AUTHOR'S RESPONSE TO RC1:

Interactive comment on "Groundwater influence on soil moisture memory and land–atmosphere interactions in the Iberian Peninsula" *by* Alberto Martínez-de la Torre and Gonzalo Miguez-Macho

Anonymous Referee #1

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General comments

This manuscript assesses the groundwater influence on soil moisture memory and land atmosphere interactions in the Iberian Peninsula by using the LEAFHYDRO model. The simulation was performed at 2.5-km over the Iberian Peninsula for a 10 year period. The authors found significantly wetter soil and enhanced ET over shallow water table regions suggesting that groundwater might have an impact on climate over the Iberian Peninsula.

This study follows two previous studies carried out in United Sates (Miguez-Macho et al., 2007) and over the Amazon basin (Miguez-Macho and Fan, 2012) where the same model was used to depict the influence of groundwater on soil moisture and atmospheric variables. The methodology and science questions of the present paper are very similar to these two previous papers but applied for the Iberian Peninsula. Regarding the main conclusion obtained from the present paper, most of them are consistent and confirm the findings in numerous previous studies, including the two previous studies using the LEAFHYDRO model. However, no significant new findings can be drawn from this modeling, hence the novelty cannot be said to be high. In my opinion, this is the first major issue of the paper. The authors should consider to better highlight what is the interest of using such high-resolution model over Spain with respect to the previous study using the same model (in United Sates and Amazonia). A reorganization of the introduction may help to better define the novelty introduced by the use of LEAFHYDRO over the Iberian Peninsula.

The paper is articulated in five sections: introduction, methodology, validation, results, and conclusion. Regarding this structure, I identified two general remarks that need to be solved. First, the methodology section do not give enough details on the model description and the data used. In my opinion, while the main purpose of the paper is related to groundwater-surface land relationships, this part is not enough detailed in the paper. Secondly, the results section introduces some elements of discussion that are not at all linked with the literature. No references are cited, neither in this results section, nor in the conclusion. Regarding the bunch of paper related to this subject (i.e. groundwater-soil moisture influence), the paper lacks of references. This is the second major issue.

Besides these general comments, I identified specific comments and technical errors in the text and in the figures that I put in comment in the subsequent sections. In particular, I wish to see all the figures wider, regarding the size of the simulated area.

Based on the above statement, I think major revisions are needed to solve the two previous major issues and the below specific comments and errors before the paper can be eventually published in HESS.

Authors: Thanks for this complete assessment. We understand the issues pointed out by the reviewer and have introduced substantial editions and changes to the manuscript to address them. We discuss such changes in response to the reviewer's specific comments below.

Specific comments

Generally speaking, and regarding the bunch of papers on the subject, the Introduction part lacks of references on land surface-atmosphere coupling and soil moisture mem- ory influences on groundwater and atmosphere. As an example the following papers should be considered:

Maxwell, R. M., Lundquist, J. K., Mirocha, J. D., Smith, S. G., Woodward, C. S. and Tompson, A. F. B.: Development of a Coupled Groundwater–Atmosphere Model, Mon. Wea. Rev., 139(1), 96–116, doi:10.1175/2010MWR3392.1, 2010.

Vergnes, J.-P., Decharme, B. and Habets, F.: Introduction of groundwater capillary rises using subgrid spatial variability of topography into the ISBA land surface model, J. Geophys. Res.

Atmos., 119(19), 2014JD021573, doi:10.1002/2014JD021573, 2014.

Authors: Agreed. We have included the suggested references and others in the reviewed manuscript where they were relevant. Other references included:

Ying Fan, Gonzalo Miguez-Macho, Esteban G. Jobbágy, Robert B. Jackson, and Carlos Otero-Casal: Hydrologic regulation of plant rooting depth, PNAS 114 (40) 10572-10577, 2017 https://doi.org/10.1073/pnas.1712381114

Sobrino, J., Gómez, M., Jiménez-Muñoz, J., and Olioso, A.: Application of a simple algorithm to estimate daily evapotranspiration from NOAA-AVHRR images for the Iberian Peninsula, Remote Sensing of Environment, 110, 139–148, 2007. https://doi.org/https://doi.org/10.1016/j.rse.2007.02.017

Westerhoff, R., White, P., and Miguez-Macho, G.: Application of an improved global-scale groundwater model for water table estimation across New Zealand, Hydrol. Earth Syst. Sci., 22, 6449-6472, https://doi.org/10.5194/hess-22-6449-2018, 2018. https://www.hydrol-earth-syst-sci.net/22/6449/2018/

Page 2, line 4 to 5: This is the purpose of the paper. I suggest to move this part near the end of the introduction, after the definition of the science questions.

Page 3 line 21 to the end: "Here, we present a modelling study linking groundwater to soil moisture, land-atmosphere interactions and surface water" : You introduce the purpose of the paper in the first sentence and then explain why you chose your case study. To better highlight the subject of the paper and enhance the problematics that occurred in Spain and the opportunity to simulate groundwater and soil moisture at this scale, you should consider to move all this part before introducing the purpose of the paper.

Authors: Thanks. We agree that the characteristics of the region should be introduced first and then presenting what we have done for the Iberian Peninsula at the end of the introduction. We have deleted the mentioned sentences and included them as the last paragraph of the introduction:

"In this paper, we present a modelling study linking groundwater to soil moisture, land-atmosphere interactions and surface water at the regional scale in the Iberian Peninsula. We investigate the role of groundwater in the hydrology of the region, focusing first, on its impact on soil moisture spatial variability, dynamics and long-term memory, second, on its effects on land-atmosphere ET fluxes, and third, on its direct impact on river flow."

Page 4 line 9: "Model description and settings". This part describes the model and data used in the study. Most of the formulation of the model's equations are described in (Miguez-Macho et al., 2007) and (Fan et al., 2007), so only the mass balance of the dynamic groundwater reservoir is given here. However, it could have been useful to have a description of how the water table head is calculated since it the main variable that is evaluated in the following sections. Information on how hydrodynamic parameters (transmissivity and porosity) are taken into account in the model could be added.

Page 4 Line 27 – Page 5 line 7: The coupling of the water table and the soil layers is unclear. Why the layer B is added? This part needs more details on how the water content is computed.

Page 5 line 7-14 : This part lacks of details about the calculation of the river- groundwater exchanges. It is the so-called river conductance model used in MOD- FLOW? Are river heights variables (using Manning's Formula) or prescribed? How are the river conductances determined?

Authors: Thanks. Our initial approach was to not include too many details on the model formulations, but rather refer the reader to relevant literature where such formulations are described and focus on the results. But given this one and another reviewer's comment, we have realized that the manuscript needs some of these model details to be consistent, and therefore we have edited substantially the Methodology section in the reviewed manuscript, adding information that responds to the reviewer concerns.

Page 5, line 15 "2.2 Initial land and river parameters" Regarding the title, should it be "Land-surface and river parameters"? Generally speaking, this part lacks of many details about the parameters used for developing the model over the Iberian Peninsula. The authors should consider the following remarks and maybe add a Figure depicting the case study.

Page 5 line 16-20: Why the soil textural classes are needed in LEAFHYDRO? What is the dominant soil type/vegetation type?

Page 5 line 21-24: How does the river flow scheme work? Does it used Manning's Formula? How are the river widths determined? This part lacks of details for the Iberian Peninsula.

Authors: Thanks. The textural classes are needed to derive the parameters governing the vertical water flux through the soil layers. They also appear in the calculation of transmissivities for lateral groundwater flow. We have edited section 2.2 to clarify this and the rest of the reviewer's concerns, including a description of the methodology used to calculate the river parameters and a new Figure to follow this methodology.

Page 6 line 4: Could you add details about the method used to disaggregate the IB02 data using the ERA-Interim precipitation data? This is not clear how the link between the two of them is described.

Authors: Yes, we have clarified this point in the reviewed version as follows:

"Once the daily precipitation is read and interpolated into the model grid, the model temporally disaggregates the daily values throughout the day using 3-hourly ERA-Interim precipitation distribution. Hence, the model uses the IB02 daily analysis data for bias-correction of daily totals and ERA-Interim data for precipitation distribution throughout the day."

Page 6 line 3: You speak about the model grid without having define his resolution before (0.2° ?).

Authors: This mention refers to the IB02 data resolution. After the new edition in section 2.2, the model grid resolution has been defined before this point.

Page 6 line 12-17: What is the resolution of the model grid? How was the global climatic recharge at low resolution used? Was it disaggregated at a higher resolution? Is it an annual mean average over a period? How was the test run aggregated to the model grid? This part is not clear.

Authors: We agree that the explanation on how we calculated our initial EWTD was not clear enough. We have edited the text from lines 11 to 17. The second paragraph in section 2.4 answers the reviewer's questions now and reads as follows:

"We used topography data at high spatial resolution (9 arc seconds) in the EWTD calculation to properly capture topographic variability and local hillslope gradients (Gestal-Souto et al., 2010) A three-step process was followed, where first, a low resolution (1º) global climatic recharge from the Mosaic LSM was used to calculate a first estimate of EWTD by ingesting it to the 2D model using the high resolution topography; second, the resulting first high-resolution estimate of EWTD is simply aggregated to a grid of 2.5km to serve as initial water table condition for LEAFHYDRO full LSM 10-year test run (1989-1998), and third, a new high resolution EWTD was recalculated forcing the 2D model with the groundwater net recharge obtained with the LEAFHYDRO test run at 2.5 km and the high resolution topography. The test run uses precipitation analysis and other forcings (see section 2.3) at higher resolution than the 1º climatic recharge from MOSAIC initially feeding the EWTD model, and produces a much more realistic recharge, totally compatible with our simulation settings"

Page 6 line 25-28: Much details are needed on how soil moisture is calculated in LEAFHYDRO. This remark is linked to the model description in section 2.1. Some details could be added to illustrate soil moisture.

Authors: We have now added details about this in the first paragraph of section 2.1.

Page 6, line 29: 10 year is a rather short period to validate the model. I know some water table characterized by multi-year annual cycles of 20 years. Could you explained why you choose this time period? What is the time step?

Authors: The 10 year choice was a compromise between the computational capabilities at our disposal and the science issue of choosing a period long enough to include wet and dry years in order to study soil moisture and water table memory. The time resolution for resolving heat and water fluxes in the soil and at the land surface was 60 s. The time step for groundwater-stream exchange, groundwater mass balance and water table adjustment in the WT run is 900 s. We have included this information in Section 2.5.

Page 7 line 24: "in order to rule out measurements in confined aquifers as much as possible": does it means that you used some observations of confined aquifers to validate unconfined aquifers? It should be clarified.

Authors: We used water table depth data from the IGME (*Institute of Geology and Mining of Spain*), several *Confederaciones Hidrológicas* (Spanish agencies managing the main watersheds within the country) and the SNIRH (*National Information System for Hydrological Resources of Portugal*). We had no information about the confinement of the aquifers, hence we decided to neglect those stations with observations with wtd lower than 100 m.

Page 8 line 3: "With regard to the observations, 203 of the studied stations present a shallow water table (wtd < 8 m) during the simulation period": does it mean that the mean water table depth is lower than 8 m?

Authors: Yes, exactly. We have added the word "mean" in the reviewed manuscript to clarify this point.

Page 8 line 10: Do these 3 different observation sites in Point 15 grid cell belong to the same aquifer or maybe to different layers? Coarse spatial resolution is a factor that could explain these differences, but the different piezometers can also monitored different aquifers. It should be verified. The same remarks applied for the other points with several observations.

Authors: That is true, thanks for the remark. LEAFHYDRO can only resolve one water table per grid cell. If observations at one point come from different aquifers within the same column, as the reviewer point out, the "vertical design of the model" would be the difficulty we were trying to point out in this paragraph, as well as the coarse resolution. We have added this point to the manuscript.

Page 8 line 14-line 17: The presentation of these percentage need to be clarified.

Authors: Agreed. We have tried to clarify, as:

"*Approximately one third of the stations present a shallow mean wtd (< 8 m), and 66.0 % of them are also found to have shallow mean water table by the model.*

In terms of mean wtd error, 14.0 % of stations present less than 2 m difference between simulated and observed mean wtd at the available observation times (red points in Fig. X. If we only consider shallow water table observations (mean wtd < 8 m), 33.0 % of them present less than 2 m difference with the mean simulated wtd."

Page 8 line 17: "capturing the mean water table depth": is it rather "capturing the water table depth time evolution"?

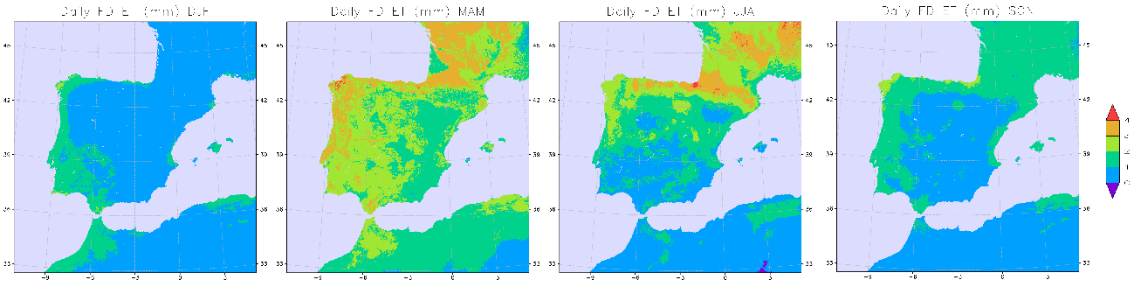
Authors: We meant "capturing the mean water table depth" here, for points 1-12. Then in the next sentences we talk about time evolution and mention points 1-14, therefore points 1-12 are in both red (capturing mean wtd) and green (capturing time evolution) categories.

Page 8, line 26-27: this statement should be better connected with the results.

Authors: The following results section focused on the shallower water table points or regions, where the groundwater is connected to the top-soil hydrology. With this statement we aimed to summarize some of the figures presented in the previous paragraphs, particularly the percentages that were discussed two responses above.

Page 10, line 14-16: Recharge mean annual cycles is linked to ET and precipitation mean annual cycles, but Figure 6 only shows the climatology of the recharge variable. Results for ET and precipitation should be mentioned here, maybe in the Figure, or with some details in the text.

Authors: We have seasonal plots of the evapotranspiration fluxes in the model:



However, we decided not to include them, as we did not intend to include too many figures. We have added some text about the ET cycle in the manuscript: "*The seasonal character of ET in the Iberian Peninsula (Sobrino et al, 2007) is induced by water availability and incoming radiation; maximum values and higher spatial variability are found in spring and summer, whereas minimum values and variability appear in autumn and winter, when the incoming radiation is lower and the leaf area index decreases*". The Sobrino (2007) reference presents ET seasonal patterns using NOAA satellite images for the Iberian Peninsula, in agreement with the LEAFHYDRO patterns shown here. Of course we can add the figures as supplementary material if the reviewer see it necessary.

Page 10, line 19-23: "As the water table gets deeper": does it correspond to the EWTD of Figure 2 ? Or a time evolution? It must be clarified.

Authors: Yes, thanks for spotting this. We meant "Where the water table is deeper (Fig. 2)", and have corrected it in the reviewed manuscript.

Page 10, line 22: ET evolution is mentioned but no Figure show it.

Authors: See response 2 comments above.

Page 11, line 24: Anomalies are computed with respect to the annual mean or the mean annual cycle? It must be clarified in this subsection.

Authors: With respect to the annual mean. It has been clarified in the revised manuscript.

Page 12, line 29: The authors should add a sentence on the location of this region (reference to Figure 10).

Authors: Done in revised manuscript. Thank you.

Page 13 line 24: "but drainage is slowed down". This result need to be reinforced with further results, maybe with a water budget or a time evolution of the recharge.

Authors: We meant that drainage is slowed down in comparison with the FD run, as there are no upward capillary fluxes from below the top soil column or shallow water tables in free-drain approach. Drainage should then be faster than with the presence of a water table, at least in the regions where the water table is shallow. We have edited slightly the sentence as:

"During the wet season (autumn-winter) the water table rises due to precipitation infiltration, but since drainage is slowed down as compared with the free-draining FD run, the soil moisture difference between both experiments also follows an upward trend"

Page 14 line 15: "one year frequencies and at decadal timescales". Decadal timescale appear on these power spectrum analysis, but I wonder the pertinence of finding decadal timescale with a 10-year time series. A period of at least 20 years would have been more appropriate.

Authors: Yes, of course. Thanks for pointing this out. Decadal timescale results are not relevant in this analysis. We have deleted the comment.

Page 14, line 15-16: "The annual cycle, linked to that of the surface water balance": Could you better explain this statement? Maybe by linking it with previous results?

Authors: We were referring to the cycle apparent in the previous Fig. 13 (on ET and soil moisture). We have added this reference in the revised manuscript.

Page 14, line 24-25: "The higher weight of longer timescales of variation in the WT soil moisture series": same remark as above. A 10-year simulation appear rather short to establish this result.

Authors: The statement is still true for most basins at lower frequencies, particularly the Mediterranean basins at around 3yr frequencies.

Page 14, line 28: For this section, Figure15 is not necessary since it is the same as Figure 5. You should consider to had the FD simulation in Figure 5 directly. Figure 15 could be replaced by a Figure showing the stream-groundwater exchanges in order to discuss this flux.

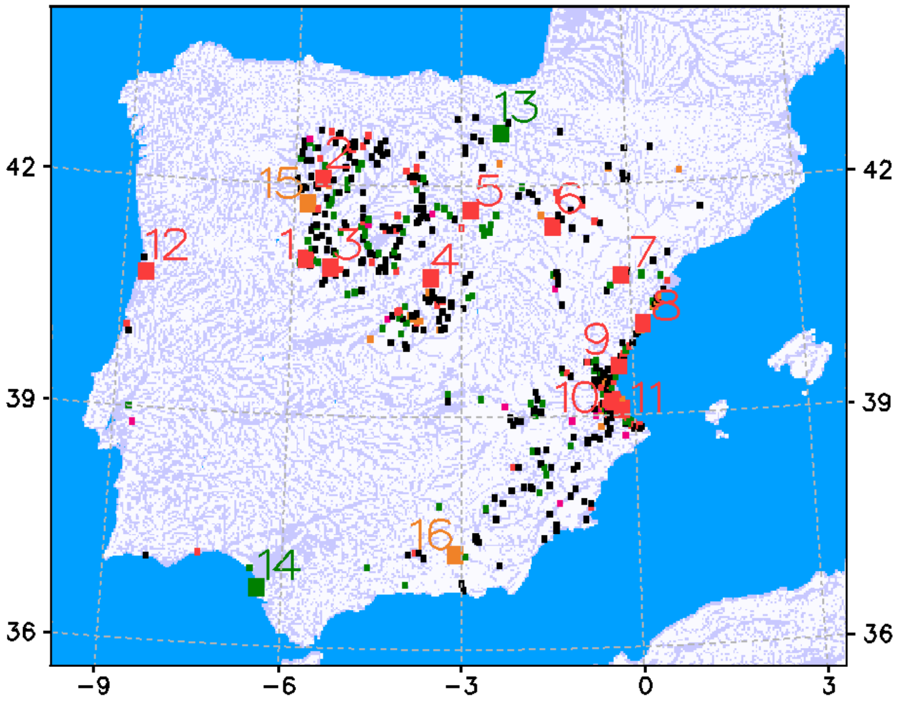
Authors: We believe after consideration that having the 2 figures makes it easier for the reader. We present in Fig 5 the streamflow comparison for WT run only as this is the flow we obtain as output of our main simulation we extract conclusions from. We then present fig. 15 (now 16) when we study the main basins, focusing on the differences between WT and FD representations of river flow.

Page 23, Figure 2: The legend refers to EWTD and topographic data, but only one map is shown that corresponds to EWTD. Why describing topographic data here? This Figure could be wider and extend to the full wide of the page. Add a unit to the colorbar and a title.

Authors: The topography data was used to calculate EWTD as a balance between the climatic recharge and the lateral flow driven by topography, using the 2-D model in Fan et al (2007), as explained in section 2.4. Therefore, the original resolution of the EWTD data shown in the figure is the resolution of the used topography, we have clarified this point in the caption in the revised manuscript. We have also widen the figure and added the units to the colourbar.

Page 24, Figure 3: The authors describe a grid centered in the Iberian Peninsula. Figure 3 shows this peninsula, but also parts of France and North Africa. Could you add the limits of the simulated domain? Are the France and North Africa part also simulated? Generally speaking, Figure 3 should be reorganized to better highlight the results. A wider map centered on Spain could improve the reading. Using different color points for different information on the same map is confusing. I suggest to use different maps for the different informations (wtd, correlation, steep, number of station par cells) and grouping them into a single figure.

Authors: Yes, the portions of France and North Africa in the figure are also part of the domain. But the reviewer is right in that the study is not about them, and particularly for this figure, their inclusion makes the information harder to read. We have cropped the figure to focus it on the peninsula, and made it wider in the manuscript, so that the information can be clearer seen. Still, we have decided to keep the colour code to avoid presenting too many maps. We believe that it can be better understood now:



Page 25, Figure 4: Point 8 and Point 11: the model seems to overestimate the amplitude of the piezometric head evolution. It should be mentioned and explained.

Authors: We have included in the revised text that at these very shallow water table points the amplitude of the wtd variations are larger in the model than in the observations.

Page 26, Figure 5: only correlation scores are given. The Nash-Sutcliffe (Nash and Sutcliffe, 1970) score could be used and commented in the text to quantify the quality of the simulation.

Authors: There are two important issues related to streamflow in these simulations. They are discussed in section 3.2 in the paper, but perhaps they need further clarification. The first one is related to the precipitation forcing data. From figure 5 it is obvious that there is a large amount of missing water in the model results. Only basin 5 (Guadalquivir) shows less streamflow in the observations than in the model, but this is because in this strongly regulated basin, water is heavily used for irrigation. While there can be some errors due to evaporation biases, we have evidence from local independent observation networks that this missing water is more related to the precipitation forcing (please, see the discussion about the same bias in the IB02 dataset in Rios-Entenza and Miguez-Macho, 2014). In the mountains, especially in the north, the IB02 dataset does not properly capture orographic enhancement, since it was obtained using simple interpolation algorithms.

The second problem is due to model parameterizations and is also commented in the paper. Surface runoff from excess saturation in thin soil or in subgrid near saturated areas is unrepresented. Due to unresolving hillslope hydrologic gradients at the 2.5km resolution, the connection between rivers and groundwater in cells where the mean water table is deep does not produce a good result either.

Since both forcing and model problems affect mostly mountain areas where terrain is complex, we are confident that the main conclusions in our work about groundwater and soil moisture are sound. However, we cannot say the same about riverflow, since the contribution from the mountainous areas to their total water budget is very important.

We have now calculated other skill scores for both experiments, as suggested by the reviewers. In the FD simulation, the lack of surface runoff is compensated by the fact that infiltration is readily incorporated into the rivers. Because precipitation amounts are biased low, winter peaks may look better in this FD simulation and some skill scores are better than in the WT simulation, but this does not mean that the result is physically correct.

Station - Basin	Basin Catchment Area (km^2)	E WT	r WT	r_{mm} WT	E FD	r FD	r_{mm} FD
Foz de Mouro - MIÑO	15.407	-0.13	0.89	0.98	0.55	0.93	0.95
Puentepino - DUERO	63.160	-0.52	0.73	0.96	0.18	0.72	0.69
Almourol - TAJO	67.482	0.28	0.91	0.93	0.80	0.91	0.89
Pulo do Lobo - GUADIANA	61.885	0.07	0.65	0.71	0.21	0.54	0.66
Cantillana - GUADALQUIVIR	44.871	0.44	0.76	0.66	0.15	0.56	0.67
Tortosa - EBRO	84.230	0.36	0.74	0.93	0.55	0.82	0.87

For all the aforementioned reasons, we purposely wanted to limit our discussion about streamflow in the paper and just show the WT results. The only point that we wanted to make with the FD simulation is that in the Mediterranean climate of the Iberian Peninsula, summer stream flow is sustained by groundwater and, without it, in a simulation with a free drain approach, rivers dry out. We are confident that this result holds true, despite all the problems in the forcing and model parameterizations. We show the Ebro basin to illustrate this point because it is the one showing less streamflow total annual underestimation and annual cycle better matching observations in the control WT run, especially in winter. It so happens that it is also the largest basin the Peninsula, so the example is significant.

Page 29, Figure 7: add units for the maps and the y-axis of the bars. The (a), (b) and (c) letters need to be added to the titles.

Authors: Ok. Done in revised manuscript.

Page 30, Figure 8: the authors should think to show the seasonality of ET in Figure 8, or elsewhere, as said earlier.

Authors: Replied earlier. Thanks.

Page 34, Figure 12: add a title.

Authors: Ok. Done in revised manuscript.

Page 37, Figure 15: suppress this Figure and add the FD simulation to Figure 5. #

Authors: Responded above

Technical corrections

Page 1, line 2: “a key role” not “an key role”

Page 8, line 19: “simulated time series” instead of “simulated series”
Page 13, line 1: “for the large” instead of “for the the large” References

Authors: All technical corrections have been included in the revised manuscript. Thanks.

AUTHOR'S RESPONSE TO RC2:

Manuscript hess-2018-626 by Martinez-de la Torre & Miguez-Macho: "**Groundwater influence on soil moisture memory and land–atmosphere interactions in the Iberian Peninsula**"

The LEAFHYDRO model was among the first ones to couple a physically-based 2D groundwater (GW) flow model with a land surface model (LEAF2). Transient applications so far focused on the USA (2007 papers), the Amazon (2012 papers), while the groundwater model has been coupled to Noah over South-America (Martinez et al 2016), and over New-Zealand (Westerhoff et al., 2018, not cited). The present paper reports the application of the LEAFHYDRO over the Iberian Peninsula (IB), with novel insights regarding the propagation of precipitation anomalies to water table depth (WTD) and soil moisture anomalies, at a pluri-annual timescale. This effect is all the more pronounced as the climate is more arid, as are the more "classical" impacts of GW on ET, soil moisture, and river discharge at seasonal or shorter timescales.

Authors: Thanks. We have included the Westerhoff (2018) reference in Section 2.4, when we describe the 2D groundwater model (uncoupled to LSMs). This work was finally published while finishing up our manuscript initial writing.

This makes this paper very commendable for HESS, but on the other hand, the paper lacks (i) good quality figures, (ii) sufficient information on the model and forcing datasets, (iii) solid quantification of the reported impacts and model validation, (iv) a real discussion of the results, including the limitations of the approach. Other problems include a structure that is not always very logic, and a tendency to overstatement. Apart from a few spelling errors, the language is very clear. **Eventually, I advise to substantially revise the paper before publication in HESS**. None of the suggested revisions is very complicated, but many of them are advisable, as detailed below.

Authors: Thanks for this complete assessment. We acknowledge the issues pointed out by the reviewer and have introduced substantial editions and changes to the manuscript to address them, making the paper stronger in our view. We discuss such changes in response to the reviewer's specific comments below.

1. Figures:

(a) Most IB maps are too small, and it's almost impossible to see something. Please remove Southern France, Northern Africa and oceans, and magnify the remaining IB. When possible, please use the same color scale for comparable variables (e.g. equilibrium and non- equilibrium WTD). It would also be very informative to add the mean and std of each map over the IB.

Authors: Thanks. In the revised manuscript, we have cropped the figures including parts of Africa and France to make the results over the Iberian Peninsula more visible. The non-equilibrium color scale was chosen in order to contrast with the mean top-2m soil moisture plot in the same map. The means of the variables represented in each plot are included in the bars below on the anomaly figures (Figs. 10 and 11 in the original submission).

(b) Fig. 3 is too small as well, and the color code of the points locating the points with observed does not seem well adapted, since a point can meet several conditions: for instance, what is the color of a point where bias is less than 2 m (red), and correlation with observed time series is more than 0.5 (green), which must be possible? There also seems to be some black points, in which case their meaning should be explained. But maybe they are purple… It would also be useful to report the classification used for Fig. 3 on the various panels of Fig 4 (insert for each point the bias, the correlation coefficient, and the wtd slope).

Authors: Thanks. In the revised manuscript, we have cropped figures 3 (now 4) and made it larger. The colour of the dots is easier to identify now, and we have also explained in the caption the meaning of red dots (no validation criteria matched) and the hierarchy of the criteria (in the case pointed out by the reviewer the dots appear as red, this happens in most red dots on the next figure showing time series and it is also explained now in the text when describing the figure). New caption: "*Shallow water table zones (light blue shades) and Iberian Peninsula wtd observation stations (dots). Red dots are locations where observed and simulated wtd differences are within 2 m; green dots are stations with correlation over 0.5 between observed and simulated wtd series; purple dots are stations with steep wtd slope (>=0.035 m month-1), well captured by the model; orange dots are cells containing more than one observation station; black dots are cells where none of the above criteria is met by the model. Over cells where more than one validation criteria is reached the point adopts the colour of the first criterium met (in the order presented here); for instance, cells with mean wtd differences lower than 2 m and also correlations above 0.5, are shown as red on the map*"

(c) For Fig3, Fig 5, Fig 15 (and potentially Fig4), it must be clarified if the reported correlation coefficient is calculated on the full time series (120 monthly values), or on the mean seasonal cycle (12 monthly mean values).

Authors: The correlations used in the wtd validation (Fig. 3, now 4) were calculated with the full time series available, where the time scale varied amongst the stations (see Fig. 4, now 5). The correlations reported in the river flow time series are calculated on the mean seasonal cycle, and that was the reason to show them inside the seasonal plots. We have clarified both scales in the revised manuscript and figure captions. Thanks

(d) Fig. 6: R seems negative if downward, which seems odd for the flux which recharges the GW.

Authors: Yes, that is true. We acknowledge the groundwater recharge is often referred to as the positive flux into the groundwater reservoir. In this work, we have followed the model criteria for signs in fluxes, so that upward is positive (like evapotranspiration from the surface) and downward is negative (like the water flux through the soil layers and then into the groundwater). We have changed the name of the flux to "net recharge" in the revised manuscript in order to clarify this point at different instances. The first time the net recharged is referred to in the manuscript in Section 2.1: "*The water flux through the water table or net recharge R is the sum of gravitational downward groundwater recharge and capillary flux, and depending on soil wetness and atmospheric demand, it can be downwards, causing the water table to rise, or upwards, causing the water table to deepen*"

(e) Fig. 7c: why not show a real mean seasonal cycle, with 12 monthly mean values, instead of 4 seasonal mean values? And couldn't you plot the seasonal cycle of the shallow WTD as well?

Authors: We think that the plot focusing on the 4 seasonal means is stronger, illustrating the greater groundwater influence in water-scarce seasons. Also, the presentation as 4 seasons follows the net recharge figures (Fig. 6, 7 now), connecting with the seasonal variability in the net recharge and making the point clearer for the reader.

(f) Fig. 8: the color scale is not clear, we cannot distinguish the values that are not zero. Besides, could you add a scatter plot of summer ET difference against summer WTD, to show if there is a kind a threshold WTD inducing a marked ET difference?

Authors: We have cropped and made the figure larger in the revised manuscript, making the green scale more distinguishable for the reader.

(g) Fig. 9 is very noisy: could you add the difference between center and left panels?

Authors: We have noticed a mistake in the caption, the left and centre panels descriptions were switched. We have corrected it in the revised manuscript. Of course we could add the difference plot suggested by the reviewer, but would not this make the figure noisier? The idea is that the plot on the right highlights with high values those areas of difference between the centre and left plots.

(h) Fig. 11: please add the lon/lat of the mapped area, either on the maps, or on the caption.

Authors: Yes, done. Thank you.

(i) Consider merging top panel of Fig 5 and Fig12; same for Fig 5 and Fig 15.

Authors: That was our initial approach in the first draft, but we believe after consideration that having the 2 figures makes it easier for the reader, as we present Fig 15 (now 16) when we study the main basins, while the plot on top of Fig. 5 (now 6) is about rivers and gauging stations.

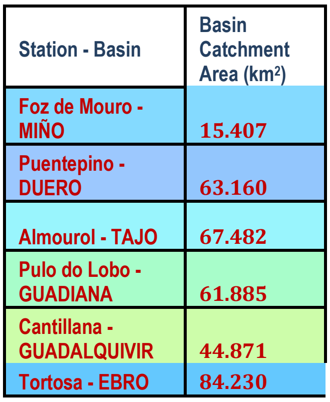
> By the way, why not show the FD simulations at all stations? And correct the statement that Ebro at Tortosa is where the model exhibits the best scores (L32-33 p 14): based on correlation coefficient, this station is only the third best for simulation WT based on Fig 5; besides, the ms discusses two models, so clarification is needed. Finally, the correlation coefficient is far from enough to support a performance analysis, and I strongly recommend that other classical criteria are documented (bias, important since ET changes between the two simulations; RMSE; Nash and/or KGE, which are classical skill criteria in river hydrology).

Authors: There are two important issues related to streamflow in these simulations. They are discussed in section 3.2 in the paper, but perhaps they need further clarification. The first one is related to the precipitation forcing data. From figure 5 it is obvious that there is a large amount of missing water in the model results. Only basin 5 (Guadalquivir) shows less streamflow in the observations than in the model, but this is because in this strongly regulated basin, water is heavily used for irrigation. While there can be some errors due to evaporation biases, we have evidence from local independent observation networks that this missing water is more related to the precipitation forcing (please, see the discussion about the same bias in the IB02 dataset in Rios-Entenza and Miguez-Macho, 2014). In the mountains, especially in the north, the IB02 dataset does not properly capture orographic enhancement, since it was obtained using simple interpolation algorithms.

The second problem is due to model parameterizations and is also commented in the paper. Surface runoff from excess saturation in thin soil or in subgrid near saturated areas is unrepresented. Due to unresolving hillslope hydrologic gradients at the 2.5km resolution, the connection between rivers and groundwater in cells where the mean water table is deep does not produce a good result either.

Since both forcing and model problems affect mostly mountain areas where terrain is complex, we are confident that the main conclusions in our work about groundwater and soil moisture are sound. However, we cannot say the same about riverflow, since the contribution from the mountainous areas to their total water budget is very important.

We have now calculated other skill scores for both experiments, as suggested by the reviewer. In the FD simulation, the lack of surface runoff is compensated by the fact that infiltration is readily incorporated into the rivers. Because precipitation amounts are biased low, winter peaks may look better in this FD simulation and some skill scores are better than in the WT simulation, but this does not mean that the result is physically correct.



Station - Basin	Basin Catchment Area (km²)	E WT	r WT	r_{mm} WT	E FD	r FD	r_{mm} FD
Foz de Mouro - MIÑO	15.407	-0.13	0.89	0.98	0.55	0.93	0.95
Puentepino - DUERO	63.160	-0.52	0.73	0.96	0.18	0.72	0.69
Almourol - TAJO	67.482	0.28	0.91	0.93	0.80	0.91	0.89
Pulo do Lobo - GUADIANA	61.885	0.07	0.65	0.71	0.21	0.54	0.66
Cantillana - GUADALQUIVIR	44.871	0.44	0.76	0.66	0.15	0.56	0.67
Tortosa - EBRO	84.230	0.36	0.74	0.93	0.55	0.82	0.87

For all the aforementioned reasons, we purposely wanted to limit our discussion about streamflow in the paper and just show the WT results. The only point that we wanted to make with the FD simulation is that in the Mediterranean climate of the Iberian Peninsula, summer stream flow is sustained by groundwater and, without it, in a simulation with a free drain approach, rivers dry out. We are confident that this result holds true, despite all the problems in the forcing and model parameterizations. We show the Ebro basin to illustrate this point because it is the one showing less streamflow total annual underestimation and annual cycle better matching observations in the control WT run, especially in winter. It so happens that it is also the largest basin the Peninsula, so the example is significant.

(j) Fig. 13: a full paragraph is devoted to analyzing the seasonal variations of the different variables (L21-31 p 13), but we cannot see them. Please add the mean seasonal cycle next to the 10-yr time series to support this discussion. It would also help to magnify the scale of SM differences. The caption says the precipitation anomalies are calculated over the entire basins, while the other anomalies are calculated in the fraction with shallow WT (ca 1/3): why not calculate them over the same domain, to avoid any doubts. Finally, the text says the WTD of Ebro and Segura recover after the pluri-annual central drought, but it is not discernible in the panels.

Authors: We chose to plot only shallow wtd regions within the basins to highlight the effects of the interaction with the water on soil moisture and ET; however, seasonal precipitation is computed over the whole basin because lateral groundwater flow and river infiltration redistribute infiltration horizontally, making precipitation over all cells in the basin potentially relevant for the results over shallow water table cells. The recovery over the last 3 years is, we believe, clear in most all basins that suffered the central drought; however, the reviewer is right in that in the Ebro and Segura basins only a change in tendency from deepening to stabilizing or slightly rising is discernible. We have clarified this in the revised version.

2. Methods:

The LEAFHYDRO model has already been published, but a paper needs to be self-consistent, and more info is needed on the parts that are relevant to the conclusions.

The recharge calculation, in particular, is far from being clear, at least to me, although I have looked for more information in Miguez-Macho et al. 2007, Part 2. This should be clarified in the article, and the following questions might help the authors:

(a) The calculation is different depending if the WTD is larger or not than the soil depth, but I couldn't understand scenario b with larger WTD. In this case, how are the water content of points B and C estimated? It's written the one of point C "is determined by mass balance from the fluxes above and below" (L5-6 p 5) but these fluxes also need to be estimated, and there seem to be too many unknowns: please clarify the system, including flux equations, boundary conditions, or any assumption regarding water content profiles, etc.

(b) In both cases, the water content of the unsaturated zone and WTD must be coupled, so what is the effective sequence of calculations over time? I struggle with "R is the amount of water from or to the unsaturated portion of layer 1 necessary to cause the rise or fall of the water table from its former position", knowing that WTD is updated based on equation 1 which depends on R.

Authors: [(a) and (b)] Yes, we agree that, since we initially tried to avoid a methodology section too long and filled with equations already published in Miguez-Macho et al (2007), the methodology section is not as explanatory as it should. The reviewer is right to point out that some clarifications are needed. We have changed Section 2.1 and we believe that the issues raised by this and other reviewers about the model formulation and steps have been addressed in the revised manuscript.

(c) Since R is calculated differently if the WTD is larger or smaller than 4m, can we see a discontinuity of net recharge values at 4m (plotting R as a function of WTD)?

Authors: Possibly, but the model formulation is designed precisely to avoid any discontinuity in water table depth or recharge. When the water table goes below 4m, calculations are identical to when it was in the layer above, and only as it goes below 4.5m they start to differ, but they do it very gradually. No discontinuity is observed in water table depth as it goes deeper (or shallower) than 4 or 4.5 m, which is a good indication that there isn't one in recharge either.

(d) This flux R is defined as the result of downward gravitational flux and capillary flux, which can be either up or downward. The resulting flux is called recharge in the results, but "flux through the water table in section 2.1 (L22 p 14): I invite the authors to harmonize throughout the ms, and use recharge, but as mentioned in my comment 1d, this "net" recharge, which can be positive or negative, should positive when down, to match the meaning of GW recharge.

Authors: We have followed the reviewer's suggestion and called the flux "net recharge" throughout the text, presenting it initially in Section 2.1 as "*The water flux through the water table or net recharge R*". We would prefer though to keep the signs as they are, positive upwards and negative downwards, as these are the signs in the model calculations too, where upward fluxes like ET are positive and downward fluxes like infiltration are negative.

(e) As an interested reader, I would also appreciate some explanations regarding the links between R and evapotranspiration, which must be tightly coupled as well: how is transpiration described? How is rooting depth described? What is the vegetation description at the surface: PFTs, mosaic approach, constant or varying over time, which input datasets?

Authors: The model parameterizes the calculation of transpiration and evaporation from canopy interception using PFTs and the vegetation data described in Section 2.2. We have added a paragraph at the end of Section 2.1 pointing out this: "*When there is vegetation on the surface, the water and heat exchanges between vegetation and the surrounding canopy air parameterization is based on Avissar et al. (1985). This methodology uses PFTs (Plant Functional Types) constant through the simulation period, assigning a type to each cell that will determine parameters like the root depth, the minimal stomatal conductance (that will be increased by atmospheric factors) and the LAI (Leaf Area Index), that will affect the calculation of canopy resistance, transpiration and evaporation from the canopy surface. The transpiration is taken from the moistest level in the root zone.*"

The persistence induced by the GW component must somehow be related to its long residence time (as written p12, L27):

(f) Is there a way to quantify it, at least at first order? How does persistence link with the transmissivity of the GW system (it would be useful to give information on it, how is Ks estimated, based on soil texture? which effective thickness?) and the GW-river flux (Qr), for which some quantitative parameter values would also be useful.

Authors: As in the response to (a) and (b), after this and other reviewer's comments, more information has been added in Section 2.1 about the transmissivity and Qr flux and how they are calculated. We believe this has made the paper more consistent.

River flow scheme:

(g) It is said that river width is taken form HydroSHEDS, but this variable does not belong to the standard dataset (https://hydrosheds.org/pages/availability). Please be more specific.

Authors: A complete description of how the river parameters have been calculated (including the new Fig. 2) has been added to Section 2.2 in the revised document.

The simulations are forced by an atmospheric reanalysis, ERA-Interim, without any bias correction except for precipitation:

(h) The reported horizontal resolution is about 0.7° x 1°, but the authors should check L30-31 p5, since I don't see why the resolution would be fixed in latitude and varying in longitude, it's usually the opposite which is done if seeking for constant grid-cell areas, but on the other hand, a factor of two over IB seem excessive.

Authors: Thanks for pointed this out. The resolution of the driving ERA-Interim data is now reported in Section 2.3, from Berrisford et al. (2011), as: "*ERA-Interim is presented in a reduced Gaussian grid with approximately uniform 79 km spacing for surface grid cells*". And the actual LEAFHYDRO model resolution, to which driving data are interpolated, is reported in Section 2.5 as: "*The simulation domain is a Lambert-Conformal grid centered in the Iberian Peninsula with a spatial resolution of 2.5 km*."

(i) Precipitation is bias-corrected and downscaled to the 0.2° resolution. At 40°N (inside IB), the area of a 0.2°x0.2° grid-cell is a bit less than 20^2 km², thus includes 64 LEAFHYDRO grid-cells (2.5^2 km², cf. resolution introduced L6 p7, when presenting the simulations). This resolution mismatch should be discussed, as it can have an impact on validation performances.

Authors: Yes, of course. In fact, as mentioned earlier, we believe that this is the main reason for the underestimation of winter streamflow in our simulations. We discuss it in Section 3.2: "*There is a clear underestimation of the winter river flow by the model. Two factors contribute to this bias. First, a lack of precipitation in the forcing data, since the IB02 analysis dataset original resolution (0.2º) is coarser than our model simulations and the station density (7 km in Spain and 11.7 km in Portugal) is not sufficient to capture precipitation peaks due to orographic enhancement over the mountains, which is very pronounced in the northern cordilleras.*"

(j) Better meteorological forcing data sets probably exist in Spain, as the SAFRAN dataset of Quintana-Segui et al. 2017, containing all the variables required to force a LSM at the 5km resolution and 1-hourly time step, for 1979-2014. Else, WFDEI (Weedon et al., 2014) is a ready-to-use forcing data set, with bias-correction and downscaling to the 0.5° resolution, based of ERA-Interim. The submitted paper should include a justification for choosing ERA- Interim compared to other products, especially given that Gonzalo Miguez-Macho, co-author of the submitted paper, is also co-author of Quintana-Segui et al. 2017.

Authors: Yes, we are aware of such datasets. The decision of using ERA-Interim an IB02 was adopted at the time of conceptualization and set up for this study, when the other (newer) datasets were not available. Both mentioned datasets, however, and also the newly developed MSWEP dataset (Beck et al., 2017), have been more recently used with LEAFHYDRO simulations in a study focused on droughts: *The Utility of Land-Surface Model Simulations to Provide Drought Information in a Water Management Context Using Global and Local Forcing Datasets* (Quintana-Segui et al., 2019)

(k) I couldn't find the time step of LEAFHYDRO, and it is required for a modelling paper. If the model time step is shorter than the one of the forcing dataset, the downscaling should be mentioned.

Authors: The time resolution for resolving heat and water fluxes in the soil and at the land surface was 60 s. The time step for groundwater-streams exchange, groundwater mass balance and water table adjustment in the WT run is 900 s. We have included this information in Section 2.5.

The meteorological driving data are linearly temporally interpolated to the model time steps.

Initial WTD: section 2.4 is not crystal clear for me, and some rewriting is advisable. In particular, the order of what is done is hard to follow, and the reasons to do what is done are not justified:

(l) There seems to be three successive initial WTD estimates at three different resolutions (1°; 9 arc-sec; the 2.5-km resolution of the simulations) but I don't understand at all what relates to the last two resolutions in the explanations of L12-16 p6. Can you please clarify?

(m) Why using recharge from a model without GW (Mosaic LSM) at 1°? Why not relying instead on the FD version of LEAFHYDRO model? At L10 p 6, is Qsr surface runoff?

(n) If topography is very important for the WTD patterns (L12 p 6), why using a higher resolution for the initial WTD and not for the transient simulation? Is it a problem of a computing power?

(o) The differences between the initial WTD (EWTD from Fig2) with the mean WTD over the 10 years (Fig 7b) should be discussed.

Authors: Yes, we agree that Section 2.4, in the original version, would gain with some clarifications and we have rewritten it. Hopefully the reviewer and the readers will find it now clearer.

In response to particular comments:

(l) the 1 degree resolution corresponds only to the initial recharge dataset from the Mosaic LSM that is used to feed the 2D groundwater model (Fan et al., 2007). This 2D steady-state model runs at 9 arc-sec and produces initial conditions for wtd at this resolution, resolving hillslope gradients.

(m) We needed an initial guess for climatological recharge to feed the 2D groundwater model. We had tried other datasets and results using Mosaic recharge, despite being very coarse, gave the best skill scores in validation with point observations. Running LEAFHYDRO with FD would mean an extra step that we deemed unnecessary.

Yes, Qsr is surface runoff.

(n) Of course the 2.5km resolution for the LEAFHYDRO simulations is a compromise needed for lack of computational resources. This is explained in Section 2.5 (now renamed "Simulations set-up")

(o) The differences come mostly from the colorscale and resolution difference in the plots.

The way to obtain the power spectra of Fig. 14 is not at all explained but a few words wouldn't hurt.

(p) Shouldn't the compared curves have the same integral if they are calculated from time series of the same length?

Authors: We used the intrinsic function "spectrum" from the MathWorks software, which computes the power spectrum of a given time series, and it is simply based on performing the Fourier transform. We have added a comment about this in the manuscript.

3. Quantification of results

(a) The difference maps are interesting since they reveal clear sensitivity patterns related to WTD. Yet, an important part of the results is about water budgets, and means of the differences over IB would be interesting. This can be achieved either on the maps, or in a summary Table.

Authors: Yes, we agree. This was the reason to add the colour bars below each plot in figures 9 and 10 (now 10 and 11), representing the mean anomaly value for the peninsula or the zoomed area.

(b) An important question is about the significance of the reported changes in front of variability (seasonal and inter-annual), which can be assessed using inference tests. With simulations of only 10 years, non-parametric tests are probably advisable, and another solution would be to extend the simulation period, with additional advantages for persistence and long-term memory analysis.

Authors: Unfortunately, the simulation period could not be extended due to computational limitations.

(c) The validation of the models should involve more quantitative criteria. In particular, Fig 5 shows that WT strongly underestimates observed river flow (written p9 L7). Since ET is higher in WT than FD, one would expect that the river flow bias is smaller with FD (less ET with the same precip means more runoff and river flow): is it what is found? By how much? It doesn't seem true for the Ebro based on Fig. 15, which is weird.

Authors: The presence of the groundwater reservoir in the WT simulation buffers out variations in climate. Even with the same ET in both WT and FD run, in dry periods there can be more baseflow input in the WT simulation, coming from groundwater. The opposite can also be true. In a wet year, there can be less baseflow in the WT run if the groundwater reservoir levels are low from a previous drought. The mean flow for a given period should be about the same if there is no trend in groundwater levels. But this is not guaranteed either, because there can be some extra store or depletion of water in the layer between the water table and the bottom of the soil column at 4m, which is not existent in the FD run.

In Fig. 15, there is a declining trend in the water table, albeit small. In shallow water table areas, the lowering water table might be partially sustaining ET; however, where the water table is deeper, the lowering groundwater store is sustaining streamflow. This trend explains why there is more water in the annual mean total streamflow in the Ebro in the WT run, and is common to the other Mediterranean basins, more affected by the drought. We will now discuss this issue, related to the relatively short period of simulation, in the revised manuscript. The point that we wanted to make with the figure is still true, though, as it is apparent from the comparison with FD run that groundwater sustains streamflow not only through summers, but also longer dry periods.

(d) Eventually, what is the best simulation if we try to combine several performance criteria (correlation and bias, and also RMSE and Nash efficiency, or KGE which directly combines these scores, cf. Gupta et al., 2009)?

Authors: In terms of simulating river flow, we obtain better metrics (Nash-Sutcliffe efficiency) with FD, but in terms of simulating surface flow exchanges, we have shown how a more realistic soil moisture in the presence of the groundwater influence will result in different surface-atmosphere coupling effects, which is ultimately the issue we are focusing on. As mentioned earlier, streamflow results are more complex to analyze, and a better score with bad forcing does not mean that the simulation is more physically realistic.

(e) P8 L27-28 claims that "the model's performance is reasonably good at shallow water table depth points, but significantly worse where the water table is deeper": I don't think it is supported by any figure or result.

Authors: With this statement we refer to the improvement in the wtd validation reported when we consider only shallow water table points as compared with all points, deep and shallow are considered. We have rewritten the paragraph where we provide this wtd validation results and the point should be clearer in the revised manuscript.

(f) P10 L7-8: can you prove/justify/quantify how "small" is the long-term upward flux in flat areas?

Authors: The flat areas we refer to present values between 0 and 150 mm/yr, or between 0 and 0.5 mm/day in the case of the seasonal plots, in both cases, closer to 0, than to the upper value of the range. Our point was to separate them from the river valley areas we mention in the following sentences, where faster lateral drainage due to the steepness of the terrain result in much higher upward flux values.

(g) P12, L3: "precisely where the correlation between soil moisture and precipitation are reduced": this is not obvious from Fig. 9, and additional diagnostics would be interesting to prove this conclusion.

Authors: This sentence refers to the "missing plot" of differences between right and center maps in the figure that the reviewer mentioned in the concern (1g). We think that once the error in the caption has been corrected the intended exercise of focusing on differences between both maps is easier for the reader.

4. Structure and writing

(a) In absence of land-atmosphere coupling, the title is not well supported for the "land-atmosphere interactions", and should be modified.

Authors: We did debate about this wording during the writing process. We have now changed the word "interactions" for "fluxes" in the title in the revised manuscript.

(b) The introduction is long and messy, and would benefit from serious reshaping. The discussion on the need for realistic water table simulations (L34 p2 to L5 p3) is not well articulated with the rest, and is actually contestable. Besides, it raises questions since the WTD and river flow simulated by LEAFHYDRO (section 3.1) are not particularly realistic, although not very bad either. The paragraph at L13-20 p3 is very general and seems odd when the introduction starts to present the specificities of the presented work (starting at "Our work, p3, L5). The last part of the introduction (p2 L21 to P4 L8) reviews Spanish hydrology, and finishes on irrigation. Eventually, the specific research questions of the paper are not clearly stated by the end of the introduction.

Authors: We have reshaped the introduction as we agree with this and other reviewers in that the paper would benefit from it. Now the structure is clearer and simpler. It still starts from general statements on groundwater interactions, soil moisture memory and observational evidences of groundwater-soil coupling. Then we review other modelling efforts. Then we introduce particularities about the Iberian Peninsula and literature on it. Finally, we introduce the research questions (that we did introduce in the first paragraph in the original submission) and the particularity of LEAFHYDRO calculating lateral drainage that makes it a candidate to tackle challenges presented earlier.

(c) The paper frequently refers to a "bimodal" memory of soil moisture induced by GW persistence, but this term "bimodal" is not very clear: why isn't it just normal memory? I urge the authors to define what they really mean.

Authors: The author is right in that the term memory should suffice, but we introduced the term "bimodal" to insist on the capability of the fluxes to go two-ways and the soil moisture to not only remember dry conditions but also wet conditions providing water to the system during dry years following wet ones.

(d) Consider gathering the validation of river flow and sensitivity of river flow to WT vs FD.

Authors: Responded above.

(e) Consider presenting Fig. 10 before Fig. 9, which makes a nice introduction to Fig. 10, and justifies why time correlation is analyzed on time series of annual means, while many papers in the literature consider time lags of months. The paper may insist on memory at pluri- annual timescale, which is quite novel in the literature surface-GW interactions.

Authors: Yes, this is a good point about changing the order. We originally considered that we should send the message of the water table affecting the annual correlations and then presenting the annual maps in Figs. 10 and 11 (now 11 and 12) for the reader to better appreciate these effects. Of course we could change them if the reviewer insists. Thanks for the tip, we have included "at pluri-annual timescale" in the title of Section 4.2.

(f) The conclusion is mostly a summary of what was just presented in sections 3 and 4. The summary part should be strongly shortened, to better highlight the main findings instead of again comparing % changes. Another advantage would be to leave space for a real discussion of the results, which is cruelly lacking.

(g) In particular, the results and the conclusion they support are likely dependent on the model, its assumptions, and the forcing datasets (meteorology, soils, vegetation). This must be said and leads to compare the conclusions of the paper to the literature.

(h) For instance, the underestimation of riverflow (Figs 5 and 15) means that ET is too strong in the model(s) or precipitation too weak: can't it create a bias in the sensitivity of ET to WTD? This should be discussed, in relationship with the quality of meteorological and vegetation forcing datasets, or the fact that irrigation is not taken into account (cf. p9 L31-32).

(i) The perspectives could also be developed… Are "coupled land hydrology-climate models" (p16, L29) the only to move forward?

Authors: We have divided Section 5 into "Discussion", where we have discussed the results maintaining our structure of groundwater influences on three parts of the land surface hydrology system and have added comparisons with external work cited in the introduction, and a shorter "Summary and conclusions" section at the end. Please see the revised version of the manuscript.

The attribution of the improvements to our WT run, and therefore suggesting that the ET enhancement is right during the dry season is based mostly in our wtd validation. Therefore a validation of ET fluxes with suitable data is, of course, another perspective for future work. We just were not able to do it for this paper for lack of data and did not think it was necessary to mention in the text.

We believe, as has been pointed out in the text, that the driving precipitation is biased low.

AUTHOR'S RESPONSE TO RC3:

Manuscript hess-2018-626 by Martinez-de la Torre & Miguez-Macho: "**Groundwater influence on soil moisture memory and land–atmosphere interactions in the Iberian Peninsula**"

This paper discusses the role the water table plays in the terrestrial water cycle through the provision of vertical fluxes it provides for crops to evapo-transpire. The authors apply a Land Surface Model LEAFHYDRO that also simulates the dynamics of water table. They present results that show the difference between the simulated soil moisture values with and without the inclusion of the water table. I think this paper addresses relevant scientific questions within the scope of HESS, it represents interesting tools and ideas; however, the presented methodology and data fall short from supporting the reached conclusions.

It is clear that significant work has been undertaken to produce the results; however, I think because the authors are dealing with many processes including land surface, unsaturated zone, and saturated processes, the paper as it stands lacks a lot of information that are necessary to convince the reader with the applied methodology and possibly the repeatability of the experiment. In addition, there are concerns related to the structure of the paper where introduction, results, and discussions are all mixed together.

Authors: Thanks for the reviewer's complete assessment. We understand the issues pointed out by the reviewer and have introduced substantial editions and changes to the manuscript to address them. We discuss such changes in response to the reviewer's specific comments below.

My points below make these comments clear:

At the beginning of the introduction, the authors state that "groundwater exchanges with the land surface occur via vertical fluxes through the water table surface, and horizontal water redistribution via gravity driven lateral flow". The authors must be specific regarding the type of the lateral flows. Are these flows in the saturated zones only? Are they in the main aquifers or perched aquifers? Or do they also include what is called through flows, i.e. lateral movement of infiltrated due to the existence of low permeability materials above the water table?

Authors: In the introduction and the rest of the paper, we mean lateral flow *within the saturated zone,* as explained in the methodology section. We have added this to the text pointed out by the reviewer. The model does not represent lateral transport in the unsaturated zone.

The scale the authors are dealing with is a national scale. It is expected that many types of hydro-geological conditions will be met at this scale. It is not expected that they will deal with all possible hydro-geological settings, however, the paper must clearly state the selected hydro-geological condition the model is applied to. A diagram showing a conceptual model of this hydrogeological setting is needed. All the results to be presented and discussed has to be put always within the context of this conceptual model.

Authors: Yes, agreed, thank you. The original submission did not go into enough detail about the methodologies of the model. After this and the rest of reviewer´s comments, we have edited substantially the methodology section 2.1, adding information about how the model represents the hydro-geological conditions using the conductivity parameters. Please see the revised manuscript.

The introduction must be more focused. The paper states the aim of the paper in the first paragraph of the paper. The introduction then tries to explain the reasons for undertaking the work afterwards. I think the argument should be built the other way round. In addition the introduction includes description of the methodology applied (Page 3 Lines 5 to 12) and site description (paragraph starting from Line 20 on Page 3). I have difficulties with some of the definitions and terminology used. For example, on Line 34 Page 3, the authors write "reflecting the importance of groundwater memory". Why do they need to call it memory? It is the groundwater storage that reduces the impact of extreme weather events. The use of positive and negative recharge is also confusing (although clearly defined) and not intuitive.

Authors: We fully agree and have edited the introduction section, stating the research questions and the particularities of our approach (Page 3 L5-12 of the original submission) at the end. The discussion about the Iberian Peninsula and its hydrological characteristics has been slightly modified, but we still think it should be part of the Introduction as it focuses the reader on the problems that the paper has to deal with.

Yes, the reviewer is right, we have rephrased "reflecting the importance of groundwater memory", it now reads "reflecting the importance of groundwater influence on surface hydrology".

About the use of positive and negative recharge, we acknowledge that the groundwater recharge is often referred to as the positive flux into the groundwater reservoir. In this work, we have followed the model signs for fluxes, as in upward is positive (like evapotranspiration from the surface) and downward is negative (like the water flux through the soil layers and then into the groundwater). We have changed the name of the flux to “net recharge” in the revised manuscript in order to clarify this point at different instances. This is now clarified the first time the net recharged is referred to in the manuscript in Section 2.1: “*The water flux through the water table or net recharge R is the sum of gravitational downward groundwater recharge and capillary flux, and depending on soil wetness and atmospheric demand, it can be downwards, causing the water table to rise, or upwards, causing the water table to deepen*”

Section 2 must be split into two sections one describing the study area including the information that are presented in the “Introduction”, in addition to the conceptual model. The other section must be dedicated to the Methodology, which must include a lot more information than what is already presented. For example:
Equation 1 shows the temporal variations of groundwater storage as a response to recharge. What about the soil moisture temporal variations?

Authors: Information has been added in Section 2.1 about the flux calculations within the unsaturated zone, following the Richards’ equation.

How does the model calculate evapotranspiration? Does it calculate runoff? Does it account for overland routing? Is overland water added to the groundwater flows emerging in the rivers to calculate total flows at the gauging station?

Authors: Information has been added at the end of Section 2.1 about the ET methodology.

Details on the river routing scheme and a sketch on the river parameters calculation have been added in Section 2.2.

The model does not calculate overland routing, but it does calculates surface runoff as infiltration excess, which is added to groundwater baseflow in the cell to calculate streamflow. Further details are part of the original model LEAF, described in the reference given as Walko et al., 2000.

How is the capillary flux calculated? Is it dependent on the position of the water table? (It is clear it is but at least it must be described in the methodology)

Authors: Details on this have been added to Section 2.1.

How capillary forces are presented in the model? When a water table exists, the water is available to evapo-transpire wherever the water table depth is?

Authors: Yes, regardless of the water table position, the vegetation has access to the soil water within the root zone depth. Of course if the water table is there, this means higher water availability for the plants.

It is not clear how the high resolution steady state simulation results are used in the low resolution time variant results (This is explained later, but what is mentioned in Section 2 is not enough to clarify this approach.

Authors: Yes, agreed. We have realized that Section 2.4 was not completely clear in the original submission. In the revised manuscript we have rewritten Section 2.4 to make it more explanatory.

It is stated that the shallow water table slows down drainage. If the soil is not fully saturated and the water does not pond on the surface, how the shallow water slows down drainage?

Authors: If soil moisture increases with depth when approaching the water table, as it is usually the case, capillary fluxes are upward. The always downward gravitational flux may dominate the net flux, but the latter is certainly smaller than when there is no groundwater. In the FD run, the net flux at the bottom of the soil columns is just the gravitational flux, with no upward capillary flux to counteract it, at least partially, thus drainage is faster. Furthermore, when the water table is within the resolved layers, drainage at 4m is zero, and if the water table reaches the surface, infiltration ceases altogether. In the FD run, drainage at 4m is always occurring when the bottom layer is above field capacity.

It must be explained here that rivers could be influent and effluent

Authors: It was very briefly explained in the original submission, refering to "gaining" and "losing" streams. After the reviewer suggestion, we have added the following information in Section 2.1:

"*This flux can occur as groundwater discharge (subsurface runoff) into gaining streams when the water table is above the river, sustaining stream baseflow, or as river infiltration into the groundwater reservoir in losing streams when the water table is below river bed. For gaining streams, LEAFHYDRO approach combines the physically based parameters of Darcy's law into a parameter called river conductance, commonly used in groundwater modeling literature, like the MODFLOW model (Harbaugh et al., 2000). Even though the river conductance is physically based and observable, detailed data on river geometry and bed sediments are lacking for the region studied, hence it needs to be parametrized. Such parametrization consists in a representation of the river conductance that includes two contributions; an equilibrium part, and a dynamic part that depends on the water table deviation from equilibrium at the time. Further details on this dynamic river conductance parametrization and discussion on its choice are found in Miguez-Macho et al. (2007). For losing streams, the distance of flow or river bed thickness in Eq. 10 is the same as the water table minus riverbed elevation difference (third parenthesis in Eq. 10, only with negative sign provided that wth < z_{r}), and hence these factors cancel out one another, leaving the flux calculation to be given by*

(new Eq. 11).

Therefore, the losing stream flux Q_{r} in the model is not dependant on the water table position, once the latter is below riverbed, but on the groundwater-rivers hydraulic connection."

Are the groundwater flows also driven using Darcy's law or is it based on hydraulic gradient only? What is the calibration procedure used to find the spatially distributed hydraulic conduct values?

Authors: Further explained in the revised version of the manuscript (Section 2.1)

Section 2.2 provides information about the source of data but no information about the data are provided. For example information about the spatial distribution of landuse is important to understand the amount of water extracted by evapo-transpiration from the soil store. Nothing is mentioned about the hydrogeological data used in the model such as the values of the hydraulic conductivity and storage coefficient of the aquifer, river bed conductance values, etc.

Authors: Thanks. We believe that with the inclusion of Equations 1 and 2 and the last paragraph about ET and PFTs in Section 2.1 , the model approach is clearer now. We have edited also the first paragraph in Section 2.2 as follows:

"*The 11 soil textural classes used in LEAFHYDRO, necessary to derive soil parameters in Eq. 2 controlling the vertical water fluxes, are defined by the United States Department of Agriculture (USDA) from fractions of silt, clay and sand. The data for top (0-0.30 m depth) and bottom (0.30-4 m depth) soil layers comes originally from the Food and Agricultural Organization of the United Nations (FAO) world database (http://fao.org/soils-portal/soil-survey). Other processes in the model, such as evapotranspiration, need parameters dependent on the vegetation type (PFTs) at the land surface. For vegetation type we usethe COordination of INformation on the Environment (CORINE) Land Cover Project database (EEA, 1994)*"

Details about lateral groundwater flow calculations and aquifer properties are also included as follows:

“Lateral groundwater flow Q_n *is determined by the slope of the water table surface, applying Darcy‘s law the water flux from the* n^{th} *neighbour into a model cell is given by*

$Q_n = cT(wtd_n - wtd)/l$

where c (m) is the flow cross-section connecting the cells, T ($m^2\ s^{-1}$) *is the flow transmissivity between the cells, wtd and 30* wtd_n *(m) are the water table depths for the centre cell and the* n^{th} *neighbour cell, respectively, and l (m) is the distance between cells. T is calculated as an integration of the lateral hydraulic conductivity at saturation, for which the model uses observedvalues of the anisotropy ratio relating vertical and lateral conductivities (Fan et al., 2007), and assumes exponential decay of the vertical hydraulic conductivity at saturation* KV_f *with depth, as*

$KV_f = K_0 exp(-z'/f)$

where K_0 *(m* s^{-1}*) is the known value at 1.5 m deep,* z' *(m) is the depth below 1.5 m and f (m) is the e-folding depth, 5 calculated as a function of terrain slope β as* $f = 75/(1 + 150\beta)$*, where f is limited to 4 m when* $\beta \geq 0.118$*. “*

In Section 2.4, can you state please which groundwater model is used with the Mosaic LSM recharge model to calculate the initial EWTD? On Lines 10 to 18 (Page 6) it is unclear which model has the high resolution and which one has the low resolution. A diagram that shows the steps followed in methodology will be helpful. Text from Line 18 onward in this section are results. Why are they included in this section?

Authors: Section 2.4 has been edited as pointed out before. Please see the revised manuscript. Even though we agree that our EWTD is a result, we decided to include it at this point in the methodology section, since it is used as an initial condition for the main experiment.

In Section 3 the authors dip into discussing the validation of a model while no infor- mation about the hydraulic parameters used in the model are provided. These include parameters controlling overland, subsurface, and unsaturated flows as well as soil and landuse data. They claim that the temporal variabilities are reproduced. However, with the lack of the parameter values and the definition of the context (assumptions and conceptual model) within which the model is built, this conclusion is easily challenged.

Authors: Thanks. We again refer to the revised and more detailed new Section 2 that now includes discussions about all the required parameters in calculations.

In Section 4.1 (Lines 25 to 30 on Page 9), the authors define positive and negative recharge in an unintuitive way since in groundwater, recharge is referred to as inflow to the groundwater reservoir and the opposite is a discharge from the water store and that could be in any direction (like the upward capillary fluxes). The sentences on Lines 10 to 14 on Page 10 are not very well formulated and together with the comment above, it is difficult to understand the point the authors are trying to make. On Line 15, the argument “this cycle is more pronounced the shallower the water table” is not very strong since Figures 6c to f all show seasonal variations across the whole peninsula.

Authors: Yes, we have responded to this concern about the signs of the recharge flux above. The point we try to make in the referred lines is to differentiate between large areas of low positive flux and river valleys with high positive flux. We have slightly edited the sentences and we believe the point is clearer now:

"*However, in river valleys where steep slopes in the water table head drive strong local lateral groundwater flow convergence, groundwater-fed ET can exceed precipitation by large amounts, resulting in higher values for the positive recharge. This is apparent n Fig. 7a along the main river valleys crisscrossing the dry Mediterranean areas of the Iberian Peninsula.*"

We agree with the reviewer in that the point we made in Page 6 line 15 (original submission) is not sufficiently supported by the figure. We have deleted the sentence. The point about seasonality and the influence from shallow water tables is made in the following sentences. Thanks

In Section 4.3: can you please state how annual anomalies are calculated? Is it a difference from a long term average value or the difference from an average calculated on the day the anomaly is determined?

Authors: Anomalies are differences between the given year values and annual means in the simulations. It has been clarified in the revised manuscript.

Line 28 Page 11: are anomalies in precipitation and anomalies in soil moisture corre- lated or are the anomalies in soil moisture correlated with precipitation. Please clarify

Authors: The correlations are calculated between anomalies. In this case, anomalies in precipitation and anomalies in soil moisture. It has been clarified in the revised manuscript.

Section 4.4 Line 21: “water table depth (red lines)” are observed or simulated? If simulated is it from the model with water table or with free drainage?

Authors: It is the water table depth simulated in the WT run. The FD run does not simulate any water table. It has been clarified in the revised manuscript.

Figure 9: Please correct the caption for the left figure which should be related to the free drainage (FD)

Authors: Corrected. Thanks for spotting this.

In Figure 11, I expect the soil moisture anomalies calculated from the simulation with a water table to be lower in absolute value than those calculated from the simulation with free drainage. This appears to hold true for all hydrological years except Years 8 and 9 (Compare row 3 to row 2). Why?

Authors: The soil moisture anomalies when the water table is considered do not necessarily have to be smaller than in the FD simulation. In areas where the water table is shallow, while this is the case, it is true that variations are buffered. However, if a shallow water table deepens as a result of a prolonged drought, so that the connection with the top soil is lost, soil moisture anomalies are going to be larger than in a FD simulation. Soil moisture values in both runs would be similar, but the anomaly is going be larger in the WT run where the soil is typically wetter due to the presence of a shallow water table. This is what happens in years 8 and 9, after the drought. In the FD run, soil moisture anomalies rapidly follow those in climate. In the WT run, however, the water table has not fully recovered, and soils are still much more anomalously dry.

Finally, I think the paper has to include a Discussion section where the analysis of the results has to be aligned with the assumptions listed in the conceptual model together with the hydraulic characteristics of the studied domain and the landuse controlling the amount of evapotranspiration from the soil zone. While the amount of work that has been taken and presented must be recognised and appreciated, I think the addition of a discussion section and rewriting the conclusion section to address the main findings concisely will greatly improve the presentation of this work.

Authors: Yes, agreed. We have re-structured the paper, including a Discussion section after the results and a shorter conclusion section at the end. Please check the revised manuscript.

Groundwater influence on soil moisture memory and land-atmosphere ~~interactions~~ fluxes in the Iberian Peninsula

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Abstract. Groundwater plays an important role in the terrestrial water cycle, interacting with the land surface via vertical fluxes through the water table and distributing water resources spatially via gravity-driven lateral transport. It is therefore essential to have a correct representation of groundwater processes in land surface models, as land-atmosphere coupling is a key factor in climate research. Here we use the Land Surface and Groundwater Model LEAFHYDRO to study the groundwater influence on soil moisture distribution and memory, and evapotranspiration (ET) fluxes in the Iberian Peninsula over a 10-year period. We validate our results with time series of observed water table depth from 623 stations covering different regions of the Iberian Peninsula, showing that the model produces a realistic water table, shallower in valleys and deeper under hilltops. We find patterns of shallow water table and strong groundwater-land surface coupling over extended interior semi-arid regions and river valleys. We show a strong seasonal and interannual persistence of the water table, which induces bimodal memory in the soil moisture fields; soil moisture "remembers" past wet conditions, buffering drought effects, and also past dry conditions, causing a delay in drought recovery. The effects on land-atmosphere fluxes are found to be significant, on average over the region, ET is 17.4 % higher when compared with a baseline simulation with LEAFHYDRO's groundwater scheme deactivated. The maximum ET increase occurs in summer (34.9 %; 0.54 mm day^{-1}). The ET enhancement is larger over the drier southern basins, where ET is water limited (e.g., the Guadalquivir basin and the Mediterranean Segura basin), than in the northern Miño/Minho basin, where ET is more energy limited than water limited. In terms of river flow, we show how dry season baseflow is sustained by groundwater originating from accumulated recharge during the wet season, improving significantly on a free-drain approach, where baseflow comes from water draining through the top soil, resulting in rivers drying out in summer. Convective precipitation enhancement through local moisture recycling over the semiarid interior regions and summer cooling are potential implications of these groundwater effects on climate over the Iberian Peninsula. Fully coupled land surface and climate model simulations are needed to elucidate this question.

1 Introduction

Groundwater dynamics and its interactions with the land-atmosphere system play ~~an~~ a key role in the terrestrial water cycle. Groundwater exchanges with the land surface occur via vertical fluxes through the water table surface, and horizontal water redistribution, via gravity-driven lateral transport within the saturated zone. A shallow water table slows down drainage and affects soil moisture and evapotranspiration (ET), particularly in water limited environments. The Iberian Peninsula, with a typical Mediterranean climate of dry growing season, is one such region where ET is largely constrained by water availability. ~~In this paper, we investigate the role of groundwater in the hydrology of the Iberian Peninsula, focusing first, on its impact on soil moisture spatial variability, dynamics and long-term memory, second, on its effects on land-atmosphere ET fluxes, and third, on its direct impact on river flow.~~

Soil moisture memory refers to the persistence of wet or dry anomalies in the soil, after the atmospheric conditions that originated them have passed. In turn, if there is high land-atmosphere coupling, that is, if the conditions of the soil can have a significant impact on atmospheric dynamics, then soil moisture memory can influence weather conditions, with major implications for seasonal and long-term forecasting (e.g., **?**). The Mediterranean region, a transitional zone between year-long wet and dry climates, presents high soil moisture memory and high land-atmosphere coupling (**?**). This is mostly on account of the high seasonality of precipitation, with a pronounced dry and warm summer and a wetter and colder winter. ET is highly water limited and hence dependent on soil moisture availability and precipitation from previous seasons. At the subsurface, soil moisture is linked to the water table when the latter is relatively shallow, hence the weak time variability of groundwater (**?**) might enhance greatly this high soil moisture memory.

The water table depth is the main indicator of the intensity of groundwater-soil moisture coupling, and consequently of how much memory the long timescales of variation of groundwater can induce in soil moisture. The water table is linked to the unsaturated zone above by two-way fluxes: the downward gravitational flux and the capillary flux. The net flux is downward in the wet season and for some time afterwards, when groundwater continues to be recharged, but upward capillary fluxes can dominate in the dry season and, if the water table is sufficiently shallow, groundwater will reach the root zone to meet surface ET demands. There is observational evidence from field experiments showing that groundwater can be one of the main sources for ecosystem ET in water limited environments (e.g., **??**), and that the groundwater table depth determines strong sensitivities of local rooting depths (**?**). In the Iberian Peninsula in particular, **?** found that during the summer drought in a plot in southern Portugal, daily soil moisture fluctuations in the top-1 m related to transpiration could be attributed to groundwater via isotopic analysis. These authors estimated that up to 70 % of the evapotranspired water had its origin in groundwater over that area. Beyond experimental plots, observational evidence of the connection between groundwater and soil moisture over a larger area is reported by **?**, using remote sensing soil moisture products to predict groundwater heads in time and space over Germany, and reproducing groundwater head fluctuations reasonably well, particularly in shallow water table areas, where soil moisture dynamics are tightly connected to groundwater head positions.

Many modelling reports concerning soil moisture memory lack the interaction of the top-soil crust with the water table. However, groundwater dynamics are increasingly being taking into consideration in climate and ecosystem modelling studies. There are several studies that do explicitly include groundwater processes ~~(e.g. ????????)~~(e.g., **??????????**). In general they all conclude that the interaction with a shallow water table drastically changes soil moisture dynamics and affects ET fluxes in water limited conditions. Notwithstanding, most modelling schemes fail to produce a realistic water table spatial distribution, which compromises the generality of their results. One important reason why this happens is that most Land Surface Models (LSMs) treat the evolution of the water table as a process dominated by vertical fluxes, as they do with soil moisture, ignoring or misrepresenting the lateral gravitational groundwater flow, which is the main driver of the water table distribution across the landscape (**???**). The main modelling challenge thus remains to couple groundwater to soil moisture with a realistic water table; only then the importance of their mutual interaction for climate can be reliably assessed in the large scale. ~~Our work uses the LEAFHYDRO model, which includes water table dynamics considering explicitly lateral flow (**?????**). The model formulation and parametrization of groundwater relies on a high resolution steady state simulation of the equilibrium position of the water table. In the lower resolution, time-evolving run with the full model, the water table pattern stems from the high resolution simulation, where local drainage is better resolved, and is therefore realistic, reflecting topography with deeper water table under hilltops and shallower in valleys. Preceding our discussions on groundwater-soil moisture interactions over the Iberian Peninsula, in this study we validate the modelled water table with available time series of observations in Spain and Portugal.~~

Groundwater impacts directly surface water. **?** explicitly evaluated the influence of groundwater on the Amazon's surface water dynamics and showed that the water table buffers the impact of the seasonal drought on surface waters due to its longer timescale of evolution, and supports wetlands in lowlands and valley floors, where a persistently shallow water table is found because of lateral flow convergence or slow drainage associated with the flatness of the terrain and low elevation. **?** also pointed out the potential significance of the groundwater store as an uncertainty in simulating continental hydrological systems. **?** improved the spatio-temporal variability of streamflow and, particularly over France's main rivers, summer baseflow, when using a river routing model that included groundwater-river exchanges.

~~Here, we present a modelling study linking groundwater to soil moisture, land-atmosphere interactions and surface water at the regional scale in the Iberian Peninsula . This~~ The Iberian Peninsula is a region of high precipitation seasonality and land-atmosphere coupling (**?**), where the importance of an accurate representation of soil moisture is well known ~~(e.g. **??**)~~(e.g., **??**). **?** used in situ soil moisture measurements to validate a water balance model over a shallow water table region in the Duero/Douro basin during 2002, and found that their model underestimated soil moisture. We speculate that the role of groundwater in these kind of modelling studies should be taken into account and may change soil moisture behaviour in shallow water table regions. Groundwater memory of long past surface episodes has also been recorded in Doñana National Park, Spain, by **?**, finding higher observed wet phase duration correlations with the previous two years' rainfall than with the previous one year's rainfall. Moreover, over the upper Guadiana basin, **?** showed how during the hydrological years 2009-2010 and 2010-2011 with rainfall 50 % above climatology, the water table depth recovered 4 m and 8 m, respectively, and during the 2011-2012 hydrologically dry year, the water table still recovered 2.5 m up to spring level, in a way not observed since 1983 at the location (**?**). Additionally, the recovery of several ponds in La Mancha Húmeda (Biosphere Reserve in the upper Guadiana basin) during the dry year 2012 was reported in the Spanish press, reflecting the importance of groundwater ~~memory~~influence on surface hydrology. A modelling study (**?**) in the Sardon basin (a small shallow water table basin in the central Iberian Peninsula; ∼80 km^2) incorporated groundwater interactions with the soil and surface water, finding significant figures for groundwater recharge (16 % of precipitation), exfiltration (∼11 % of precipitation) and groundwater evapotranspiration (∼5 % of precipitation).

Understanding the relevant processes within the water cycle becomes of major importance for the integrated management of water resources provided the high irrigation withdrawal from wells or directly from surface waters in the Iberian Peninsula

~~(e.g. ???)~~(e.g., **???**). There has been a spectacular increase over the last decades in intensive groundwater use for irrigation in most arid and semi-arid regions of Spain, carried out mainly by individual farmers, often with little planning and control on the part of governmental water authorities (**?**).

In this paper, we present a modelling study linking groundwater to soil moisture, land-atmosphere interactions and surface water at the regional scale in the Iberian Peninsula. We investigate the role of groundwater in the hydrology of the region, focusing first, on its impact on soil moisture spatial variability, dynamics and long-term memory, second, on its effects on land-atmosphere ET fluxes, and third, on its direct impact on river flow.

Our work uses the LEAFHYDRO model, which includes water table dynamics considering explicitly lateral flow (**?????**). The model formulation and parametrization of groundwater relies on a high resolution steady state simulation of the equilibrium position of the water table. In the lower resolution, time-evolving run with the full model, the water table pattern stems from the high resolution simulation, where local drainage is better resolved, and is therefore realistic, reflecting topography with deeper water table under hilltops and shallower in valleys. Preceding our discussions on groundwater-soil moisture interactions over the Iberian Peninsula, in this study we validate the modelled water table with available time series of observations in Spain and Portugal.

2 Model description and settings

2.1 Groundwater and Land Surface Model LEAFHYDRO

LEAF (Land-Ecosystem-Atmosphere-Feedback) is the LSM included in the Regional Atmosphere Modeling System (RAMS) (http://rams.atmos.colostate.edu/). It calculates heat and water fluxes and storages in the land surface, resolving several vertical soil layers of variable depth. The vertical flux F between adjacent unsaturated soil layers is given by the Richards' Equation:

$$F = -\rho_w K_\eta \frac{\partial(\Psi + z)}{\partial z} \tag{1}$$

where ρ_w (kg m^{-3}) is the density of liquid water, K_η (m s^{-1}) is the hydraulic conductivity at a given volumetric water content η, Ψ (m) is the soil capillary potential and z (m) is height. Parameters K_η and Ψ depend on the water content and the pore-size index of the soil. To compute such parameters, the model follows the **?** formulation:

$$K_\eta = K_f \left(\frac{\eta}{\eta_f}\right)^{2b+3}, \qquad \Psi = \Psi_f \left(\frac{\eta_f}{\eta}\right)^{b} \tag{2}$$

where b is the soil pore-size index and subscript f denotes quantity at saturation. A canopy layer including vegetation and surface air interacts with the soil/surface water below and the atmosphere above. Derived from the version 2 of LEAF (**?**), LEAFHYDRO incorporates a groundwater dynamics scheme, based on the formulation presented by **?**.

LEAFHYDRO introduces a prognostic water table depth that fluctuates in the model as a result of three main interactions: 1) two-way water flux between the saturated and the unsaturated zones, 2) two-way water flux between the groundwater reservoir and rivers, and 3) lateral groundwater flow within the saturated zone. Hence, the mass balance of the dynamic groundwater reservoir in a LEAFHYDRO cell is given by

$$\frac{dS_G}{dt} = \Delta x \Delta y R + \sum_{n=1}^{8} Q_n - Q_r \tag{3}$$

where S_G (m^3) is the groundwater storage in a model column, $\Delta x \Delta y$ (m^2) is the horizontal resolution of the model, R (m s^{-1}) is the flux through the water table, Q_n (m^3 s^{-1}) is the lateral flow from or to the nth neighbouring model cell, and Q_r (m^3 s^{-1}) is the groundwater-rivers exchange. Fluxes in Equation 3 are assumed to be positive when going into the groundwater reservoir and negative when going out of it. Fig. 1 (left) represents the groundwater balance in a model cell (cell 1).

The water flux through the water table or net recharge R is the sum of gravitational downward groundwater recharge and capillary flux, and depending on soil wetness and atmospheric demand, it can be downwards, causing the water table to rise, or upwards, causing the water table to deepen. LEAFHYDRO calculates R under the 2 possible scenarios in Fig. 1 (right).

In scenario a, the water table appears within the soil layers resolved by the model (4 m) and its position is diagnosed at a given time step as that yielding the equilibrium soil water content (η_{eq1}) in the unsaturated portion of layer 1. Hence, there is no vertical water flux between layers 1 ~~(the value resulting in a zero net flux between full~~ and 2, and from Eq. 1:

$$\frac{\partial(\Psi + z)}{\partial z} = 0, \quad or \quad \Psi_1 - \Psi_2 = z_2 - z_1 \tag{4}$$

Applying the relationship between Ψ and η in Eq. 2, the equilibrium soil water content in the unsaturated portion of layer 1 ~~and saturated~~ is obtained as

$$\eta_{eq1} = \eta_{f1} \left(\frac{\Psi_{f1}}{\Psi_{f2} + z_2 - z_1} \right)^{1/b_1} \tag{5}$$

Then, assuming even distribution of total soil water in layer 1, the η_1 that the model calculated in the soil fluxes routine following Richards' Equations can also be calculated as

$$\eta_1 = \eta_{eq1} \left(\frac{h_1 - wtd}{h_1 - h_2} \right) + \eta_{f1} \left(\frac{wtd - h_2}{h_1 - h_2} \right) \tag{6}$$

where wtd (m) is the water table depth, h_1 (m) is the head of layer 1 height and h_2 (m) is the head of layer 2 ~~).~~ height. Now, from Eq. 6, the water table depth is diagnosed as

$$wtd = \frac{\eta_{f1} h_2 - \eta_{eq1} h_1 + \eta_1 (h_1 - h_2)}{\eta_{f1} - \eta_{eq1}} \tag{7}$$

And finally R is the amount of water ~~flow~~ flowing from or to the unsaturated portion of layer 1 necessary to cause the rise or fall of the water table from ~~its former position .~~ the position in the previous time step to the position calculated in Eq. 7 (Δwtd):

$$R = \Delta wtd (\eta_{f1} - \eta_{eq1}) \tag{8}$$

In scenario b, the water table lies below the resolved soil layers~~, and an extra layer centered at point B (~~. A bottom layer is added that extends from the resolved soil layers depth to the water table position, centred in point C. This is a virtual layer, of variable thickness in space and time, and since it can be much thicker than the layer above and therefore cause instability issues for finite difference schemes, an auxiliary layer of the same thickness as the deepest resolved layer ~~, centered at point A) is added to calculate the water flux between the two. In the same manner, a virtual layer centered in point C that extends from the bottom of the resolved soil crust to the water table and an auxiliary saturated layer of the same thickness~~ is added, centred at point B. The water content of point B is initially obtained by linear interpolation between A and C (water content in the virtual layer containing C is part of the model initialization). Then, given the water content at A and B, the flux between the two can be calculated. Similarly, an auxiliary layer of equal thickness as the virtual layer and centered in point D ~~are added to calculate~~ is added below the water table. The water content gradient between C and D (layer containing D is saturated) determines the flux between the two, which is the net recharge R~~. Then the new water content in the virtual layer (η_C) is determined by mass balance from the~~ . Knowing the fluxes above and below~~and the~~ , the new water content η_C of the layer containing C can be determined by mass balance. The change in water content in the virtual layer is ~~added~~ finally added to or taken away from the groundwater ~~to determine the water table rise or fall.~~ reservoir, calculated similarly to Eq. 8 as

$$\Delta wtd = \frac{R}{\eta_{fdeep} - \eta_C} \tag{9}$$

where η_{fdeep} is the saturation soil water content for the soil at the water table position depth.

Groundwater-rivers exchange Q_r follows Darcy's law and it is proportional to the elevation difference between the water table and the river water surface in the cell~~. It~~ , as

$$Q_r = \frac{\bar{K_{rb}}}{\bar{b_{rb}}}\left(\bar{w_r}\sum L_r\right)(wth - \bar{z_r}) \tag{10}$$

where $\bar{K_{rb}}$ (m s$_{-1}$)is the mean river bed hydraulic conductivity in the cell, $\bar{b_{rb}}$ (m) is the mean thickness of river bed sediments in the cell, $\bar{w_r}$ (m) is the mean river width within the cell, L_r (m) is the length of individual channels in the cell (the river depth is neglected for the calculation of contact area), wth (m) is the water table head in the cell (as $wth = z + wtd$, where z (m) is the cell elevation), and $\bar{z_r}$ (m) is the mean river elevation in the cell. This flux can occur as groundwater discharge (subsurface runoff) into gaining streams when the water table is above the river, sustaining stream baseflow, or as river infiltration into the groundwater reservoir in losing streams when the water table is below river bed. For gaining streams, LEAFHYDRO approach combines the physically based parameters of Darcy's law into a parameter called river conductance, commonly used in groundwater modeling literature, like the MODFLOW model (**?**). Even though the river conductance is physically based and observable, detailed data on river geometry and bed sediments are lacking for the region studied, hence it needs to be parametrized. Such parametrization consists in a representation of the river conductance that includes two contributions; an equilibrium part, and a dynamic part that depends on the water table deviation from equilibrium at the time. Further details on this dynamic river conductance parametrization and discussion on its choice are found in **?**. For losing streams, the distance of flow or river bed thickness in Eq. 10 is the same as the water table minus riverbed elevation difference (third parenthesis in Eq. 10, only with negative sign provided that $wth < \bar{z_r}$), and hence these factors cancel out one another, leaving the flux calculation to be given by

$$Q_r = -\bar{K_{rb}}\bar{w_r}\sum L_r \tag{11}$$

Therefore, the losing stream flux Q_r in the model is not dependant on the water table position, once the latter is below riverbed, but on the groundwater-rivers hydraulic connection.

Lateral groundwater flow Q_n is determined by the slope of the water table surface~~; all water~~ , applying Darcy‘s law the water flux from the nth neighbour into a model cell is given by

$$Q_n = cT\frac{wtd_n - wtd}{l} \tag{12}$$

where c (m) is the flow cross-section connecting the cells, T (m^2 s^{-1}) is the flow transmissivity between the cells, wtd and wtd_n (m) are the water table depths for the centre cell and the nth neighbour cell, respectively, and l (m) is the distance between cells. T is calculated as an integration of the lateral hydraulic conductivity at saturation, for which the model uses observed values of the anisotropy ratio relating vertical and lateral conductivities (**?**), and assumes exponential decay of the vertical hydraulic conductivity at saturation K_{V_f} with depth, as

$$K_{V_f} = K_0 exp\left(-\frac{z'}{f}\right) \tag{13}$$

where K_0 (m s^{-1}) is the known value at 1.5 m deep, z' (m) is the depth below 1.5 m and f (m) is the e-folding depth, calculated as a function of terrain slope β as $f = 75/(1+150\beta)$, where f is limited to 4 m when $\beta \geq 0.118$. Further details on this formulation of Q_n and parametrization choices are found in **?** and **?**. All water fluxes represented by arrows in Fig. 1 (left) are referred to cell 1, thus the groundwater lateral flux Q_2 is an incoming flux from the neighbouring cell 2 with a higher water table head ($wth2$), and Q_3 is an outgoing flux towards the neighbouring cell 3, which presents a lower water table head ($wth3$). ~~Formulations for R and Q_r are further detailed in **?**, and for Q_n in **?**~~

When there is vegetation on the surface, the water and heat exchanges between vegetation and the surrounding canopy air parameterization is based on **?**. This methodology uses PFTs (Plant Functional Types) constant through the simulation period, assigning a type to each cell that will determine parameters like the root depth, the minimal stomatal conductance (that will be increased by atmospheric factors) and the LAI (Leaf Area Index), that will affect the calculation of canopy resistance, transpiration and evaporation from the canopy surface. The transpiration is taken from the moistest level in the root zone.

2.2 Initial land surface and river parameters

The 11 soil textural classes used in LEAFHYDRO, necessary to derive soil parameters in Eq. 2 controlling the vertical water fluxes, are defined by the United States Department of Agriculture (USDA) from fractions of silt, clay and sand. The data for top (0-0.30 m depth) and bottom (0.30-4 m depth) soil layers comes originally from the Food and Agricultural Organization of the United Nations (FAO) world database (http://fao.org/soils-portal/soil-survey). Other processes in the model, such as evapotranspiration, need parameters dependent on the vegetation type (PFTs) at the land surface. For vegetation type we use the COordination of INformation on the Environment (CORINE) Land Cover Project database (**?**).

The river flow scheme included in LEAFHYDRO (**??**) uses the Manning's Equation. For the river flow scheme and in order to calculate the equilibrium river conductance and the groundwater-streams flux in gaining streams detailed in section 2.1, the model requires the following initial parameters: flow direction~~and~~ , river width, ~~length and slope. For the calculation of~~ river length and river slope. To calculate such parameters in the domain, we used the United States Geological Survey (USGS) HydroSHEDS 15 arc second resolution data (**?**). The variables extracted from the HydroSHEDS database were: fd (flow direction), acc (accumulated drainage area) and dem (void filled elevation). The methodology to calculate the requested parameters (Fig. 2) follows the following steps: 1) First, the high resolution (15 arc second) cell with the largest acc within a low resolution cell (model grid is 2.5 km) is spotted; 2) The fd of this cell (black arrows in Fig. 2), together with the location of the low resolution cell containing the high resolution cell where it flows to, determine the flow direction of the low resolution cell (blue arrows in Fig. 2); 3) The flow of the main high resolution stream within every low resolution cell is then followed, highlighting the stream (red streams in Fig. 2); 4) The distance made by this high resolution main stream is taken as the low resolution river length L; 5) The low resolution river slope s_r is taken as the average slope for all high resolution cells that take part in the main high resolution stream, where the high resolution slopes have been previously calculated from the flow direction fd and the elevation dem; 6) The low resolution drainage area A_d is calculated aggregating the area of all high resolution cells within a low resolution cell, and then accumulating it from all cells addressed to a given cell with the use of the low resolution fd; 7) Finally, the river width w_r is calculated using an estimation of the net recharge R (a 1° resolution global climatic recharge from the Mosaic LSM) and the drainage area A_d in each low resolution cell, as discussed by **?**: $w_r = (0.00013Q_m + 6.0)Q_m^{1/2}$, where Q_m is the annual mean discharge passing through a river section, approximated for this calculation by the accumulation of flow $Q = RA_d$ for the cells along the low resolution stream.

2.3 Atmospheric forcing data

The atmospheric forcing data for the LEAFHYDRO simulations were extracted from the ECMWF ERA-Interim reanalysis database ~~(http://ecmwf. int/research/era/do/get/era-interim).~~ (**?**). Surface pressure, 2 m temperature and surface wind speed data are reanalysis fields at 6-hourly time resolution. The incoming surface radiation (shortwave and longwave) and precipitation (convective and large-scale) fields are forecasts from reanalysis datasets and are available at 3-hour time resolution. ERA-Interim ~~grid horizontal resolution is approximately 0.7° in latitude and varying in longitude from 0.75° at the southern boundary of the domain to 1.58° at the northern boundary~~is presented in a reduced Gaussian grid with approximately uniform 79 km spacing for surface grid cells.

The precipitation data to drive our simulations must account for the orographic heterogeneity of the Iberian Peninsula as much as possible. We use a regional high resolution analysis dataset of daily precipitation over Spain and Portugal (IB02: **??**). The IB02 dataset was built using all stations from the climatic monitoring network of both the Spanish Meteorological Agency (AEMET) and the Portuguese Meteorological Institute (IPMA), and presents a horizontal resolution of 0.2°. Once the daily precipitation is read and interpolated into the model grid, the model temporally disaggregates the ~~data~~ daily values throughout the day using 3-hourly ERA-Interim precipitation ~~data~~distribution. Hence, the model uses the IB02 daily analysis data for ~~precipitation amounts~~ bias-correction of daily totals and ERA-Interim data for ~~3-hourly precipitation distribution~~ precipitation distribution throughout the day.

2.4 Equilibrium Water Table Depth and initial soil moisture

In order to initialize the model, we used a climatic or Equilibrium Water Table Depth (EWTD) for the Iberian Peninsula. It was calculated using a simple two-dimensional groundwater model ~~(??)~~described by **??**, which finds EWTD as the long-term balance between the atmospheric influence in the form of climatic groundwater recharge ($R = P - ET - Q_{sr}$~~,~~; recharge equals precipitation minus evapotranspiration minus surface runoff) and the topographic influence given by gravity-driven lateral convergence. ~~High~~ This two-dimensional groundwater model has been recently applied to New Zealand by **?**, providing improved water table estimations for data-sparse regions.

We used topography data at high spatial resolution (9 arc seconds) ~~was used~~ in the EWTD calculation to properly capture topographic variability and local ~~topographic~~ hillslope gradients (**?**). A three-step process was followed, where first, a low resolution (1°) global climatic recharge from the Mosaic LSM was used to calculate ~~an initial EWTD~~ a first estimate of EWTD by ingesting it to the 2D model using the high resolution topography; second, ~~a LEAFHYDRO 10-year test run (1989-1998) was carried out from that initial EWTD , aggregated to the model grid~~ the resulting first high-resolution estimate of EWTD is simply aggregated to a grid of 2.5 km to serve as initial water table condition ~~;~~ for LEAFHYDRO full LSM 10-year test run (1989-1998), and third, a new high resolution EWTD was recalculated forcing the 2D model with the groundwater net recharge obtained with the ~~test run~~LEAFHYDRO test run at 2.5 km and the high resolution topography. The test run ~~used high resolution~~ uses precipitation analysis and other forcings (see section 2.3) at higher resolution than the 1° climatic recharge from MOSAIC initially feeding the EWTD model, and produces a much more realistic recharge, totally compatible with our simulation settings. The resulting EWTD is the basis of the initial water table condition for the final LEAFHYDRO simulation and is shown in Fig. 3. The water table is relatively close to the surface in many areas, such as in the Inner Plateau (northern and southern subregions), where in spite of the semi-arid climate, the water table is shallow due to the slow drainage and lateral groundwater convergence from the surrounding mountains. Low elevation coastal plains and river valleys also present a shallow water table. Topography dominates the water table depth spatial heterogeneity; however, the climatic pattern, in general wetter and with higher recharge toward the Atlantic than in the Mediterranean, also has an influence, with shallower water table depths in the west and deeper in the east of the Iberian Peninsula.

The initial soil moisture profiles are of major importance in LSM studies ~~(e.g. ??)~~(e.g., **??**). Here, we initialized the soil solving numerically the Richards equation, prescribing the climatic net recharge as top and saturation at the EWTD as lower boundary condition. Thus, the initial soil moisture content in our simulations is in equilibrium with the water table below.

2.5 ~~10-year simulations~~Simulations set-up

We performed a 10-year period simulation (referred to hereafter as WT, Water-Table) using LEAFHYDRO to investigate the role of groundwater dynamics in the Iberian Peninsula soil moisture fields, land-atmosphere fluxes and surface water. In addition, to help isolate the role of the groundwater, another simulation was performed with the groundwater scheme deactivated (referred to hereafter as FD, Free-Drain). The FD simulation uses the commonly adopted free-drain approach, where soil water is allowed to drain out of the soil column and into the local rivers at a rate set by the hydraulic conductivity at the water content of the bottom soil layer. The potential drawback of this approach is that the escaping water is no longer available to sustain subsequent dry period ET. It should work very well where the water table is deep and the soil is sandy, but where the water table is shallow and the soil is clay rich, it may underestimate soil water storage and overlook persistence.

The simulation domain is a Lambert-Conformal grid centered in the Iberian Peninsula (Fig. 4) with a spatial resolution of 2.5 km. The simulated period starts in January 1989 and finishes in December 1998. This timeframe was chosen long enough to include wet and dry years in order to better isolate the groundwater influence on soil moisture memory. It includes the 1991-1995 drought, reported as the most severe in the Iberian Peninsula during the last 60 years (Libro Blanco del Agua en España, **?**; published by the Spanish Department of Natural Environment), as well as other dry and wet spells over different pluviometric Iberian regions, hence allowing for a study of groundwater effects under different climatic conditions. The length of the time period of simulation is a significant improvement with respect to the prior LEAFHYDRO seasonal study over North America (**?**).

The time resolution for resolving heat and water fluxes in the soil and at the land surface is 60 s. The time step for groundwater-streams exchange, groundwater mass balance and water table adjustment in the WT run is 900 s.

3 Validation

3.1 Water table depth and time evolution validation

A realistic water table depth (~~wtd hereafter~~*wtd*) estimation is essential to couple groundwater and soil moisture in modelling studies. A modelled dynamic water table should oscillate around its equilibrium position (EWTD) at different timescales in response to rainfall events, unsaturated soil demands and multi-year dry or wet spells, as it does in nature (**???**). Thus, a validation of the time evolution of the simulated ~~wtd~~ *wtd* across the studied region is necessary to support the findings of this work. We use ~~wtd~~ *wtd* observations in this section to validate the model performance in terms of water table depth and time evolution across the Iberian Peninsula. The observational ~~wtd~~ *wtd* data were provided by the Institute of Geology and Mining of Spain (IGME), several Confederaciones Hidrográficas (Spanish agencies managing the main basins within the country) and the National Information System for Hydrological Resources of Portugal (SNIRH). The time and space coverage of these datasets are irregular. For validation, we eliminated stations with a water table deeper than 100 m in order to rule out measurements in confined aquifers as much as possible, since they are not hydrologically connected to the land surface. We also discarded stations with a sustained declining trend steeper than 0.05 m month^{-1}, very likely caused by pumping. After these eliminations, we only use stations with at least 3 years of data within the 10-year simulation period, leaving 623 stations suitable for ~~wtd~~ *wtd* validation (Fig. 4).

Some studies that incorporate explicitly groundwater dynamics in land surface modelling find groundwater impacts on the top soil and land-atmosphere fluxes to be negligible when the wtd is below 5 m (**??**). However, the contribution of water tables below 5 m deep to ET by upward capillary flux has been reported to be significant at sites over Amazonia (**?**), where groundwater sustains significant fractions of the observed ET even when the water table is at depths of around 10 m. As a compromise, we consider in our analysis water tables above 8 m deep to be shallow in this Iberian Peninsula study. A total of 31.4 % of the Iberian Peninsula territory is found in the WT simulation to have shallow mean water table (Fig. 4), which gives an estimate of the high potential for groundwater influence on top soil hydrology and land-surface fluxes in the region. With regard to the observations, 203 of the studied stations present a shallow water table (~~wtd~~ mean *wtd* $\leq$ 8 m) during the simulation period.

The water table evolution at a given grid cell in the model must be understood as an approximation to the different possible behaviours of the natural water table within the cell. This situation is a handicap for ~~wtd~~ *wtd* validation, since the 2.5 km resolution of the WT simulation is coarse in comparison with the scale of the observed variability in topography and ~~wtd.~~ *wtd*. Also, the vertical design of the model detailed in section 2.1 only allows for one water table to be found per grid cell. Out of the 623 stations analysed, 136 do not correspond uniquely to one model cell and are contained in only 60 cells (2 or 3 stations per cell, orange points in Fig. 4). These different observation sites contained in one model cell do not always present the same mean ~~wtd or wtd~~ *wtd* or *wtd* time evolution (Points 15 and 16 in Fig. 5). Inside the Point 15 grid cell (Inner Plateau, northern subregion), there are 3 different observation sites that present very different (up to 20 m difference) ~~wtd~~ *wtd* values along the simulation period (red, green and purple series), making it very difficult to assess the accuracy of the model result (blue series). Inside the Point 16 grid cell in the southeast, there are 2 observation sites, and the model underestimates the depth of both but reflects correctly the annual cycle and the long-term trends, deepening from 1992 to 1996 and reaching shallower depths from 1996 to 1998.

Approximately one third of the stations present a shallow mean *wtd* ($\leq$ 8 m), and 66.0 % of them are also found to have shallow mean water table by the model.

In terms of mean ~~wtd~~ *wtd* error, 14.0 % of stations present less than 2 m difference between simulated and observed mean ~~wtd~~ *wtd* at the available observation times (red points in Fig. 4). ~~The percentage increases to 33.0 % when we consider only~~ If we only consider shallow water table ~~points. Up to 66.0 % of grid cells containing those shallow observational points present also a shallow water table in the model (~~observations (mean *wtd* $\leq$ 8 m), 33.0 % of them present less than 2 m difference with the mean simulated *wtd*. Fig. 5 shows examples of time series of the model performance at ~~capturing the~~ points where the model captures the mean water table depth (Points 1 to 12). Focusing not on the mean ~~wtd~~ *wtd* values but on their time evolution, we find that 32.3 % of the station time series present a correlation coefficient over 0.5 with the simulated time series (green points in Fig. 4; the correlation is calculated using the full time series available in the observed data). Points in different shallow water table areas over the Iberian Peninsula show the model accuracy at representing the seasonal fluctuations and the long-term deepening and rising trends (Points 1 to 14 in Fig. 5; note that Points 1 to 12 fall into both red and green categories).

Point 12 near the Duero/Douro river mouth in Portugal is an example on capturing the seasonal cycle and a slightly upward ~~wtd~~ wtd trend throughout the simulation. At some of the very shallow water table points in 5, the amplitudes of the wtd variations are larger in the model than in the observations.

A total of 94 stations present a steep ~~wtd~~ wtd long-term trend (slope $\geq$ 0.035 m month^{-1}) within the prescribed limits to avoid spurious trends due to pumping (slope $\leq$ 0.05 m month^{-1}), and 26.6 % of them are captured in the simulation (purple points in Fig. 4) by a mean slope difference between the observation and simulation series lower than 0.02 m month^{-1}.

In spite of the aforementioned challenges in validating the simulated water table with point observations, we can conclude that the model's performance is reasonably good at shallow water table points, but significantly worse where the water table is deeper. The spatial pattern of deep water table under hilltops and shallow in valleys is thus realistic in the model, however inaccurate water table levels might be where groundwater is deep. Seasonal cycles and long-term trends in groundwater are in general better captured. Notwithstanding, for the purpose of this work, LEAFHYDRO's skill in representing the shallow water table regions in the Iberian Peninsula is the key factor, since when it is deeper, the two way linkage with the top soil, which is the focus of our study, weakens considerably.

3.2 River flow comparison

The groundwater-surface water link in LEAFHYDRO has been presented and validated over North America using river flow observations (**?**). Similarly, for this work over the Iberian Peninsula, all calculations and ~~parameterizations~~ parametrizations are physically based and no model calibration has been carried out for any basin. For validation, we use monthly river flow observational data at 6 gauge stations along the main rivers of the region (Fig. 6), provided by the Centre for Hydrographics Studies (CEH, Spanish Department of Natural Environment).

There is a clear underestimation of the winter river flow by the model. Two factors contribute to this bias. First, a lack of precipitation in the forcing data, since the IB02 analysis dataset original resolution (0.2º) is coarser than our model simulations and the station density (7 km in Spain and 11.7 km in Portugal) is not sufficient to capture precipitation peaks due to orographic enhancement over the mountains, which is very pronounced in the northern cordilleras. In addition, the model does not incorporate a ~~parameterization~~ parametrization for subgrid saturation excess runoff (**?**), likely associated to heavy precipitation (**?**). Secondly, there are also model deficiencies in the representation of the river-groundwater linkage when the water table is deep. It is often the case, especially in complex terrain, that the mean water table of the cell is too high above the river, hence resulting in a fairly constant baseflow throughout the year, with very smooth rainy season peaks. This produces summer baseflow that is realistic, matching observations in some cases (right graphs in Fig. 6), but more often yields a bias in the modelled streamflow.

Another important issue affecting river flow validation is the existing high anthropogenic intervention in river regimes, both direct, through regulation reservoirs, power generation plants or irrigation withdrawals, and indirect, from groundwater extraction in wells. According to Libro Blanco del Agua en España (**?**), the fraction of natural flow under this affected regime is high in northern rivers (Duero/Douro, Miño/Minho, Llobregat), but low in southern rivers: 52 % in the Guadiana (Badajoz station, Extremadura, Spain), 44 % in the Guadalquivir (Alcalá del Río station, Andalucía, Spain) and only 4 % in the Segura at the river mouth (Guardamar station, Valencia, Spain). In consequence, a comparison with observations might not be very meaningful for some rivers, such as the Gualdaquivir, where the observed river flow at station 5 is much lower than the model result, producing the poorest correlation index.

4 Results

4.1 Long-term net recharge and seasonal variability

The study of the net recharge variable, defined as the flux across the water table, gives us an understanding of the connection between groundwater and soil. This connection is bimodal, and depends on soil wetness conditions; 1) negative recharge occurs when the net flux is downward and the groundwater reservoir acts as a sink for precipitation infiltration; 2) positive recharge results when upward capillary fluxes dominate and the groundwater reservoir takes the role of water source for soil moisture, feeding ET demands.

An accurate estimation of the net recharge is of major importance for water management systems, mainly over high irrigation areas such as the semi-arid regions of the Iberian Peninsula, as it will help to understand where unconfined aquifers are at risk of being overexploited. Here, as a first result, we present the net recharge estimation produced by our long-term LSM simulation with a fully dynamic water table (WT), where upward capillary fluxes are accounted for (Fig. 7a). Long-term negative (downward) recharge patterns resemble precipitation patterns (Fig. 7b), although with the amount diminished by surface runoff and ET. Streamflow seepage when the water table is below riverbed results also in a net negative recharge in some locations. Long-term positive recharges occur where a net upward capillary flux to satisfy ET demands is sustained by groundwater lateral convergence from surrounding cells of higher water table head. These lateral fluxes represent a more remote water source than vertical drainage through the soil above and are particularly relevant in water limited regions. The long-term upward flux in Fig. 7a is small over wide flat areas, since regional lateral groundwater convergence from the distant surrounding mountains is slow. This is the case of the Inner Plateau (northern and southern subregions), which has a dry climate with insufficient rainfall to sustain high ET for long. However, in river valleys where steep slopes in the water table head drive strong local lateral groundwater flow convergence, groundwater-fed ET can exceed precipitation by large amounts, ~~and result in large positive recharges~~resulting in higher values for the positive recharge. This is apparent in Fig. 7a along the main river valleys crisscrossing the dry Mediterranean areas of the Iberian Peninsula~~, which are well resolved in the simulation~~.

The net recharge presents strong seasonal variability (Fig. 7c-f). It undergoes a clear seasonal cycle following precipitation and ET cycles, which, in Mediterranean climates, are typically in opposite phases. ~~This cycle is more pronounced the shallower the water table~~The seasonal character of ET in the Iberian Peninsula (**?**) is induced by water availability and incoming radiation; maximum values and higher spatial variability are found in spring and summer, whereas minimum values and variability appear in autumn and winter, when the incoming radiation is lower and the leaf area index decreases. Downward fluxes (negative recharge) are strong during winter and spring in the humid areas in the west and north, responding to wet season infiltration, which furthermore is not diminished by any significant ET. Late spring precipitation and the little summer rainfall are mostly consumed by the high ET demands in the growing season, thereby substantially weakening any negative recharge during summer and autumn. ~~As~~ Where the water table ~~gets deeper~~ is deeper 3, the wet season peak in recharge is delayed and variations are buffered, until it becomes a rather constant and diminished flux with much less variability throughout the year. The later is also true for shallower water tables in drier areas. Fluxes reverse and become upward mainly over shallow water table regions in spring, once the high ET consumes top soil moisture, and reach the maximum in summer when the surface water balance is minimal ($P - ET = -0.80$ mm day^{-1}). Any upward flux decreases significantly during autumn because of the lower ET, and only in a few locations groundwater still feeds the reduced winter ET demands. The net annual flux might be upward, as discussed above, in areas where significant groundwater convergence compensates the lack of precipitation to sustain ET.

4.2 Water table control on soil moisture and ET

The large scale soil moisture pattern over the Iberian Peninsula is dominated by seasonal climatic variations and a non-seasonal dependence on soil texture. The influence of groundwater is however very relevant at shorter spatial scales, as shown by the difference between the soil moisture fields from the WT and FD runs (Fig. 8a). The relation with the water table depth distribution (Fig. 8b) is very apparent. Soil moisture differences reach higher values where the water table is shallower, and are minimum or negligible in regions with deeper water table. The similarity between the patterns of soil moisture differences (WT-FD runs) and ~~wtd~~ wtd (WT run) illustrates the controlling role of groundwater on soil moisture spatial variability, by wetting the soil from below in regions of shallow water table: 1) low elevation flatlands, such as coastal plains and the low Guadalquivir basin, where sea level limits drainage 2) narrow river valleys where lateral groundwater flow convergence is strong, 3) wider plains surrounded by mountains (Inner Plateau), due to a combination of poor drainage, streamflow infiltration losses and lateral groundwater convergence, albeit slow, from the high terrain around, and 4) the humid areas with high recharge rates in the northwest of the Iberian Peninsula (Galicia and northern Portugal).

The seasonal cycle of soil moisture differences between the WT and FD runs, averaged over shallow water table regions (as defined in Section 3.1: ~~wtd~~ $wtd \leq 8$ m, about 30 % of the total area of the Iberian Peninsula), is shown in Fig. 8c. Only shallow water table points are considered because the effect of groundwater on soil moisture where the water table is deep is very small. Soils are always wetter in general when the water table is close to the surface, as the positive value of the differences at all times indicate. In absolute terms (purple curve), the differences in soil moisture are maximum in spring, similarly strong in winter and summer, and weaker in autumn. In relative terms (blue bars), however, groundwater reveals its stronger influence at water scarcity times, reducing soil moisture seasonality: 24.4 % soil moisture increase in spring and 23.9 % in summer. In the wet season, during autumn and winter, when soils are in general wetter, the impact of upward capillary fluxes from the water table is to slow down drainage, therefore increasing somewhat top soil moisture. In the dry season, which in the region coincides with the spring and summer growing period, root zone soil moisture and drainage can be drastically reduced. Upward capillary fluxes from a shallow water table thus dominate and may reach the root zone, sustaining, at least partially, ET demands. It is then that the effect of these upward fluxes from groundwater is more relevant, resulting in soil moisture that is significantly higher than otherwise would be if the water table were deeper.

The difference in summer ET between the WT and the FD simulations (Fig. 9) reveals an important enhancement over shallow water table regions, where there is more soil moisture availability (Fig. 8). In summer, the mean daily ET, averaged over the whole Iberian Peninsula, in increased by 34.9 % (0.54 mm day^{-1}) as a result of the connection between the soil and the water table. This ET enhancement is maximum in summer, as discussed above, but considering the whole year is still as high as 17.4 % (0.24 mm day^{-1}).

4.3 Water table persistence and soil moisture memory at pluri-annual timescale

The choice of a 10-year simulation period allows us to analyze groundwater persistence and influence on soil moisture at a timescale of several years. For this purpose, we first calculate the time correlation indexes between the annual anomalies (differences with respect to the annual means) of soil moisture and ~~those of the~~ two key players affecting its time evolution: precipitation and water table depth, for the full 9 hydrological years simulated (September 1989 to August 1998; hy1 to hy9)~~simulated~~. In the FD simulation without groundwater, annual anomalies of soil moisture and precipitation are positively correlated at every point of the Iberian Peninsula (Fig. 10, left), with lower indexes over the northern mountains, where freezing conditions and snow cover during part of the year prevent infiltration and make soil moisture insensitive to precipitation. However, when the same relationship is evaluated using the WT simulation with groundwater, the correlation values between precipitation and soil moisture anomalies decrease in all shallow water table regions (Fig. 10, centre), indicating that soil moisture reliance on precipitation is diminished there. The correlation index between precipitation and soil moisture annual anomalies averaged over the whole Iberian Peninsula decreases from 0.81 in the FD run to 0.72 in the WT run, and from 0.82 to 0.60 when averaging only over shallow water table regions. In the WT experiment with groundwater, soil moisture anomalies are highly and positively correlated (values over 0.5) with ~~wtd~~ *wtd* anomalies (Fig 10, right) over many shallow water table regions in the southern half of the Iberian Peninsula, the ~~Northern Sub-Plateau~~ Southern and Northern Sub-Plateaus or Galicia in the northwest, precisely where the correlation between soil moisture and precipitation anomalies is reduced. In this WT simulation, the averaged correlation index between ~~wtd~~ *wtd* and soil moisture anomalies is 0.43 over the whole area, and 0.93 when averaging only over shallow water table regions. In shallow water table areas, where soil and groundwater are connected, soil moisture anomalies are thus more linked to groundwater anomalies (0.93 correlation index) than to precipitation anomalies (0.6 correlation index), suggesting that, by wetting the soil from below, groundwater buffers soil moisture reliance on precipitation, decoupling somewhat soil and atmospheric conditions.

To better describe the connection between precipitation and groundwater timescales of variation, Fig. 11 shows a collection of paired ~~wtd~~ *wtd* and precipitation anomaly plots over the Iberian Peninsula, chronologically ordered for the 9 hydrological years considered. These include the 1992-1995 drought (hy2 to hy6), one of the worst in the last century. Following an initial overall wet year - wetter than the mean in the centre and south (positive anomalies in the top row) but drier in the north (negative anomalies) -, precipitation anomalies in the Iberian Peninsula are clearly negative from hy2 to hy6 during the drought period, and then become clearly positive during the last 3 years. This precipitation regime is transfered with a 1-2 year delay to the groundwater. The water table (anomalies shown in the bottom row), deepens slowly during the drought, up to hy6 and then starts to rise from the very wet hy7, but it never reaches the initial position with a positive anomaly, since recovering from the severe drought episode would likely take longer. The water table delayed response is clearly reflected in the area averaged anomalies, which do not become negative until two years into the drought. Intense climate events at the surface are buffered in the groundwater, where they may be "remembered" for some years. For instance, on the eastern coast, the hy1 and hy2 positive precipitation anomalies cause the water table to be shallower than the mean up to the end of hy4, even though precipitation anomalies in the region are negative during hy3 and hy4. Furthermore, over the northern Cantabrian coast, the very high precipitation anomaly during hy4 translates into shallow ~~wtd~~ wtd anomalies in hy4 and hy5, in spite of negative precipitation anomalies during hy5 over most of the area. Another example is the high precipitation anomaly during hy5 in the northwestern part of the Iberian Peninsula, which is not sufficient to produce a shallow anomaly in ~~wtd~~wtd, since the region comes from 2 consecutive very dry years (hy3 and hy4), and the water table stays deeper than the mean over most of the region even after hy5.

Groundwater's long timescales of variation result in water table persistence through atmospheric wet and dry periods. Since the water table is connected to the top soil via capillary fluxes where it is relatively shallow, groundwater's delayed and extended response to climatic events affects soil moisture evolution (Fig. 10). To further evaluate the influence of water table persistence on soil moisture memory at pluri-annual timescale, we study a 250 x 225 km^2 region containing La Mancha Húmeda (Fig. 12; region highlighted in Fig. 11, first plot of bottom row), a well know wetland area within the otherwise dry Southern Plateau inland Spain. The water table is very close to the surface over significant portions of this region (Fig. 8b), and therefore it is a marked wet spot that helps understanding the water table's influence on soil moisture memory at a fine scale. Soil moisture anomalies in the FD run where groundwater is not considered (second row) are a direct response to precipitation anomalies (top row). However, the soil moisture evolution patterns in the WT run with groundwater (third row) reflect a combination of precipitation and ~~wtd~~ wtd patterns (bottom row), which in turn are also affected by earlier precipitation anomalies. Indeed, focusing on the series of ~~wtd~~ wtd anomalies (bottom row), it is apparent that for the ~~the~~ large shallow water table area in the center of the figures, wetter than normal conditions from hy1 extend one year into the drought period (hy3), and dry anomalies only develop after the third dry year (hy5). Due to the severity of the drought, depressed water tables persist even three years after the starting of the wet period in hy7. The regional pattern of soil moisture anomalies (third row) reflects primarily direct climatic influence over deeper water table areas, but also groundwater connections over shallow water table regions, and it's therefore a mosaic of areas of direct and delayed response to climate anomalies. These figures illustrate how depending of the extent of shallow water table regions, regionally averaged soil moisture anomalies can be decoupled from present precipitation anomalies, reflecting instead past climatic events.

4.4 Analysis by basin

River basins can be considered as independent, topography-driven regions integrating the hydrological system behaviour. Considering that the Iberian Peninsula presents very different precipitation regimes, we analyse in this section the WT and FD run results averaged over the main Iberian basins (Fig. 13). Since soil moisture dynamics are changed by the interaction with a shallow water table, land-atmosphere fluxes, and in particular ET, are thus also expected to be altered (as shown in Section 4.2). The focus is to understand the effects of groundwater-soil interactions on ET over different climatic regions and periods.

As mentioned earlier, the most significant impact of groundwater on soil moisture and hence land-atmosphere fluxes takes place over shallow water table regions (~~wtd~~ $wtd \leq$ 8 m), where groundwater is hydraulically connected to the upper soil through upward capillary fluxes. The fraction of shallow water table cells is approximately one third of the total in the Atlantic basins, ranging from 31.6 % in the Guadiana basin to 34.7 % in the Miño/Minho basin, and one fourth in Mediterranean basins: 24.3 % in the Ebro, 27.5 % in the Júcar and 28.1 % in the Segura basin, since the drier eastern half of the Iberian Peninsula presents an overall deeper water table.

Fig. 14 shows the evolution of precipitation (seasonally accumulated, blue bars), water table depth in the WT run (red lines) and the differences between WT and FD runs in soil moisture (orange lines) and ET (green bars), averaged for the shallow water areas of the main Iberian basins for the 10 years of simulation. During the wet season (autumn-winter) the water table rises due to precipitation infiltration, but since drainage is slowed down as compared with the free-draining FD run, ~~and therefore~~ the soil moisture difference between both experiments also follows an upward trend. This soil moisture difference is maximal at the start of the growing period in spring because of accumulation during the wet season, meaning that there is more soil water availability to meet ET demands in the WT run, which results in a marked peak in ET difference. During late summer, the higher soil water availability in the WT run continues due to capillary rise and there is ET enhancement until the next wet season, when the cycle starts again. The increase in ET is more significant in the drier southern basins, where ET is more water limited (an overall 21.4 % ET enhancement in the Atlantic Guadalquivir and 28.4 % in the Mediterranean Segura basins). In the northern Miño/Minho basin, where ET is not so much water limited as energy limited, the ET enhancement is less significant (13.3 %).

Focusing on longer time-scale patterns, in terms of climatic conditions, the 10-year simulation period presents a long drought from 1990 to 1995/1996 in all basins except the Miño/Minho (see precipitation, blue bars in Fig. 14). The water table follows the long-term precipitation trend, with a slow ~~wtd~~ *wtd* decline during the drought, and then a gradual recovery ~~in the~~ (or at least a change in tendency from deepening to stabilizing or slightly rising in the cases of Ebro and Segura) in the last 3 years of simulation, when precipitation is high. This long-term ~~wtd~~ *wtd* tendencies are passed on to soil moisture: differences between WT and FD values are smaller when the water table is depressed and increase as it becomes shallower. Therefore, soil moisture availability "remembers" past dry and wet years due to the strong connection with groundwater, and in turn, this soil moisture memory induces ET memory, more clearly so in the southern drier basin, where the intensity of land-atmosphere fluxes depends not only on precipitation from the previous wet season but also on the long-term ~~wtd~~ *wtd* evolution. For example, in the Guadiana basin, ET differences during 1996 are clearly lower than during 1990, even though there was much higher precipitation in the previous wet season in 1996 than in 1990. This is explained by the soil moisture memory induced by groundwater; in 1996 the water table is depressed after several years of drought; hence the soil and ET fluxes behave more like in a free-drain approach, without connection to the water table. The high infiltration from a very wet winter is thus rapidly lost and unavailable to rise back up by capillarity in the growing season. In contrast, in 1990, the water table is shallower and thus infiltration slower, soils wetter and as they dry, upward capillary fluxes can reach the top soil to feed ET demands.

Fig. 15 shows power spectrum analyses of soil moisture and ~~wtd~~ *wtd* time series for the same basins as in Fig. 14. The power spectrum of a given time series was simply based on performing the Fourier transform. Again, only shallow water table areas are considered. The figure illustrates more clearly the coupling between groundwater and soil in shallow water table regions and the long-term memory induced by groundwater in the combined system. Water table power spectra (insets in Fig. 15) peak at one year frequencies~~and at decadal timescales~~. The annual cycle, linked to that of the surface water balance (shown in Fig. 14 on ET and soil moisture), is very marked in the humid Miño basin, in the north, with an oceanic climate with abundant precipitation and rare water scarcity. Longer timescales of evolution dominate as the climate gets drier towards the south and east of Iberia, where multi-year droughts alternating with wetter periods are the norm. Soil moisture spectra show evidence of a pronounced annual cycle in both the WT experiment with groundwater (blue lines) and the FD run with a free-drain approach (red lines). This is explained by the seasonality of precipitation and ET, which in a Mediterranean climate are in opposite phases, as mentioned earlier. There is an increased relevance of long frequencies of variation in the southern and Mediterranean basins as a consequence of the irregularity of precipitation in these regions. Very little difference exists between the spectra of WT and FD simulations in the humid Miño basin; they however diverge in drier climates, with soil moisture in the WT run presenting significantly higher amplitudes at long timescales than in the FD experiment without groundwater. The higher weight of longer timescales of variation in the WT soil moisture series reflects those in the water table series (insets) and is an indication of the strength of the coupling between soil and a shallow water table in semiarid climates. This is particularly evident in the Segura basin, in the southeast, the driest area of the Iberian Peninsula.

4.5 Groundwater influence on river flow

Finally, we briefly discuss groundwater's modulation of streamflow. The water table and rivers are linked in LEAFHYDRO through the groundwater-rivers flux Q_r, which can go in either direction. In the experiment with a free-drain (FD) approach, however, the water draining through the bottom soil layer at 4 m depth, goes directly into the rivers, without delay. Loosing streams are not contemplated either in FD. We choose the Ebro river for this discussion because this is where the model exhibits the best ~~skill scores of~~ performance (i.e. less winter underestimation and best matching of seasonal cycle) of all major Iberian rivers. Besides, it has the largest draining basin in the domain. Fig. 16 shows results from observations and from both experiments for the Ebro river, close to its mouth. The winter river flow underestimation general to all rivers in the WT run (Section 3.2) is not as pronounced in the FD run. In contrast, the summer baseflow in the WT run is higher and closer to observations than that of the FD simulation; without groundwater, rivers dry out in summer practically every year in the FD run. In the WT run, the groundwater reservoir feeds rivers during the dry season with accumulated wet season infiltration, sustaining summer flows. After summer, the WT river flow rises with autumn precipitation from September-October, while in the FD simulation it takes longer to recover from the dry summer, since soils are too dry and infiltration is delayed. The better representation of the seasonal river flow by the WT run is reflected in the improvement in the monthly mean time series correlation index with observations (Fig. 16, left).

~~In this paper, we studied the influence of groundwater on soil moisture distribution and memory, ET fluxes and surface waters over the Iberian Peninsula. We used the LEAFHYDRO Land Surface Model, which represents the water table interactions with the unsaturated soil above and rivers, and lateral groundwater flow. We performed 10-year simulations with the groundwater scheme activated (WT run), and without groundwater, with a free drain lower boundary condition for the soil columns (FD run). The initial state of water table depth in the WT run is an equilibrium value calculated using a groundwater model (??) that~~

~~finds a balance between the vertical groundwater recharge, driven by climate, and the lateral groundwater divergence, driven by topography.~~

5 Discussion

~~We have shown that LEAFHYDRO is a solid tool to assess the groundwater-land surface link. Validation with observational water table depth data shows that the model simulates a realistic water table distribution, with shallow groundwater in valleys and deeper under hilltops. The water table seasonal evolution and longer-term trends are also well captured, particularly over shallow water table regions (wtd $\leq$ 8 m).~~

~~We estimated the annual climatology recharge and its mean seasonal cycle, and identified areas of strong groundwater-land surface coupling as those where the net flux from the water table is upward. Annual net~~ The strong groundwater-soil ~~fluxes can be positive (upward flux) to meet ET demands where gravity-driven lateral groundwater flow and river sipping represent a groundwater source in addition to infiltration. In the Iberian Peninsula, this occurs markedly in some river valleys, especially in those with strong groundwater convergence and in drier climates. Upward capillary fluxes can also dominate, albeit not so pronouncedly, over extensive interior semi-arid regions of shallow water table, where precipitation is insufficient to meet ET demands and there is lateral groundwater flow from neighboring mountains. Seasonally, groundwater-soil coupling is strong in spring, when ET is high, maximal in summer, when ET demands are even higher and precipitation is at a minimum, moderate in autumn, when precipitation mostly covers ET, and minimal in winter, which is the season of highest precipitation and lowest ET.~~

~~We have shown direct groundwater influence on land surface hydrology:~~

~~***Groundwater influence on soil moisture distribution and memory***. The strong groundwater-soil~~ coupling has a noticeable impact on soil moisture patterns across the Iberian Peninsula. Where the water table is close to the surface, soil moisture availability increases; thus soil moisture fields have the signature of the presence of shallow groundwater, a pattern superimposed on those due to soil physical properties or climatic conditions. The interaction with groundwater reduces soil moisture seasonality. Upward fluxes from the water table have a larger impact on soil moisture in water scarce seasons (spring and summer). ~~On average over shallow water table regions (31.4 % of the Iberian Peninsula), the soil moisture increase from groundwater is 24.4 % in spring and 23.9 % in summer, whereas in winter and autumn this increase is 19.3 % and 20.9 %, respectively.~~This effect was also found by other studies with LEAFHYDRO and other models accounting for groundwater influence (e.g., ??).

The water table depth shows generally strong seasonal and interannual persistence, responding to long-term climatic conditions but not immediately to seasonal or annual highs and lows in precipitation. Over shallow water table regions, this water table persistence modulates soil moisture long-term evolution. Soil moisture memory is bimodal; soil moisture "remembers" past wet conditions through interaction with a shallow water table, buffering drought effects, and on the other hand, past dry conditions reflected in a depressed water table are passed on to soil moisture, delaying drought recovery.

~~***Groundwater influence on ET fluxes***.~~ The wetter soil induced by the proximity of a shallow water table results in higher ET during the dry growing season, due to higher water availability for vegetation transpiration. The spatial patterns of this

ET enhancement over the studied region resemble those of shallow water table, where there is also strong groundwater-soil coupling. On average over the Iberian Peninsula, our model experiments estimate a 17.4 % (0.24 mm day^{-1}) increase in ET attributable to groundwater. ET maximum enhancement occurs in summer (34.9 %; 0.54 mm day^{-1}). We find the largest impact over the drier southern basins, where ET is water limited: 21.4 % yearly ET enhancement in the Guadalquivir basin and 28.4 % in the Segura basin. The northern Miño/Minho basin, where ET is more ~~energy limited than water limited~~energy-limited than water-limited, presents the lowest groundwater impact on ET, of 13.3 %. In terms of time evolution, the influence of the water table on ET follows the trends of groundwater and soil moisture, which, as discussed previously, show significant persistence from year to year. Therefore, ET enhancement from groundwater "remembers" past dry and wet years and is decoupled from current climate conditions. This result of transpiration enhancement from the groundwater reservoir and its lateral convergence has been reported by the use of other groundwater-land surface coupled models (e.g., **?**).

~~***Groundwater influence on river flow.***~~ Groundwater sustains dry season streamflow. Wet season infiltration recharges groundwater, which is later on drained out by the river network during the dry season where the water table is above riverbed. When comparing with river flow observations, this seasonal behaviour improves on the results from the experiment without groundwater, in which rivers dry out in summer. Notwithstanding, the model produces in general ~~a too constant stream~~ an overly constant river flow and peak events are smoothed out. This problem is related to deficiencies in formulating the connection between groundwater and rivers where the water table in the cell is deep, since subgrid variability to represent riparian and valley zones where rivers and groundwater are in contact, is not considered.

~~Our results of~~ In shallow water table areas, a declining trend in the water table, as the one found over the Ebro basin (see Fig. 14), would be partially sustaining ET; however where the water table is deeper, the lowering groundwater store is sustaining streamflow, explaining why there is more water in the annual mean total river flow in the Ebro in the WT run (Fig. 16). This issue is common to the other Mediterranean basins, more affected by the drought.

Our results show significantly wetter soil and enhanced ET over shallow water table regions. Here, we have supported this results with the validation of water table depth positions across the Iberian Peninsula. These results suggest that groundwater might have a ~~seizable~~ sizable impact on climate over the Iberian Peninsula. For instance, it can enhance convective precipitation through local moisture recycling or lead to summer cooling lowering sensible fluxes and producing more cloudiness. Coupled land hydrology-climate models are needed to elucidate this question. We stress that this line of research might find similar results ~~and conclusions~~ if a dynamic groundwater model is applied in other semi-arid regions of the world, which cover around 15 % of the global land area (**?**).

6 Summary and conclusions

In this paper, we have studied the influence of groundwater on soil moisture distribution and memory, ET fluxes and surface waters over the Iberian Peninsula. We used the LEAFHYDRO Land Surface Model, which represents the water table interactions with the unsaturated soil above and rivers, and lateral groundwater flow. We performed 10-year simulations with the groundwater scheme activated (WT run), and without groundwater, using a free-drain lower boundary condition for the soil column (FD run). The initial state of water table depth in the WT run is an equilibrium value calculated using a groundwater model (**??**) that finds a balance between the vertical groundwater recharge, driven by climate, and the lateral groundwater divergence, driven by topography.

We have shown that LEAFHYDRO is a solid tool to assess the groundwater-land surface link. Validation with observational water table depth data shows that the model simulates a realistic water table distribution, with shallow groundwater in valleys and deeper under hilltops. The water table seasonal evolution and longer-term trends are also well captured, particularly over shallow water table regions ($wtd \lesssim 8$ m).

We estimated the annual climatology net recharge and its mean seasonal cycle, and identified areas of strong groundwater-land surface coupling as those where the net flux from the water table is upward. Annual net groundwater-soil fluxes can be positive (upward flux) to meet ET demands where gravity-driven lateral groundwater flow and river sipping represent a groundwater source in addition to infiltration. In the Iberian Peninsula, this occurs markedly in some river valleys, especially in those with strong groundwater convergence and in drier climates. Upward capillary fluxes can also dominate, albeit not so pronouncedly, over extensive interior semi-arid regions of shallow water table, where precipitation is insufficient to meet ET demands and there is lateral groundwater flow from neighboring mountains. Seasonally, groundwater-soil coupling is strong in spring, when ET is high, maximal in summer, when ET demands are even higher and precipitation is at a minimum, moderate in autumn, when precipitation mostly covers ET, and minimal in winter, which is the season of highest precipitation and lowest ET.

We have shown direct groundwater influence on land surface hydrology; controlling soil moisture distribution, providing strong seasonal and interannual memory to the soil wetness that ultimately reflects in enhanced ET fluxes during precipitation scarcity periods, and sustaining the dry season streamflow.

Code and data availability. This study uses LEAFHYDRO, which is a Land Surface and Groundwater model developed from the LEAF v2 LSM (see Section 2.1). The atmospheric forcing dataset ERA-Interim is available after registration with the European Centre for Medium-Range Weather Forecast (ECMWF) here: http://ecmwf.int/research/era/. The forcing IB02 precipitation dataset and the site water table and river flow data used for validation were collected by the authors via request to references given in Sections 2.3 and 3. LEAFHYDRO output data for this work are available from the corresponding author upon request.

Competing interests. The authors declare that they have no conflict of interest.

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5 References

Libro Blanco del Agua en España [In Spanish], Centro de Publicaciones del Ministerio de Medio Ambiente, Spain, 2000.

Avissar, R., Avissar, P., Mahrer, Y., and Bravdo, B. A.: A model to simulate response of plant stomata to environmental conditions, Agricultural and Forest Meteorology, 34, 21 – 29, https://doi.org/10.1016/0168-1923(85)90051-6, 1985.

Beljaars, A. C. M., Viterbo, P., Miller, M. J., and Betts, A. K.: The Anomalous Rainfall over the United States during July 1993: Sensitivity to Land Surface Parameterization and Soil Moisture Anomalies, Monthly Weather Review, 124, 362–383, https://doi.org/10.1175/1520-0493(1996)124<0362:TAROTU>2.0.CO;2, 1996.

Belo-Pereira, M., Dutra, E., and Viterbo, P.: Evaluation of global precipitation data sets over the Iberian Peninsula, Journal of Geophysical Research: Atmospheres, 116, https://doi.org/10.1029/2010JD015481, d20101, 2011.

Berrisford, P., Dee, D., Poli, P., Brugge, R., Fielding, M., Fuentes, M., Kållberg, P., Kobayashi, S., Uppala, S., and Simmons, A.: The ERA-Interim archive Version 2.0, ECMWF Report, ERA Report Series, p. 23, https://www.ecmwf.int/node/8174, 2011.

Betts, A. K.: Understanding Hydrometeorology Using Global Models, Bulletin of the American Meteorological Society, 85, 1673–1688, https://doi.org/10.1175/BAMS-85-11-1673, 2004.

Clapp, R. B. and Hornberger, G. M.: Empirical equations for some soil hydraulic properties, Water Resources Research, 14, 601–604, https://doi.org/10.1029/WR014i004p00601, 1978.

Clark, D. B. and Gedney, N.: Representing the effects of subgrid variability of soil moisture on runoff generation in a land surface model, Journal of Geophysical Research: Atmospheres, 113, https://doi.org/10.1029/2007JD008940, d10111, 2008.

Daccache, A., Ciurana, J. S., Diaz, J. A. R., and Knox, J. W.: Water and energy footprint of irrigated agriculture in the Mediterranean region, Environmental Research Letters, 9, 124 014, 2014.

David, T. S., Henriques, M. O., Kurz-Besson, C., Nunes, J., Valente, F., Vaz, M., Pereira, J. S., Siegwolf, R., Chaves, M. M., Gazarini, L. C., and David, J. S.: Water-use strategies in two co-occurring Mediterranean evergreen oaks: surviving the summer drought, Tree Physiology, 27, 793–803, https://doi.org/10.1093/treephys/27.6.793, 2007.

de Graaf, I. E. M., Sutanudjaja, E. H., van Beek, L. P. H., and Bierkens, M. F. P.: A high-resolution global-scale groundwater model, Hydrology and Earth System Sciences, 19, 823–837, https://doi.org/10.5194/hess-19-823-2015, 2015.

Decharme, B., Alkama, R., Douville, H., Becker, M., and Cazenave, A.: Global Evaluation of the ISBA-TRIP Continental Hydrological System. Part II: Uncertainties in River Routing Simulation Related to Flow Velocity and Groundwater Storage, Journal of Hydrometeorology, 11, 601–617, https://doi.org/10.1175/2010JHM1212.1, 2010.

Decker, M.: Development and evaluation of a new soil moisture and runoff parameterization for the CABLE LSM including subgrid-scale processes, Journal of Advances in Modeling Earth Systems, 7, 1788–1809, https://doi.org/10.1002/2015MS000507, 2015.

EEA: Corine Land Cover report – Part 2: Nomenclature, http://www.eea.europa.eu/publica- tions/COR0-part2 (Date: 31.05.2016), 1994.

EMG: Global Drylands: A UN system-wide response, United Nations Environment Management Group, https://unemg.org/images/emgdocs/publications/Global_Drylands_Full_Report.pdf, 2011.

Fan, Y. and Miguez-Macho, G.: Potential groundwater contribution to Amazon evapotranspiration, Hydrology and Earth System Sciences, 14, 2039–2056, https://doi.org/10.5194/hess-14-2039-2010, 2010.

Fan, Y., Miguez-Macho, G., Weaver, C. P., Walko, R., and Robock, A.: Incorporating water table dynamics in climate modeling: 1. Water table observations and equilibrium water table simulations, Journal of Geophysical Research: Atmospheres, 112, https://doi.org/10.1029/2006JD008111, d10125, 2007.

Fan, Y., Li, H., and Miguez-Macho, G.: Global Patterns of Groundwater Table Depth, Science, 339, 940–943, https://doi.org/10.1126/science.1229881, 2013.

Fan, Y., Miguez-Macho, G., Jobbágy, E. G., Jackson, R. B., and Otero-Casal, C.: Hydrologic regulation of plant rooting depth, Proceedings of the National Academy of Sciences, 114, 10 572–10 577, https://doi.org/10.1073/pnas.1712381114, 2017.

Garrido, A., Martínez-Santos, P., and Llamas, M. R.: Groundwater irrigation and its implications for water policy in semiarid countries: the Spanish experience, Hydrogeology Journal, 14, 340, https://doi.org/10.1007/s10040-005-0006-z, 2006.

Gestal-Souto, L., Martínez-de la Torre, A., and Ríos-Entenza, A.: The role of groundwater on the Iberian climate, precipitation regime and land-atmosphere interactions, Revista Real Academia Galega de Ciencias [In Galician], 29, 89–198, 2010.

Harbaugh, A. W., Banta, E. R., Hill, M. C., and McDonals, M. G.: Modflow-2000, the U.S. Geological Survey modular groundwater model—User guide to modularization concepts and the groundwater flow process, U.S. Geolological Survey Open File Report, pp. 00–92, https://doi.org/10.3133/ofr200092, 2000.

Hassan, S. T., Lubczynski, M. W., Niswonger, R. G., and Su, Z.: Surface–groundwater interactions in hard rocks in Sardon Catchment of western Spain: An integrated modeling approach, Journal of Hydrology, 517, 390 – 410, https://doi.org/10.1016/j.jhydrol.2014.05.026, 2014.

Herrera, S., Gutiérrez, J. M., Ancell, R., Pons, M. R., Frías, M. D., and Fernández, J.: Development and analysis of a 50-year high-resolution daily gridded precipitation dataset over Spain (Spain02), International Journal of Climatology, 32, 74–85, https://doi.org/10.1002/joc.2256, 2012.

Hunink, J. E., Contreras, S., Soto-García, M., Martin-Gorriz, B., Martinez-Álvarez, V., and Baille, A.: Estimating groundwater use patterns of perennial and seasonal crops in a Mediterranean irrigation scheme, using remote sensing, Agricultural Water Management, 162, 47 – 56, https://doi.org/10.1016/j.agwat.2015.08.003, 2015.

Jiménez, P. A., de Arellano, J. V.-G., González-Rouco, J. F., Navarro, J., Montávez, J. P., García-Bustamante, E., and Dudhia, J.: The Effect of Heat Waves and Drought on Surface Wind Circulations in the Northeast of the Iberian Peninsula during the Summer of 2003, Journal of Climate, 24, 5416–5422, https://doi.org/10.1175/2011JCLI4061.1, 2011.

Koster, R. D., Mahanama, S. P. P., Yamada, T. J., Balsamo, G., Berg, A. A., Boisserie, M., Dirmeyer, P. A., Doblas-Reyes, F. J., Drewitt, G., Gordon, C. T., Guo, Z., Jeong, J.-H., Lawrence, D. M., Lee, W.-S., Li, Z., Luo, L., Malyshev, S., Merryfield, W. J., Seneviratne, S. I., Stanelle, T., van den Hurk, B. J. J. M., Vitart, F., and Wood, E. F.: Contribution of land surface initialization to subseasonal forecast skill: First results from a multi-model experiment, Geophysical Research Letters, 37, https://doi.org/10.1029/2009GL041677, l02402, 2010.

Lehner, B., Verdin, K., and Jarvis, A.: New Global Hydrography Derived From Spaceborne Elevation Data, Eos, Transactions American Geophysical Union, 89, 93–94, https://doi.org/10.1029/2008EO100001, 2008.

Leung, L. R., Huang, M., Qian, Y., and Liang, X.: Climate–soil–vegetation control on groundwater table dynamics and its feedbacks in a climate model, Climate Dynamics, 36, 57–81, https://doi.org/10.1007/s00382-010-0746-x, 2011.

Liu, Z., Chen, H., Huo, Z., Wang, F., and Shock, C. C.: Analysis of the contribution of groundwater to evapotranspiration in an arid irrigation district with shallow water table, Agricultural Water Management, 171, 131 – 141, https://doi.org/10.1016/j.agwat.2016.04.002, 2016.

Lo, M.-H. and Famiglietti, J. S.: Effect of water table dynamics on land surface hydrologic memory, Journal of Geophysical Research: Atmospheres, 115, https://doi.org/10.1029/2010JD014191, d22118, 2010.

Lubczynski, M. W.: The hydrogeological role of trees in water-limited environments, Hydrogeology Journal, 17, 247, https://doi.org/10.1007/s10040-008-0357-3, 2008.

LucasPicher, P., Arora, V. K., Caya, D., and Laprise, R.: Implementation of a largescale variable velocity river flow routing algorithm in the Canadian Regional Climate Model (CRCM), Atmosphere-Ocean, 41, 139–153, https://doi.org/10.3137/ao.410203, 2003.

Martinez, J. A., Dominguez, F., and Miguez-Macho, G.: Effects of a Groundwater Scheme on the Simulation of Soil Moisture and Evapotranspiration over Southern South America, Journal of Hydrometeorology, 17, 2941–2957, https://doi.org/10.1175/JHM-D-16-0051.1, 2016.

Martínez-de la Torre, A., Blyth, E. M., and Weedon, G. P.: Using observed river flow data to improve the hydrological functioning of the JULES land surface model (vn4.3) used for regional coupled modelling in Great Britain (UKC2), Geoscientific Model Development, 12, 765–784, https://doi.org/10.5194/gmd-12-765-2019, 2019.

Martínez-Cortina, L., Mejías-Moreno, M., Díaz-Muñoz, J. A., Morales-García, R., and Ruiz-Hernández, J. M.: Estimation of groundwater resources in the upper Guadiana basin together with some observations concerning the definitions of renewable and available resources, Boletín Geológico y Minero [In Spanish], 122, 2011.

Maxwell, R. M. and Condon, L. E.: Connections between groundwater flow and transpiration partitioning, Science, 353, 377–380, https://doi.org/10.1126/science.aaf7891, 2016.

Maxwell, R. M. and Kollet, S. J.: Interdependence of groundwater dynamics and land-energy feedbacks under climate change, Nature Geoscience, 1, 665–669, https://doi.org/10.1038/ngeo315, 2008.

Maxwell, R. M. and Miller, N. L.: Development of a Coupled Land Surface and Groundwater Model, Journal of Hydrometeorology, 6, 233–247, https://doi.org/10.1175/JHM422.1, 2005.

Maxwell, R. M., Lundquist, J. K., Mirocha, J. D., Smith, S. G., Woodward, C. S., and Tompson, A. F. B.: Development of a Coupled Groundwater-Atmosphere Model, Monthly Weather Review, 139, 96–116, https://doi.org/10.1175/2010MWR3392.1, 2011.

Mejías-Moreno, M., López-Gutiérrez, J., and Martínez-Cortina, L.: Hydrogeological characteristics and groundwater evolution of the Western La Mancha unit: The influence of the wet period 2009-2011, Boletín Geológico y Minero [In Spanish], 123, 2012.

Miguez-Macho, G. and Fan, Y.: The role of groundwater in the Amazon water cycle: 2. Influence on seasonal soil moisture and evapotranspiration, Journal of Geophysical Research: Atmospheres, 117, https://doi.org/10.1029/2012JD017540, d15114, 2012a.

Miguez-Macho, G. and Fan, Y.: The role of groundwater in the Amazon water cycle: 1. Influence on seasonal streamflow, flooding and wetlands, Journal of Geophysical Research: Atmospheres, 117, https://doi.org/10.1029/2012JD017539, d15113, 2012b.

Miguez-Macho, G., Fan, Y., Weaver, C. P., Walko, R., and Robock, A.: Incorporating water table dynamics in climate modeling: 2. Formulation, validation, and soil moisture simulation, Journal of Geophysical Research: Atmospheres, 112, https://doi.org/10.1029/2006JD008112, d13108, 2007.

Niu, G.-Y., Yang, Z.-L., Dickinson, R. E., Gulden, L. E., and Su, H.: Development of a simple groundwater model for use in climate models and evaluation with Gravity Recovery and Climate Experiment data, Journal of Geophysical Research: Atmospheres, 112, https://doi.org/10.1029/2006JD007522, d07103, 2007.

Rios-Entenza, A. and Miguez-Macho, G.: Moisture recycling and the maximum of precipitation in spring in the Iberian Peninsula, Climate Dynamics, 42, 3207–3231, https://doi.org/10.1007/s00382-013-1971-x, 2014.

Seneviratne, S. I., Lüthi, D., Litschi, M., and Schär, C.: Land–atmosphere coupling and climate change in Europe, Nature, 443, 205–209, https://doi.org/10.1038/nature05095, 2006.

Serrano, L. and Zunzunegui, M.: The relevance of preserving temporary ponds during drought: hydrological and vegetation changes over a 16-year period in the Doñana National Park (south-west Spain), Aquatic Conservation: Marine and Freshwater Ecosystems, 18, 261–279, https://doi.org/10.1002/aqc.830, 2008.

Sobrino, J., Gómez, M., Jiménez-Muñoz, J., and Olioso, A.: Application of a simple algorithm to estimate daily evapotranspiration from NOAAâ€“AVHRR images for the Iberian Peninsula, Remote Sensing of Environment, 110, 139 – 148, https://doi.org/https://doi.org/10.1016/j.rse.2007.02.017, 2007.

Sutanudjaja, E., de Jong, S., van Geer, F., and Bierkens, M.: Using ERS spaceborne microwave soil moisture observations to predict groundwater head in space and time, Remote Sensing of Environment, 138, 172 – 188, https://doi.org/10.1016/j.rse.2013.07.022, 2013.

Sánchez, N., Martínez-Fernández, J., Calera, A., Torres, E., and Pérez-Gutiérrez, C.: Combining remote sensing and in situ soil moisture data for the application and validation of a distributed water balance model (HIDROMORE), Agricultural Water Management, 98, 69 – 78, https://doi.org/10.1016/j.agwat.2010.07.014, 2010.

Vergnes, J.-P., Decharme, B., Alkama, R., Martin, E., Habets, F., and Douville, H.: A Simple Groundwater Scheme for Hydrological and Climate Applications: Description and Offline Evaluation over France, Journal of Hydrometeorology, 13, 1149–1171, https://doi.org/10.1175/JHM-D-11-0149.1, 2012.

Vergnes, J.-P., Decharme, B., and Habets, F.: Introduction of groundwater capillary rises using subgrid spatial variability of topography into the ISBA land surface model, Journal of Geophysical Research: Atmospheres, 119, 11,065–11,086, https://doi.org/10.1002/2014JD021573, 2014.

Vincke, C. and Thiry, Y.: Water table is a relevant source for water uptake by a Scots pine (Pinus sylvestris L.) stand: Evidences from continuous evapotranspiration and water table monitoring, Agricultural and Forest Meteorology, 148, 1419 – 1432, https://doi.org/10.1016/j.agrformet.2008.04.009, 2008.

Walko, R. L., Band, L. E., Baron, J., Kittel, T. G. F., Lammers, R., Lee, T. J., Ojima, D., Sr., R. A. P., Taylor, C., Tague, C., Tremback, C. J., and Vidale, P. L.: Coupled Atmosphere–Biophysics–Hydrology Models for Environmental Modeling, Journal of Applied Meteorology, 39, 931–944, https://doi.org/10.1175/1520-0450(2000)039<0931:CABHMF>2.0.CO;2, 2000.

Westerhoff, R., White, P., and Miguez-Macho, G.: Application of an improved global-scale groundwater model for water table estimation across New Zealand, Hydrology and Earth System Sciences, 22, 6449–6472, https://doi.org/10.5194/hess-22-6449-2018, 2018.

Yuan, X., Xie, Z., Zheng, J., Tian, X., and Yang, Z.: Effects of water table dynamics on regional climate: A case study over east Asian monsoon area, Journal of Geophysical Research: Atmospheres, 113, https://doi.org/10.1029/2008JD010180, d21112, 2008.

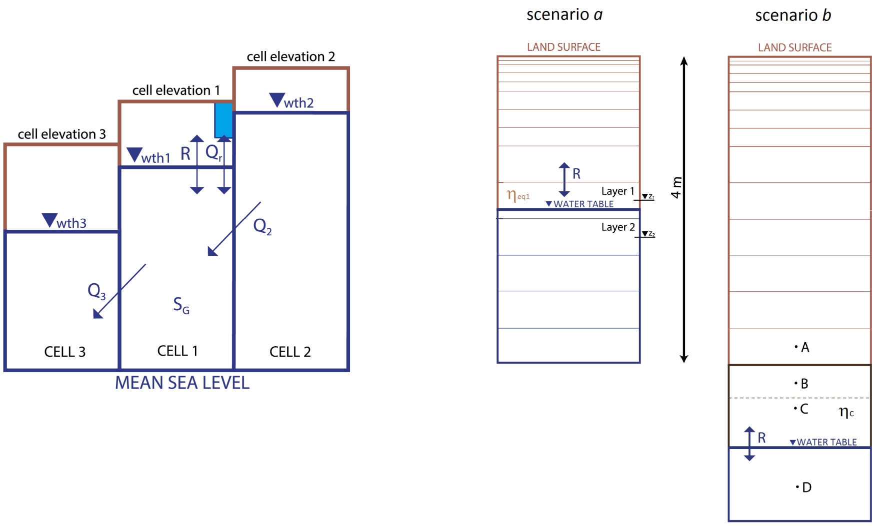


Figure 1. Left: LEAFHYDRO groundwater balance in a model cell (cell 1). Right: LEAFHYDRO double scenario to calculate the water flux through the water table (R).

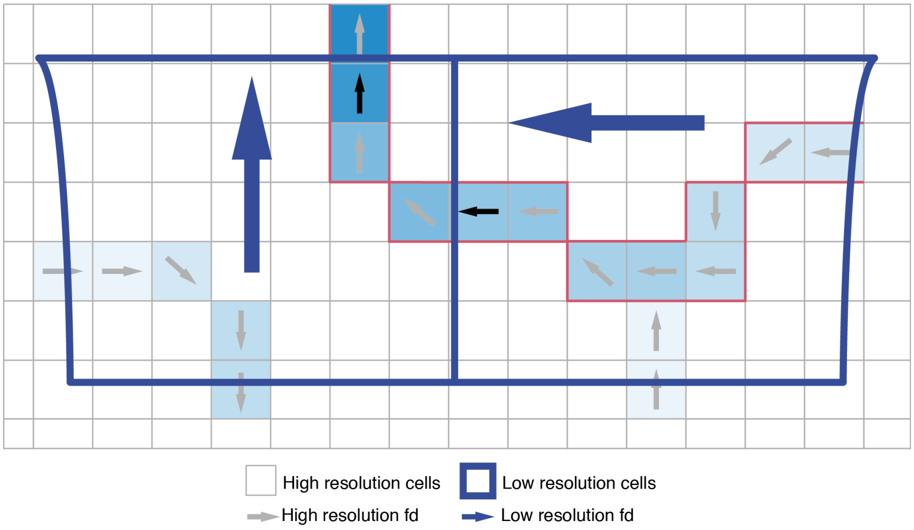


Figure 2. Sketch for the methodology to calculate river parameters from the HydroSHEDS high resolution database to the 2.5 km grid domain in LEAFHYDRO.

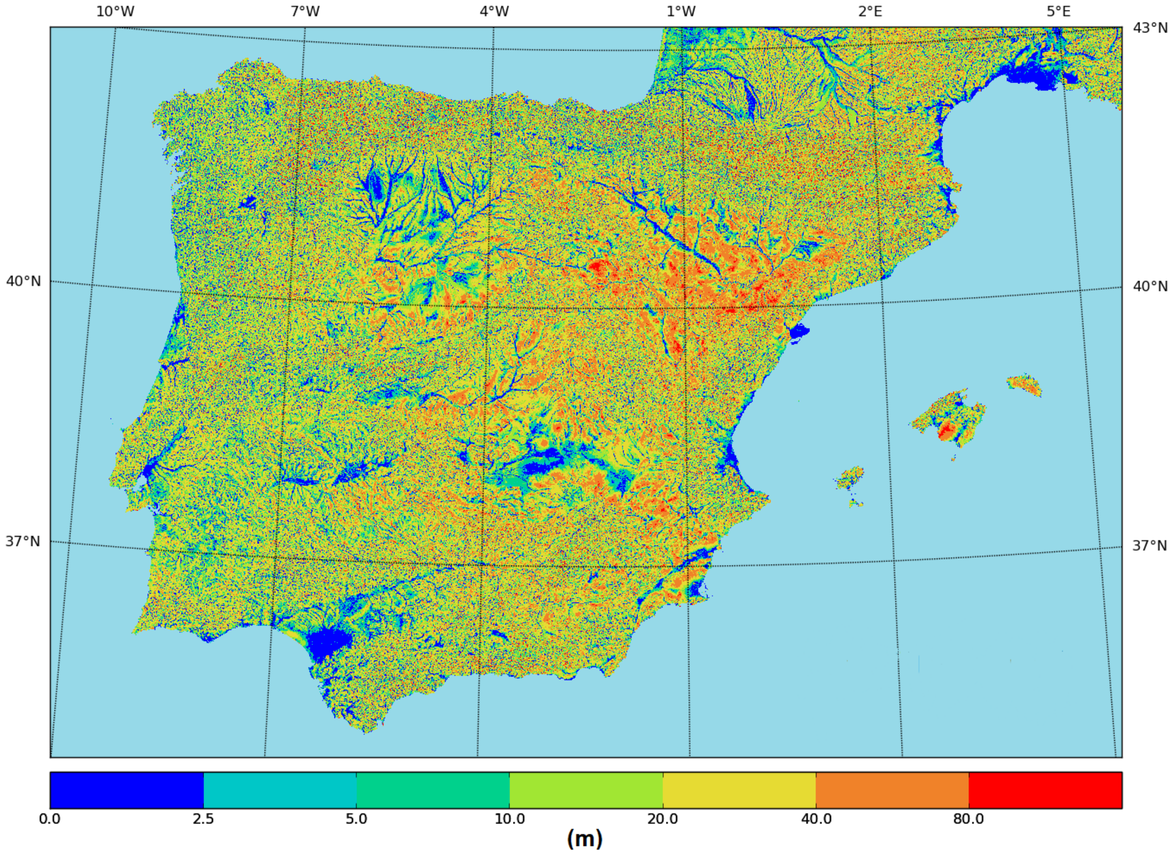


Figure 3. Iberian Peninsula Equilibrium Water Table Depth (m). The spatial resolution ~~of the~~ comes from topography data used for the Iberian Peninsula EWTD calculation ~~is~~ (9 arc second~~(~~; ∼213x278 m at 40°N)~~and it~~. This EWTD was validated with 2601 observation points (**?**).

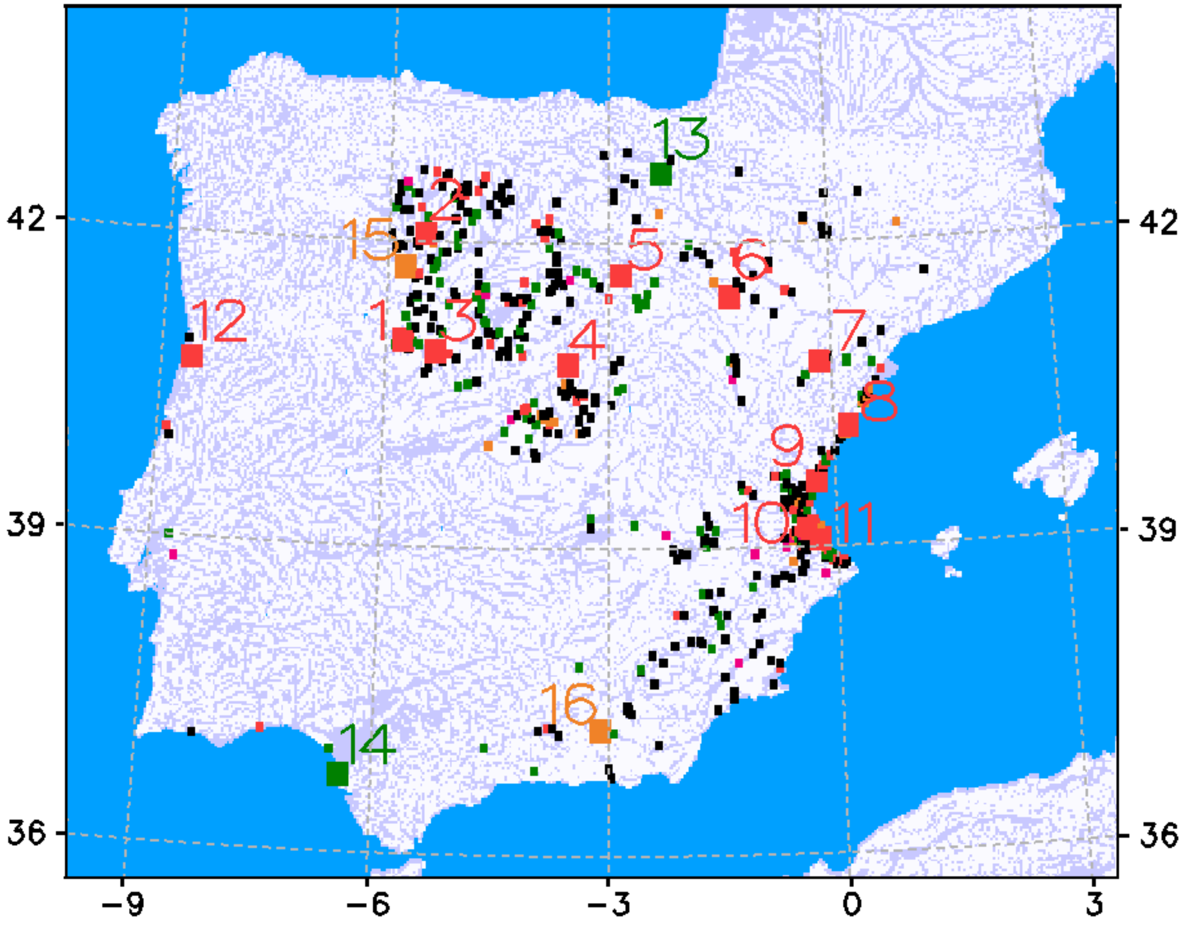


Figure 4. Shallow water table zones (light blue shades) and Iberian Peninsula ~~wtd~~ *wtd* observation stations (dots). Red ~~points~~ dots are locations where observed and simulated ~~wtd~~ *wtd* differences are within 2 m; green ~~points~~ dots are stations with correlation over 0.5 between observed and simulated ~~wtd~~ *wtd* series (full time series available in the observed data); purple ~~points~~ dots are stations with steep ~~wtd~~ *wtd* slope ($\geq$0.035 m month^{-1}), well captured by the model; orange ~~points~~ dots are cells containing more than one observation station; black dots are cells where none of the above criteria is met by the model. Over cells where more than one validation criteria is reached the point adopts the colour of the first criterium met (in the order presented here); for instance, cells with mean *wtd* differences lower than 2 m and also correlations above 0.5, are shown as red on the map.

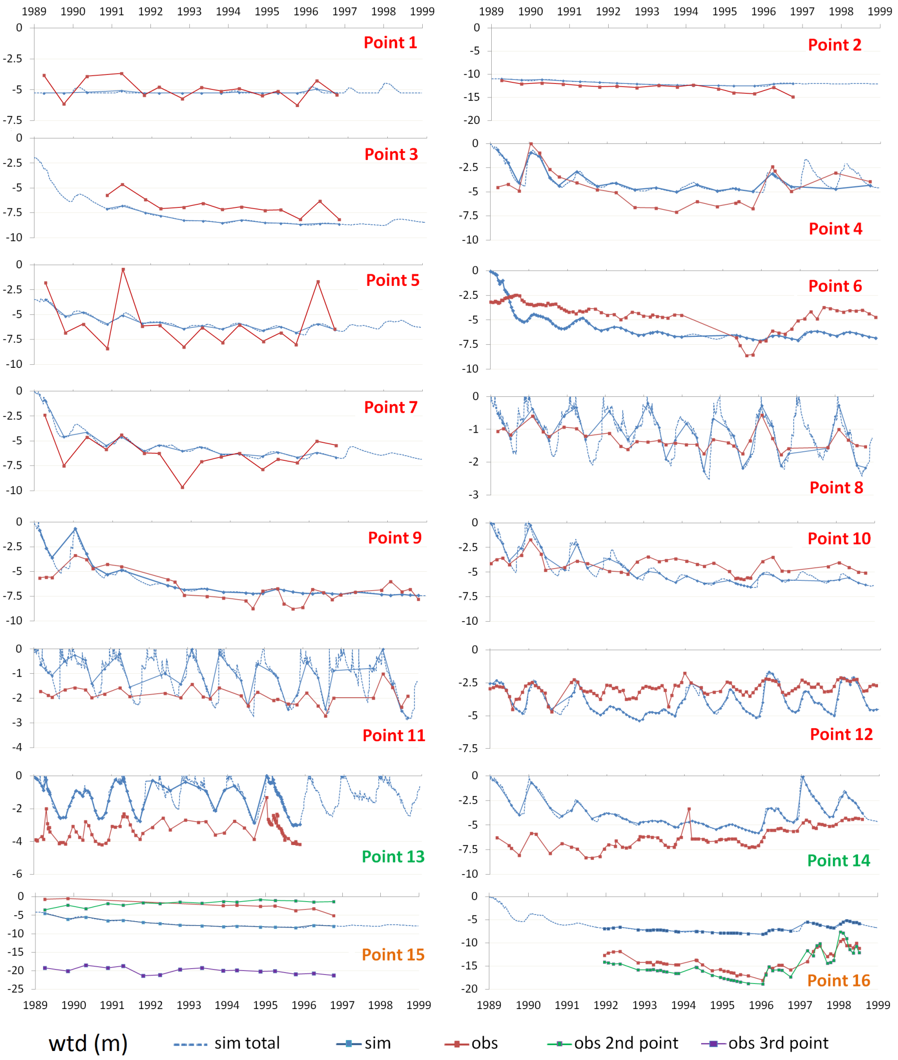


Figure 5. Water table depth (m) time series along the 10-year period at the stations numbered in Fig. 4 (1 to 16); observed (connected red dots), simulated at observation times (connected blue dots), simulated daily (dashed blue line), and observed at the second and third observation points within one model cell (connected green and purple dots, respectively).

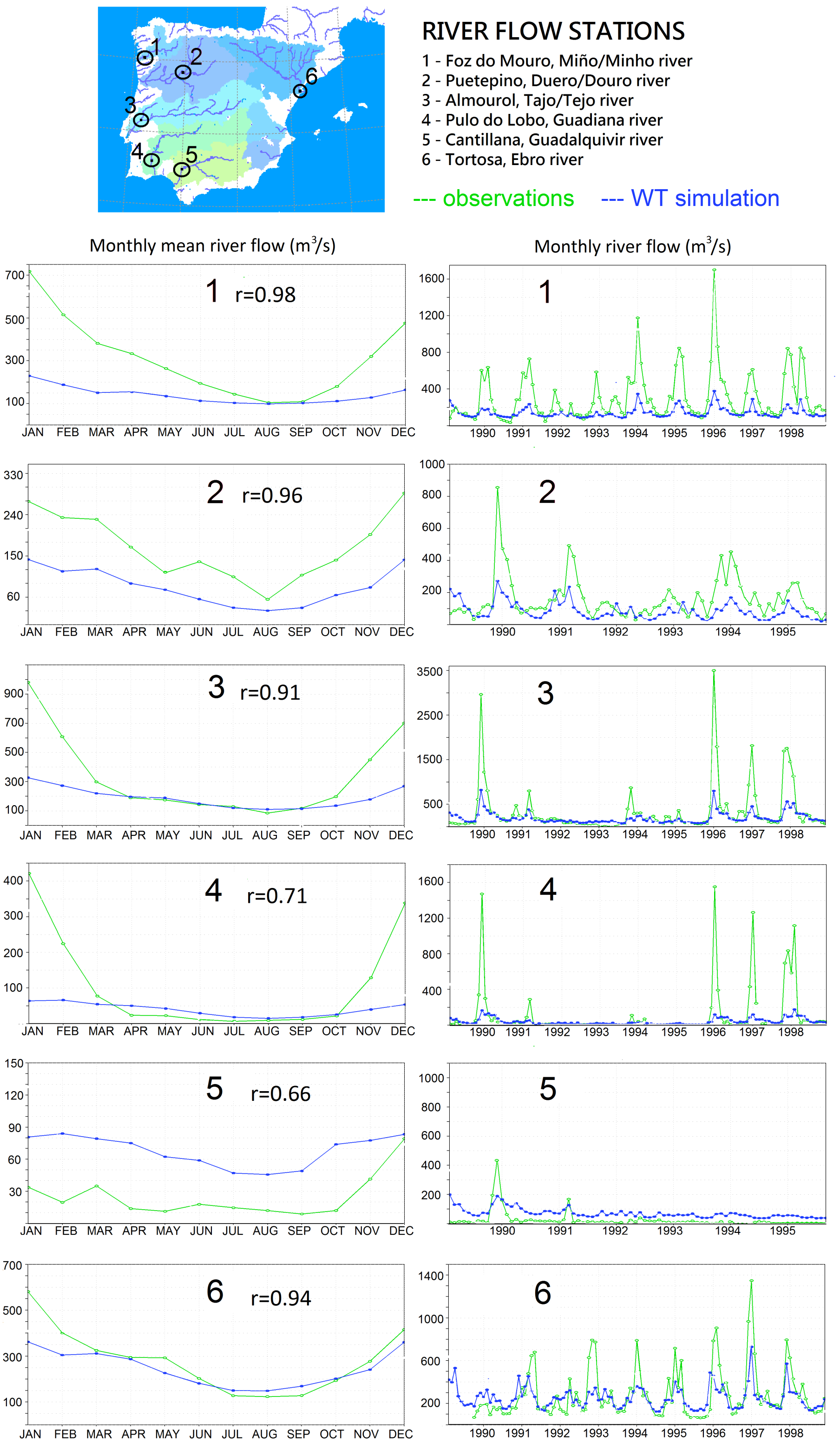

RIVER FLOW STATIONS
1 - Foz do Mouro, Miño/Minho river
2 - Puetepino, Duero/Douro river
3 - Almourol, Tajo/Tejo river
4 - Pulo do Lobo, Guadiana river
5 - Cantillana, Guadalquivir river
6 - Tortosa, Ebro river
--- observations
--- WT simulation
Monthly mean river flow (m3/s)
Monthly river flow (m3/s)
1 r=0.98
2 r=0.96
3 r=0.91
4 r=0.71
5 r=0.66
6 r=0.94
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
1990 1991 1992 1993 1994 1995 1996 1997 1998

Figure 6. Top: River flow gauge stations at the 6 largest Iberian rivers selected for validation: Foz do Mouro station close to the Miño/Minho river mouth (station 1, drainage area of 15,407 km^2), Puentepino station in the Duero/Douro river basin (station 2, drainage area of 63,160 km^2), Almourol station in the Tajo/Tejo basin (station 3, drainage area of 67,482 km^2), Pulo do Lobo station in the Guadiana basin (station 4, drainage area of 61,885 km^2), Cantillana station in the Guadalquivir basin (station 5, drainage area of 44,871 km^2), and Tortosa station by the Ebro river mouth (station 6, drainage area of 84,230 km^2). Graphs on the left: Mean monthly river flow (m^3 s^{-1}) and correlation index between observed and simulated time series (we use the mean seasonal cycle for the index). Graphs on the right: Monthly river flow (m^3 s^{-1}) time series. Blue for the WT simulation, green for observations. The Puentepino and Cantillana stations data availability ends in 1995.

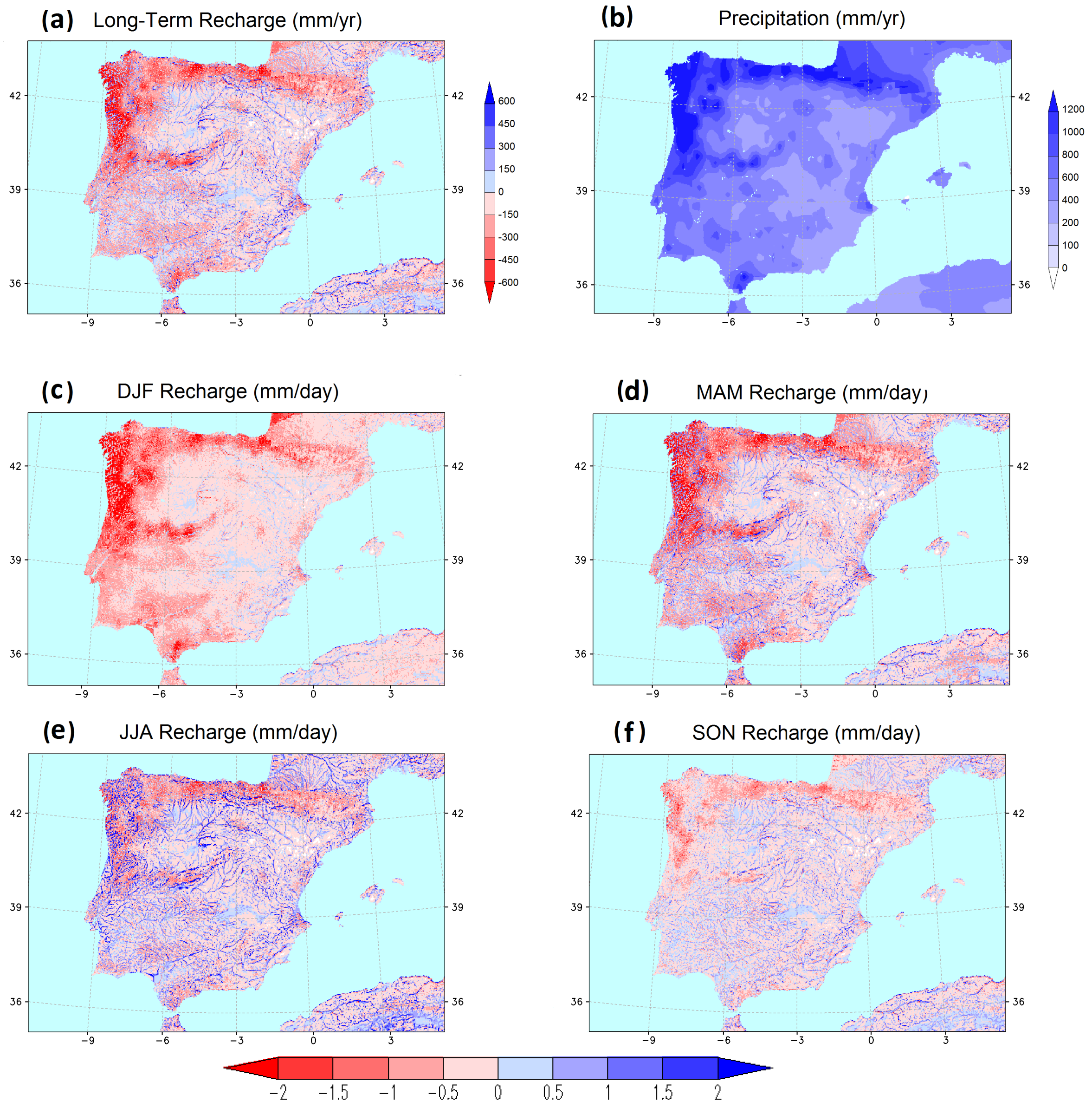


Figure 7. (a) Long-term recharge (mm yr^{-1}), defined as net moisture flux at the water table. (b) Mean precipitation (mm yr^{-1}). From (c) to (f): Mean seasonal recharge (mm day^{-1}) for winter (DJF), spring (MAM), summer (JJA) and autumn (SON). In the recharge plots, red colours indicate negative (downward) recharge and blue colours correspond to positive (upward) flux. All values are calculated for the 10-year simulation period

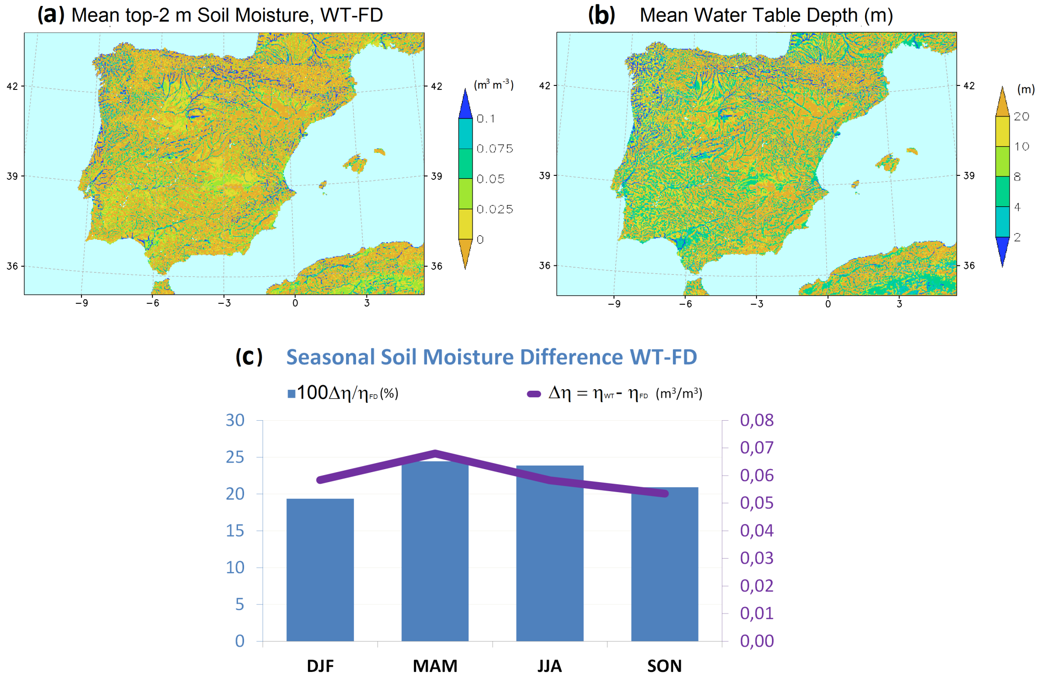


Figure 8. (a) Mean top-2 m soil moisture difference (WT-FD; m^3 m^{-3}) . (b) Mean ~~wtd~~ wtd (m). (c) Seasonal top-2m soil moisture differences between the experiments with and without groundwater (WT-FD), averaged over the Iberian Peninsula shallow water table regions (~~wtd~~ $wtd \leq 8$ m): percent of soil moisture increase (%; blue columns) and soil moisture absolute difference (m^3 m^{-3}; purple line).

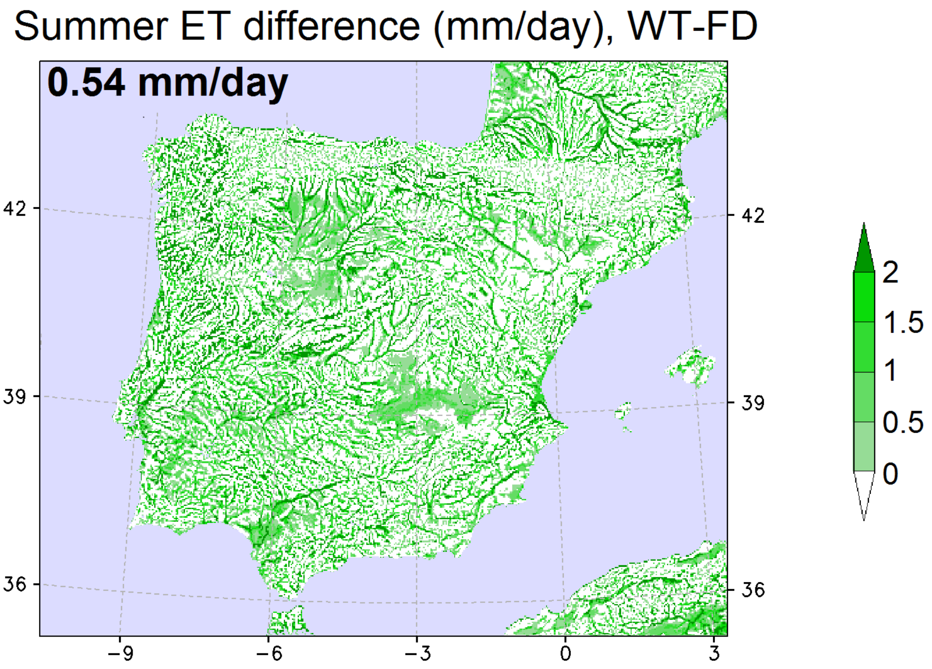


Figure 9. Mean summer (JJA) ET difference (mm day^{-1}) between the experiments with and without groundwate (WT - FD) for the 10-year simulation period, and averaged value over the Iberian Peninsula (black text in top-left corner).

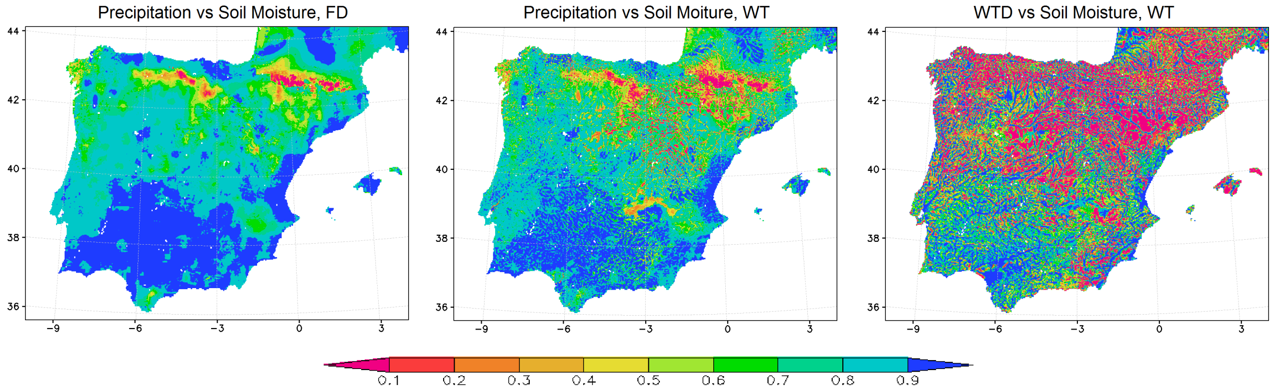
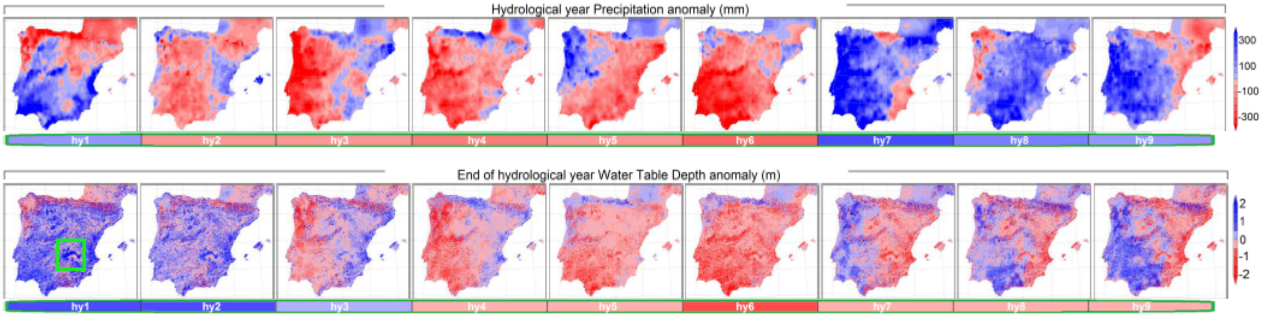
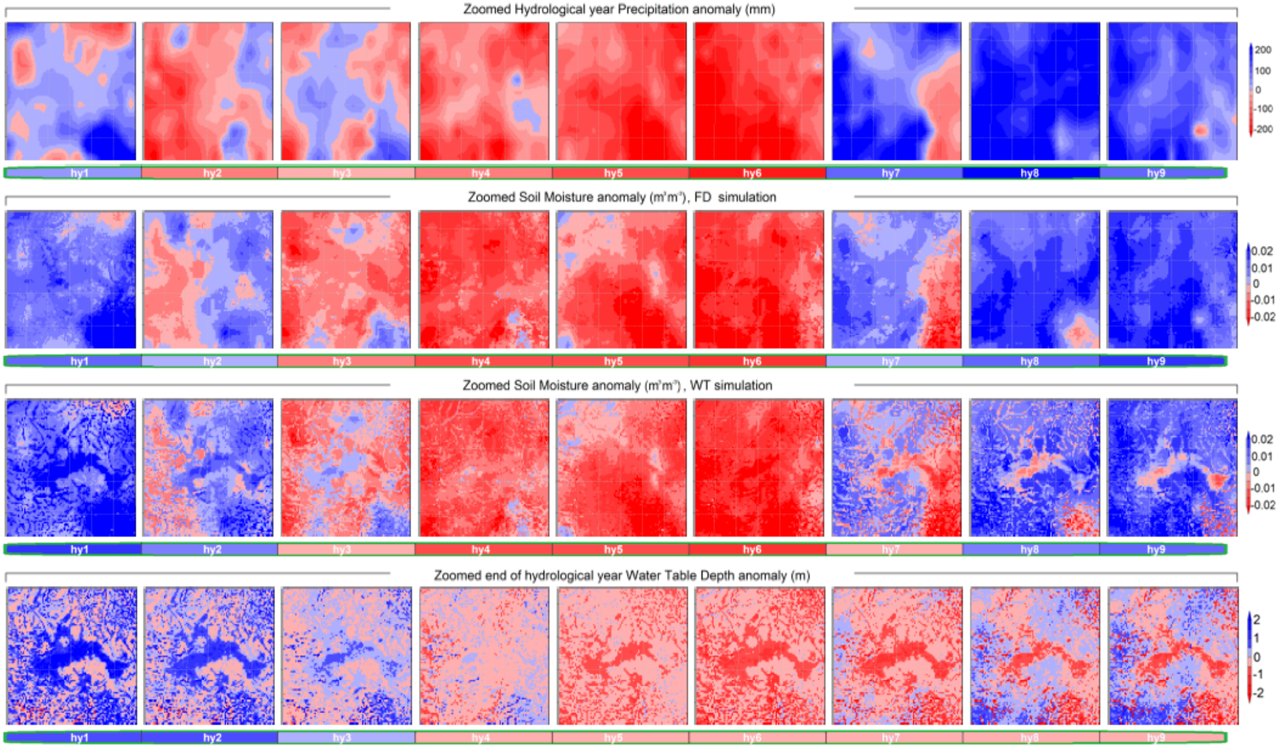


Figure 10. Correlation maps of the yearly anomaly time series for the Iberian Peninsula along the 9 complete hydrological years simulated. Left: between precipitation and soil moisture in the ~~groundwater~~ free-drain (~~WT~~FD) run. Centre: between precipitation and soil moisture in the ~~free drain~~ groundwater (~~FD~~WT) run. Right: between ~~wtd~~ *wtd* and soil moisture in the grounwater (WT) run.


Hydrological year Precipitation anomaly (mm)

End of hydrological year Water Table Depth anomaly (m)

Figure 11. Hydrological year anomaly plots. Each column corresponds to a complete hydrological year (hy1 to hy9). Top row: total yearly precipitation anomalies (mm). Bottom row: end of hydrological year (September 1st) ~~wtd~~ *wtd* anomalies (m). Colour bars below each plot represent the averaged anomaly value for the Iberian Peninsula.


Zoomed Hydrological year Precipitation anomaly (mm)

Zoomed Soil Moisture anomaly (m^{3}m^{-3}), FD simulation

Zoomed Soil Moisture anomaly (m^{3}m^{-3}), WT simulation

Zoomed end of hydrological year Water Table Depth anomaly (m)

Figure 12. Zoomed hydrological year anomaly plots in the 250x225 km^2 region highlighted in light green in Fig. 11 (bottom row, first plot), containing La Mancha Húmeda, approximately between 38° and 40.2° latitude and -4.5° and -1.5° longitude. Each column corresponds to a complete hydrological year (hy1 to hy9). Rows from top to bottom: total yearly precipitation anomalies (mm), top-2 m soil moisture anomalies (m^3 m^{-3}) in the FD run, top-2 m year soil moisture anomalies (m^3 m^{-3}) in the WT run, and end of hydrological year (September 1st) ~~wtd~~ *wtd* anomalies (m). Colour bars below each plot represent the averaged anomaly value for the zoomed area.

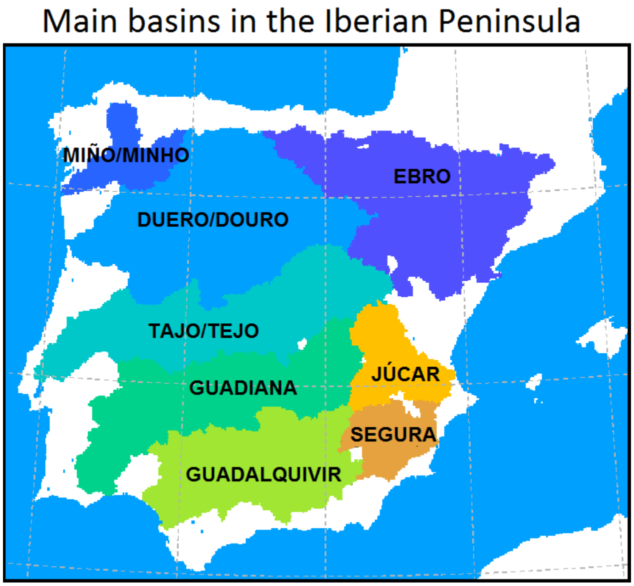


Figure 13. Main river basins in the Iberian Peninsula.

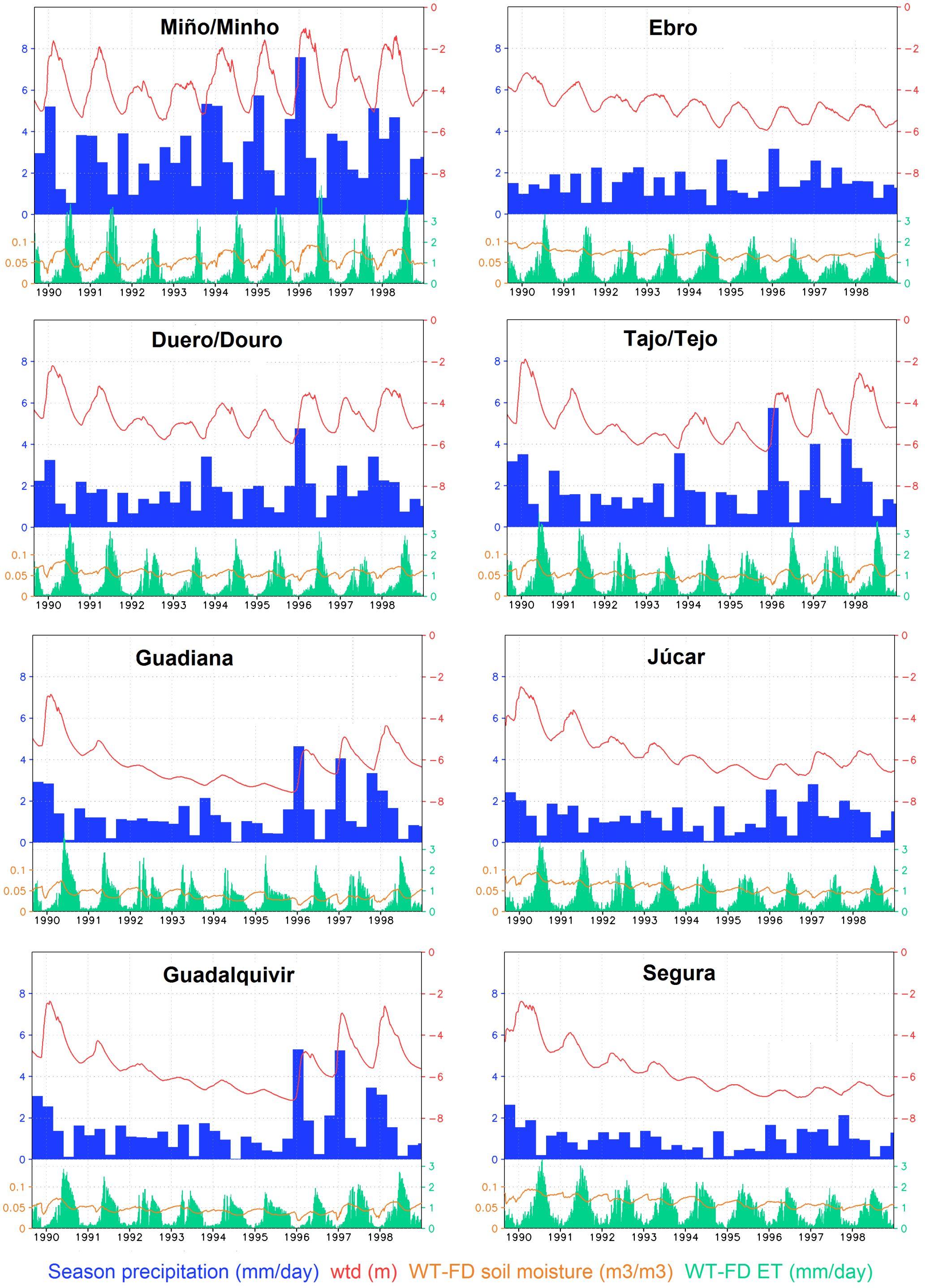


Figure 14. Results for the river basins in Fig. 13. Time series of seasonal precipitation averaged over the entire basin (mm day^{-1}; blue bars), and averages over shallow water table cells only (~~wtd~~ $wtd \leq 8$ m) of ~~wtd~~ wtd (m; red line), WT-FD top-2 m soil moisture difference (m^{3} m^{-3}; orange line) and WT-FD ET difference (mm day^{-1}; light green bars).

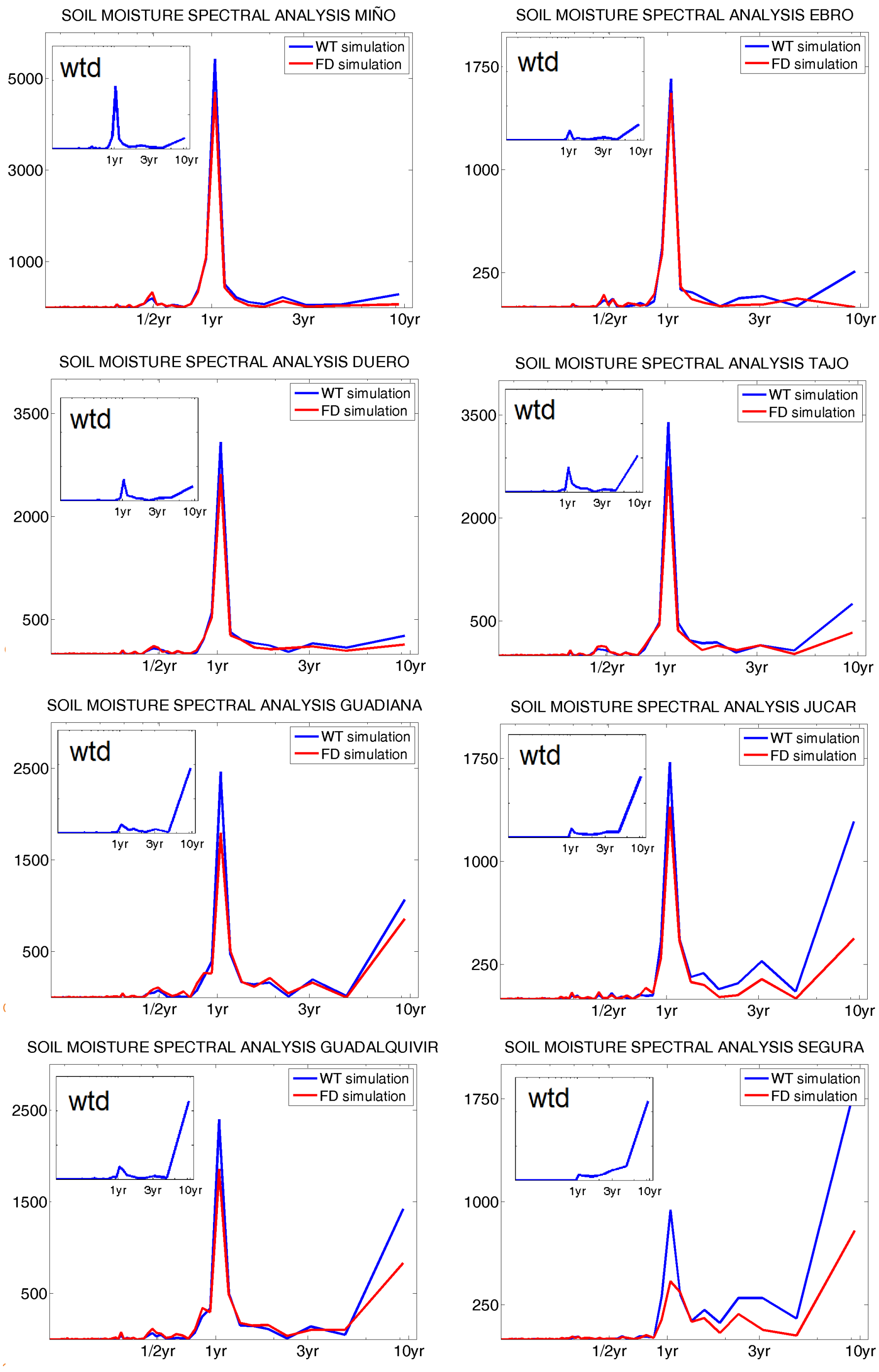


Figure 15. Power spectrum analyses over the main Iberian basins of top-2 m soil moisture (WT run in blue and FD run in red) and ~~wtd~~ *wtd* (insets). Only shallow water table cells (~~wtd~~ *wtd* $\leq$ 8 m) within the basin are used. Basins are ordered, as in Fig. 14, from north (top) to south (bottom) and those on the left drain to the Atlantic and on the right to the Mediterranean, except for the Tajo, which is also an Atlantic basin.

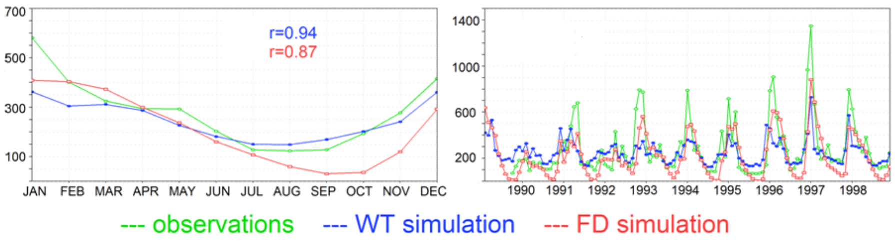


Figure 16. Modelled and observed river flow for the Ebro station 6 in Fig. 6. Left: Monthly mean river flow ($\mathrm{m}^3\ \mathrm{s}^{-1}$) and correlation indexes between the observed and simulated time series (we used the mean seasonal cycle for the index). Right: Monthly river flow ($\mathrm{m}^3\ \mathrm{s}^{-1}$). Blue for the WT simulation, red for the FD simulation and green for observations.