely, combination NAT+PAST, with the lowest percentage of exotic plantations considered (10 %), a moderate percentage of native forest (31 %), and high percentage of pastureland (59 %) exhibits the highest Y90m for low precipitation amounts and the lowest Y90m for higher ones. This indicates that the potential of forests to reduce high flows decreases as annual precipitation increases (Fig 3a), and therefore, in the area studied, when high annual precipitation is considered, this potential is quite low. Robinson et al., 2003 found that, under realistic forest management procedures, the potential for forests to reduce peak flows in North Western Europe was lower than usually claimed.

Similar conclusions can be reached from seasonal data analysis. Land cover coefficients are significant only for the winter period; during autumn, spring, and summer, land cover does not appear as a significant variable influencing the magnitude of high flows. For winter (W90m), results differ depending on precipitation (in this case considered as the sum of winter and previous autumn precipitation). Under low precipitation amounts, W90m increases (up to 31 %) in combinations (e.g., cases NAT and EXO+NAT) where the decrease in exotic plantations is compensated for mainly by an increase in native forests (Table 4). This implies that high flows are attenuated under land cover combinations with high percentages of exotic plantations, which is favourable for flood regulation (Carvalho-Santos et al., 2016). Under high precipitation amounts, the situation remains practically unchanged for all land cover combinations. In this sense Carrick et al., (2017) after a met-analysis of 156 papers, concluded that a weak direct evidence of the effects of tree cover on flood risk, due to the high uncertainty found in results.

4.4 Effect of land cover on low flows

With regard to satisfying aquatic ecosystem or socio-economic water demands, and, in turn, the ecological status of water bodies (European Commission, 2000), it is important to consider low flow values. For annual low flows, a small variation in Y10m (Table 4) was observed when the percentage of pasturelands increases at the expense of exotic plantations (combination EXO+PAST), and a decrease in Y10m (up to 50 %) in combination NAT with 66 % of native forests under the lowest annual precipitation amount. In contrast, for higher YP values, the land cover combination with the higher percentage of exotic plantations (EXO) is one of the combinations with the lowest Y10m. Under high precipitation amounts (Table 4), low flows exhibit least change when decreases in exotics are compensated for by increases in native forests (combinations EXO+NAT, NAT, EXO+NAT+PAST) and Y10m increases when exotic plantations decrease and pasturelands increase (combinations EXO+PAST, NAT+PAST). Therefore, in line with the findings of Brogna et al., (2017), this study shows exotic plantations have a slightly positive effect on low flows under low annual precipitation amounts; with annual precipitation of less than 700 mm, other land covers provide smaller values of Y10m than the base combination (EXO). These positive effects disappear, however, under higher annual precipitation regimes. The positive effects of forests on base flow, strongly related to annual low flows, have been associated with better infiltration of forested soils (Price, 2011), while negative effects have been linked to higher evapotranspiration rates (Hicks et al., 1991).

During winter, low flows (W10m) increase as exotic forests decrease in all land cover combinations and as native forests (combination NAT) or pasturelands (combination NAT+PAST) increase; the increase for W10m is greater with higher precipitation amounts (Table 4). During spring, native forests (combinations EXO+NAT, NAT) seem to have a negative effect (up to 87 %) on Sp10m when precipitation is low, but this negative effect disappears in areas with higher precipitation (Table 4). Greater pastureland (combinations EXO+PAST and NAT+PAST) positively affects springtime low flows under low and high precipitation rates by as much as 90 %. Land cover combination NAT, which has the highest percentage of native forests (66 %) shows the greatest change in Y10m across the precipitation gradient of the study area (Table 4, Fig. 3b), while catchments with high percentages of exotic plantations (EXO), show the least change in low flows across the precipitation gradient.

No statistically significant influences were observed on median, high, or low autumn and summer flows or on other hydrological indices related to the timing of low flows or other changes to the hydrograph; however, this does not rule out the possibility of relationships between land cover and the hydrological indices. As shown in Appendix C, precipitation (volume and distribution) is the main driver of the system, and thus the influence of other drivers, such as land cover, may fail to emerge as statistically significant. Additionally, there may be other environmental factors, such as soil depth, as Hawtree et al., (2015) found in a catchment of north-central Portugal.

4.5 Land cover effects on hydrological services. Implications.

Clear conclusions about the effect of each land cover combination on hydrological services cannot be drawn without considering the amount of precipitation. However, results show that in the Bay of Biscay area, the presence of any kind of forest decreases water provisioning service (Y50m), and this effect is more evident with exotic plantations as the annual precipitation increases. Additionally, similar to other studies (Robinson et al., 2003; Carrick et al., 2017), this study indicates that the potential for forests to reduce flooding risk is low; however, the effect of land cover on high flows also changes with precipitation. For low precipitation amounts, forests, especially exotic plantations, show greater potential to reduce annual and wintertime high flows than pasturelands, but this potential decreases as annual or seasonal precipitation increases. Moreover, when high annual precipitation is considered, the potential of exotic plantations to reduce flood magnitude is lower than that of native forests or pasturelands. Further, the results also show that exotic plantations have a slight positive effect on annual low flows under low annual precipitation conditions; however, low flows increase as annual precipitation increases and when exotic forests are replaced by pasturelands. This effect is most evident in winter and spring, and when the combination of pasturelands and native forests account for most of the catchment area.

As Ellison et al. (2017) stated, the impact of land management politics on hydrological services is not usually considered, however, taking into account local findings on the relationship between land cover and water-related ecosystem services is necessary for an adequate integrated catchment management. Results observed in Table 4 and Figures 2 and 3, are in this sense useful to be considered when planning land management, in order to have some knowledge on different trends on hydrologic services that can be derived from different decisions under areas with different precipitation amounts. There is no unique "best combination" for all locations and all services, water provision, flood risk protection, ecological status conservation. However, the effect of different land cover combinations, apart from those analysed in this paper, and always inside the limits those included in the multiple regression models proposed, on different hydrological services may be applied. Results obtained, should be in the range of those shown in figures 2 and 3, and could be used to compare the benefits and disadvantages in each of the commented services.

Further study is needed in the Bay of Biscay area to determine how the characteristics of specific tree species (e.g., their phenology and physiology) affect various components of the hydrological cycle. Analyses are also needed to establish the relationship between forest types, land management issues and soil development. For instance, clearcutting of exotic species in the study area is usually accompanied by harvesting with chainsaws, skidding, and mechanical site preparation (prior to replanting) such as scarification and ripping (Gartzia-Bengoetexea et al., 2009). These logging operations alter the physical properties of soil, affecting processes such as infiltration, evapotranspiration, percolation, and lateral flow, and in turn, catchment water balance and temporal distribution river discharge. A deepened understanding of those relationships will help achieve a solid understanding of how trees characteristics, forest types and related management strategies, and soil properties influence water flows.

5 Conclusions

This study identifies the relationships among different land cover combinations (forests–native and exotic–and pasturelands) and hydrological services in an area with a steep precipitation gradient (900–2600 mm yr^{-1}). Annual and seasonal hydrological indices were estimated using discharge data from 20 catchments in the Bay of Biscay area. Results indicate that precipitation has a significant positive impact on median, high, and low flows and is the main driver of annual and seasonal discharge. That strong influence may obscure the relationship between land cover and the hydrological responses of catchments in high precipitation gradient areas. From a policy-making perspective, it is important to assess how land cover changes affect streamflows, as these changes are strongly influenced by human intervention (e.g., through land use planning or public policies to enhance certain land uses and constrain damaging practices, etc.).

Unravelling the effects of land cover on hydrological services is especially important in a climatic transition zone like the Bay of Biscay (Meaurio et al., 2017), which is characterised by a steep precipitation gradient and is subject to the uncertain effects of climate change in terms of magnitude and temporal distribution of precipitation projections. In this regard, the methodology developed in this study to deal with the interactions between the two drivers (i.e., precipitation and land cover) increases the understanding of how various land cover combinations affect hydrological services across an entire precipitation gradient.

The consideration of precipitation amounts turns necessary in order to draw some conclusion about the effect of each land cover combination on hydrological services. Results show that:

- in the study area, forest decreases annual water provisioning, with a higher effect when exotic plantations and high precipitation amounts come together.
- the potential for forests to reduce annual and wintertime flooding risk is low, being higher for low precipitation amounts, especially with a high presence of exotic plantations. For high precipitation amounts, native forest or pasturelands show higher flood reduction potential.
- exotic plantations have a slight positive effect on annual low flows under low annual precipitation conditions; conversely, for high precipitation amounts, low flows increase (especially during winter and spring) when the combination of pasturelands and native forests account for most of the catchment area.

Results from this study show that a trade-off among the different hydrological services may emerge as a result of changes in land cover, and that such services are highly dependent on the amount of precipitation. Hence, to design appropriate water management policies (e.g., to ensure the provision of water resources or to avoid the impact of extreme events), policy-makers need to focus on catchment-scale measures that consider the effect of land cover on hydrological services across a precipitation gradient. There is no unique “best combination” for all locations and all services. This is especially relevant under a climate change scenario, as precipitation projections remain largely uncertain both in magnitude and direction (e.g., positive or negative changes). It is time for land planning and forest policies to place water at the centre of the decision-making agenda.

Data availability: All original data are publicly available. Discharge and precipitation data for gauging stations can be obtained in the Environment and Hydraulic Works Department of Gipuzkoa Provincial Council website (https://www.gipuzkoa.eus/es/web/obrahidraulikoak/hidrologia-y-calidad/datos-en-tiempo-real) and original landuse data for the study area can be found in the forest inventories of 2005 (IFN3, 2005) and (2011).

Author contribution: Ane Zabaleta, Eneko Garmendia and Ibon Tamayo worked on the conceptualization of the research. Ibon Tamayo made the data curation (obtained all the hydrological indices, calculated the land cover percentages for each catchment from the original data) and prepared the land cover maps. Petr Mariel prepared the formal analysis, designing and writing the scripts for carrying out the statistics and Ane Zabaleta run the statistics and obtained the results. Iñaki Antiguedad supervised the design of the work. Eneko Garmendia, Iñaki Antiguedad and Ane Zabaleta discussed the results. Ane Zabaleta prepared the manuscript with contributions of all the authors.

ACKNOWLEDGEMENTS

This research was supported by the Basque Government (Consolidated Groups IT1029/16, IT-642-13) and the Spanish Ministry of Economy and Competitiveness (ECO2017-82111-R). Eneko Garmendia acknowledges financial support from SOSTEPASTOS project (MIMECO AGL2013-48361-C2-1-R). The authors would like to thank Iñaki Aizpuru for his help with land cover data and the Environment and Hydraulic Work Department of the Gipuzkoa Provincial Council for providing hydrologic data series.

References

Ainz Ibarrondo, M. J.: The monoculture of radiata pine in the Basque Country: origin and keys of the survival of a system of exploitation in opposite with sustainable development, Estudios Geográficos, 265, 335–356, doi:10.3989/estgeogr.0426, 2008.

Andréassian, V.: Waters and forests: from historical controversy to scientific debate, J. Hydrol., 291, 1–27, doi:10.1016/j.jhydrol.2003.12.015, 2004.

Banfield, C. C., Braun, A. C., Barra, R., Castillo, A., and Vogt, J.: Erosion proxies in an exotic tree plantation question the appropriate land use in Central Chile, Catena, 161, 77–84. doi:10.1016/j.catena.2017.10.017, 2018

Bates, B. C., Kundzewicz, Z. W., Wu, S., and Palutikof, J. P. Eds.: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp, 2008.

Bauman, K. A., Gretchen, C. D., Duarte, T. K., and Mooney, H. A.: The nature and value of ecosystem services: an overview highlighting hydrologic services, Annu. Rev. Environ. Resour., 32, 6.1–6.32, doi:10.1146/annurev.energy.32.031306.102758, 2007.

Bosch, J. M., and Hewlett, J. D.: A review of catchment experiment to determine the effect of vegetation changes on water yield and evapotranspiration, J. Hydrol., 55, 3–23, doi:10.1016/0022-1694(82)90117-2, 1982.

Brogna, D., Vincke, C., Brostaux, Y., Soyeurt, H., Dufrêne, M., and Dendoncker, N.: How does forest cover impact water flows and ecosystem services? Insights from “real-life” catchments in Wallonia (Belgium), Ecol. Indic., 72, 675–685, doi:10.1016/j.ecolind.2016.08.011, 2017.

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., and Vertessy, R. A.: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, J. Hydrol., 310, 28–61, doi:10.1016/j.jhydrol.2004.12.010, 2005.

Calder, I. R.: Blue Revolution: Integrated Land and Water Resource Management, 2nd edition Earthscan, London, 382 pp., 2005.

Calder, I. R., Rosier, P. T. W., Prasanna, K. T., and Parameswarappa, S.: Eucalyptus water use greater than rainfall input a possible explanation from southern India, Hydrol. Earth Syst. Sci., 1, 249–256, doi:10.5194/hess-1-249-1997, 1997.

Carrascal, M.: Estructura de las comunidades de aves de las repoblaciones de Pinus radiata del País Vasco, Munibe (Ciencias Naturales), 38, 3–8, 1986.

Carrick, J., Bin Abdul Rahim, M. S. A., Adjei, C., Ashraa Kalee, H. H. H., Banks, S. J., Bolam, F. C., Campos Luna, I. M., Clark, B., Cowton, J., Domingos, I. F. N., Golicha, D. D., Gupta, G., Grainger, M., Hasanaliyeva, G., Hodgson, D.J., Lopez-Capel, E., Magistrali, A. J., Merrell, I. G., Oikeh, I., Othman, M. S., Ranathunga Mudiyanselage, T. K. R., Samuel, C. W. C., Sufar, E. K., Watson, P. A., Zakaria, N. N. A. B., Stewart, G.: Is Planting Trees the Solution to Reducing Flood Risks? J. Flood Risk Manag. 1–10, https://doi.org/10.1111/jfr3.12484, 2018.

Carvalho-Santos, C., Nunes, J. P., Monteiro, A. T., Hein, L., and Honrado, J. P.: Assessing the effects of land cover and future climate conditions on the provision of hydrological services in a medium-sized watershed of Portugal, Hydrol. Process., 30, 720–738, doi:10.1002/hyp.10621, 2016.

Delzon, S., and Loustau, D.: Age-related decline in stand water use: sap flow and transpiration in a pine forest chronosequence, Agric. For. Meteorol., 129, 105–119, doi:10.1016/j.agrformet.2005.01.002, 2005.

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., van Noordwijk, M., Creed, I. F., Pokorny, J., Gaveau, D., Spracklen, D. V., Bargués Tobella, A., Ilstedt, U., Teuling, A. J., Gebreyohannis Gebrehiwot, S., Sands, D. C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., and Sullivan, C. A.: Trees, forests and water: Cool insights for a hot world, Global Environ. Change., 43, 51–61, doi:10.1016/j.gloenvcha.2017.01.002, 2017.

Enters, T., and Durst, P.(Eds.): What Does It Take? The Role of Incentives in Forest Plantation Development in the Asia-Pacific Region. FAO RAP Publication 2004/27, FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, 2004.

European Commission: Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy, Off. J. Eur. Communities, 2000.

EVE (Ente Vasco de la Energía) [BasqueEnergy Agency]. 1990. Mapa geológico simplificado del País Vasco. Escala 1:40000. EVE: Bilbao.

FAO: Guidelines for Soil Profile Description. Food and Agriculture Organization of the United Nations, Rome, Italy, 1977.

FAO: Global Forest Resources Assessment 2015: How Are the World's Forests Changing? 2nd Ed., Food and Agriculture Organization of the United Nations, Rome, Italy, 2016.

Farley, K. A., Jobbágy, E. G., and Jackson, R. B.: Effect of afforestation on water yield: a global synthesis with implications for policy, Global Change Biol., 11, 1565–1576, doi:10.1111/j.1365-2486.2005.01011.x, 2005.

Fidelis, T., and Roebeling, P.: Water resources and land use planning systems in Portugal—Exploring better synergies through Ria de Aveiro, Land Use Policy, 39, 84–95, doi:10.1016/j.landusepol.2014.03.010, 2014.

Gallart, F., and Llorens, P.: Catchment management under environmental change: Impact of land cover change on water resources, Water Int., 28 (3), 334–340, doi:10.1080/02508060308691707, 2003.

Gallart, F., and Llorens, P.: Observations on land cover changes and water resources in the headwaters of the Ebro catchment, Iberian Peninsula, Phys. Chem. Earth, 29, 769–773, doi:10.1016/j.pce.2004.05.004, 2004.

Garmendia, E., Mariel, P., Tamayo, I., Aizpuru, I., and Zabaleta, A.: Assessing the effect of alternative land uses in the provision of water resources: evidence and policy implications from southern Europe, Land Use Policy, 29(4), 761–770, doi:10.1016/j.landusepol.2011.12.001, 2012.

Gartzia-Bengoetxea, N., Gonzalez-Arias, A., Kandeler, E., and Martínez de Arano, I.: Potential indicators of soil quality in temperate forest ecosystems: a case study in the Basque Country, Ann. For. Sci., 66, 303, doi:010.1051/forest/2009008, 2009.

Hawtree, D., Nunes, J. P., Keizer, J. J., Jacinto, R., Santos, J., Rial-Rivas, M. E., Boulet, A.-K., Tavares-Wahren, F., and Feger, K.-H.: Time series analysis of the long-term hydrologic impacts of afforestation in the Águeda watershed of north-central Portugal, Hydrol. Earth Syst. Sci., 19, 3033-3045, https://doi.org/10.5194/hess-19-3033-2015, 2015.

Hicks, B.J., Beschta, R.L., and Harr, R.D.: Long-term changes in streamflow following logging in western oregon and associated fisheries implications, J. Am. Water Resour. Assoc., 27, 217–226, doi:10.1111/j.1752-1688.1991.tb03126.x, 1991.

Hirsch, F., Clark, D., and Vihervaara, P.: Payments for Forest related Ecosystem Services: What Role for a Green Economy? Background Paper for the Workshop on Payments for Ecosystem Services, UNECE/FAO Forestry and Timber Section, Geneva, 2011.

http://www.mapama.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/, last access: 18 January 2018.

Huber, A., Iroumé, A., and Bathurst, J.: Effect of *Pinus radiata* plantation on water balance in Chile, Hydrol. Process., 22, 142–148, doi:10.1002/hyp.6582, 2008.

IFN3, 2005. www.euskadi.eus/inventario-forestal-cae-2005/web01-a3estbin/es/, last access: 29 November 2017.

IFN4, 2011. http://www.euskadi.eus/inventario-forestal-2011/web01-a3estbin/es/, last access: 29 November 2017.

Iroumé, A., and Huber, A.: Comparison of interception losses in a broadleaved native forest and a *Pseudotsuga menziesii* (Douglas fir) plantation in the Andes mountains of southern Chile, Hydrol. Process., 16 (12), 2347–2361, doi:10.1002/hyp.1007, 2002.

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., Maitre, B. A., le McCarl, D. C., Murray, B. A., and Murray, B. C.: Trading water for carbon with biological carbon sequestration, Science, 310, 1944–1947, doi:10.1126/science.1119282, 2005.

Keestra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., and Cerdà, A.: The superior effect of nature based solutions in land management for enhancing ecosystem services, Sci. Total Environ., 610–611, 997–1009, doi:10.1016/j.scitotenv.2017.08.077, 2018.

Kuczera, G.: Prediction of water yield reductions following a bushfire in ash mixed species eucalypt forest, J. Hydrol., 94, 215–236, doi:10.1016/0022-1694(87)90054-0, 1987.

Lara, A., Little, C., Urrutia, R., McPhee, J., Álvarez-Garretón, C., Oyarzún, C., Soto, D., Donoso, P., Nahuelhual, L., Pino, M., and Arismendi, I.: Assessment of ecosystem services as an opportunity for the conservation and management of native forest in Chile, For. Ecol. Manage., 258, 415–424, doi:10.1016/j.foreco.2009.01.004, 2009.

Little, C., Lara, A., McPhee, J., and Urrutia, R.: Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile, J. Hydrol., 374, 162–170, doi:10.1016/j.jhydrol.2009.06.011, 2009.

Li, Q., Wei, X., Zhang, M., Liu, W., Fan, H., Zhou, G., Giles-Hansen, K., Liu, S., and Wang, Y.: Forest cover change and water yield in large forested watersheds: A global synthetic assessment, Ecohydrology. doi:10.1002/eco.1838, 2017.

Liu, H. L., Bao, A. M., Pan, X. L., and Chen, X.: Effect of land-use change and artificial recharge on the groundwater in an arid inland river basin, Water Resour. Manage., 27, 3775–3790. doi:10.1007/s11269-013-0380-6, 2013.

Liu, Y., Xiao, J., Ju, W., Xu, K., Zhou, Y., and Zhao, Y.: Recent trends in vegetation greenness in China significantly altered annual evapotranspiration and water yield, Environ. Res. Lett., 11, 094010, doi:10.1088/1748-9326/11/9/094010, 2016.

Locatelli, B., Catterall, C. P., Imbach, P., Kumar, C., Lasco, R., Marín-Spiotta, E., Mercer, B., Powers, J. S., Schwartz, N., and Uriarte, M.: Tropical reforestation and climate change: beyond carbon., Restor. Ecol., 23, 337–343, doi:10.1111/rec.12209, 2015.

Locatelli, B., Fedele, G., Fayolle, V., and Baglee, A.: Synergies between adaptation and mitigation in climate change finance, Int. J. Clim. Change Strategies Manage., 8, 112–128, doi:10.1108/IJCCSM-07-2014-0088, 2016.

López-Moreno, J. I., Vicente-Serrano, S. M., Morán-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., and García-Ruíz, J. M.: Impact of climate evolution and land-use changes on water yield in the Ebro basin, Hydrol. Earth Syst. Sci., 15, 311–322, doi:10.5194/hess-15-311-2011, 2011.

MAGRAMA: Cuarto Inventario Forestal Nacional. Comunidad Autónoma del País Vasco / Euskadi. Ed.: Ministerio de Agricultura, Alimentación y Medio Ambiente, Secretaría General Técnica, Centro de Publicaciones, Madrid. 59 pp. ISBN: 978-84-491-1293-5, 2013.

Meaurio, M., Zabaleta, A., Boithias, L., Epelde, A. M., Sauvage, S., Sanchez-Perez, J. M., Srinivasan, R., and Antiguedad, I.: Assessing the hydrological response from an ensemble of CMIP5 climate projections in the transition zone of the Atlantic region (Bay of Biscay), J. Hydrol., 548, 46–62, doi:10.1016/j.jhydrol.2017.02.029, 2017.

Morán-Tejeda, E., Ceballos-Barbancho, A., Llorente-Pinto, J.M., and López-Moreno, J.I.: Land-cover changes and recent hydrological evolution in the Duero Basin (Spain), Reg. Environ. Change, 12, 17–33, 2012.

Morán-Tejeda, E., Zabalza., J, Rahman, K., Gago-Silva, A., Ignacio López-Moreno, J., Vicente-Serrano, S., Lehmann, A., Tague, C. L., and Beniston, M.: Hydrological impacts of climate and land use changes in a mountain watershed: uncertainty estimation based on model comparison, Ecohydrology, doi:10.1002/eco1590, 2014.

Nadal-Romero, E., González-Hidalgo, J. C., Cortesi, N., Desir, G., Gómez, J. A., Lasanta, T., Lucía, A., Marín, C., Martínez-Murillo, J. F., Pacheco, E., Rodríguez-Blanco, M. L., Romero Díaz, A., Ruiz-Sinoga, J. D., Taguas, E. V., Taboada-Castro, M. M., Taboada-Castro, M. T., Úbeda, X., and Zabaleta, A.: Relationship of runoff, erosion and sediment yield to weather types in the Iberian Peninsula. Geomorphology, 228, 372–381, doi:10.1016/j.geomorph.2014.09.011, 2015.

Neary, D. G., Ice, G. G., and Jackson, C. R.: Linkages between forest soils and water quality and quantity, For. Ecol. Manage., 258, 2269–2281, doi:10.1016/j.foreco.2009.05.027, 2009.

Olden, J. D., and Poff, N. L.: Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Res. Appl., 19 (2), 1535–1467, doi:10.1002/rra.700, 2003.

Price, K.: Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review, Prog. Phys. Geogr. 35, 465–492, doi:10.1177/0309133311402714, 2011.

Rind, D., Goldberg, R., Hansen, J., Rosenzweig, C., and Ruedy, R.: Potential evapotranspiration and the likelihood of future drought., J. Geophys. Res. Atmos., 95, 9983–10004, doi:10.1029/JD095iD07p09983, 1990.

Ritcher, B. D., Baumgartner, J. V., Powell, J., and Braun, D. P.: A method for assessing hydrologic alteration within ecosystem, Conserv. Biol., 10, 1163–1174, doi.org/10.1046/j.1523-1739.1996.10041163.x, 1996.

Robinson, M., Cognard-Plancq, A. -L., Cosandey, C., David, J., Durand, P., Führer, H. -W., Hall, R., Hendriques, M. O., Marc, V., McCarthy, R., McDonnell, M., Martin, C., Nisbet, T., O'Dea, P., Rodgers, M., and Zollner, A.: Studies of the impact of forests on peak flows and baseflows: a European perspective, Forest Ecol. Manage., 186 (1–3), 85–97, doi:10.1016/S0378-1127(03)00238-X, 2003.

Ruiz Urrestarazu, E.: Adaptación y gestión de las medidas agroambientales y de forestación en el País Vasco in Corbera, M. (Ed.) Cambios en los espacios rurales cantábricos tras la integración de España en la UE, Santander, Universidad de Cantabria, 1999.

Schilling, K. E., and Libra, R. D.: Increased baseflow in Iowa over the second half of the 20th century, J. Am. Water Resour. Assoc., 39, 851–860, doi:10.1111/j.1752-1688.2003.tb04410.x, 2003.

Schirmer, J., and Bull, L.: Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects, Global Environ. Change., 24, 306–320, doi:10.1016/j.gloenvcha.2013.11.009, 2014.

Scott, D. F., and Prinsloo, F. W.: Longer-term effects of pine and eucalypt plantations on streamflow, Water Resour. Res., 44, W00A08, doi:10.1029/ 2007wr006781, 2008.

Tomer, M. D., and Schilling, K. E.: A simple approach to distinguish land-use and climate change effects on watershed hydrology, J. Hydrol., 376, 24–33, doi:10.1016/j.jhydrol.2009.07.029, 2009.

Trabucco, A., Zomer, R. J., Bossio, D. A., van Straaten, O., and Verchot, L. V.: Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies, Int. Agric. Ecosyst. Environ., 126, 81–97, doi:10.1016/j.agee.2008.01.015, 2008.

van Dijk, A. I. J. M., and Keenan, R. J.: Planted forests and water in perspective, Forest Ecol. Manage., 251 (1–2), 1–9, doi:10.1016/j.foreco.2007.06.010, 2007.

Vertessy, R. A., Watson, F.G.R., and O’Sullivan, S. K.: Factors determining relations between stand age and catchment water balance in mountain ash forests. Forest Ecol. Manage., 143, 13–26, doi:10.1016/S0378-1127(00)00501-6, 2001.

Ward, A. D., and Trimble, S. W.: Environmental Hydrology, 2nd ed., Lewis Publishers/CRC Press Company, London/New York, p. 472, 2004.

Zabaleta, A., Antiguedad, I., Barrio, I., and Probst, J. -L.: Suspended sediment delivery from small catchments to the Bay of Biscay. What are the controlling factors?, Earth Surf. Process. Landforms, 41, 1894–1910, doi: 10.1002/esp.3957, 2016.

Tables

Table 1. Catchment descriptions. Code of the gauging station, catchment name, catchment area, primary land cover types percentages for 2002 (IFN3, 2005) and 2009 (IFN4, 2011) at the 1:25000 scale.

			Primary Cover Types (%)							
		Catchment area (km^2)	2002				2009			
			Forest Cover			Pasture Cover	Forest Cover			Pasture Cover
Code	Catchment		Native	Exotic	**Total**		Native	Exotic	**Total**	
A1Z1	San Prudentzio	121.78	21	49	**70**	24	21	46	**67**	26
A1Z2	Oñati	105.78	27	46	**73**	25	27	45	**72**	26
A1Z3	Urkulu	9	43	14	**57**	42	47	10	**57**	42
A2Z1	Aixola	5.03	6	76	**82**	12	7	73	**80**	15
A3Z1	Altzola	464.25	19	52	**71**	23	20	50	**70**	24
B1T1	Barrendiola	3.8	48	18	**66**	0	48	18	**66**	0
B1Z1	Aitzu	56.13	19	56	**75**	18	19	55	**74**	19
B1Z2	Ibai-Eder	62.73	25	53	**78**	20	25	53	**78**	20
B2Z1	Aizarnazabal	269.77	19	50	**69**	26	20	49	**69**	26
C1P3	Arriaran	2.77	24	62	**86**	12	24	62	**86**	12
C1Z2	Estanda	55.02	16	54	**70**	23	17	52	**69**	24
C2Z1	Agauntza	69.64	57	24	**81**	18	57	23	**80**	18
C5Z1	Alegia	333.34	30	39	**69**	27	30	36	**66**	29
C7Z1	Berastegi	33.34	25	35	**60**	38	25	34	**59**	37
C8Z1	Leitzaran	110.01	39	39	**78**	20	46	33	**79**	20
C9Z1	Lasarte	796.5	32	34	**66**	30	33	31	**64**	31
D1W1	Añarbe	47.69	66	19	**85**	15	66	19	**85**	15
D2W1	Ereñozu	218.42	48	30	**78**	21	50	27	**77**	21
E1W1	Oiartzun	56.6	26	33	**59**	35	31	28	**59**	35
F1W1	Endara	6.19	15	53	**68**	32	15	53	**68**	32

Note: Only forest (native and exotic) or pasture land covers are shown. Other types of land cover are not shown as they are usually less than 10 %, except for Barrendiola catchment where about 30 % of the catchment is bare rock.

Table 2. Statistics of hydrological indices, land cover types, and precipitation amounts used in this study. Statistics of hydrological indices and precipitation amounts were calculated for the entire study period (from 2000–2001 to 2004–2005 and from 2007–2008 to 2011–2012).

	Index	Mean	s.d.	Min	Max
Hydrologic indices	YR, mm	839	320	246	1873
	Y10m, L s^{-1} km^{-2}	4.93	4.40	0.14	28.22
	A10m, L s^{-1} km^{-2}	6.90	7.75	0.28	67.48
	W10m, L s^{-1} km^{-2}	13.55	10.31	1.91	90.89
	Sp10m, L s^{-1} km^{-2}	8.42	6.63	0.34	36.18
	Su10m, L s^{-1} km^{-2}	4.41	4.42	0.02	36.22
	Y50m, L s^{-1} km^{-2}	14.68	9.72	2.71	58.98
	A50m, L s^{-1} km^{-2}	18.94	16.63	2.18	118.74
	W50m, L s^{-1} km^{-2}	27.22	15.63	5.59	125.77
	Sp50m, L s^{-1} km^{-2}	17.50	12.29	2.85	66.43
	Su50m, L s^{-1} km^{-2}	6.22	6.26	0.21	49.69
	Y90m, L s^{-1} km^{-2}	59.81	24.62	15.27	153.27
	A90m, L s^{-1} km^{-2}	74.40	45.14	7.22	217.21
	W90m, L s^{-1} km^{-2}	87.18	34.28	17.38	190.39
	Sp90m, L s^{-1} km^{-2}	49.17	24.24	7.61	113.48
	Su90m, L s^{-1} km^{-2}	12.54	16.09	0.8	120.83
	CVY	1.54	0.42	0.63	3.02
	CVA	1.40	0.59	0.17	3.08
	CVW	1.11	0.41	0.15	2.44
	CVSp	1.17	0.53	0.36	3.54
	CVSu	0.79	0.60	0.1	3.95
	skn	4.57	2.00	0.92	12.43
	JY10m	251	46	52	343
Land cover	Forest, %	72	8	56	85
	Native (NAT), %	31	15	6	66
	Exotic (EXO), %	41	16	10	76
	Pasturelands (PAST), %	23	9	0	42
	Others, %	5	7	0	34
Precipitation	YP, mm	1538	345	958	2611
	AP + SuP, mm	776	228	323	1681
	WP + AP, mm	975	253	441	1874
	SpP + WP, mm	767	171	402	1406

SuP + SpP, mm	560	179	285	1146

Abreviation description: YR: annual runoff; Y10m, A10m, W10m, Sp10m and Su10m: 10th percentile for annual, autumn, winter, spring and summer discharge series; Y50m, A50m, W50m, Sp50m and Su50m: 50th percentile for annual, autumn, winter, spring and summer discharge series; Y90m, A90m, W90m, Sp90m and Su90m: 90th percentile for annual, autumn, winter, spring and summer discharge series; CVY, CVA, CVW, CVSp and CVSu: coefficient of variation for annual, autumn, winter, spring and summer discharge series; skn: skewnwss of the annual discharge series; JY10m: Julian day of the beginning of the low flow period. YP: annual precipitation amount for the catchment; AP + SuP: summer plus previous autumn precipitation amount for the catchment; WP + AP: winter plus previous autumn precipitation amount for the catchment; SpP + WP: spring plus previous winter precipitation amount for the catchment; SuP + SpP: summer plus previous spring precipitation amount for the catchment. See the text for more information.

Table 3. Percentage of different land cover types for each land cover combination. Note that base land cover combination in the text refers to combination EXO. The name given to each combination refers to the main land use types considered. EXO = exotic plantation; NAT = native forests; PAST = pasturelands.

Land use combination	EXO	EXO+ PAST	EXO+ NAT	NAT	NAT+ PAST	EXO+ NAT+PAST
Exotic (%)	76	40.8	40.8	10	10	40.8
Native (%)	6	6	41.2	66	30.84	30.84
Pasturelands (%)	18	53.2	18	24	59.16	28.36

Table 4. Results obtained, from multiple regression models, for alternative land cover combinations in the variation in percentage with respect to the base land cover combination (EXO) in the annual median, high and low flows for low (1st quartile) and high (3rd quartile) precipitation amounts (see Fig. 2 and Fig. 3).

			Low Precipitation (1st quartile)						High Precipitation (3rd quartile)					
			Result for base land cover ($\text{L s}^{-1}\text{ km}^{-2}$)	Differences from base land cover (%)					Result for base land cover ($\text{L s}^{-1}\text{ km}^{-2}$)	Differences from base land cover (%)				
		Combination	EXO	EXO+ PAST	EXO+ NAT	NAT	NAT+ PAST	EXO+ NAT+PAST	EXO	EXO+ PAST	EXO+ NAT	NAT	NAT+ PAST	EXO+ NAT+PAST
Hydrologic differences	Annual	Y50m	7.81	44 %	–15 %	–18 %	41 %	2 %	14.59	52 %	9 %	24 %	67 %	22 %
		Y90m	39.1	23 %	17 %	33 %	39 %	19 %	70.87	–11 %	–2 %	–5 %	–10 %	–3 %
		Y10m	2.93	–4 %	–31 %	–53 %	–27 %	–22 %	6.25	45 %	–9 %	–8 %	46 %	7 %
	Winter	W90m	67.7	–5 %	18 %	31 %	8 %	12 %	106.34	–7 %	2 %	3 %	–6 %	–0.4 %
		W10m	8.5	19 %	21 %	39 %	37 %	21 %	10.94	42 %	40 %	75 %	77 %	41 %
	Spring	Sp50m	9.95	55 %	–32 %	–45 %	42 %	–6 %	15.6	56 %	15 %	35 %	76 %	27 %
		Sp10m	4.98	69 %	–58 %	–87 %	40 %	–20 %	8.12	77 %	0 %	13 %	90 %	22 %

Note: Only results for regression with statistically significant coefficients for land cover variables and determination coefficient higher than 0.5 are included. Precipitations considered in each case are: 1279 and 1719 for annual low and high precipitations, respectively; 814 and 1147 for winter low and high precipitations, respectively; 646 and 852 for winter low and high precipitations, respectively.

Figure Captions

Figure 1. a) Location and digital terrain model (5x5 m of resolution) of the study area with the main drainage network, location of gauging stations, catchments, and average precipitation values. b) Land cover map of the study area in 2002 (IFN3, 2005) and 2009(IFN4, 2011) at the 1:25000 scale.

Figure 2. Expected values of a) annual average flows (Y50m, L s^{-1} km^{-2}) and b) average discharge for spring (Sp50m, L s^{-1} km^{-2}) for the land cover combinations described in Table 3 and a gradient of precipitation, as a result of the multiple regression models shown in Appendix D (a) and b), respectively). Statistics of the regression model are included. Significance of variables in the model are shown: *** means significant at the 0.001 level, ** at the 0.01, * at the 0.05 and ¨ at the 0.1 level.

Figure 3. Expected values of a) annual high flows (Y90m, L s^{-1} km^{-2}) and b) low flows for spring (Sp10m, L s^{-1} km^{-2}) for the land cover combinations described in Table 3 and a gradient of precipitation, as a result of the multiple regression models shown in Appendix D (c) and d), respectively). Statistics of the regression model are included. Significance of variables in the model are shown: *** means significant at the 0.001 level, ** at the 0.01, * at the 0.05 and ¨ at the 0.1 level.

Appendix

Appendix A: Hydrographs for the 20 catchments in Table 1 for the hydrological year 2000–2001. The meaning of some of the calculated hydrological indicators is also indicated in the figure.

Appendix B: Boxplots representing the statistics of a) annual and b) seasonal precipitation for the 20 studied catchments during the hydrological years considered. A = Autumn, W = Winter, Sp = Spring and Sm = Summer.

Appendix C: Linear regressions obtained between a) annual precipitation (YP, mm) and runoff (YR, mm) b) precipitation from spring and winter (SpP + WP) and average discharge in spring (Sp50m) c) precipitation from winter and autumn (WP + AP) and wintertime high flows (W90m) and d) precipitation from spring and winter (SpP + WP) and low flows in spring (Sp10m).

Appendix D: Multiple regression models. a) Multiple regression model for annual average flows (Y50m) considering alternative land cover and its interaction with annual precipitation (YP). b) Multiple regression model for average discharge for spring (Sp50m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt). c) Multiple regression model for annual high flows (Y90m) considering alternative land cover and its interaction with annual precipitation (YP). d) Multiple regression model for low flows for spring (Sp10m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt).

Figure 1.

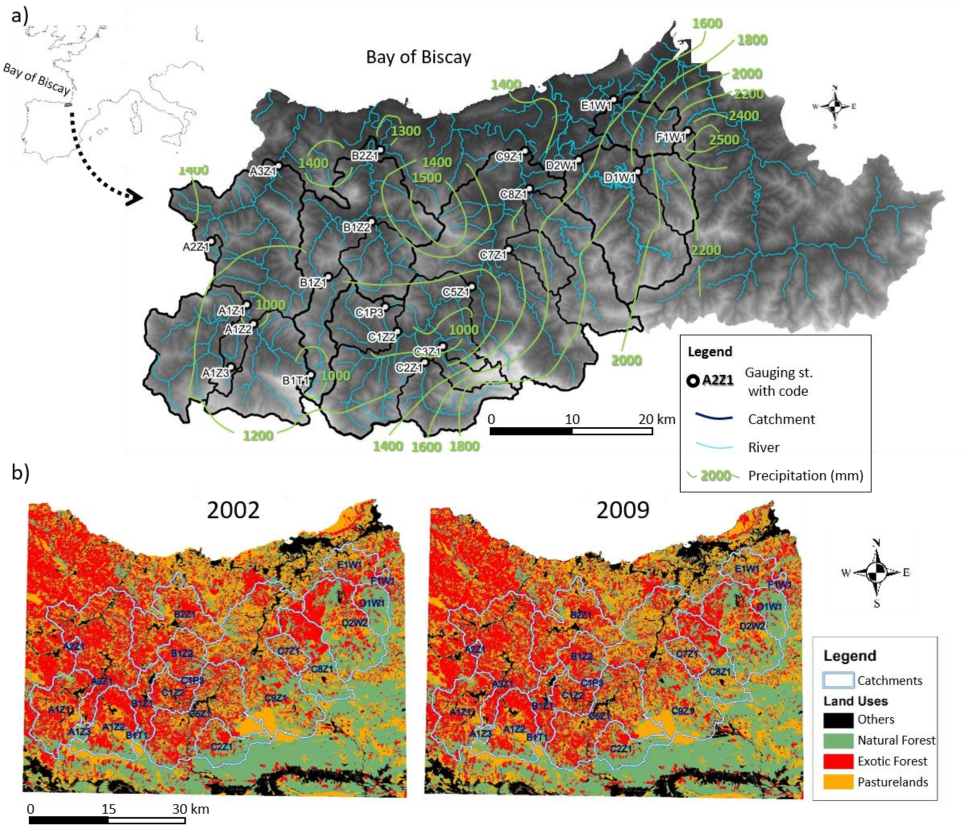
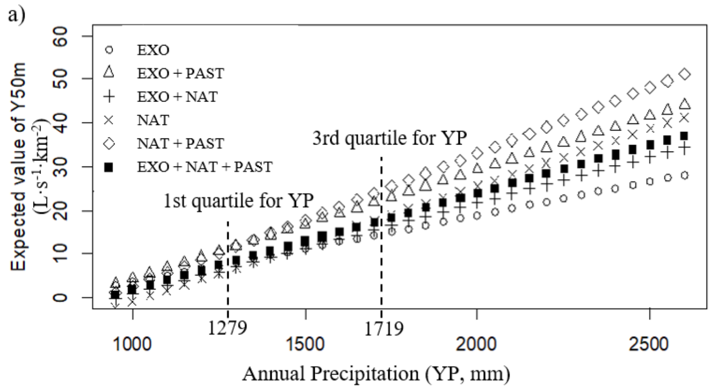

a)
Bay of Biscay
Bay of Biscay
A3Z1
A2Z1
A1Z1
A1Z2
A1Z3
B2Z1
B1Z2
B1Z1
B1T1
C1P3
C1Z2
C2Z1
C3Z1
C5Z1
C7Z1
C8Z1
C9Z1
D2W1
D1W1
E1W1
F1W1
1000
1200
1300
1400
1500
1600
1800
2000
2200
2400
2500
0
10
20 km
N
W
E
S
Legend
A2Z1
Gauging st. with code
Catchment
River
2000
Precipitation (mm)
b)
2002
2009
Legend
Catchments
Land Uses
Others
Natural Forest
Exotic Forest
Pasturelands
0
15
30 km

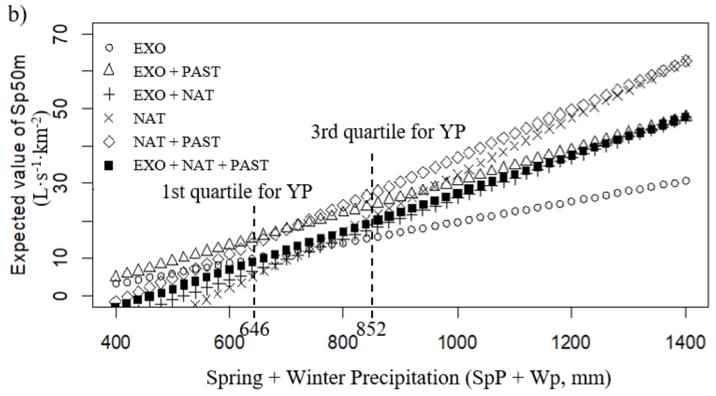
Figure 2.



Adjusted R-squared: 0.7704

F-statistic: 89.69 on 7 and 178 DF, p-value: < 2.2e-16

NAT**; EXO*; PAST***; I(NAT * YP)**; I(EXO * YP)¨; I(PAST * YP)***

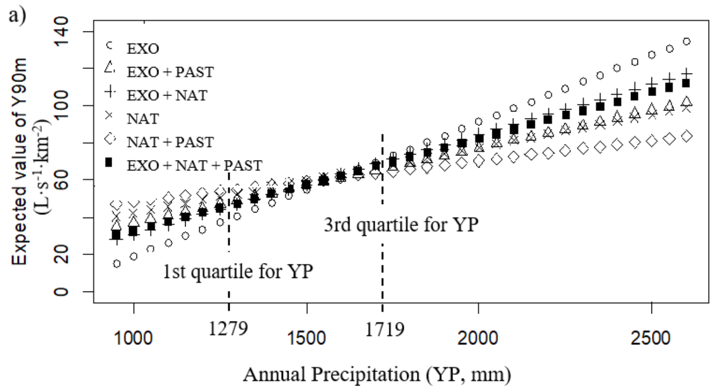


Adjusted R-squared: 0.4936

F-statistic: 25.09 on 7 and 166 DF, p-value: < 2.2e-16

YP¨; NAT¨; PAST**; I(NAT * YP)*; I(EXO * YP)¨; I(Pasturelands * YP)**

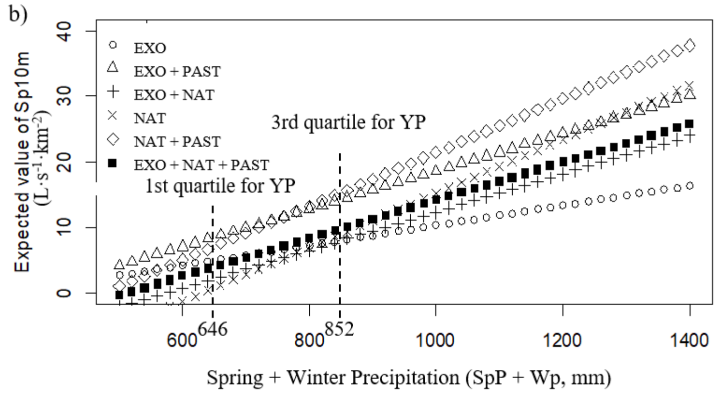
Figure 3.



Adjusted R-squared: 0.6713

F-statistic: 54.97 on 7 and 178 DF, p-value: < 2.2e-16

YP***; NAT*; EXO¨; PAST**; I(NAT * YP)**; I(EXO * YP)¨; I(PAST * YP)**

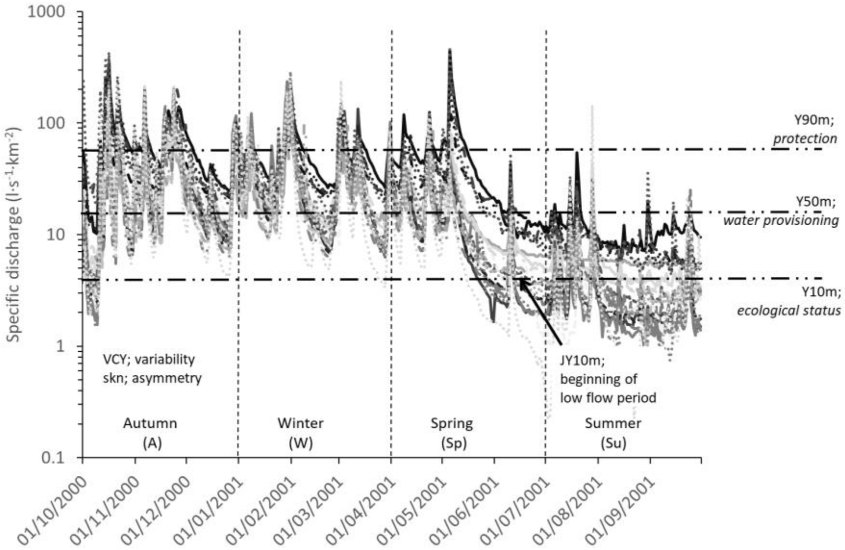


Adjusted R-squared: 0.558

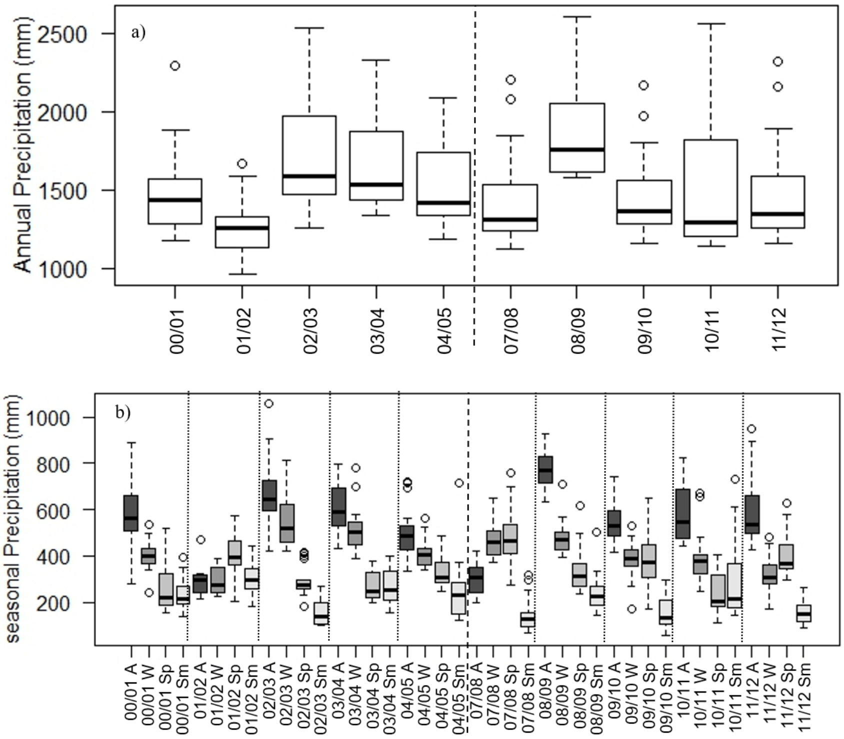
F-statistic: 32.2 on 7 and 166 DF, p-value: < 2.2e-16

NAT*; EXO¨; PAST*; I(NAT x (SpP+WP))*; I(Pasturelands x (SpP+WP))*

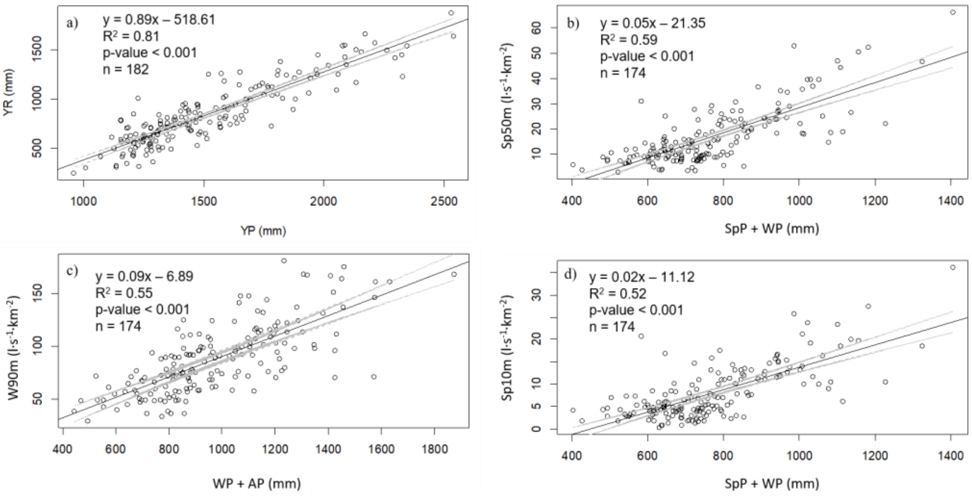
Appendix A:


1000
100
10
1
0.1
Specific discharge (l·s-1·km-2)
Y90m;
protection
Y50m;
water provisioning
Y10m;
ecological status
VCY; variability
skn; asymmetry
JY10m;
beginning of
low flow period
Autumn
(A)
Winter
(W)
Spring
(Sp)
Summer
(Su)
01/10/2000
01/11/2000
01/12/2000
01/01/2001
01/02/2001
01/03/2001
01/04/2001
01/05/2001
01/06/2001
01/07/2001
01/08/2001
01/09/2001

Appendix B:


a)
Annual Precipitation (mm)
1000
1500
2000
2500
00/01
01/02
02/03
03/04
04/05
07/08
08/09
09/10
10/11
11/12
b)
seasonal Precipitation (mm)
200
400
600
800
1000
00/01 A
00/01 W
00/01 Sp
00/01 Sm
01/02 A
01/02 W
01/02 Sp
01/02 Sm
02/03 A
02/03 W
02/03 Sp
02/03 Sm
03/04 A
03/04 W
03/04 Sp
03/04 Sm
04/05 A
04/05 W
04/05 Sp
04/05 Sm
07/08 A
07/08 W
07/08 Sp
07/08 Sm
08/09 A
08/09 W
08/09 Sp
08/09 Sm
09/10 A
09/10 W
09/10 Sp
09/10 Sm
10/11 A
10/11 W
10/11 Sp
10/11 Sm
11/12 A
11/12 W
11/12 Sp
11/12 Sm

Appendix C:


a)
y = 0.89x – 518.61
R² = 0.81
p-value < 0.001
n = 182
YR (mm)
500
1000
1500
1000
1500
2000
2500
YP (mm)
b)
y = 0.05x – 21.35
R² = 0.59
p-value < 0.001
n = 174
Sp50m (l·s⁻¹·km⁻²)
10
20
30
40
50
60
400
600
800
1000
1200
1400
SpP + WP (mm)
c)
y = 0.09x – 6.89
R² = 0.55
p-value < 0.001
n = 174
W90m (l·s⁻¹·km⁻²)
50
100
150
400
600
800
1000
1200
1400
1600
1800
WP + AP (mm)
d)
y = 0.02x – 11.12
R² = 0.52
p-value < 0.001
n = 174
Sp10m (l·s⁻¹·km⁻²)
0
5
10
20
30
400
600
800
1000
1200
1400
SpP + WP (mm)

Appendix D.

a) Multiple regression model for annual average flows (Y50m) considering alternative land cover and its interaction with annual precipitation (YP).

D1	Estimate	Std. Error	t value	p value	Significance
(Intercept)	50.67649	21.3388	2.3749	0.01862	*
YP	-0.02049	0.0150	-1.3635	0.17446	
Native	-0.80268	0.2677	-2.9985	0.00310	**
Exotic	-0.56718	0.2329	-2.4354	0.01586	*
Pasturelands	-0.81356	0.2181	-3.7296	0.00026	***
I(Native * YP)	0.00046	0.0002	2.6403	0.00902	**
I(Exotic *YP)	0.00030	0.0002	1.8558	0.06513	.
I(Pasturelands * YP)	0.00057	0.0002	3.4285	0.00075	***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 3.96 on 178 degrees of freedom
Multiple R-squared: 0.7791, Adjusted R-squared: 0.7704
F-statistic: 89.69 on 7 and 178 DF, p-value: < 2.2e-16

b) Multiple regression model for average discharge for spring (Sp50m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt).

	Estimate	Std. Error	t value	p value	Significance
(Intercept)	84.01452	43.1914	1.9452	0.05345	.
SpPt (SpP+WP)	-0.06791	0.0586	-1.1585	0.24833	
Native	-1.44268	0.5367	-2.6879	0.00792	**
Exotic	-0.86076	0.5230	-1.6457	0.10172	
Pasturelands	-0.98659	0.3952	-2.4965	0.01352	*
I(Native * SpPt)	0.00159	0.0007	2.3249	0.02129	*
I(Exotic *SpPt)	0.00083	0.0007	1.1590	0.24811	
I(Pasturelands * SpPt)	0.00127	0.0006	2.2893	0.02332	*

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 6.784 on 166 degrees of freedom
Multiple R-squared: 0.6407, Adjusted R-squared: 0.6256
F-statistic: 42.29 on 7 and 166 DF, p-value: < 2.2e-16

c) Multiple regression model for annual high flows (Y90m) considering alternative land cover and its interaction with annual precipitation (YP).

	Estimate	Std. Error	t value	p value	Significance
(Intercept)	-2.86E+02	1.06E+02	-2.707	0.007451	**
YP	2.46E-01	7.31E-02	3.364	0.000941	***
Native	2.88E+00	1.14E+00	2.5281	0.01234	*
Exotic	2.02E+00	1.14E+00	1.766	0.079105	.
Pasturelands	3.44E+00	1.19E+00	2.8874	0.004367	**
I(Native * YP)	-2.07E-03	7.54E-04	-2.7403	0.006764	**
I(Exotic *YP)	-1.54E-03	7.85E-04	-1.9637	0.051117	.
I(Pasturelands * YP)	-2.45E-03	8.50E-04	-2.8772	0.004503	**

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 13.5 on 178 degrees of freedom
Multiple R-squared: 0.6837,   Adjusted R-squared: 0.6713
F-statistic: 54.97 on 7 and 178 DF, p-value: < 2.2e-16

d) Multiple regression model for low flows for spring (Sp10m) considering alternative land cover and its interaction with seasonal precipitation (spring + winter precipitation, SpPt).

	Estimate	Std. Error	t value	p value	Significance
(Intercept)	65.57420	33.1084	1.9806	0.04929	*
SpPt (SpP+WP)	-0.06361	0.0458	-1.3876	0.16712	
Native	-0.99263	0.3915	-2.5358	0.01214	*
Exotic	-0.65681	0.3678	-1.7858	0.07596	.
Pasturelands	-0.80725	0.3327	-2.4266	0.01631	*
I(Native * SpPt)	0.00109	0.0005	2.1315	0.03452	*
I(Exotic *SpPt)	0.00070	0.0005	1.3761	0.17065	
I(Pasturelands * SpPt)	0.00108	0.0005	2.2733	0.02429	*

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 3.955 on 166 degrees of freedom
Multiple R-squared: 0.5759,   Adjusted R-squared: 0.558
F-statistic: 32.2 on 7 and 166 DF, p-value: < 2.2e-16