Dear editor and reviewers of *Hydrology and Earth System Sciences*,

Please find enclosed our responses to the reviewers' comments regarding the paper "Riparian evapotranspiration shapes stream flow dynamics and water budgets in a Mediterranean catchment" (hess-2017-735), which in the new version will be entitled "Riparian evapotranspiration is essential to simulate stream flow dynamics and water budgets in a Mediterranean catchment". Overall, we feel happy with the positive reviews and that the reviewers found the study interesting and a potential contribution to *Hydrology and Earth System Sciences* journal. Their suggestions on the paper as well as their editing corrections have been of great help for us.

We have taken into consideration all the comments raised by the reviewers and we have worked thoughtfully to address them all. Following the reviewers' suggestions, we have carefully rewritten both the introduction and discussion sections to better frame our work within the modelling community as well as to better highlight the novelties of the study. Moreover, we do now better describe the data used to calibrate the model, provide a detail definition of the vegetative period, and explain how the three sub-catchment were characterized. We have also included new supplementary materials with detailed information of the model conceptualization (including a new conceptual figure) and parametrization in order to better describe the model set up and, at the same time, clarify the model description in the main text. Finally, we do now explicitly address the influence of the riparian zone on flow simulations during the dormant period in both the results and discussion sections.

Below you will find detailed responses to each of your general comments as well as to the most substantial specific comments. Overall, we believe that we can successfully solve all the points raised by the reviewers and generate an improved version of the manuscript including all their suggestions.

Please, do not hesitate to contact us if further clarifications are needed at this stage.

Sincerely,

Anna Lupon

CC: José L. J. Ledesma and Susana Bernal

Anonymous Referee #1

General comment: *The paper investigates the effect of riparian zones on hydrometric streamflow responses and catchment water budgets with a particular focus on riparian evapotranspiration. The authors use a semi-distributed conceptual bucket-type model to simulate a Mediterranean catchment with different setups. First, they demonstrate that the inclusion of a riparian compartment improves the model performance, especially during the vegetation period. Second, they demonstrate that the catchment response is sensitive to the evapotranspiration parameters of the riparian zone during the vegetation period. Third, they performed several climate scenario simulations to discuss the effect of riparian evapotranspiration on water budgets with climate change. Overall, the article is well structured, the text reads fluently and figures and tables are clear. I read the paper with great interest. It nicely demonstrates that riparian zones and their ET should be considered in catchment models and I think studies like this are necessary to raise the hydrological model community's awareness for the role of riparian zones in a catchment. However, while reading I came across two major issues that concerned me several times throughout the text. These two major concerns and several minor issues should be addressed and clarified before publication.*

Answer: Many thanks for your positive comments. We are glad that you enjoyed the paper and that you consider that "studies like this are necessary" to improve catchment hydrological models. We deeply appreciate your tremendously detailed and constructive review. We have carefully considered all your suggestions and worked to incorporate them in the new version of the manuscript.

Major issues:

1) *The first issue is related to the aim of the study and the chosen approaches to accomplish it. In the introduction it is stated that it is known from several studies that riparian ET has an impact on stream flow dynamics and water budgets, but that there is a lack of respective studies at catchment scale. This suggests that the study focusses on the aspect of the catchment scale (such as the seasonal influence of riparian ET on hydrological connectivity between uplands and stream networks (cf. L77-78) or the discussed percentage contribution of riparian ET to total catchment water depletion). Yet, large parts of the paper analyze and discuss the impact of riparian ET on stream flow dynamics without a clear relation to catchment scale specific aspects. Model validation follows the unusual idea of validating the performance of the riparian ET over the same period that was calibrated against discharge (and also some ET characteristics), instead of validating the performance of the calibrated response (discharge) for another period than the calibration period. I think this approach is valid since the performance of riparian ET is of specific interest for this study. Certainly, a validation of the discharge response would be good as well, especially since the model is used for climate scenario simulations where it is of interest that discharge (and ET) simulates well also under different conditions than experienced in the calibration period. However, my bigger concern is that model validation relies on the idea that daily variations of stream flow can be used as proxy for riparian ET. If the relation between riparian ET and streamflow*

dynamics is already approved enough to be used for the creation of validation data, this necessarily raises the question why the effect of riparian ET on streamflow dynamics has to be analyzed in additional studies. Again, the introduction states that this effect is known, but title and large parts of the paper (partly even the introduction, cf. L71) read as if this is one of the main points of the study. Especially in the discussion section the results are mainly compared to agreeing studies of riparian ET and I missed a clear delineation in which way this study brings up new insight in the role of riparian ET for catchment water budgets and streamflow responses. In addition, the authors often use the inclusion/exclusion of the riparian compartment as equivalent to an inclusion/exclusion of riparian ET (L22-23, L143-145, L158-160, L326). In my opinion, the inclusion of the riparian compartment can only be used to analyze the effect of the riparian zone as a total, since the riparian compartment represents more fluxes than only ET. It is true that the model mainly improved during the vegetation period and that this suggests a major influence of riparian ET. However, at least the RDV improved also during the dormant season, which could be explained by the additional storage/buffer component of the riparian compartment. Moreover, a different parameterization of the riparian ET (less strong riparian ET compared to upland ET during the vegetation period) might have a different effect (e.g. similar improvement of the model during vegetative and dormant period). My suggestion would be to keep the presented methods and results unchanged, but to shift the focus in the discussion and introduction (and other explanations throughout the text) from the role of riparian ET on discharge dynamics to 1) the role of riparian zones and its ET for hydrological modelling of catchments and 2) how this might vary under different climate conditions.

Answer: We thank the reviewer for highlighting this issue, and also for suggesting how to improve the introduction and discussion, which has been very helpful. As the reviewer pointed, previous studies have already shown that processes occurring in riparian zones can drive diel and seasonal patterns in stream flow (e.g. Flewelling et al., 2014; Lupon et al., 2016; Rassam et al., 2006). However, there are few hydrological catchment models explicitly considering the riparian compartment, which ultimately limits our ability to quantify the influence of riparian zones on stream flow and catchment water export across regions. Specifically, applying hydrological models that consider the riparian compartment to water limited catchments could be a helpful tool to better understand how riparian zones can shape catchment water budgets and availability for both in- and off-stream uses, as well as to achieve feasible predictions of hydrological and ecological responses to future climate. In this sense, our study demonstrates that the riparian zone is a key compartment to properly simulate both catchment hydrology and stream flow dynamics, and consequently, that this landscape unit should be considered in hydrological models. Moreover, the successful simulations obtained for Font del Regàs provide evidence that hydrological models can be an appropriate tool for exploring how specific hydrological processes, such as riparian ET, can influence stream hydrology under different climatic conditions. Following the reviewer suggestion, we have rewritten parts of the introduction (L44-49, L59-64, L70-74) and discussion (L321-328, L368-372, L409) sections to better highlight this point. Moreover, we now state that the aim of our study was to explore the role of riparian ET on successfully simulating present and future stream flow dynamics and catchment water exports in a Mediterranean forested headwater catchment (L76-78). With these improvements, we believe that both introduction and discussion are now better framed within the context of hydrological modelling and explicitly address the rational that was implicit in our study design.

We also agree with the reviewer that the inclusion/exclusion of the riparian compartment is not equivalent to an inclusion/exclusion of riparian ET because there are other riparian processes (e.g. longer water travel times) that can additionally affect stream flow responses. We carefully checked all the manuscript to avoid confusions (e.g., L21-24, L192-194). Moreover, we do now highlight that, during the dormant period, the model efficiency (RDV) improved from 12% to 7% when the riparian zone was included (L270-272). This result suggests that increased water storage within riparian zones can also influence stream flow dynamics during wet conditions (L334-338).

Finally, we discarded the idea to split the time series in order to calibrate and validate against two independent data sets. First, and similar to other authors (Oreskes et al., 1994), we are skeptical about the possibility of meaningful validation of environmental models, especially when the model performs better for the validation data set than for the calibration data set. Moreover, our data set was relatively short and showed strong inter- and intra-annual variability, which make difficult to split the data in order to have a full range of environmental conditions for both the calibration and validation procedures. Thus, we are more confident to get a more robust parametrization for both present and future projections by using the entire available dataset for model calibration. This procedure has been shown to be appropriate and successful in previous studies (e.g., Larssen et al. 2007; Ledesma and Futter, 2017). We chose to use daily variations in stream flow to validate the simulated riparian ET rates, which is one of the main outputs of the model together with stream flow. These daily variations in stream flow were independent from the model input data and further, they are robust estimates of riparian ET (e.g. Flewelling et al., 2014; Lupon et al. 2016). Thus, we believe they were a neat, alternative way to validate model results. Following your suggestion, we have clarified the model validation procedure in the text (L201-209).

2) *The second main issue concerns the model setup. I especially had problems to understand how the three sub-catchments were defined. According to the naming of the sub-catchments (e.g. downstream sub-catchment, downstream site), Table 1 and the way how validation data were calculated (L197-201), I understood the sub-catchments as three individual parts summing up to the total catchment. According to the description of the calibration data (L134-140), the aim of the study (influence of riparian ET in a catchment) and some applied methods and presented results, I guess the sub-catchments include the total upstream drainage area (i.e. the downstream sub-catchment is equivalent to the total catchment). Besides a clarification of the definition of the sub-catchments in the text, I think a figure showing the conceptual setup of the models would be very useful. Such a figure would also make it easier to understand the differentiation between landscape units, layers and compartments and the flux connections between them (especially for L145-160). Additionally, I missed a more detailed description of the model parameters and the represented fluxes. Since the study focusses on the influence of ET, at least the conceptualization of ET and the related ET parameters (degree day rates, threshold*

temperature parameters) should be explained in more detail in the text and/or in a figure. For example, it is discussed that the length of the vegetative period increased in the climate scenarios at that this was mostly a consequence of a changed tree phenology, i.e. an earlier onset of the leaf out period, thus tree phenology (l.371-380). It is not clear to me if and how the length of the vegetation period and the tree phenology (e.g. leaf out period) were considered in the model structure and thus it is difficult to follow the argumentation.

Answer: We agree with the reviewer that further clarification was needed in this regard. The three catchments are nested, and thus, the downstream sub-catchment is equivalent to the total drainage area. Given that the flow at each sampling site integrates all processes occurring within its drainage area, the PERSiST model simulate flows based on (i) the flow coming from the upstream nested-catchment and (ii) the proportion of each landscape unit of the local drainage area. For example, flows at the downstream sub-catchment outlet were simulated based on midstream sub-catchment flows and the proportion of evergreen, deciduous, and riparian forests in the local drainage area of the downstream sub-catchment. To avoid confusions, we have clarified this issue throughout the manuscript. Now, we refer to (i) local vs. total drainage area and (ii) single sub-catchment vs. whole catchment (e.g., L101-111, Table 1).

We have produced new supplementary information to clarify the model set up and conceptualization (Supplement 1 and 2). This includes tables for model inputs, model calibration data, relevant model parameters (and corresponding description), and model outputs (Supplement 2). Moreover, and following the reviewers' suggestion, we have included a conceptual figure illustrating the model structure including and excluding the riparian compartment (Figure S1). Finally, we have clarified and better structured the material and methods subsections related to model description, configuration, and calibration (sections 3.1, 3.2 and 3.3). Specifically, we do now explain that PERSiST conceptualizes the landscape in four spatial levels: catchment, sub-catchment, landscape unit, and bucket/soil box (L117-120).

Finally, we agree with both reviewers #1 and #2 that the association between the extension of the vegetative period and riparian tree phenology was not clearly explained. Simulations for future climate change scenarios showed that the number of days with ET > 0 mm d^{-1} would mostly increase during spring (Figure 5, main manuscript). The reason for such increase is a larger amount of days with temperatures above the "growing degree threshold", a parameter indicating the temperature threshold above which ET occurs. We have rewrite the discussion in order to clarify this issue (L384-387). Moreover, we do now state that these results suggest a potential enlargement of the vegetative period, which is consistent with previous observations showing that climate change can affect riparian tree phenology by promoting the advancement of the riparian leaf out period (Perry et al., 2012; Serrat-Capdevila et al., 2007) (L387-390).

Minor comments:

3) I suggest to change the title to: How riparian evapotranspiration shapes stream flow dynamics and water budgets in a Mediterranean catchment model, cf. comment (1) **Answer:** Thanks for the suggestion; we have changed the title to “Riparian evapotranspiration is essential to simulate stream flow dynamics and water budgets in a Mediterranean catchment”.

4) L25: *Shouldn’t it be the same value as in L286?* **Answer:** Right, thanks for noticing. We changed the value to “5.5–8.4%” (L25).

5) L28-29: *I would consider more relevant that this increases the contribution of riparian ET to catchment water depletion by 1-2%.* **Answer:** Ok, we do now state that “Simulations considering climate change scenarios suggest increases in riparian ET during the dormant period as well as in <u>its contribution to annual water budgets</u>, especially in the driest years” (L26-28).

6) L36-37, l.47-48: Please provide some references **Answer:** Ok (e.g. Kampf and Burges, 2007; Ledesma and Futter, 2017) (L38).

7) L46-47: *Why only in regions potentially suffering from water scarcity? An explanation is coming in L58-59, maybe this can be put closer together (e.g. moving L44-48 at the end of the second paragraph). A small rearrangement of the two first paragraphs of the introduction could also prevent that the sentence in L49-50 seems somehow contradictory to the first part of the introduction (L36-39).* **Answer:** Following the reviewer suggestion, we moved this sentence at the end of the second paragraph (L61-63). The first paragraph now points out that despite previous empirical studies have shown that hydrological processes occurring in the riparian zone can be critical to understand stream flow dynamics at both daily and seasonal scales (e.g. Flewelling et al., 2014; Lupon et al., 2016; Rassam et al., 2006), there are still few hydrological catchment models explicitly considering the riparian compartment, which ultimately limits our ability to quantify the influence of riparian zones on stream flow and catchment water export across regions (L45-50).

8) L76-78: *If I understood the functioning of the used model correctly, the connectivity between uplands and stream networks is mainly controlled by the riparian zone and its ET. In that case, the model setup (higher riparian ET during the vegetation period) makes this expectation somehow self-evident.* **Answer:** That’s right, the expectation was quite obvious. We have removed it.

9) *Figure 1: The color code in the legend (riparian zone = black) does not match the colors in the map (riparian zone = dark grey).* **Answer:** Right, we changed the color of the riparian zone in the legend. Moreover, and following reviewer #2 suggestions, we changed the color code of the figure, labeled the countries, and numbered the stream sites. We hope that those changes improved the visualization and conceptualization of the figure.

10) L91: *Upland means only the part covered by beech forests and heathlands or all the catchment except of the riparian zone? Please clarify.* **Answer:** Upland represent all land covers except of the riparian zone (i.e., evergreen oak and beech forests). We do now clarify the “upland” meaning in the text (93).

11) L94: *Increases 12-fold compared to what?* **Answer:** We meant that total basal area of riparian trees increases by 12-fold from headwaters to the valley bottom. We modified the text to clarify that both riparian width and total basal area of riparian trees markedly increase along the catchment (L95-96).

12) L92 and L97: *Are there also B and C horizons?* **Answer:** We analyzed the soil profile of the top 120-150 cm of the soil in both upland and riparian forests. For these range of depths, we identified horizons O, A, and B. This information has been included to the study site section (L94, L100).

13) L98-107: *This describes the sub-catchments clearly as three independent sub-catchments. If it is meant in a different way (cf. comment 2), please clarify in this section.* **Answer:** They were three nested catchments. We clarified this issue along the text (please, see our answer to your general comment #2 for more information).

14) L114: *'other catchment water pools' is identical to landscape units? Or to soil layers? Or to the upland compartment? And which are the water fluxes represented in these other water pools, also subsurface flow and ET?* **Answer:** "Catchment water pools" referred to catchment compartments (e.g. upland forest, riparian zone, and stream). We have clarified this point in the text (L119-120). Moreover, we have built a new figure in the supplementary material that conceptualizes the model set up (Figure S1, in Supplement 1).

15) L.122-123 *'a specified fraction of rainfall can be directly transported to stream runoff': Does this mean overland flow? Or is it direct precipitation on the stream? If it is the latter, shouldn't it also be accounted for during wet conditions?* **Answer:** We meant that a fraction of rainfall can be directly transported to stream runoff via overland flow. We have rewritten the sentence to clarify this point (L121-123).

16) L152-157: *From the description I understand that overland flow was basically disabled. Why is it then necessary to include a layer representing overland flow (L149)?* **Answer:** Good point. By design, PERSiST always needs to include a "quick bucket" that receives water from precipitation. From this layer, water can be transported to the stream (i.e., overland flow) and/or percolated to the upper soil box. Based on previous knowledge from the field, we considered that all water percolated to the upper soil layer. We have clarified this issue in the manuscript (L121-125, L160-162, and Supplement 1).

17) L176: *I would expect different values for the riparian ET-related parameters than for the upland ET-related parameters in order to allow different ETs. However, in Table S1 the best riparian and upland ET-related parameters seem to be identical.* **Answer:** This is a good remark, neatly caught by the reviewer. Values shown in former Table S1 are actually correct (i.e., identical values for riparian and upland ET-related parameters). This is because, unfortunately, ET-related parameters are configured as landscape unit-specific, whereas riparian zone is configured as an extra "soil box" that communicates the upland soil compartment with either groundwater or stream compartments. Thus, in the model configuration including the riparian zone, each of the landscape units (evergreen or deciduous) had both an upland and a riparian box, but only one set of ET-related parameters associated to both boxes. To be able to simulate realistic ET values during parameterization for the

three forest types (i.e, evergreen, deciduous, and riparian), we tuned two different soil box-specific parameters: (i) the "Retained water depth", a parameter representing the water depth in a soil box below which water no longer freely drains but can be lost via ET; and (ii) the "Time constant" parameter, which represents the water residence time within a soil box. By giving higher values of those two parameters in the riparian soil box compared to the upland soil box, we could simulate higher ET rates in the riparian compartment as a result of (i) a greater water availability and (ii) a longer water residence times in the riparian than in the upland soil boxes. These two phenomenon likely occur in the reality as a result of changes in soil texture and the proximity to streams, and thus, we feel confident that it was an effective way to simulate different ET rates given the model constrains. New supplemental materials (Supplement 1 and 2) have been crafted in order to better describe the model configuration.

18) L184-185: *Do you refer to all water fluxes other than ET? In addition, it is very difficult to make use of the given information about the adapted parameters, without a more detailed description (cf. comment 2).* **Answer:** We adjusted all model parameters (including those related to ET) to optimize the overall fit between observed and simulated hydrographs. This point has been clarified in the text (L185-188). Moreover, we do now include a set of supplementary material to better explain the model description (please, see our reply to comment #2).

19) *Both in section 3.4 and 3.5 it is not clear which of the 3 model instances including a riparian compartment are used. I assume it is the downstream sub-catchment (in the sense of being the total catchment, cf. comment 2), but please specify.* **Answer:** The sensitivity analyses (section 3.4) were performed only for the downstream site. On the other hand, the contribution of riparian ET on total catchment depletions (section 3.5) was calculated at the whole catchment scale. To do so, we summed up values of simulated upland ET and riparian ET in appropriate proportions at the three sub-catchments, plus the stream flow at the downstream site (i.e. catchment outlet). We have rewritten the methods section to clarify which sub-catchment (and why) was considered in each case (L215-217, L241-243).

20) L202: *This sounds like you refer to model calibration, however, it is confusing since you talk about validation in the paragraph above.* **Answer:** As we previously mentioned (response to comment #1), we discarded the possibility to validate model performance by splitting the data set. Our time series was relatively short and span a large range of environmental conditions, and thus, we decided to use the whole data set for the calibration in order to obtain a more robust (and realistic) parameter set for future simulations. Please, see our response to you comment #1 for more information on this regard.

21) L210: *Why the ET parameters are fixed to mean values of the landscape units instead of taking the optimal parameter for each landscape unit?* **Answer:** We fixed the ET parameters to mean values in order to have a set of homogenous non-calibrated values that we can use as a "control" in the sensitivity analyses. If the optimal values would have been used, model performance would have not been independent of ET parameter values, as they would have already been tuned (calibrated) to maximize model performance.

22) L211-213: I *do not understand the formulation '100 iterations of 1000 runs'. Does it mean you tested 100 times 1000 different parameter sets? If yes, what was the criteria to split the total of 100000 simulations in sets of 1000?* **Answer:** Yes, we tested 100 times, 1000 different parameter sets. We split the total number of simulations because the MC tool only retain the best parameter set (in terms of model efficiency provided) from each of the iterations for the further analysis (i.e., the sensitivity analysis). This has been clarified in the manuscript (Supplement 3). Moreover, we chose to run 100 iterations because it has been shown that running more than 100 iterations does not add extra information.

23) L214-216: *I think it is difficult to restrict this effect to riparian ET. It should be related to ET in general, both from the upland and riparian compartments, since the ET parameters were fixed for both compartments.* **Answer:** That's completely right. We have clarified this point throughout the manuscript (L210-220, L284-289, Figure 4, and Supplement 3).

24) L253: *I would be careful to say that the strong decline in stream flow is characteristic for the vegetative period only. In 2012 the stream flow is declining from the beginning of the year. Maybe it would be good to include the precipitation time series in Figure 2 in order to explain this behavior.* **Answer:** That's right; we do now state that the seasonal pattern was characterized by lower stream flow during the vegetative than during the dormant period (L255-256). Moreover, and following the reviewer suggestion, we have included the temporal pattern of precipitation in Figure 2.

25) L256-25*7: Complementary there were underestimations at all three sampling sites for the dormant season, which were in similar RDV ranges for the up- and midstream catchment but much lower in the downstream catchment compared to the vegetative period. It would be great to mention and discuss this, also with regard to the improvements that were achieved for the vegetative and dormant season with the inclusion of the riparian compartment (cf. comment 1 and 32).* **Answer:** Following the reviewer suggestion, we do now state that "during the dormant period, the inclusion of the riparian compartment reduced the underestimation of stream flow from 12% to 7%" at the downstream site" (L270-272). Also, we do now discuss these results in section 5.1 (please see our responses to comment #1 and #32).

26) *Figure 2 would be clearer with reduced sizes of the observation points.* **Answer:** Ok.

27) L265: P*lease specify which the low flow periods are. This will also help to distinguish between the low flow periods (captured) and the lowest flows (not captured) (L329).* **Answer:** Ok (June-September) (L268).

28) L266: *In Table 3, L23 and L326 you give a value of 26%. Even though, I am not sure that this is a correct formulation. It should be 'reduced daily stream flow by 26 percentage points' or 'reduced stream flow overestimations to 27 % during the vegetative period'. See also L340-342, where you give a different percentage value, which is actually the correct one when talking about a change in percentage compared to RDV = -0.53 as reference.* **Answer:** Following the reviewer suggestion, we do now state that "the inclusion of the riparian

compartment reduced daily stream flow overestimations from 53% to 27% during the vegetative period at the downstream site" (L269-271). We have also clarified this result in the abstract (L24) and discussion (338-340).

29) L293: *Also here I guess it should 1-2 percentage points?* **Answer:** To avoid confusions, we do now state that "the contribution of riparian ET to catchment water budgets could increase from 7.1% (reference period) to 8.2% (scenario RCP 8.5 percentile 0.75)" (L300-302).

30) L294-295: *Is your definition of the vegetative period really an ET rate > 0 mm/d? During the dormant season there should normally also be days with ET > 0 mm/d. Moreover, for the model performance calculations you define the vegetative period as ranging from April-October (L192).* **Answer:** We agree with both reviewers #1 and #2 that the vegetative period could have been better defined. We consider that the vegetative period was comprised between the beginning of the riparian leaf-out (April) and peak of leaf litter fall (October), which coincided with the onset and offset of riparian tree transpiration, respectively. This definition can be found in the methods section of the new manuscript (L197-199). Moreover, and in order to avoid confusions, we have rewritten the results to better explain that future increases in warming and drying will smooth the seasonality of riparian ET and increase the number of days with ET rates > 0 mm d-1 by 6–106 days (depending on the scenario and year) (L302-304).

31) *Figure 5 and l.296-304: What about the 0.25 percentile and 0.75 percentile scenarios? Shouldn't the RCP 2.5 percentile 0.25 be the most moderate and the RCP 8.5 percentile 0.75 be the most extreme scenario?* **Answer:** Following the reviewer advice, Figure 5 does now show the percentile 0.25 and 0.75 for RCP 2.5 and 8.5 scenarios, respectively.

32) L321-322: *For log(NS) I agree, for RDV I would say there was an improvement also during the dormant season. This could be related to riparian effects (fluxes and additional storage) other than ET (cf. also comment 1 and 25) and should be discussed.* **Answer:** Agreed. We do now argue that, during the dormant period, the inclusion of the riparian compartment helped to improve the simulation of stream flow volumes to some extent, with RDV values changing from +12% (riparian zone excluded) to +7% (riparian zone included) (L331-333). These results suggest that the riparian zone can be important for shaping stream flows during wet conditions, likely because it contributes to increase water storage, and thus water residence time, within the catchment (L333-335).

33) L340 *'when riparian ET parameters were allowed to vary': Also the uphill ET parameters were allowed to vary or fixed (cf. comment 23). It should be discussed, why this setup allows to conclude on the riparian ET only.* **Answer:** That is correct, thanks. Please, see our response to comment #17 for a detailed explanation on this issue.

34) L353-355: *This sounds like if it is superfluous to consider the riparian compartment.* **Answer:** That's right; we removed this sentence from the manuscript. Thanks.

35) L405: *You show that there is an effect of riparian ET on the catchment water budget (8-19%) and that this effect can slightly increase (1-2%), but I would not say that you can call this a major control (cf. also your discussion l.381-389).* **Answer:** Ok, we have toned down our conclusion (L418-420).

36) L406-407: *Maybe I missed it, but I cannot remember that you mentioned this before*. **Answer:** That's right. We do now mention in the results that "future climate change scenarios predict that upland ET would increase from 4% to 11% compared to the reference period, while stream flow would decrease from 3% to 13%" (L299-300).

Anonymous Referee #2

General comment: *This paper seeks to determine the influence of riparian evapotranspiration (ET) in streamflow dynamics and the prediction of water budgets at a catchment scale. The authors used a flexible landscape scale rainfall-runoff model to simulate daily stream exports with and without the influence of riparian ET. The results demonstrate that when the riparian ET compartment is considered in the model, then the prediction across seasons and sub-catchments are improved. Moreover, the article studies the influence of this compartment under climate scenarios and demonstrates that riparian ET could play a significant role when estimating catchment hydrology with respect to climate change, especially under extreme drought conditions. The paper is well-written and straightforward, and the scientific findings represent a valuable contribution to the field. I recommend publication with minor revisions.*

Answer: Thank you for your positive and constructive comments! We feel flattered that you find our study interesting.

Specific comments:

(1) *My main concern in this manuscript relates to the model's description. With the information provided, it is difficult to follow how each piece of information falls into place for the simulation. For example, L135-138 mention procedures which include water pressure sensors to determine stream water level, the use of an ISCO sampler, and an empirical relationship between flow and water level using a slug chloride addition. The connection between these sentences seems unclear; was the water level data measured while conducting tracer injections? It is also not clear to me if these parameters were used as model inputs or if they were used further to compare between the observed and the simulated stream flows (L144). If they do not belong to the model inputs, I recommend placing that information in a different section. I believe section 3.3, "Calibration procedure," could start at L141 (remove redundant information from L162), and then the technical information regarding streamflow evaluation could be included in L144. If, on the other hand, my interpretation about the use of these parameters is inaccurate and they belong to section 3.2, please clarify their role as model inputs*

and include how the observed streamflow data was gathered (e.g. nearby gaging station, instream discharge measurements).

Answer: We agree that this part of the methods could be better explained. As the reviewer pointed, stream flow data was used to calibrate the model (not as model inputs). To clarify this issue, we changed the heading of section 3.2 to “Model inputs, model configuration, and calibration data”. Moreover, we do now explicitly state that “we calibrated PERSiST to match stream flow data for two complete hydrological years at the outlet of the up-, mid-, and downstream sub-catchments” (L136-137). Finally, we better explain that stream flow was measured in situ with water pressure sensors (Teledyne Isco, Model 1612; more details in Lupon et al., 2016) (L137-139).

(2) *In addition, it seems unclear if the model is capable of considering different types of vegetation and its influence on riparian ET. It would be very useful to condense the information expressed in sections 3.2 and 3.3. I also recommend the creation of a conceptual figure or table that lists all the variables used for input, calibration, and the model output, as well as a short description of ET related parameters and model capabilities in term of predictions regarding vegetation changes. Consider replacing the titles within the “Materials and methods” section to: “3.2 Model inputs” and “3.3 Model configuration and calibration procedure”.*

Answer: Following this suggestion as well as that from reviewer #1, we have now included substantial new materials (including a conceptual figure) that addresses the reviewer concerns (see Supplement 1 and 2 as well as our response to comment #2 of reviewer #1). To improve clarification, section 3.2 is now named “3.2 Model inputs, model configuration, and calibration data”.

Technical corrections:

L48: *Please provide some references*. **Answer:** Ok, we included Flewelling et al. (2014); Lupon et al. (2016), and Rassam et al. (2006) (L47).

Figure 1: *The location map on the top right needs more context; it would be useful to label key landmarks (i.e. names of countries or cities) for better reference. The color code used is difficult to follow. It is hard to identify the areas where the riparian zone is present since the color selected is masked by the color used for stream delineation (in the printed version, the riparian zone color code looks black). It might also be useful to number your stream sites in the figure and then add the corresponding label in the legend (e.g. 1 Upstream; 2 Midstream; 3 Downstream). The map also includes contour lines that seem to be representative of the catchment elevation, however, these are not mentioned in the figure caption, please clarify.* **Answer:** Following the reviewer suggestion, we changed the color code of the figure, labeled the countries, and numbered the stream sites. Moreover, we do now specify in the caption that (i) dotted lines indicate the catchment elevation and (ii) the inset map shows the location of the Font del Regàs catchment within Spain. We believe that these changes will clarify the figure.

L147: *Consider changing "divided" to "categorized".* **Answer:** Ok.

L162: *Insert "in the literature" after "ET values reported".* **Answer:** Ok.

L165: *Change "the" to "model" in "Note that the instances. . .".* **Answer:** Ok.

L175-176: *It is unclear how the authors defined dormant and vegetative period. Please add more clarification in regards to this. Also, L192 attributes the specific month of the data set to the periods under discussion. It would be more useful to state this classification the first time the periods were mentioned in the text (i.e. L175-176).* **Answer:** We agree with both reviewers #1 and #2 regarding this point. Please, see our earlier response to reviewer #1 (comment #30).

L195: *Is riparian ET one of PERSiST's outputs, or was it calculated using modeled streamflow data? So far, only streamflow (catchment water fluxes) has been introduced as a model result. Please briefly list output parameters of interest under the model description in section 3.1.* **Answer:** Yes, riparian ET is one of the PERSIST's model outputs. The model provides daily values of ET or each soil box. PERSiST also provides simulated daily values of stream flow, water depth in soil boxes, and percolating water between soil boxes. Following your suggestion, we do now provide a brief list of output parameters in the supplementary information (Supplement 2) and refer to it in the manuscript if needed.

L294: *Is the length of vegetative period determined only by the simulated values of ET (e.g. ET rates > 0 mm d-1)? I think this could be clearer with more insights on what the authors used to classify this period.* **Answer:** No, the vegetative period was determined by the onset and offset of riparian tree transpiration (i.e. from the beginning of the riparian leaf-out to the peak of leaf litter fall). To avoid further confusions, we do now provide a definition of "vegetative period" in the method section (L197-199).

L373-374: *It is unclear how the extension of the vegetative period in the climate model's scenarios can be associated to early onset of the leaf out period after considering the limitations of the model in L330-334. Please clarify.* **Answer:** We agree with both reviewers #1 and #2 in this regard. The simulations show that, in the future, the number of days with ET > 0 mm d^{-1} will increase during spring as a consequence of warmer temperatures. Please, see the response to the comment #2 from reviewer #1 for further information.

L376: *The role of vegetation in the model's performance or predictive capabilities has been understated throughout the text, hence arguing that model results "strongly support" an effect of climate change in tree phenology seems uncertain. Please provide clarification or references that help support this statement.* **Answer:** Following the reviewer advice, we have toned down our statement. We do now argue that our results suggest a potential enlargement of the vegetative period, an idea that is consistent with previous observations showing that climate change can affect riparian tree phenology by promoting the advancement of the riparian leaf out period (Perry et al., 2012; Serrat-Capdevila et al., 2007) (L384-394).

L384-385: *This seems to contradict the statement on L376.* **Answer:** That's right. Our model simulations showed that future warming will increase the number of days with riparian ET > 0 mm d^{-1}, which is consistent with previous observations showing a potential enlargement of the riparian vegetative period in the future (e.g. Perry et al., 2012). However, our model was not able to simulate changes in vegetation community, a phenomenon that will likely occur in the studied region due to future drought conditions (e.g. Peñuelas and Boada, 2003). The enlargement of the vegetation period and the change in vegetation community are not exclusive, and thus, they can occur simultaneously in the future. We have clarified these two ideas in the main text (L384-394, L396-402).

Anonymous Referee #3

General comment: *The paper by Lupon, et al. uses a hydrological runoff model to examine the importance of evapotranspiration in riparian zones on water budgets in several catchments. The description of the exercise was well written and generally easy to follow, although the agonizing detail (necessary, but no less agonizing) of the model testing and calibration makes this paper quite a chore to work through. Given that demonstrating that the model does a good job of predicting flow in the catchments studied is certainly important, it may be difficult to cut the highly detailed exposition. In the end, however, that detail overshadows the actual results obtained when the model was exercised to address the question. I would like to see the authors place more emphasis on the outcome of the exercise so as to help readers who may not need the detailed methods to find and appreciate what the authors have generated. Indeed, some of the modelling detail might be placed into supplementary material.*

Answer: We are happy the reviewer considers our manuscript "well written and easy to follow" and has a general positive overview of it. Despite we acknowledge that the model description is quite long, we also agree with reviewers #1 and #2 that some extra information regarding the model configuration is needed to fully understand the results. Following their suggestion, we created new supplementary material that contained a detailed description of the model parameters as well as a new conceptual figure showing the model configuration. At the same time, we have clarified and better structured the model descriptions in the main text. We believe that with those changes, the model configuration will be easier to understand and, certainly, less agonizing.

Specific comments:

(1) The paper makes a very useful statement, but there are supporting reports of empirical work that the authors could use to support the conclusions of their work in the absence of original data. In particular, a paper by Flewelling et al. (Hydrol. Proc., 2013, doi:10.1002/hyp.9763) shows exactly what the effect of near-field evapotranspiration can have on water delivery to the adjacent stream, and to biogeochemical reactions occurring in the stream sediments. It is entirely consistent with the present manuscript. **Answer:** We do now

include the Flewelling et al. (2014) paper to support our statements in both the introduction and discussion sections. Thanks for the suggestion!

(2) The use of the Nash Sutcliffe Index is appropriate here, but many people will not recognize it. Because this paper should have a broad audience, the N-S index should be defined better. Give the equation – I had to look it up, as it was new to me. **Answer:** That's right, the Nash Sutcliffe Index is a common index used to evaluate hydrological models, but not all the audience should know it. We have clarified it in the text and we have reported some references that explain in detail the calculations (e.g., Nash and Sutcliffe, 1970) (L184-185) However, we decided to not include the formula in the main manuscript to avoid including more details in the methods section.

(3) Other reviewers have provided a detailed, line by line commentary on the manuscript. Given my general agreement with those comments, I will not repeat them here. **Answer:** Ok, thanks.

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Title: Riparian evapotranspiration is essential to simulate stream flow dynamics and water budgets in a Mediterranean catchment

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Abstract

Riparian trees can regulate stream flow dynamics and water budgets by taking up large amounts of water from both soil and groundwater compartments. However, their role has not been fully recognized in the hydrologic literature and the catchment modeling community. In this study, we explored the influence of riparian evapotranspiration (ET) on stream flow by simulating daily stream water exports from three nested Mediterranean sub-catchments, both including and excluding the riparian compartment in the structure of the rainfall-runoff model PERSiST. The model goodness of fit for the calibration period (Sep 2010–Aug 2012) significantly improved with the inclusion of the riparian compartment, especially during the vegetative period when, according to our simulations, the riparian zone significantly reduced the overestimation of mean daily stream flow (from 53% to 27%). At the catchment scale, simulated riparian ET accounted for 5.5–8.4% of annual water depletions, its contribution being especially noticeable during summer (8–26%). Simulations considering climate change scenarios suggest increases in riparian ET during the dormant period as well as in its contribution to annual water budgets, especially in the driest years. Overall, our results highlight that a good assessment of riparian ET is essential for understanding catchment hydrology and stream flow dynamics in Mediterranean regions. Thus, the inclusion of the riparian compartment in hydrological models is strongly recommended in order to establish proper management strategies in water-limited regions.

Keywords: PERSiST model, riparian evapotranspiration, water resources, stream flow, Mediterranean regions, climate change, aridity index.

1 Introduction

Precipitation and upland tree evapotranspiration (ET) are considered the two most important components controlling annual water budgets in catchment hydrology (e.g. Kampf and Burges, 2007; Ledesma and Futter, 2017). This conceptualization is supported by the fact that, in most regions, landscape units other than uplands (e.g. riparian zones) occupy a small percentage of the catchment area (< 3%) (Tockner and Stanford, 2002). However, empirical studies have shown that water storage and ET within riparian zones can influence stream flow dynamics by lowering groundwater levels and increasing groundwater residence times (Bernal et al., 2004; Burt et al., 2002). Moreover, water demand by riparian trees can drive diel fluctuations in stream flow by taking up water from both riparian groundwater and streams (Flewelling et al., 2014; Gribovszki et al., 2010). These empirical studies suggest that hydrological processes occurring in the riparian zone, and specifically those induced by riparian ET, can be critical to understand stream flow dynamics at both daily and seasonal scales (e.g. Flewelling et al., 2014; Lupon et al., 2016; Rassam et al., 2006). However, there are few hydrological catchment models explicitly considering the riparian compartment, which ultimately limits our ability to quantify the influence of riparian zones on stream flow and catchment water export across regions.

Riparian trees can play an important role in catchment water budgets because their water requirements are generally high compared to upland tree species (Baldocchi and Ryu, 2011; Doody and Benyon, 2011). However, the contribution of riparian ET to catchment annual water budgets varies widely among biomes (from 0% to > 30%) depending on the amount of water available for vegetation (Dahm et al., 2002; Cadol et al., 2012; Contreras et al., 2011). In tropical systems, for instance, soil water content is usually high in both upland and riparian zones, and hence, these two compartments show similar ET rates (2–5 mm d^{-1}; Cadol et al., 2012; da Rocha et al., 2004). Conversely, in arid systems, riparian zones stay relatively wet compared to upland areas and can support ET rates between 1 and 7 mm d^{-1}, as much as one order of magnitude higher than those in the surrounding upland (0.1–0.4 mm d^{-1}; Dahm et al., 2002; Kurc and Small, 2004). Moreover, relatively large water demand by riparian trees can contribute to disconnect saturated soils from streams and promote the displacement of stream water towards the riparian zone (Butturini et al., 2003; Lupon et al., 2016; Rassam et al., 2006). These studies suggest that the potential of riparian forests to shape water budgets likely increases with increasing water scarcity, and thus, resolving the role of riparian zones within catchment hydrology modelling is essential to properly manage current and future water resources.

Mediterranean catchments are unique natural laboratories for evaluating the influence of riparian ET on stream and catchment hydrology as well as to test the response of riparian ET to changes in climatic drivers, namely temperature and precipitation. Mediterranean regions exhibit marked seasonal patterns in both hydrology and vegetative activity, and they hold an intermediate position in the climatic gradient, which makes them especially vulnerable to future changes in climate (IPCC, 2013). Furthermore, previous studies have shown that riparian ET causes abrupt changes in groundwater tables in summer, which are essential to predict daily stream flow in Mediterranean areas (Lupon et al., 2016; Medici et al., 2008). Thus, hydrological models that consider the riparian compartment could be helpful to better understand the influence of riparian zones on catchment water budgets and water availability for both in- and off-stream uses.

The aim of this study was to explore the role of riparian ET on simulating present and future stream flow dynamics and catchment water exports in a Mediterranean forested headwater on a seasonal and annual basis. To do so, we used the rainfall-runoff model PERSiST (Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport; Futter et al., 2014) to reproduce the observed stream hydrographs and ET rates at three nested catchments along which the area covered by riparian forests increased from 0 to 10%. In addition, we simulated different climate scenarios for the region in order to explore changes in the relative contribution of riparian ET to future total catchment water budgets with increasing drying.

2 Study site

The Font del Regàs catchment is located in the Montseny Natural Park, NE Spain (41º50’N, 2º30’E). The climate is subhumid Mediterranean, with mild winters, wet springs, and dry summers. Annual precipitation is 925 ± 151 mm (mean ± SD), less than 1% falling as snow. Mean annual temperature averages 12.1 ± 2.5 ºC (period 1940–2000, Catalan Metereologic Service).

Total catchment area is 14.2 km^2 and altitude ranges from 500 to 1500 m above the sea level (a.s.l.) (Figure 1). The geology is dominated by biotitic granite and the topography includes steep slopes (28%) (Institut Cartografic de Catalunya, 2010). Evergreen oak forests (*Quercus ilex*) cover the lower part of the catchment (54% of the catchment area), whereas the upper part is covered mainly by deciduous European beech (*Fagus sylvatica*) forests and heathlands (38 and 2% of the catchment area, respectively) (Figure 1). Upland soils (i.e., oak and beech forests) are sandy, with a 3 cm deep O horizon followed by a 5–15 cm deep and >100 cm deep A and B horizons, respectively. Riparian forest covers 6% of the total catchment area and it is relatively flat (slope < 10%). Both riparian width and the total basal area of riparian trees markedly increases along the catchment (Table 1). Black alder (*Alnus glutinosa*), European ash (*Fraxinus excelsior*), black locust (*Robinea pseudoacacia*), and black poplar (*Populus nigra)* are the most abundant tree species in the riparian forest, with a basal area of 14, 4, 3 and 2 m^2 ha^{-1}, respectively. Riparian soils are sandy-loam, with a 5 cm deep organic layer followed by a 30 cm deep and a >90 cm deep A and B horizons, respectively.

For this study, we selected three nested catchments (total drainage area 12.96 km^2) along a 5.6 km stretch of the Font del Regàs stream (Figure 1). The upstream sub-catchment (800–1500 m a.s.l, local drainage area 1.8 km^2) was mostly composed by beech forest (93%) and had no riparian forest (Table 1). Vegetation in the midstream sub-catchment (650–800 m a.s.l., local drainage area 6.74 km^2) included both oak (52.5%) and beech (42.5%) forests (Table 1). The stream at the midstream sub-catchment had a wetted width of 2–3 m and was flanked by a mixed riparian forest (5%, 5–15 m wide) of *Alnus glutinosa* and *Fraxinus excelsior*. The downstream sub-catchment (500–650 m a.s.l., local drainage area 4.42 km^2) was mainly covered by oak forest (58%) and, to a lesser extent, by beech forest (32%) (Table 1). The stream at the downstream sub-catchment had a wetted width of 3–3.5 m and was flanked by a well-developed riparian forest (10%, 15–30 m wide) consisting mainly of *Robinea pseudoacacia*, *Populus nigra*, and *Alnus glutinosa*.

3 Materials and methods

3.1 PERSiST model description

PERSiST is a conceptual, semi-distributed, bucket-type model that simulates daily catchment water fluxes (Futter et al., 2014). The flexible model framework allows representing the runoff generation process as a specified number of vertically and horizontally interconnected buckets (representing soil boxes) within a mosaic of landscape units at daily time steps. In this way, PERSiST conceptualizes the landscape in four spatial levels: whole-catchment (level 1), sub-catchment (level 2), landscape unit (level 3), and bucket/soil box (level 4). The flexible framework allows differentiating the riparian compartment (or "bucket") from other catchment water compartments (such as uplands or streams) (Supplement 1).

In short, the model works as follows. Rainfall can be intercepted by canopy or directed to a "quick bucket", which in its turn can route the water to the stream via overland flow or infiltrate it to the upper soil box. From the upper soil box, water can infiltrate to lower soil boxes, move downhill to other catchment compartments (i.e., riparian zone or streams), or return to the atmosphere via ET (Supplement 1). Landscape unit-specific square matrixes are used to specify the fraction of water moving between contiguous soil layers and with the stream at every time step. Water movement is also controlled by field capacities, hydrological connectivity, and landscape unit-specific parameters related to both infiltration and ET (Supplement 2). Within the model, ET is controlled by two parameters related to temperature ("degree day rates" and "threshold temperature") and by water availability. Moreover, the parameter "retained water depth" allows simulating ET during dry conditions by limiting ET rates at the bucket/soil box level. Finally, catchment and landscape unit-specific rain multipliers are used to correct for potential rainfall measurement biases. A more detailed description of the water fluxes considered within the model as well as physical parameters controlling water movement between contiguous soil layers and towards the stream can be found in Supplement 2.

3.2 Model inputs, model configuration, and calibration data

We calibrated PERSiST to match stream flow data for two complete hydrological years (Sep 2010–Aug 2012) at the outlet of the up-, mid-, and downstream sub-catchments (Figure 1). At each outlet, stream flows (calibration data) were measured in situ with water pressure sensors (Teledyne Isco, Model 1612; Lupon et al., 2016). To run the model, we used time series of daily precipitation (mm) and mean daily air temperature (ºC) as input data. Both precipitation and temperature were recorded at 15-min intervals at a meteorological station located at the valley bottom of the catchment (Figure 1) and converted to daily values for model simulation. Model simulation was started in January 2010 to have an 8-month warm-up period prior the calibration period. A list of all input, output, and calibration data of the model is provided in Supplement ~~2~~1.

We calibrated the model for the three sub-catchments (referred as to "stream sites" hereafter) both including and excluding the riparian compartment in the model structure (Supplement 1). In the first model configuration (i.e., not including riparian zone), we used a simple one-compartment approach to represent the catchment area in all three sub-catchments. For each sub-catchment, the upland compartment was categorized into two landscape units representing evergreen and deciduous forests in appropriate proportions (Table 1), and the soil was divided into three buckets representing quick, soil, and groundwater strata (Supplement 1). In the second model configuration (i.e., including riparian zone), a riparian compartment was added for the mid- and downstream sub-catchments within their respective evergreen and deciduous landscape units to make up 5 and 10% of local drainage area, respectively (Table 1, Supplement 1). In this configuration, the riparian soil layer could receive water inputs from precipitation, the upland soil layer, and the groundwater, being the later shared between both upland and riparian compartments. Areal normalized ET was simulated from uplands and riparian soil boxes separately, thus obtaining simulated values of ET for evergreen upland, deciduous upland, evergreen riparian, and deciduous riparian landscape units. The evergreen and deciduous riparian ET values were combined and averaged in appropriate proportions to obtain a single value of riparian ET at daily time steps. Following knowledge of the area, overland flow was not used in any of the model configurations, and thus all water entering the quick bucket was routed directly to the upper soil box layer (upland or riparian).

3.3 Calibration procedure

Model calibration was done manually for all six model instances (3 sub-catchments x 2 model configurations) in order to (i) match ET values reported in the literature for the different forest types ("soft calibration") and (ii) optimize a combination of statistical metrics (i.e. model efficiency) that compare simulated and observed flows ("hard calibration"). Manual calibration has been proved as a robust method for obtaining acceptable simulations within the Integrated Catchment (INCA) family of models (Cremona et al., 2017; Futter et al., 2014; Ledesma et al., 2012), of which PERSiST is the common hydrological model.

For the soft calibration, the parameterization of both upland (evergreen and deciduous) and riparian ET was adjusted to obtain values of water demand within the ranges reported for evergreen forest (i.e. evergreen oak; 550–650 mm yr^{-1}), deciduous forest (i.e. beech; 600–750 mm yr^{-1}), and riparian forests (i.e. poplar, alder and ash; 750–1000 mm yr^{-1}) at Montseny or nearby (< 50 km) mountains (Àvila et al., 1996; Folch and Ferrer, 2015; Llorens and Domingo, 2007; Sabater and Bernal, 2011). We calibrated the model assuming (i) a higher ET from evergreen forest than from deciduous and riparian forests during the dormant period and (ii) a higher riparian ET than evergreen and deciduous ET during the vegetative period. The first assumption was based on the premise that deciduous trees cannot transpire during the dormant period, while the second assumption was based on the idea that riparian trees are closer to water sources, and thus, they are not as water limited as upland trees (both evergreen oak and deciduous beech) in summer. Other parameterization requirements during soft calibration included matching reported annual canopy rainfall interception values for similar forest types (Àvila et al., 1996; Terradas, 1984; Terradas and Savé, 1992) and a rainfall correction for south- and north-facing slopes which roughly corresponded to evergreen and deciduous forests, respectively (Piñol et al., 1992).

For the hard calibration, all model parameters were adjusted to optimize the Nash-Sutcliffe (NS, Nash and Sutcliffe, 1970) efficiency index (important to fit high flows), the log(NS) (important to fit low flows), the relative volume differences of observed versus simulated stream flow (RVD) (important to maintain the water balance), and the overall graphical fit between observed and simulated hydrographs (Oni et al., 2016). For both NS and log(NS), higher values indicate a better goodness of fit, with a potential maximum of 1 for a perfect fit. For RVD, positive and negative values indicate that the model under- and overestimated the stream flow, respectively.

The importance of the riparian compartment on simulating stream water flow and catchment water budgets was determined by comparing the specific statistical metrics of goodness of fit from the two model configurations (including and excluding the riparian compartment). We compared the two model configurations for the overall calibration period as well as for the vegetative and dormant periods separately because the hydrological processes by which riparian zones influence stream flow may differ between the two periods. We considered that the vegetative period expanded between the beginning of the riparian leaf-out (April) and the peak of leaf litter fall (October), which coincides with the onset and offset of riparian tree ET, respectively (Nadal-Sala et al., 2013).

3.4 Model validation and sensitivity analysis

To validate the model, we compared monthly mean values of areal normalized riparian ET simulated with PERSiST (output of the model) with those obtained empirically from daily stream flow variations. Daily variations of stream flow can be used as a proxy for ET from near-stream zones (Cadol et al., 2012; Flewelling et al., 2014; Gribovszki et al., 2010) and they correlate well with direct sap flow measurements at the study site (Lupon et al., 2016). Daily stream flow variations measured at one particular point integrates riparian ET upstream from that point. Thus, we assumed that differences in specific daily stream flow variations between the up- and midstream sites, and the mid- and downstream sites were comparable to the specific riparian ET simulated with PERSiST for the midstream and downstream sub-catchments, respectively.

To test the sensitivity of the model to the parameters related to ET, we compared model efficiencies (i.e. log(NS)) obtained from two sets of Monte Carlo (MC) analyses. In the first set, all model parameters potentially influencing stream flow were allowed to vary ± 25% with respect to the best performing parameter set from manual calibration (non-fixed ET analysis). In the second set, ET-related parameters (i.e. degree day rates, threshold temperatures, and ET adjustments) were kept constant, while the other parameters were allowed to vary ± 25% (fixed ET analysis. We used Tukey HSD text to compare the model efficiencies between fixed and non-fixed ET analyses obtained for the downstream sub-catchment during the overall calibration period as well as during the vegetative and dormant periods separately. We interpreted a decrease in the goodness of fit (i.e. lower values of log(NS)) for the fixed ET analysis as an indication that the outputs of the model were sensitive to ET. A more detailed description of the sensitivity analyses can be found in Supplement 3.

3.5 Modelling future projections of water budgets

The best manual parameterization of the model configuration including the riparian compartment was used to simulate future changes in catchment water budgets and to explore the contribution of riparian ET to these changes. We calculated future water balances considering predicted changes in climate for 2081–2100. Temperature and precipitation for the reference period (1981-2000) and the future period (2081-2100) at Font del Regàs were inferred by using daily meteorological data for the period 1933–2000 from Turó de l'Home (Meteocat, www.meteocat.cat), a meteorological station located < 10 km from the study site (Supplement 4). Although Turó de l’Home is usually colder and wetter than Font del Regàs, monthly precipitation and temperature showed a strong correlation between the two stations for the period 2010–2014 (in the two cases: $R^2 > 0.90$, $p < 0.001$, $n > 53$, Supplement 4). Linear regression models for these two sites were used to construct daily time series of temperature and precipitation at Font del Regàs for both the reference period (1981–2000) and the future period (2081–2100) based on Representative Concentration Pathway (RCP) projections.

RCP projections provided by IPCC (2013) are based on the reference period 1986-2005. We assumed similar projections values for our reference period (1981–2000), which was the one for which data at Turó de l’Home was available. We applied the 2.5, 4.5, 6.0, and 8.5 RCP scenarios for Mediterranean zones including percentiles 0.25, 0.50, and 0.75 (IPCC, 2013). In general, RCP scenarios forecast an increase in temperature all year round, but more pronounced in summer than in winter. Precipitation is predicted to decrease in April–September, while small changes are expected in October–March (Table 2).

For each year and RCP scenario, we calculated (i) the Aridity Index (AI) as a proxy of water availability (UNEP, 1992), and (ii) the relative contribution of simulated riparian ET to annual water catchment depletions at the whole catchment level, which was calculated as the sum of total simulated ET (upland and riparian at the three sub-catchments) and stream flow at the downstream site (i.e. catchment outlet). The AI relates annual precipitation and potential ET (PET), which was estimated using the Penman-Monteith equation on daily time steps (Allen et al., 1998). We assumed constant wind velocity (1 m s^{-1}) and relative humidity (75%). These values were based on a 5-year time series from the Font del Regàs meteorological station (period 2010–2014; wind velocity = 1.0 ± 0.4 m s^{-1}; relative humidity = 75 ± 9%). We examined the relationship between the relative contribution of riparian ET to annual water catchment depletions and AI by fitting a two segment piecewise linear regression model. All statistical analyses were carried out with the R 3.3.0 statistical software (R Core Team, 2012).

4 Results

4.1 Data–model fusion

For the calibration period (Sep 2010 – Aug 2012), mean annual flow was 23 ± 17, 82 ± 66, and 105 ± 113 L s^{-1} at the up-, mid-, and downstream sites, respectively. The three sites showed the same seasonal pattern, characterized by lower stream flow during the vegetative than during the dormant period (Figure 2). The model configuration excluding the riparian compartment successfully reproduced the seasonal pattern of stream flow at the three sampling sites (Table 3 and Figure 2). However, there were mismatches between simulated and observed values, especially during the vegetative period, when stream flows were overestimated (RVD < 0, Table 3). The mismatches were especially noticeable in the downstream site, where simulated values were, on average, 53% higher than observed ones in the vegetative period (Table 3). During the dormant period, the model slightly underestimated stream flow at the three sampling sites (+0.12 < RVD < +0.16, Table 3).

The efficiency indexes indicated that the inclusion of the riparian compartment was essential to improve the fit between simulated and observed flows at the mid- and downstream sites. The model including the riparian compartment showed higher NS and log(NS) metric values and RDV values closer to 0 (more accurate stream water volumes) than the one without riparian compartment (Table 3). Moreover, the model structure including the riparian compartment captured both the magnitude and seasonal pattern exhibited by stream flow, even during low flow periods (June-September), especially in 2012 (Figure 2). On average, the inclusion of the riparian compartment reduced daily stream flow overestimations from 53% to 27% during the vegetative period at the downstream site (Table 3). The improvement of the model was less noticeable during the dormant period, when the inclusion of the riparian compartment reduced the underestimations of stream flow from 12% to 7%.

4.2 Model validation and sensitivity analysis

There was a good agreement between simulated daily rates of riparian ET and those obtained independently of model outputs for both the mid- and downstream sub-catchments (Figure 3). Simulated rates of riparian ET were lower during the dormant (0.89 ± 0.97 mm d^{-1}) than during the vegetative period (3.7 ± 1.3 mm d^{-1}). The lowest simulated ET values occurred in January and February (0.1–0.3 mm d^{-1}), while June and August showed the highest ones (5–7 mm d^{-1}) (Supplement 5). The daily variation of stream flow followed a seasonal pattern similar to that exhibited by simulated daily riparian ET. Consequently, there was a strong and positive relationship between monthly mean values of simulated daily riparian ET and measured daily stream flow variations for both the midstream sub-catchment (linear regression [l.r.], $R^2 = 0.83$, $p < 0.001$, $n = 24$) and the downstream sub-catchment (l.r., $R^2 = 0.88$, $p < 0.001$, $n = 24$) (Figure 3).

The sensitivity analysis showed no differences in log(NS) values between the analysis with fixed and non-fixed ET parameters for the whole calibration period (Figure 4). The same occurred when comparing fixed and non-fixed ET simulations for the dormant period. For the vegetative period, the simulation of stream flow worsen when the ET parameters were fixed as indicated by the decrease in log(NS) efficiencies (Figure 4), indicating that the model was sensitive to the ET parameters. Similar results were obtained for the NS metric (not shown).

4.3 Present and future contribution of riparian ET to catchment water budgets

Simulated rates of riparian ET averaged 931 mm yr^{-1} for the calibration period and contributed 5.91% to annual water losses. This contribution falls within the range of simulated values (5.54–8.42%) obtained for the reference period (1981–2000; mean annual riparian ET = 862 ± 105 mm). During both calibration and reference periods, the contribution of riparian ET to water catchment depletion was maximal from July to September, when it accounted for 8–26% of water catchment losses.

According to our simulations, mean annual riparian ET in the future will range between 826 mm yr^{-1} (scenario RCP 6.0 percentile 0.25) and 977 mm yr^{-1} (scenario RCP 4.5 percentile 0.75). These values represent a relatively small increase in mean riparian ET (from 2% to 13%) compared to the reference period. Moreover, future climate change scenarios predict that upland ET would increase 4% to 11% compared to the reference period, while stream flow would decrease 3% to 13%. As a result, the mean annual contribution of riparian ET to catchment water budgets could increase from 7.1% (reference period) to 8.2% (scenario RCP 8.5 percentile 0.75) (Table 4). Future increases in warming and drying will smooth the seasonality of riparian ET~~ by lengthening the vegetative period ~~ and increase the number of days with ET rates > 0 mm d^{-1} by 6–106 days (depending on the scenario and year) (Figure 5).

In the most moderate scenario (RCP 2.5 percentile 0.25), mean daily riparian ET values increased by 0.3 ± 0.1 mm d^{-1} during the dormant period, which represents an increase of 19 ± 7 % compared to the reference period. During the vegetative period, the projected changes in mean daily riparian ET were smaller (-0.1 ± 0.1 mm d^{-1}) and represent a small fraction compared to the reference period (-2 ± 4 %) (Figure 5a and 5b). The most extreme scenario (RCP 8.5, percentile 0.75) simulated high riparian ET rates (> 2 mm d^{-1}) during most of the year. For this scenario, riparian ET rates increased by 0.6 ± 0.1 mm d^{-1} during the dormant period, which represents an increase of 46 ± 16 % compared to the reference period. During the vegetative period, riparian ET rates decreased by -0.4 ± 0.6 mm d^{-1}. This is a decrease of 11 ± 22 % compared to the reference period (Figure 5g and 5h).

The AI decreased from 0.65 ± 0.18 to 0.45 ± 0.15 between the reference and the most extreme climate scenario (RCP 8.5, percentile 0.75). The contribution of riparian ET to catchment water budgets was low

(6.40 ± 0.35 %) and unrelated to AI for AI > 0.83. Below this threshold, the contribution of riparian ET to catchment water budgets increased linearly with decreasing AI. This dual behavior was well captured by a two segment linear regression relating AI and riparian ET contribution to catchment water depletion with a break point at AI = 0.83 ($R^2 = 0.77$, $p < 0.001$, n = 260) (Figure 6).

5 Discussion

5.1 Relevance of the riparian zone to simulate stream flow and catchment water budgets

This study shows that the riparian zone was an important model component when simulating water exports and budgets at the Font del Regàs catchment. The inclusion of the riparian compartment in the PERSiST model structure improved the efficiency of the simulations, especially at the downstream site, where the riparian zone occupied 10% of the local catchment area. These results support the idea that riparian zones are especially important on shaping stream flow dynamics at the valley bottom of mountainous catchments, likely due to the combination of lower catchment connectivity (i.e. lower water inputs from uplands) (Bernal et al., 2012; Covino and McGlynn, 2007) and greater water demand by riparian trees (Lupon et al., 2016).

Our results showed that the contribution of the riparian zone on simulating stream flow dynamics varied between seasons. During the dormant period, the inclusion of the riparian compartment helped to improve the simulation of stream flow volumes to some extent, with RDV values changing from +0.12 (riparian zone excluded) to +0.07 (riparian zone included). This increase in model efficiency suggests that the riparian zone can be important for shaping stream flows during wet conditions, likely because it contributes to increase water storage, and thus water residence time, within the catchment. During the vegetative period, the role of the riparian zone in simulating stream flows was even more evident. ~~First,~~ ~~t~~The inclusion of the riparian compartment notably improved the log(NS) index, which is a proxy of the goodness of fit during low flow conditions. Thus, the riparian compartment was essential for simulating low flows, reducing the overestimation of stream volumes from 53% (riparian zone excluded) to 27% (riparian zone included) (Table 3). Altogether, these results suggest that riparian zones contribute to drying up the stream in summer.

Although the inclusion of the riparian compartment contributed to significantly improve the goodness of fit, the model was not able to fully capture the lowest flows at the end of the vegetative period (August-October). Hydrological processes not included so far in the PERSiST structure, such as uptake of water by trees directly from the stream (Gribovszki et al., 2010; Tabacchi et al., 2000) or reverse flux of water from the stream towards the riparian zone (Butturini et al., 2003; Rassam et al., 2006), could contribute to drop down stream flow at Font del Regàs, and therefore to the mismatches between observed and simulated flows. These hydrological processes have been shown to be relevant for reproducing stream flow dynamics in Mediterranean and semiarid areas (e.g. Medici et al. 2008), and thus PERSiST could improve its ability to simulate stream flows in water limited catchments if these processes would be implemented in the model structure.

On an annual basis, our simulations indicate that riparian ET can account for ~ 7% of annual catchment depletions at Font del Regàs (Table 4). The contribution of riparian ET to water budgets was especially noticeable during the dry period of the year, when it contributed as much as 26% to daily catchment depletions. These values are similar to those estimated for other catchments with AI = 0.6–0.8 (Folch and Ferrer, 2015; Tsang et al., 2014; Wine and Zou, 2012; Yeh and Famiglietti, 2008) and suggest that computations of catchment water budgets neglecting riparian ET will overestimate catchment water resources. Moreover, our results suggest that the hydrological processes occurring in the riparian compartment, including ET, could reduce daily stream flow by 48% during the vegetative period. This value is consistent with empirical studies showing that riparian ET can reduce the amount of water entering to streams by 30–100% (Dahm et al., 2002; Folch and Ferrer, 2015; Kellogg et al., 2008; Lupon et al., 2016). Altogether, these findings indicate that riparian ET can shape the connectivity between uplands and streams and support the idea that transpiration from saturated riparian zones can be essential to successfully represent the stream flow in water-limited catchments (Medici et al., 2008; Tsang et al., 2014).

Overall, PERSiST was able to successfully simulate stream flow dynamics in the studied Mediterranean catchment~~, regardless of whether the model structure included or not the riparian compartment (log(NS) > 0.81, RDV < 0.11)~~. Moreover, the validation analysis supported the simulation results because the model was able to successfully capture both the magnitude and the temporal patterns of riparian water demand estimated with an independent empirical approach (Figure 3). Although there are still few hydrological models considering riparian zones as specific component of catchment water budgets, the successful simulations obtained at Font del Regàs indicate that hydrological models are useful not only for understanding catchment hydrology but also for exploring how specific hydrological processes, such as riparian ET, influence stream hydrology under different climatic conditions and future scenarios.

5.2 Future changes in riparian ET

Our simulations suggest that changes in climate projected for later in this century will influence both the magnitude and temporal pattern of riparian ET rates in Font del Regàs. Riparian ET rates will decrease in June–September and increase in November–May. Simulated decreases in riparian ET during the vegetative period were related to lower soil water availability as a consequence of lower precipitation in summer. In concordance, other studies in water-limited regions have shown that low ET rates in summer could result from the disconnection between the water table and the active root zone depth (Baird and Maddock, 2005; Serrat-Capdevila et al., 2007), which can accelerate leaf litter fall (Rood et al., 2008; Sabater and Bernal, 2011) and promote stream desiccation (Medici et al., 2008; Serrat-Capdevila et al., 2007).

On the other hand, the overall warmer temperatures predicted for winter months explain the projected increase of riparian ET during this period. According to our simulations, the ~~length of the vegetative period~~ number of days with ET > 0 mm d^{-1} will increase by 6–106 days (depending on the applied scenario), mostly due to an increase of the amount of days with temperatures above the model "growing degree threshold" (Supplement 1), especially in spring. This result suggests a potential enlargement of the vegetative period, an idea that is consistent with observations showing that climate change can affect riparian tree phenology by promoting the advancement of the riparian leaf out period (Perry et al., 2012; Serrat-Capdevila et al., 2007). The simulated increase in ET induced by the future lengthening of the vegetative period could be higher than the reduction of ET rates during summer, ultimately increasing annual riparian water use by 2–13%. This warming-induced pattern is concordant with that reported for water-limited riparian forests in southern USA (Bunk, 2012; Serrat-Capdevila et al., 2011).

Finally, we found that increases in annual riparian ET under a warmer climate may have a small effect on the relative contribution of riparian ET to annual catchment water budgets. The small effect predicted by the model was likely because warming also induced higher ET from upland forests (4 ± 11%). However, our hydrological model does not account for changes in vegetation community induced by warming, a phenomenon that is expected to occur in areas experiencing increases in water stress (Benito-Garzón et al., 2008; García-Arias et al., 2014; Peñuelas and Boada, 2003, Walther et al., 2002). If water becomes limiting, especially in the upland environments, species capable to better adjust their evapotranspirative demand may be favored and become dominant (Engelbrecht et al., 2007), which would lead to decreases in ET from uplands compared to riparian zones. In fact, previous studies suggest that the contribution of riparian ET to catchment water depletion can increase disproportionally with water limitation, and that a threshold exists at intermediate arid positions (i.e. AI = 0.8) (Lupon et al., 2016). Below this threshold, the contribution of riparian ET to water budgets can markedly increase up to 40% even when riparian zones usually occupy less than 10% of the total catchment area (Tockner and Stanford, 2002). Our simulations are in line with this idea and suggest that riparian forests could switch from energy-limited to water-limited systems as warming and drying increases in the future (Budyko, 1974; Creed et al., 2014).

6 Conclusions and Implications

This study indicates that riparian zones and, in particular, riparian ET are important for simulating stream flow dynamics and water budgets in Mediterranean catchments. Moreover, our results highlight the importance of including the riparian compartment within catchment hydrological models. For the PERSiST model, the inclusion of the riparian zone improved model efficiencies and lead to a more accurate simulation of stream flow dynamics, especially during summer. The model allowed us to quantify the relative contribution of riparian ET to catchment water depletion: 7% on an annual basis, and from 8 to 19% during dry summer months. Our results add to the growing body of knowledge showing that riparian hydrology is essential for understanding and forecasting stream flow dynamics and water budgets in catchments, especially when water is limiting. Moreover, our climate simulations indicated that the importance of riparian ET on catchment water budgets could increase as water scarcity increases in the future. At Font del Regàs, for instance, projected decreases of annual stream flow by the end of this century (3–13%) could be accompanied by increases in riparian ET of the same order (2–13%). Similar predictions have been made for other water-limited catchments of America and Europe (Christensen et al., 2004; Rood et al., 2008; Serrat-Capdevila et al., 2007), forewarning the potential increase of ecological issues related to water scarcity in regions that are already water limited. Overall, this study highlights that the ecohydrology of riparian zones needs to be considered for a responsible management and conservation of water resources in Mediterranean catchments.

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Tables and Figures

Table 1 Local catchment drainage area, percentage of evergreen oak, decidious beech and riparian forest area, width of the riparian zone, and total basal area of riparian trees for the three nested ~~sub-~~catchments considered in this study.

	Local sub-catchment characteristics				**Riparian zone characteristics**	
	Drainage area (km^2)	**Evergreen (%)**	**Decidious (%)**	**Riparian (%)**	**Mean Width (m)**	**Total Basal Area (m^2 BA)**
Upstream	1.80	8.2	91.8	0.0	--	--
Midstream	6.74	52.5	42.5	5.0	12	822
Downstream	4.42	57.8	32.2	10.0	19	1354

Table 2 Representative Concentration Pathway (RCP) projections for Mediterranean zones for 2081–2100 as compared with the reference period 1981–2000. RCP values are indicated for each season for temperature and for each semester for precipitation. Values are medians and interquartile ranges [25th, 75th percentiles] (IPCC, 2013).

Projection	**Temperature (ºC)**				**Precipitation (%)**	
	Dec–Feb	**Mar–May**	**June–Aug**	**Sep–Nov**	**Oct–Mar**	**Apr–Sep**
RCP 2.5	+1.25 [+0.75, +1.25]	+0.75 [+0.75, +1.25]	+1.25 [+0.75, +1.75]	+1.25 [+0.75, +1.75]	0 [0, +5]	0 [-5, 0]
RCP 4.5	+1.75 [+1.25, +2.50]	+1.75 [+1.25, +2.50]	+2.50 [+1.75, +3.5]	+2.50 [+1.75, +2.50]	0 [-5, +5]	0 [-15, 0]
RCP 6.0	+1.75 [+1.75, +2.50]	+2.50 [+1.75, +2.50]	+3.50 [+2.50, +4.50]	+2.50[+2.50, +3.50]	-5 [-15, 0]	-5 [-15, 0]
RCP 8.5	+3.50 [+2.50, +4.50]	+3.50 [+3.50, +4.50]	+6.00 [+4.50, +6.00]	+4.50 [+3.50, +6.00]	-5 [-15, 0]	-25 [-35, -15]

Table 3 Comparison between model calibrations including and excluding the riparian compartment. Log transformed Nash-Sutcliffe (NS) model efficiency coefficient and relative volume differences (RDV) of observed versus simulated stream flow (in parenthesis) at the up-, mid-, and downstream sites for vegetative, dormant, and whole calibration periods (September 2010 – August 2012). Negative RDV values indicate an overestimation of modelled flow volumes compared to observed flow volumes, while positive RDV values indicate the opposite. The NS model efficiency values are not shown because they were similar to log(NS) values.

	Vegetative		**Dormant**		**All data**	
	No Riparian	**Riparian**	**No Riparian**	**Riparian**	**No Riparian**	**Riparian**
Upstream	0.56 (-0.19)	0.56 (-0.19)	0.82 (0.16)	0.82 (0.16)	0.82 (0.01)	0.82 (0.01)
Midstream	0.56 (-0.20)	0.70 (-0.07)	0.87 (0.15)	0.89 (0.12)	0.85 (0.09)	0.89 (0.04)
Downstream	0.00 (-0.53)	0.49 (-0.27)	0.90 (0.12)	0.91 (0.07)	0.81(-0.11)	0.88 (-0.05)

Table 4 Aridity index, annual riparian evapotranspiration (ET) rates, and relative contribution of riparian ET to annual catchment water depletions (i.e., upland ET + riparian ET + stream flow) for the reference period (1981–2000) and for each Representative Concentration Pathway (RPC) scenario during the future period (2081–2100). Values are mean ± standard deviation.

Scenario	**Percentile**	**Aridity Index**	**Annual Riparian ET (mm)**	**Riparian ET Contribution (%)**
Reference		0.65 ± 0.19	862 ± 105	7.09 ± 0.89
RCP 2.5	0.25	0.62 ± 0.20	879 ± 115	7.36 ± 0.93
	0.50	0.63 ± 0.20	910 ± 116	7.42 ± 0.94
	0.75	0.64 ± 0.20	936 ± 124	7.42 ± 0.93
RCP 4.5	0.25	0.59 ± 0.16	848 ± 120	7.67 ± 0.98
	0.50	0.60 ± 0.19	922 ± 128	7.68 ± 0.96
	0.75	0.62 ± 0.20	977 ± 136	7.68 ± 0.94
RCP 6.0	0.25	0.52 ± 0.14	826 ± 117	7.96 ± 0.96
	0.50	0.58 ± 0.16	934 ± 126	7.78 ± 0.93
	0.75	0.56 ± 0.18	969 ± 135	7.82 ± 0.93
RCP 8.5	0.25	0.50 ± 0.17	759 ± 132	8.25 ± 0.96
	0.50	0.53 ± 0.18	862 ± 145	8.16 ± 0.95
	0.75	0.45 ± 0.15	952 ± 160	8.22 ± 0.91

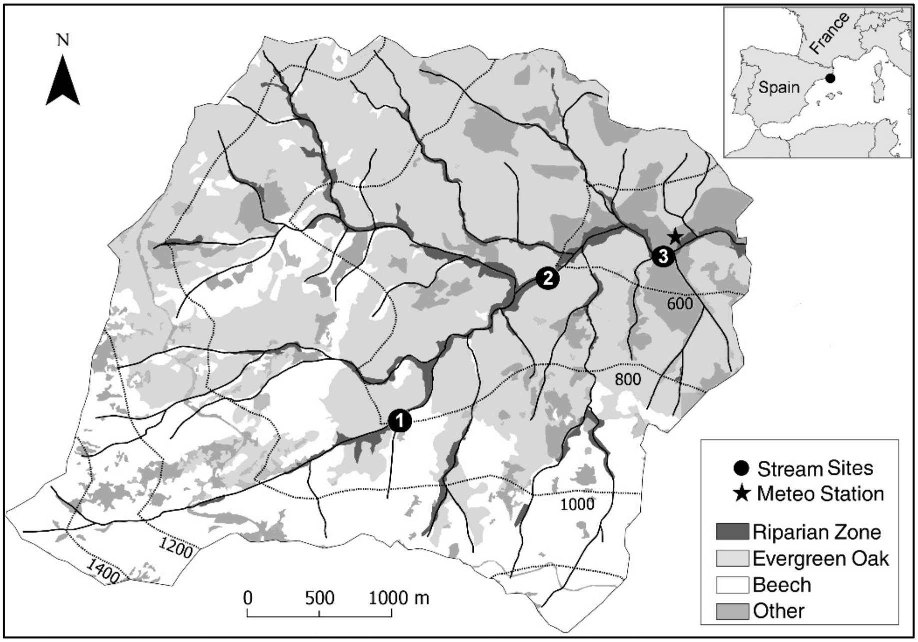

Figure 1 Map of the Font del Regàs catchment showing the different land covers (landscape units), the catchment elevation (dotted lines, 500–1500 m), the location of the three nested stream sites (black circles; 1 = upstream, 2 = midstream, and 3= downstream), and the meteorological station where precipitation and temperature was measured (star). The location of the Font del Regàs catchment within Spain is shown in the inset.

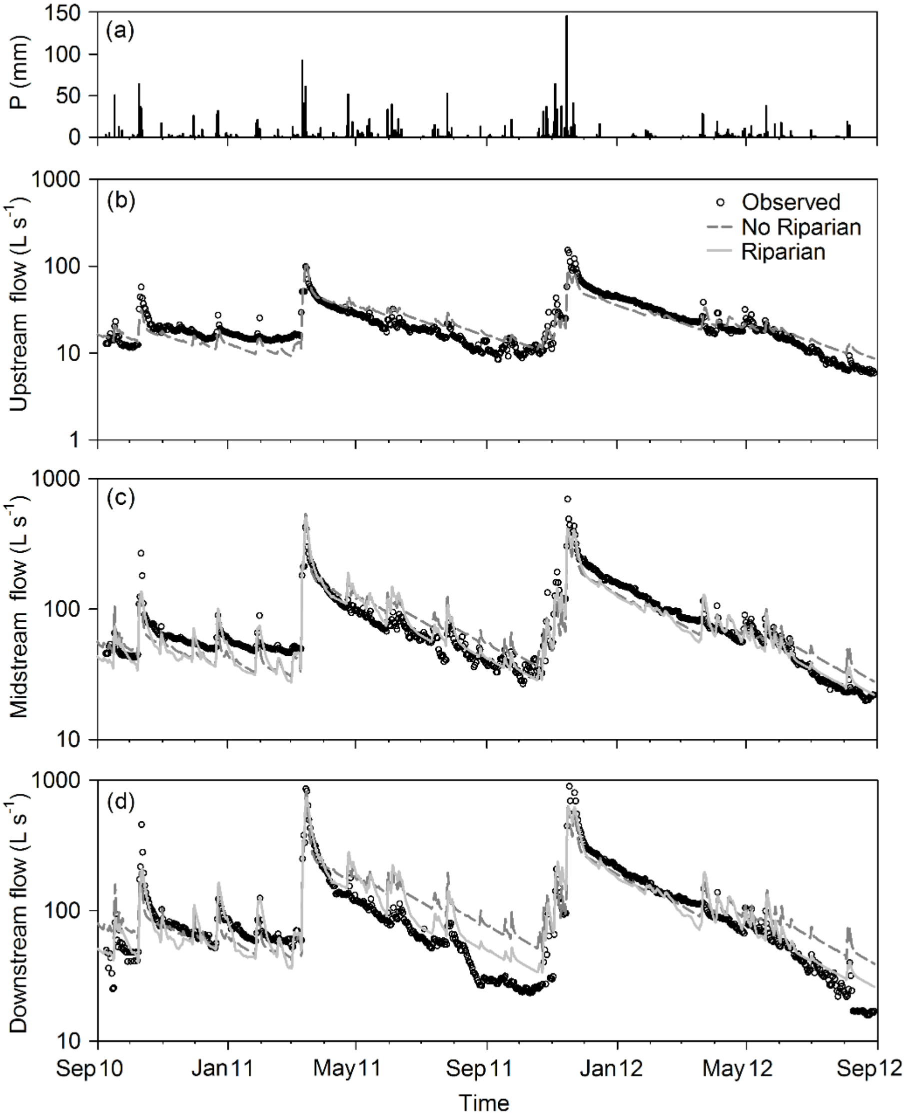

Figure 2 Temporal pattern of (a) precipitation and stream flow for the (b) upstream, (c) midstream, and (d) downstream sites during the study period. Open circles represent observed values, while lines are simulated values excluding (dashed) and including (solid) the riparian compartment in the model configuration. Note that the upstream sub-catchment had no riparian forest, and therefore, simulations with and without riparian zone are equal.

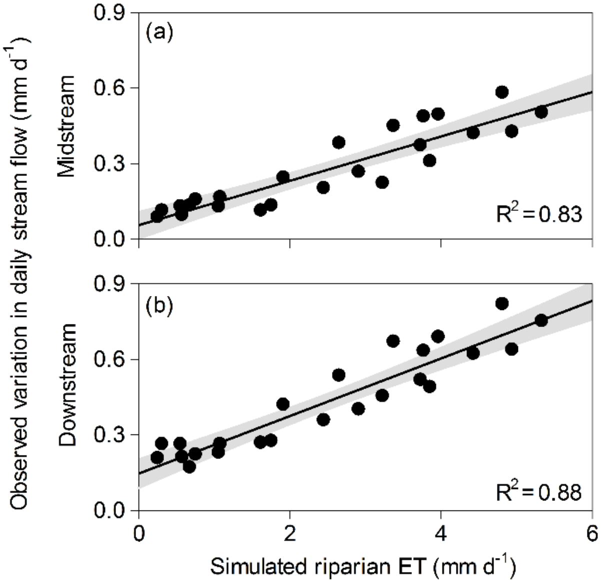

Figure 3 Relationship between monthly mean values of simulated daily riparian evapotranspiration (ET) and observed daily stream flow variations (used here as an independent proxy of riparian ET) for (a) the midstream and (b) the downstream sub-catchments for the calibration period (September 2010–August 2012). Note that simulated riparian ET is equivalent in both cases as they are presented as areal normalized values (i.e. in mm). The linear regression and the 95% confidence interval are also shown. For both mid- and downstream sites: p-value < 0.001, n = 24. The upstream sub-catchment had no riparian forest and it is not shown.

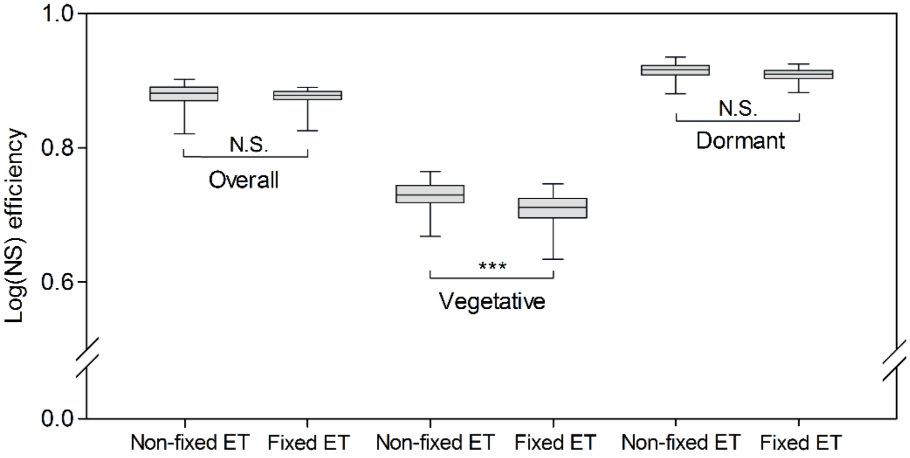

Figure 4 Box plot of the 100 best log(NS) efficiencies obtained with the Monte Carlo (MC) simulations using the model configuration that included the riparian compartment at the downstream site. MC analyses were performed using first all potentially sensitive parameters (Non-fixed ET), and second fixing evapotranspiration-related parameters (Fixed ET). Means of corresponding distribution pairs were compared using Tukey's Honestly Significant Difference tests. N.S. indicate no significant difference and *** indicate statistically significant difference ($p<0.0001$).

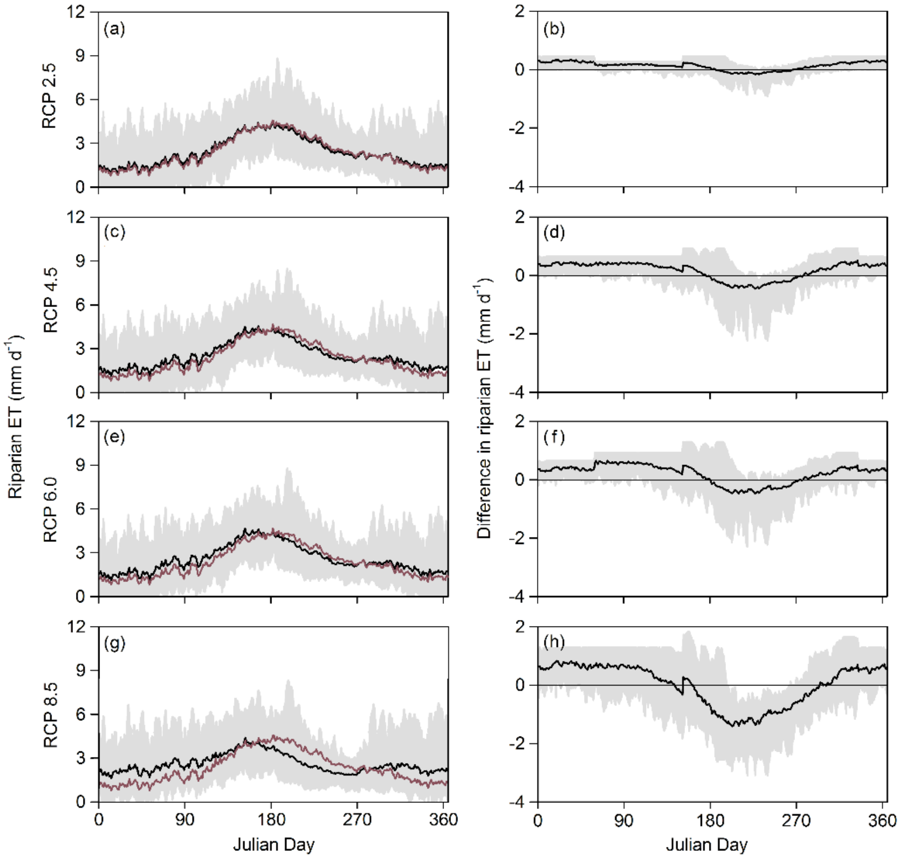

Figure 5 Seasonal pattern of (left panels) daily riparian evapotranspiration rates simulated for different climate change scenarios and (right panels) difference in the simulated values of daily riparian evapotranspiration between the reference period (1981–2000) and future climate scenarios (2081–2100). All the climate change scenarios were based on the Representative Concentration Pathway (RCP) projections provided by IPCC (2013) for the period 2081–2100 (Table 2): (a,b) percentile 0.25 of RCP 2.5 (the most moderate scenario), (c,d) percentile 0.5 of RCP 4.5, (e,f) percentile 0.5 of RCP 6.0, and (g,h) percentile 0.75 of RCP 8.5 (the most extreme scenario). Black lines are mean values and grey shadows indicate the maximum–minimum range of values simulated for the 20-years period. The red line in the left panels is the mean daily values of riparian ET for the reference period. The horizontal line in the right panel is shown as a reference.

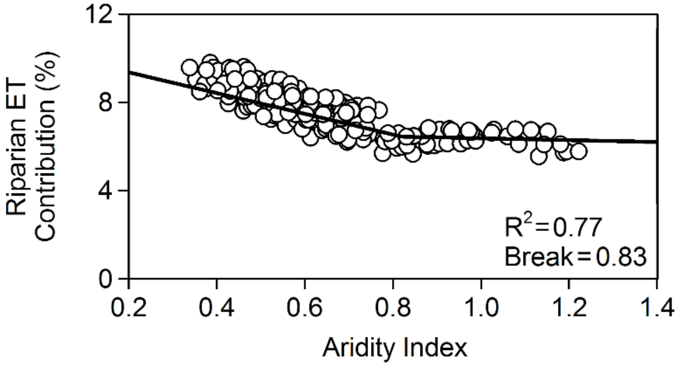

Figure 6 Relationship between the relative contribution of riparian evapotranspiration (ET) to annual catchment water depletions and the aridity index for all the projections simulated with PERSiST as well as for the reference period. Total water output fluxes from the catchment (water depletions) are the sum of stream flow, upland ET, and riparian ET. The aridity index is the ratio between annual precipitation and potential evapotranspiration (P/PET). The goodness of fit of the two segment linear model and the break point are also show.