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Subject: Revision to manuscript HESS-2016-114 “Technical Note: A hydrological routing scheme for the Ecosystem Demography model (ED2+R)”

On behalf of the co-authors, I would like to thank you for handling our manuscript during the review process. We are grateful to Dr. Bulcock and the anonymous referees for their valuable comments and suggestions that have further contributed to increase the quality of the manuscript.

We read in detail the review report and responded to each of the comments. A point by point response is available below. Please, note that in addressing the specific comments, we refer to the *clean* version (no marked-up) of the updated manuscript.

Once again thank you very much for your support in handling this manuscript under review and for giving us the possibility to publish in Hydrology and Earth System Sciences. Please do not hesitate to contact me if you have any questions.

Kind regards,

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Editor’s comments (in blue our response)

Dear Authors

After some considerable time, we have had three further reviews of your paper. Two of the authors feel that the paper can now published subject to minor corrections, whilst the other feels that major corrections are still required. Please study their reports carefully and provide a response, after which a final decision will be made.

Please note in particular:

- Clearer statements about why the paper is submitted as a Technical Note, not a case study or research article. This mirrors some of the comments from the first stage of the review.

- Linked to this, the concerns from Referee 3 about the novelty of the paper and about questions raised, but not addressed by the paper.

- Clarification on the calibration of residence times and the parameters used to do this, as raised by both Referees 3 and 4.

A further concern is the length of the paper as manuscripts of this type should be a few pages only. I know that the reviewers, including myself have asked for more background and detail on some aspects, which has added length. However, I do suggest that as you go through the referees comments, that you also consider where the paper could be trimmed and whether there are aspects that could be included as supplementary material.

Regards

Graham

Referee #2 – Dr. H. Bulcock (Report #1)

This revised version of the paper is a great improvement on the original and I am happy for it to be published subject to minor corrections.

The paper submitted by the Authors demonstrates the application of the Ecosystem Demography (ED2) Model which has been improved by including a river routing routine to form the ED2+R model.

The paper presents a scientifically rigorous procedure of calibration and validation of the ED2+R model. The calibration period used is almost 16 years of data excluding 5 years that was excluded for "model initiation". The validation period is also of a reasonable duration of 15 years. The analysis of the model performance is very thorough and includes 5 different well recognised methods. The limitations are well discussed by the authors, including the course spatial resolution of the data and the limitation of the soil depth to 6m, where the soils may be much deeper in reality. The limitation of assuming homogenous soil properties for the entire soil column is also considered. Having a model that is able to simulate the effects of CO2 on vegetation is valuable, especially in the context of climate change studies.

Response: We are extremely grateful to Dr. Bulcock for taking time to review once again our manuscript and for the positive evaluation of our work. Please find below the response to the specific comments.

Specific minor technical corrections are listed below:

1. Pg3 Line 18: remove the word "after".

Response: the sentence was modified as suggested (p. 3 l. 19)

2. Pg3 Line 31 and 32: Write Muskingham Cunge as Muskingham-Cunge (i.e. hyphenate) as has been done on page 7 line 24.

Response: the terminology was modified as suggested throughout the manuscript (p. 3 l. 32)

3. Pg4 Line 10: insert the word "a" before the word "result"

Response: the sentence was modified as suggested (p. 4 l. 10)

4. Pg4 Line 30: Delete the word "from" and replace with the word "of".

Response: the sentence was modified as suggested (p. 4 l. 28)

5. Pg5 Line 4: change the sentence…"reproducing in this way daily river flows"… to "in order to simulate daily river flows…"

Response: the sentence was modified as suggested (p. 5 l. 2-3)

6. Pg 5 Line 9: insert the word “a” before the word “computational”

Response: the sentence was modified as suggested (p. 5 l. 7-8)

7. Pg7 Line 10: change the word “hydrology models” to “hydrological models”

Response: the sentence was modified as suggested (p. 7 l. 6)

8. Pg8 Line 3: insert the abbreviation for Shuttle Radar Topography Mission. i.e. (SRTM)

Response: the abbreviation was inserted as suggested (p. 7 l. 31)

9. Pg10 Line 8: change the sentence “…FDCs are a cumulate frequency…” to “…FDC’s are cumulative frequency plots…”.

Response: the sentence was modified as suggested (p. 10 l. 4)

10. Pg10 Line 14: change the sentence “We parameterized and evaluated the ED2+R formulation…” to “The ED2+R formulation was parameterized and evaluated for the…”

Response: the sentence was modified as suggested (p. 10 l. 10)

11. Pg10 Line 19: change the word “with” to “by”

Response: the sentence was modified as suggested (p. 10 l. 15)

12. Pg10 Line 21: change sentence “…a few meters above sea level in its confluence” to “…a few meters above sea level at its confluence”

Response: the sentence was modified as suggested (p. 10 l. 17)

13. Pg10 Line 31: change “range” to “ranges”

Response: the sentence was modified as suggested (p. 10 l. 27)

14. Pg10 Line 32: change “our model” to “the ED2+R model”

Response: the sentence was modified as suggested (p. 10 l. 28)

15. Pg12 Line 19: end the sentence after “sequentially” and start a new sentence. “...The calibration process…”

Response: the sentence was modified as suggested (p. 12 l. 18)

16. Pg14 Line 23: remove the word “up”

Response: the sentence was modified as suggested (p. 14 l. 23)

17. Pg15 Line 3 change the word “increases” to “improves”

Response: the sentence was modified as suggested (p. 15 l. 3)

18. Pg15 Line 28: change the word “largely” to “greatly”

Response: the sentence was modified as suggested (p. 15 l. 28)

19. Figure 6: it is difficult to distinguish the three “blue graphs” (i.e. I don’t know which graph belongs to which catchment). I suggest that you change the markers or line texture on the three “blue graphs” so that they are easily differentiated.

Response: the figure was updated as requested (p. 30 l. 13)

Referee #3 – Anonymous (Report #2)

Pereira et al describe the extension of an existing land surface model ED2 with a river routing scheme which, results show, improves the simulation of river flows for a tributary of the Amazon. With use of global or regional land surface models advancing to the more local scale, often beyond the original scope of the models, better representation of the lateral flows and a better understanding of delays and losses in the surface water section, is essential and relevant.

Unfortunately, it remains unclear what the novel scientific findings are that would make it interesting for others to read this technical note. The river routing linkage is in itself not that novel (as mentioned in the introduction, but then again ignored in the discussion - P15L6), though the redistribution of lateral flows from the land surface model in combination with the number of calibration parameters might set it apart from some other approaches. A comparison with other models – preferably as parts of the results, or else more quantitatively in the discussion - could add necessary depth.

Response: we appreciate the reviewer's comment and encouragement for better highlighting the contribution of this Technical Note. We clarify in the abstract, introduction, and discussion the relevance and importance of the approach presented in our note, which indeed has never been presented before for the ED2 model. As the reviewer well pointed out in his/her own words, good representation of lateral flow distribution is an essential element needed in land surface models, which are increasingly being used for hydrological assessment involving land cover and climate change. The intent of this Technical Note is to present a case of how such representation could be improved for a particular land surface model. Validating a similar approach with other land surface models would indeed be a great and welcome further step in research, but doing a multi-model comparison is a lengthy and complex task that is well outside of the scope of our Technical Note.

The main finding - a better model fit - is no surprise when adding 5 more calibration parameters. The manuscripts remains vague about what hydrological processes the new 3-way redistribution represent, though, and what the selected parameter values mean. Why does part of the runoff from ED2 become intermediate flow? (is ED2 runoff not calculated well?) Where along the lateral trajectory would or could this occur?

Response: Figure 2 has been crafted, edited and explained in the manuscript with the intention of clarifying to the reader the integration of hydrological layers/reservoirs represented in ED2 and +R. In this study, we presented the integration of two distinct existing models that were independently developed for different purposes. As noted in the paper (p 7 - l. 27-31 and figure 2), the ED2 model computes the vertical water fluxes independently for each cell. The ED2 model's hydrological module is composed by a surface and a sub-surface reservoir. The routing scheme derived from the MGB-IPH model was designed using three different reservoirs (Surface, Intermediate, and Base). The partitioning of the ED2 runoff estimates (surface and subsurface) to feed the three reservoir of the +R component is only a technical procedure aimed at overcoming the structural differences of the two modeling tools.

What would be realistic 'hydrological' boundaries to parameter values, if they can be defined? How representative are the selected ranges/values for other basins? Would a better representation of surface water processes not also lead to more (or possibly less) losses because of increased (or reduced) evapotranspiration, something not incorporated by this extension? Especially in regions with a very seasonal rainfall pattern this might be an issue. More explanation and discussion on the meaning of parameters and their selected values, would make the results and discussion much more relevant for others dealing with similar issues.

Response: As explain in detail by the response to comments by Reviewer 4, the calibrated values in this model were adjustment coefficients to the cell's average residence times, estimated at the subbasin level. We now present proxy residence times associated with these calibrated values (Figure 7), which are better values to be transferred and compared with other basins and studies. The residence time adjustment parameters (CS, CI, and CB) are dimensionless and their order of magnitude is strictly determined by the specificity of our model code (this is now better specified in the manuscript, as for instance in p. 12 l. 2).

Regarding ED2's ability to correctly simulate the evapotranspiration, this was well documented in other studies (among the others: Kim et al., 2012; Knox et al., 2015; Longo, 2014; Swann et al., 2015; Zhang et al., 2015). The high accuracy of the representation of the consequences of the vegetation dynamics in the hydrological balance represented one of the main reasons to develop the modeling framework described in this Tech Note.

References:

Kim, Y., Knox, R. G., Longo, M., Medvigy, D., Hutyra, L. R., Pyle, E. H., Wofsy, S. C., Bras, R. L. and Moorcroft, P. R.: Seasonal carbon dynamics and water fluxes in an Amazon rainforest, Glob. Chang. Biol., 18(4), 1322–1334, doi:10.1111/j.1365-2486.2011.02629.x, 2012.

Knox, R. G., Longo, M., Swann, A. L. S., Zhang, K., Levine, N. M., Moorcroft, P. R. and Bras, R. L.: Hydrometeorological effects of historical land-conversion in an ecosystem-atmosphere model of Northern South America, Hydrol. Earth Syst. Sci., 19(1), 241–273, doi:10.5194/hess-19-241-2015, 2015.

Longo, M.: Amazon Forest Response to Changes in Rainfall Regime: Results from an Individual-Based Dynamic Vegetation Model, Harvard University. [online] Available from: http://dash.harvard.edu/handle/1/11744438, 2014.

Swann, A. L. S., Longo, M., Knox, R. G., Lee, E. and Moorcroft, P. R.: Future deforestation in the Amazon and consequences for South American climate, Agric. For. Meteorol., 214–215, 12–24, doi:10.1016/j.agrformet.2015.07.006, 2015.

Zhang, K., de Almeida Castanho, A. D., Galbraith, D. R., Moghim, S., Levine, N. M., Bras, R.

L., Coe, M. T., Costa, M. H., Malhi, Y., Longo, M., Knox, R. G., McKnight, S., Wang, J. and Moorcroft, P. R.: The fate of Amazonian ecosystems over the coming century arising from changes in climate, atmospheric CO2, and land use, Glob. Chang. Biol., 21(7), 2569–2587, doi:10.1111/gcb.12903, 2015.

With regard to the improved river flow results; it seems that peaks are moved to the low flows, which actually then show a worse fit, as described on page 14 and shown in figure 6 and figure 9g. Is that an acceptable outcome? I guess this would depend on what the improved model is intended to be used for. The text could be clearer on this.

Response: the tool presented in this Technical Note was designed to assess the impacts of global scale environmental changes such as climate change, and regional changes as deforestation, on the discharge of the main rivers. The scope of this tool is not to represent river dynamics at very small scales; there are many other hydrological tools that are more appropriate than the one presented here for that purpose. We aimed at exploiting the high potential that land surface models, in particular ED2, have in representing vegetation dynamics to finally have a tool that could realistically simulate the shocks that deforestation and climate change could have on the hydrology of rainforest areas. The level of details and the level of complexity of the hydrological processes represented in the tool are determined by the tradeoff between simulation accuracy and computation efficiency. In the broader project for which this technical note was produced, this tool was used to assess the possible future scenarios of hydro-energy and agricultural production in the river basin under consideration.

Regarding the specific issue of low flows, as the referee noted, we acknowledged the problem and we identified in the assumptions and model set up a possible explanation of this specific limitation of our approach. (P.14 l. 29-32; P.15 l. 24-28)

Overall, because the authors seem to have difficulty defining its main aim and novelty, the paper confuses: In the introduction the "modeling framework that represents changes in inland surface waters (e.g. surface water area and volume)" P4L13-15, is introduced as the novelty, but this is not what is done, as the basic routing scheme does not cover changes in water area and volume of inland surface waters. Please rephrase and don't raise expectations that will not be met.

Response: the sentence "*A modeling framework that represents changes in inland surface waters (e.g. surface water area and volume) comes as one of the steps to understand the interactions between surface hydrology and climate*" (P4L13) was removed as requested.

On P3L3-6 a similar 'need' is introduced (hydraulic dynamics, features, inland waters) followed by rather vague reasoning why this is partly not possible. Please delete or make clearer where this leads to.

Response: In this part of the introduction, we discussed existing literature about similar integration works. In particular, while discussing the CaMa-Flood paper (Yamazaki et al. 2011), we described what a proper representation of the river flows should be made of in an ideal modeling framework. ("*To couple the calculation of the one-dimensional water balance to the estimation of daily river flows, there is the need to simulate multiple hydrological dynamics involved in the lateral flow propagation through the landscape, **ideally*** [this was added in this updated version of the paper (p. 3 l. 6)] *including the most complex hydraulic features of floodplains, lakes, and wetlands (Yamazaki et al. 2011).*") and we explained why this is not possible in practice ("*The coarse spatial resolution of regional land surface models, due to computational constraints, does not allow for proper simulation of the complex hydrological dynamics determined by fine scale topography in river channels and floodplains (Yamazaki et al. 2011; Kauffeldt et al. 2016).*"). This apply also to our case: thus, we made clear in advance a limitation of our approach.

The final scope of our paper is to have a tool that gives an idea of the implications in terms of river flows of the global environmental changes at larger scale. With no consideration of the specificity represented by the most complex (small scale) hydrological dynamics. In this part of the introduction we just wanted to explicitly mention what should be ideally done and what we (and others) did.

In addition, this part of the introduction was explicitly requested in a previous stage of the review process. In particular the anonymous referee suggested: "*I suggest your introduction should convey the idea of why river routing modeling is important and/or needed? Yazamaki et al. 2011 Water Resour. Res. 47, W04501, doi:10.1029/2010WR009726*"

On page 5 three research questions are then presented but they are not being answered. Better leave out or summarize in one sentence, e.g. as an indication of the need for models like this. Then, in the discussion, the authors ignore their own introduction and the fact that there are already various routing schemes applied and tested stating that other models 'typically (have) "no river representation" as a main reason for this research (P15L6). Please adjust and use consistent reasoning throughout the paper.

Response: the research questions listed in the technical note are referring to the use of the tool for the broader research project within which it was developed. The analysis of hydrological implications of past and projected climate and land use change is topic of two submitted papers (- *Arias, M. E., Lee, E., Farinosi, F., Pereira, F. F., Moorcroft, P. R. and Briscoe, J.: Decoupling the effects of deforestation and climate variability in large tropical river basins (under review), J. Hydrology*

- Farinosi, F., Arias, M. E., Lee, E., Longo, M., Pereira, F. F., Livino, A., Moorcroft, P. R. and Briscoe, J.: Future climate and land use change impacts on river flows in the Tapajós Basin in the Brazilian Amazon (under review), Earth's Future).

In order to make this clear, the paragraph was modified as follows: "*The new product combines the advantages of biosphere and hydrological models, bringing together global, regional, and local scale hydrological dynamics in a single modeling framework. The resulting model is intended to be used as a computational tool to explore, in future studies, various research questions. In particular, it could be used to analyse: how current and future climate and land cover affect water availability in river systems; how land-use driven changes can influence the water availability for human activities (hydropower, food production, urban supply); what the implications of those changes are for water and land resources management.*" (p. 5 l. 7-12)

Clearly a lot of work has gone into the research and the paper has improved compared to earlier version. Results are quite well represented in graphs and table. If the authors manage to define the main aim of their paper yet more clearly/sharper and discuss their findings better, keeping this aim in mind, the manuscript might add value. Else I guess there is enough opportunity to publish it just as a technical note on the web for those who want to use ED2-R.

Response: We hope that the updated manuscript reshaped according to the suggestions collected in this further iteration of the review process could fully satisfy the Referee's expectations.

Some smaller comments:

P1L27 a verb is missing before 'to hydrological predictions'

Response: the sentence was rewritten as follows: "The purpose of the study was to create a tool capable of incorporating to hydrological predictions the terrestrial ecosystem responses to climate, carbon dioxide, and land-use change –as simulated with terrestrial biosphere models." (p1 – l. 26-28)

P4L5-6 it is unclear to me what this adds to the paper or why it is mentioned

Response: the sentence "*These studies have used historical reconstructions of land-use based on satellite information and data on agricultural production and population*" was deleted as suggested (p.4 – l. 5)

P6L22 this first sentence is not required

Response: the sentence "*A modeling framework that represents changes in inland surface waters (e.g. surface water area and volume) comes as one of the steps to understand the interactions between surface hydrology and climate*" was deleted as recommended (p.6 – l. 18)

P8L3 It is somewhat unclear to me how the 90m SRTM resolution, and flow paths, relate to the ~55km gridcell resolution of the ED2-R model.

Response: The grid-cell resolution was determined by meteorological forcing and soil characteristics data resolution (as clearly stated in p.5 l. 30 and 31). The 90-m SRTM was used to develop rasters of most probable flow direction and flow paths, used to route water laterally from one grid cell to the other.

P15L22-29 I'm not sure about this. The 6 m soil depth seems a indeed simplification that could have been avoided, but apart from that I wonder how a soil depth of 6 meters would be a mayor issue explaining deviations between simulated and observed flows downstream when subsequently lateral flows are redistributed and residence times are calibrated. This, I assume, would overrule some (or most?) of the effects of a too shallow soil. Exploring such issues further, showing the added value of the routing scheme, would exactly be the kind of work that would make this an interesting scientific paper.

Response: the 6 meters soil layer is a limitation imposed by computational efficiency. Land surface models, including ED2, are extremely complex and computationally intensive. Although we agree that would be an interesting exercise, analysing the model sensitivity to the parameterization of soil depth was out of the scope of this technical note.

P17L6-8 The 'could' and 'would' in the conclusion paragraph would better fit the discussion.

Response: The sentence "*With a fully coupled (i.e. two-way) integration, the model would be able to determine the grid cells that are likely to be saturated and use this information for the modeling of the ecosystem's dynamics. For instance, this could determine the increase of the mortality rate of plants that are sensitive to inundation. An additional limitation of the model, could be identified in its inability to reproduce highly detailed hydrological dynamics of complex river systems (as for instance, floodplain hydraulic features, or backwater effects), however, such a detailed hydrological complexity was out of the scope of this study*" is mainly a summary of the possible future development of the modeling framework. For this reason we believe it should be placed among the concluding remarks.

Referee #4 – Anonymous (Report #3)

Overall:

I found this a very informative technical note on adding a hydrological routing scheme to a terrestrial biosphere or land-surface model and felt the paper is well written. There are minor typographic errors and some methodological details that require additional specificity to avoid confusion (particularly the terminology used for the residence time adjustment parameters). Specific suggestions are given below.

For further testing of this model structure beyond this methodological technical note, I would advocate a more in-depth calibration procedure and description (how parameter ranges and parameter sets were selected for trial, etc) with more analysis of resulting parameter values between the subcatchments. I would also like to see the methodology trialed in different bioclimatic regions.

Response: We would like to thank the anonymous Referee for his/her positive evaluation of our work and for the very informative and constructive comments. We corrected the typographic errors and better specified the terminology used for the residence time adjustment parameters (please, see the response to the specific comments below). In order to give more detailed information about the calibration procedure, we gave more details in the narrative and calculated the approximate residence time for each of the sub-basin (Figure 7).

Although we agree that testing the methodology in a different bioclimatic region would be an interesting exercise that could transform this technical note to a full research paper, we think that the comparative testing is out of the scope of this study and we leave it for future research.

Specific edits and suggestions:

1. Title – consider adding something to specify that the method was applied and tested to a sample catchment in the Amazon Basin (suggests need to trial further in other regions)

Response: The title of the manuscript was modified as suggested. The new title is "*Technical Note: A hydrological routing scheme for the Ecosystem Demography model (ED2+R) tested in the Tapajós river basin, in the Brazilian Amazon*" (p. 1 l. 2-3)

2. P3 L10 typo: should be "…does not allow us to properly…" or, alternatively, "…does not allow for proper simulation of the…"

Response: The sentence was modified as suggested (p. 3, l. 11)

3. P4 L32 suggest starting a new paragraph from the sentence: "In this technical note…."

Response: The paragraph was modified as suggested (p. 4, l. 30)

4. P5 L3 colloquial English suggestion: "…, thereby reproducing daily river flows…"

Response: The sentence was modified as suggested (p. 5, l. 2-3)

5. P5 L6 typo: should be "…changes such as…"

Response: The sentence was modified as suggested (p. 5, l. 5)

6. P5 L9 typo: should be "…used as a computational…"

Response: The sentence was modified as suggested (p. 5, l. 7-8)

7. P9 L17 What weighting factors were used for the KGE? Please specify

Response: The weighting factors were not used in this specific case (set to 1). This information was added in this section as requested (p. 9, l. 11).

8. P12 L7 Specify the number of model runs used and the values selected for the other hydrological parameters (CS, CI, CB, etc) during this step of the calibration.

Response: The calibration of the alpha and beta parameters was done recursively and adjusted in sequence with the calibration of the other parameters. The final values of this calibration (the one used to draw figure 5) were associated with the nearly optimal values of the other parameters (CS, CI, CB, etc). This iteration of the calibration process was based on about 35 model runs (now specified in the text - p. 12, l. 4)

9. P12 L16-17 (& L30, etc) If I understand correctly CS, CI, and CB are not residence times, they are residence time adjustment coefficients according to Collischonn et al. (2007). They adjust an initial estimate of residence time which is based on the topographic relief of the grid cell and the grid cell size (hence flow-path length). This should be specified in the text and the C parameters should not be referred to as residence times in text, tables, or figure captions, but rather as adjustment coefficients or something along those lines. The way it is currently written, referring to them as residence times, the reader is left confused about why the different subcatchments have such extremely different CS, CI, and CB values thinking they are similar to the more typical residence time parameter in a linear reservoir equation.

Response: The reviewer's interpretation of the C's parameters is correct and the clarification is welcomed. Residence time is a function of the C's coefficients and the Kirpich formula for time concentration, which in turn is a function of elevation and grid cell size. In order to make this more explicit in the manuscript, we added details in this sentence: *"In the second step, the* *residence times (τ) of flow within the ED2+R reservoirs of each grid cell in the domain were calibrated through the adjustment of the non-dimensional parameters (CS, CI, and CB in Figure 2) used to correct the Kirpich formula for time of concentration (as explained in Collischonn et al. 2007)*" (P 12, l 14 - 16).

The C's are now defined "*residence time adjustment parameters*" throughout the text, including figures' captions (as for instance in p. 12 l. 2).

10. The comparative values of these parameters for surface, interflow, and baseflow reservoirs for some subcatchments are also somewhat surprising: there are a few where the values are quite similar when one would expect baseflow residence times to be significantly longer than shallower reservoirs. Showing the calculated average residence times (calculated using the C parameters and topography) for the different compartments for the grid cells in each subcatchment added in a table or modifying Figure 7 would be more physically meaningful for someone looking at the conceptualization of hydrological processes.

Response:

We agree with the reviewer about expected relative magnitude of the adjustment coefficients. In general, the values of the adjustment coefficients do follow the expected trend mentioned by the reviewer, with the coefficient for the surficial reservoir having the lowest value and the base reservoir the highest. In general, the value of the surficial reservoir is lower than the base reservoir, and we believe that is the most important aspect that was maintained consistent in our conceptualization of runoff routing. There are, however, two subbasins in which the intermediate and base reservoirs' values are slightly lower (3 to 7%) than the surface reservoir. Moreover, in three subbasins, the value of the intermediate reservoir is either the same as one of the other two or slightly higher (+1%) than the base flow. As pointed out in figure 2, this is primarily a compromise in the coupling of the land surface model (ED2), initially conceptualize with two runoff layers, and the selected routing scheme (+R), which uses three reservoirs. As a result, the intermediate reservoir does carry a weight from both the surface and the base reservoir, and we parametrized the model with adjustment coefficients that fell between the other two. The average residence time is only one of the factors determining the flow propagation, determined also by the initial conditions. We believe that the additional load determined by the flow partitioning is a perturbing factor of the reservoirs initial conditions especially in the subbasins with the highest concentration. This explains the unusual values in the residence time calibration.

11. P15 Discussion section – in this section there is discussion of using smaller grid cell sizes with higher resolution input data in order to improve the accuracy of the simulation. It should be noted when saying this that the ED2+R model does not route groundwater between cells, it only routes the groundwater that leaves an area via river baseflow. Not considering groundwater flow between grid cells is a more reasonable simplification when grid cells are very large, but if they were significantly reduced groundwater routing

between grid cells may need to be added to maintain or improve realism and accuracy. At finer spatial scales not all model grid cells would be expected to contain channels that drain the subsurface reservoirs being explicitly considered.

Response: We agree with the referee and stated this explicitly by adding a new sentence in the discussion. In particular, after the sentence "*Higher resolution climatological data, vegetation, and land use datasets, while allowing a finer resolution of the hydrological grid, are expected to improve the performance of the model by providing more detailed hydrological processes.*", we added: "*On the other hand, a finer spatial resolution of the hydrological grid would also require a more detailed representation of the groundwater in the model.*" (p. 16, l. 16 - 17).

12. P15 L25 colloquial English suggestion: "…too shallow to realistically…"

Response: The sentence was modified as suggested (p. 15, l. 25)

13. P16 L15 typo: should be "…performance of the model by providing…"

Response: The sentence was modified as suggested (p. 16, l. 15)

14. P16 L31 typo: should be "…typical of these kinds of models."

Response: The sentence was modified as suggested (p. 17, l. 1)

15. P29 L3-4 caption for Figure 3 (c) should not be "land use" as land usage has not been mapped or specified in the image. Instead consider, "(c) aerial imagery of Tapajos river basin illustrating land cover diversity in the catchment…." Or change the figure to include a map of the land use that was used in the model (cite Hurtts et al 2006)

Response: The caption was modified as suggested (p. 29, l. 2-3). The aerial imagery was added as requested by an anonymous referee in a previous review stage.

16. P30 L12-14 caption for Figure 6 – reword and insert the parameter abbreviation to add clarity: "Model sensitivity to the initial conditions of baseflow (QB)…"

Response: The caption was modified as suggested (p. 30, l. 13 - 15)

17. P32 L1-6 caption for Figure 7 – Specify that the C parameters are adjustment coefficients of residence time (and not actually residence times).

Response: The caption was modified as suggested: "*Calibration of the residence times (τ) of the flow within the ED2+R reservoirs of different grid cells in the domain through the adjustment of the non-dimensional C parameters. Overland, intermediate and subsurface water flows are* *calibrated respectively through the adjustment parameters CS, CI, and CB (Figure 2)*" (p. 32, l. 2 – 4)

18. Consider remaking this figure instead using the average residence time value for the grid cells in a subcatchment for the surface, interflow, and baseflow reservoir. This would still be a representation of the parameter value impact for the C parameters because the remaining values used to calculate residence time in Collischonn et al. (2007) are derived from the DEM and grid cell size and so are fixed per grid cell and not calibrated. Showing the residence time value would be more easy to analyze from a hydrologic process conceptualization point of view and to compare the processes simulated for the different subcatchments with different geologies and geomorphologies (the axes could be kept consistent between subcatchments). Otherwise the C parameter values on their own seem rather arbitrary and their values unexpected (comparing the surface flow, interflow, and baseflow values within and between catchments). This could be a very interesting and informative figure if reformatted in that way.

Response: the estimation of the approximate residence time for each of the reservoirs was calculated and added in the figure (p 31 and 32). Manuscript's body and caption were modified accordingly (p12 l 30-31; p 32 l 6-8)

19. Also specify that the colour bar below each diagram is indicative of the model Nash-Sutcliffe Equilibrium (NS) for the model realization for the given set of parameter values. In previous diagrams and text NSE is used rather than NS – one abbreviation should be used throughout.

Response: In the figure's caption, the following sentence was added "*The color bars refer to the model performance (Nash-Sutcliffe Efficiency NSE) of the specific parameter combination in the specific sub-basin. In red the chosen combinations.*" (p. 32, l. 4 - 6)

The Nash-Sutcliffe axis title was modified to "*NSE*" throughout the figure as suggested. (p. 31 - 32)

20. P34 L2 Table 1 caption – Are these the calibrated parameter values? If so specify this in the caption.

Response: The caption was modified as suggested. The new caption is: "*Table 1. ED2+R calibrated parameters (based on Zhang et al., 2015; Longo et al., 2014; Knox et al., 2012). Additional information about ED2 parameter calibration for the Amazon basin are available in Zhang et al. (2015) and Longo et al (2014).*" (p. 34, l. 2-4)

21. Again don't refer to the C values as residence times, rather call them residence time adjustment factors or something along those lines. Otherwise the values are confusing for those used to looking at residence times and linear reservoir equations.

Response: The sentence was modified as suggested: "*Residence time adjustment parameters, respectively referring to overland (CS), intermediate (CI), and groundwater flows (CB)*" (p. 35)

Technical Note: A hydrological routing scheme for the Ecosystem Demography model (ED2+R) tested in the Tapajós river basin, in the Brazilian Amazon.

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Abstract

Land surface models are excellent tools for studying how climate change and land use affect surface hydrology. However, in order to assess the impacts of earth processes on river flows, simulated changes in runoff need to be routed through the landscape. In this Technical Note, we describe the integration of the Ecosystem Demography (ED2) model with a hydrological routing scheme. The purpose of the study was to create a tool capable of incorporating to hydrological predictions the terrestrial ecosystem responses to climate, carbon dioxide, and land-use change – as simulated with terrestrial biosphere models ~~to hydrological predictions~~.

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The resulting ED2+R model calculates the lateral routing of surface and subsurface runoff resulting from the terrestrial biosphere models' vertical water balance in order to determine spatio-temporal patterns of river flows within the simulated region. We evaluated the ED2+R model in the Tapajós, a 476,674 km^2 river basin in southeastern Amazonia, Brazil. The results showed that the integration of ED2 with the lateral routing scheme results in an adequate representation (Nash Sutcliff Efficiency up to 0.76, Kling Gupta Efficiency up to 0.86, Pearson's R up to 0.88, and Volume Ratio up to 1.06) of daily to decadal river flow dynamics in the Tapajós. These results are a consistent step forward with respect to the 'no river representation' common among terrestrial biosphere models as the native version of ED2.

1 Introduction

Understanding the impacts of deforestation (e.g., Lejeune et al. 2015; Medvigy et al. 2011; Andréassian 2004) and climate change (e.g., Jiménez-Cisneros et al. 2014) on the earth's water cycle has been a topic of substantial interest in recent years because of potential implications to ecosystems and society (e.g., Wohl et al. 2012; Brown et al., 2005). Analyses of impacts of climate change on the earth's water cycle are increasingly using terrestrial biosphere models, which are capable of estimating changes in the vertical water balance as a function of climate forcing and and/or land-use induced changes in canopy structure and composition (Zulkafli et al. 2013). Terrestrial biosphere models actively used for hydrological and earth systems sciences include: the Joint UK Land Environment Simulator (JULES) (Best et al. 2011; Clark et al. 2011); the Community Land Model (CLM) (Lawrence et al. 2011; Oleson et al. 2010); the Lund-Potsdam-Jena (LPJ) land model (Gerten et al. 2004; Sitch et al. 2003); the Max Plank Institute MPI-JSBACH model (Vamborg et al. 2011; Raddatz et al. 2007); and the Integrated Biosphere Simulator (IBIS) (Kucharik et al. 2000).

Initial formulations of the hydrological processes within terrestrial biosphere models were based on simple "bucket" model formulations (Cox et al. 1999 after Carson 1982). Moisture within each climatological grid cell of the domain was simulated in a single below-ground pool in which surface temperature and specific soil moisture factors determined evaporation, while runoff was equal to the bucket overflow (Cox et al. 1999; Carson 1982). Since that formulation, the hydrologic schemes within terrestrial biosphere models have become increasingly sophisticated. In the most recent generation of land surface models, water fluxes in and out of the soil column are vertically-resolved and take into account feedbacks among the different components, for instance, through an explicit formulation of the soil-plant-atmosphere continuum that allows a detailed representation of the interactions between evapotranspiration, soil moisture and runoff (Clark et al. 2015).

To couple the calculation of the one-dimensional water balance to the estimation of daily river flows, there is the need to simulate multiple hydrological dynamics involved in the lateral flow propagation through the landscape, ideally including the most complex hydraulic features of floodplains, lakes, and wetlands (Yamazaki et al. 2011). The first step towards representing the finer scale hydrodynamic processes responsible for patterns in river gauge observations, is to consider the topographic and geomorphological features that control water flow (Arora et al. 1999). The coarse spatial resolution of regional land surface models, due to computational constraints, does not allow ~~to properly simulate~~for proper simulation of the complex hydrological dynamics determined by fine scale topography in river channels and floodplains (Yamazaki et al. 2011; Kauffeldt et al. 2016). However, the combination of the terrestrial models with routing schemes can be used to simulate the implications of global and regional environmental changes for flood/drought forecasting, water resources planning and management, and infrastructure development (Andersson et al. 2015). Consequently, several terrestrial biosphere models have been integrated with routing schemes. For example, JULES has been integrated with the Total Runoff Integrating Pathways (TRIP) to evaluate the accuracy of its estimates of annual streamflow (Oki et al. 1999). This integrated model was used ~~after~~ to investigate the status of the global water budget (Oki et al. 2001). Rost et al. (2008) also used a modelling framework composed of the global dynamic vegetation model, LPJ, and a simple water balance model to quantify the global consumption of water for rainfed and irrigated agriculture. An offline coupling of the dynamic vegetation model, ISIS, and HYDRA – which simulates the lateral transport of water through river, lakes and wetlands – was proposed in Coe et al. (2008) with the purpose of reproducing linkages between land use, hydrology and climate. Moreover, Liang et al. (1994) developed and tested the coupling of the well-known VIC model with a general circulation model (GCM) to improve the GCM's capability to capture the interactions between surface hydrology and atmosphere. For the same purpose, the MPI hydrological discharge model was validated with NCEP reanalysis and parametrized for simulating the river routing for climate analysis at global scale (Hagemann and Gates 2001; Hagemann and Dumenil 1997). Several routing schemes have been designed over time, including: normal depth, modified pulse, simple Muskingum, and ~~Muskingum~~ Muskingum-Cunge (USACE 1991). In particular, the semi-distributed kinematic wave routing ~~Muskingum~~

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Muskingum-Cunge method has been recognized for its stability over different spatial and temporal modeling resolutions (USACE 1991; Miller and Cunge 1975; Cunge 1969), and it was adopted in the most widely used regional scale hydrological models, such as VIC, SWAT, and MGB-IPH.

Recent studies have investigated regional patterns of rainfall and biosphere temperature as influenced by land-~~-~~use (Ostberg et al. 2015; Bahn et al. 2014; Pearson et al. 2013).~~ These studies have used historical reconstructions of land-use based on satellite information and data on agricultural production and population (Hurtt et al. 2006; Goldewijk 2001; Ramankutty and Foley 1999).~~ These studies evidenced the occurrence of conversion of land from its natural state over the same time frame as observed fluctuations of rainfall and air temperature occurred, aspects fully analysed by terrestrial biosphere models (Hurtt et al. 2006; Goldewijk 2001; Ramankutty and Foley 1999). However, these modeling frameworks tend to assume global and regional changes in the biosphere as a result of dynamics of vegetation in a collection of landscapes given by forests, deserts, and farmland only. Inland surface waters (e.g. rivers, lakes and wetlands) were not considered as an interactive component of the biosphere, and hence the climate system (Cole et al. 2007).~~ A modeling framework that represents changes in inland surface waters (e.g. surface water area and volume) comes as one of the steps to understand the interactions between surface hydrology and climate.~~

The Ecosystem Demography (ED2) is a terrestrial biosphere model that simulates the coupled water, carbon, and energy dynamics of terrestrial land surfaces (Longo 2014; Medvigy et al. 2009; Moorcroft et al. 2001) to describe the coupled water, carbon and energy dynamics of heterogeneous landscapes (Hurtt et al. 2013; Medvigy et al. 2009; Moorcroft et al. 2001). ED2's ability to incorporate sub-grid scale ecosystem heterogeneity arising from land-use change makes the model suited for investigating how the combined impacts of changes in climate, atmospheric carbon dioxide concentrations, and land-cover affect terrestrial ecosystems. For example, ED2 was successfully used to simulate the carbon flux dynamics in the North American continent (Hurtt et al. 2002; Albani et al. 2006), and to assess the impacts on Amazonian ecosystems of changes in climate, atmospheric carbon dioxide and land use (Zhang et al. 2015). Moreover, ED2, coupled with a regional atmospheric circulation component, has been also successfully applied to assess the impacts of deforestation on the Amazonian climate (Knox et al. 2015; Swann et al. 2015). The mentioned studies were not aimed at assessing hydrological implications of changes in land use and climate. These works proved the validity

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of ED2 as a tool able to assess impacts ~~from~~ of global and regional changes on ecosystem function, and built the basis for a possible development of an integrated tool aimed at analyzing hydrological implications.

In this technical note, we describe the integration of ED2 with a hydrological routing scheme. The hydrological routing scheme chosen was adapted from the MGB-IPH (Collischonn et al. 2007). This exercise is aimed at calculating the lateral propagation and attenuation of the surface and subsurface runoff resulting from the vertical balance calculations, ~~reproducing in this way~~in order to simulate daily river flows through a large river basin. The advantage of the proposed model is the ability to predict the sensitivity of river flows to global and regional environmental changes such as climate and land-use changes. The new product combines the advantages of biosphere and hydrological models, bringing together global, regional, and local scale hydrological dynamics in a single modeling framework. The resulting model is intended to be used ~~-~~as a computational tool to explore, in future studies, ~~the following~~various research questions. In particular, it could be used to analyse: ~~:~~

~~(1) H~~how~~ow do~~ current and future climate and land cover affect water availability in river systems~~?~~ ;

~~(2) H~~how ~~can~~ land-use driven changes can influence the water availability for human activities (hydropower, food production, urban supply); ~~?~~

~~(3) W~~what ~~are~~ the implications of those changes are for ~~management of~~ water and land resources management~~?~~ .

The identified research areas ~~se research questions~~ are in line with key problems raised in the literature, focusing on the importance of large scale modelling and remote sensing to fill knowledge gaps in water resources and hydrological dynamics (Alsdorf et al. 2007; Prigent et al. 2007). The product obtained from this exercise was tested in the Tapajós basin, a large river system in southeastern Amazonia, Brazil.

2 Ecosystem Demography (ED2) model

ED2 is a terrestrial biosphere simulation model capable of representing biological and physical processes driving the dynamics of ecosystems as a function of climate and soil properties. Rather than using a conventional “ecosystem as big-leaf” assumption, ED2 is formulated at the scale of functional and age groups of plants. Ecosystem-scale dynamics and fluxes are

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calculated through a scaling procedure to reproduce macroscopic behavior of the ecosystem within each climatological grid-cell. It simulates ecosystem structure and dynamics as well as the corresponding carbon, energy, and water fluxes (Figure 1; Hurtt et al. 2013; Medvigy et al. 2009; Moorcroft et al. 2001). ED2 simulates the dynamics of different plant functional types subdivided into tiles with a homogeneous canopy (Swann et al. 2015; Medvigy et al. 2009). The dynamic tiles represent the sub-grid scale heterogeneity in ecosystem composition within each cell. Grid cell size is determined by the resolution of meteorological forcing and soil characteristics data, typically from 1 to 0.001 degrees (~ 110 to 1 km). ED2 simulates biosphere dynamics taking into consideration natural disturbances, such as forest fires and plant mortality due to changing environmental conditions, as well as human-caused disturbances, such as deforestation and forest harvesting (Medvigy et al. 2009; Albani et al. 2006). Disturbances are expressed in the model as annual transitions between primary vegetation, secondary vegetation, and agriculture (cropland and pasture) (Albani et al. 2006). Natural disturbance, such as wildfire, is represented in the model by the transition from primary vegetation (forest in the case of the Amazon) to grassland-shrubland, and subsequently to secondary vegetation (forest re-growth); the abandonment of an agricultural area is represented with the conversion from grassland to secondary vegetation, while forest logging is represented by the transition from primary or secondary vegetation to grassland. The model is composed of several modules operating at multiple temporal and spatial scales, including plant mortality, plant growth, phenology, biodiversity, soil biogeochemistry, disturbance, and hydrology (Longo 2014; Medvigy et al. 2009). A selection of the main parameters and the input used for this study are presented in Table 1, and for a more complete description of the model, we refer the reader to the literature available (Zhang et al. 2015; Longo 2014; Kim et al. 2012; Medvigy et al. 2009; Moorcroft et al. 2001).

2.1 ED2 hydrology module

~~In this section, we describe in further detail the hydrological sub-component, most related to the topic of this specific study.~~ The hydrological module of the ED2 model is derived from the Land Ecosystem-Atmospheric Feedback model (LEAF-2) (Walko et al. 2000). The model computes the water cycle through the vegetation, air-canopy space, and soils, which results in daily estimates of subsurface and surface runoff from each grid cell, isolated from the others in the domain. The number of soil layers and their thickness influence the accuracy with which

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the model is able to represent the gradients near the surface. Soil composition was derived from Quesada et al. (2010) and from the IGBP-DIS global soil data (Global Soil Data Task 2014). As described in Zhang et al. (2015), the mean fraction values of sand and clay were assigned to each grid-cell at 1 km resolution and then aggregated at 1 degree resolution. Due to limited data availability, soils were assumed to be homogeneous for a depth of 6 meters. Hydraulic conductivity of the soil layers is a function of soil texture and moisture (Longo 2014). Groundwater exchange is a function of hydraulic conductivity, soil temperature and terrain topography. Water percolation is limited to the bottom layer by the subsurface drainage, determining the bottom boundary conditions. Vegetation historical records and land use transitions were derived from the Global Land Use Dataset (Hurtt et al. 2006). A more detailed description of the hydrological sub-component of the ED2 model is available in Longo (2014).

3 ED2 runoff routing scheme (ED2+R)

River routing schemes are commonly used to compute the lateral movement of water over land in ~~hydrology~~ hydrological models for large river basins. In this way, the prediction performance of models can be evaluated using river discharge measurements. The use of routing schemes was then extended to earth system models in order to capture the impacts of man-made structures (e.g. dams and reservoirs) and floodplain wetlands on the climate system (Li et al., 2011; Yamazaki et al., 2011).

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Daily runoff estimates from ED2 were computed for specific grid cells independently; therefore a hydrological routing scheme was linked to this model in order to estimate flow attenuation and accumulation as water moves through the landscape. The hydrological routing scheme chosen was adapted from the original formulation of the MGB-IPH, a rainfall-runoff model that has been used extensively in large river basins in South America (Collischonn et al. 2007). This model was later developed using hydrodynamic solutions and floodplain coupling (Pontes et al. 2015; Paiva et al. 2013). Although the later development increased the modeling capabilities of the MGB-IPH in representing fine scale dynamics, given the regional application of our tool, for the ED2+R we decided to use the typical application of the MGB-IPH characterized by the Muskingum-Cunge approach. The original MGB-IPH model is composed of four different sub-models: soil water balance, evapotranspiration, intra-cell flow propagation, and inter-cell routing through the river network; only the catchment and river routing methods were utilized. The resulting ED2+R model computes the daily total volume of water passing through any given grid cell in the resulting drainage network in two separate steps: first, ED2 estimates of daily surface and subsurface runoff from each grid cell are divided into three linear reservoirs with different residence times to represent overland flow, interflow and subsurface water ~~groundwater~~ flow (Figure 2). The reservoirs are used to determine the contribution and attenuation of river flow by different soil layers, characterized by different routing times. The sum of overland flow, interflow, and subsurface water ~~groundwater~~ flow is then moved from each grid cell into the drainage network, designed in the pre-processing phase using data from a digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) at a 90-meter resolution and the Cell Outlet Tracing with an Area Threshold algorithm (COTAT) (Reed 2003). Each DEM grid cell therefore becomes part of a flow path, which then accumulates water to a final downstream drainage network outlet. A complete description of the technique for defining drainage networks from DEMs employed in this study can be found in Paz et al. (2006). Once water reaches the drainage network, ED2+R adopts the Muskingum-Cunge numerical scheme for the solution of the kinematic wave equation, which also accounts for flow attenuation, using a finite-difference method as a function of river length, width, depth and roughness, as well as terrain elevation slope (Collischonn et al. 2007; Reed 2003). Statistical relationships for the river morphology were obtained as a function of the drainage area based on geomorphic data collected by Brazil's National Water Agency (ANA) and the Observation Service for the geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon basin (HyBAM) at several gauging stations in the Amazon and Tocantins basins as presented by Coe et al. (2008). Further studies successfully derived geomorphological relations to estimate river geometric parameters and carry out hydrodynamic simulations of the Amazon River system using a similar approach (Paiva et al., 2013; Paiva et al., 2011). Multiple groups of grid cells with common hydrological features, or hydrological response units, can be created in order to parameterize and calibrate ED2+R. In our approach, hydrological traits associated with soil and land cover are primarily computed in ED2, thus we calibrated ED2+R at the sub-basin level as delineated based on the DEM. Details about the calibration procedure are provided in the next section.

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Model's performance was calculated through the adoption of widely used indicators:

- Pearson's R correlation coefficient (Pearson 1895), calculated as in Equation 1:

$$R = \frac{\sum sim*obs - \frac{(\sum sim)(\sum obs)}{n}}{\sqrt[2]{\left(\sum sim^2 - \frac{(\sum sim)^2}{n}\right)\left(\sum obs^2 - \frac{(\sum obs)^2}{n}\right)}} \qquad (1)$$

Where sim and obs are the simulated and observed time series, while n is the number of time steps of the simulation period.

- Volume Ratio, calculated as ratio of the simulated (sim) and observed (obs) total water volume in the simulation period without consideration for the seasonal distribution of flow, as in Equation 2:

$$VR = Vol_{\mathrm{sim}} / Vol_{\mathrm{obs}} \qquad (2)$$

- Nash-Sutcliffe Efficiency (NSE) coefficient (Nash & Sutcliffe 1970), calculated as in Equation 3:

$$NSE = 1 - \frac{\sum_1^n |obs_i - sim_i|^2}{\sum_1^n |obs_i - \overline{obs_i}|^2} \qquad (3)$$

Where obs_i and sim_i are the observed and simulated data at time i, $\overline{obs_i}$ is the mean of the observed data, and n is number of time steps of the simulation period.

- Kling Gupta Efficiency (KGE) index, both 2009 and 2012 versions, calculated as in Equation 4:

$$KGE = 1 - \sqrt{\left(s[1](r-1)\right)^2 + \left(s[2](vr_{2009\ or\ 2012} - 1)\right)^2 + \left(s[3](\beta - 1)\right)^2} \quad (4)$$

Where, s are scaling factors (set to 1 in this case); r is the Pearson's correlation coefficient; β is the ratio between the mean of the observed values and the mean of the simulated values; vr is the variability ratio, defined as vr_{2009} (simulated vs observed standard deviation ratio, Equation 5) for the 2009 method, and vr_{2012} (ratio of coefficient of variation of simulated and coefficient of variation of observed values, Equation 6) for the 2012 method (Kling et al. 2012; Gupta et al. 2009).

$$vr_{2009} = \sigma_{sim} / \sigma_{obs} \qquad (5)$$

$$vr_{2012} = \frac{CV_{sim}}{CV_{obs}} = \frac{\sigma_{sim} / \mu_{sim}}{\sigma_{obs} / \mu_{obs}} \qquad (6)$$

The optimal value for the Pearson's R, VR, NSE, and KGE indexes is 1: the closer to this value, the more accurately the model reproduces the observed values.

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Missing observations in the river flow records (HYBAM and ANA) were filled via linear spatial and temporal interpolation between the series in neighboring gauge stations (Equation 7):

$$Obs_y(t) = K + \beta_1 \cdot Obs_z(t) + \beta_2 \cdot Obs_q(t) + \beta_3 \cdot Obs_y(t-365) + \beta_4 \cdot Obs_y(t+365) \quad (7)$$

Where *z*, *y*, and *q* are three gauge stations with time series highly correlated (Pearson's r $\geq$ 0.85), and *t* expresses time in days. The estimated β coefficients in Equation 7 were used for the estimation of the missing observations in the site *y* (Table 2). The interpolation of the gauge historical records was necessary to have continuous time series with a sufficient number of observations to calibrate and validate the ED2+R application in the basin.

For the presentation of the results, in order to compare the simulated and observed values, we also used flow duration curves (FDCs). FDC’s are ~~a~~ cumulate frequency plots that show the percentage of simulations steps (days in the case presented in this study) in which the discharge is likely to equal or exceed a specific value, without taking into consideration the sequence of the occurrence.

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4 Case Study: Tapajós river basin

~~We parameterized and evaluated~~ The ED2+R formulation was parameterized and evaluated for the Tapajós River Basin, the fifth largest tributary of the Amazon. It drains an area of 476,674 km^2 in southeastern Amazonia, within the Brazilian states of Mato Grosso, Pará and Amazonas. The main rivers in the basin are the Tapajós (with a length greater than 1,800 km and average discharge of 11,800 m^3 s^{-1}), Juruena (length of approximately 1,000 km and discharge of 4,700 m^3 s^{-1}) , and Teles Pires (also known ~~with~~ by the name Sã~~a~~o Manoel, about 1,600 km long and average discharge of 3,700 m^3 s^{-1}). The river system flows northwards, with terrain elevation ranging from about 800 meters above sea level in the southern part, to a few meters above sea level ~~in~~ at its confluence with the Amazon river (ANA, 2011). The basin ecosystems are mainly represented by tropical evergreen rainforests in the northern part (in the states of Amazonas and Pará), and Cerrado dry vegetation in the south (Mato Grosso). Precipitation ranges from about 1,500 mm y^{-1} in the headwaters (southern part), to about 2,900 mm y^{-1} towards the basin’s outlet (Figure 3 a - b). Rainfall temporal distribution is characterized by a clear seasonal distinction; total precipitation in the wet season (September to May) could be as high as 400 mm month^{-1}

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in the most tropical areas, whereas in the dry season (June to August), precipitation is close to zero in the Cerrado and as low as 50 mm month^{-1} in the wetter areas (Mohor et al., 2015). As a result of the large rainfall seasonal variability, river flows are also extremely variable: the mean monthly flow of the Tapajós river ranges between about 2,300 and 28,600 m^3 s^{-1} according to the historical records used for the calibration of ~~our~~ the ED2+R model. Soils vary from those typically seen in the Brazilian shield in the south of the basin to alluvial sediments in the north. Land-use, almost completely represented by primary forest until the 1970s, was radically changed in recent decades. As estimated from the land-use/land-cover dataset ~~set~~ used in this study (Hurtt et al. 2006), in the late 2000s only about 56% of the basin (270,000 km^2) was covered by the original vegetation cover. Large parts of the basin laying in the territory of Mato Grosso, were cleared to make room for agricultural and livestock production, while vast areas around the border between the state of Pará and Mato Grosso were cleared for cattle production. The northern portion of the basin is largely protected by natural parks or indigenous lands, but large deforestation hotspots could be identified around the cities of Santarem and Itaituba and along the main transportation routes (Figure 3c). For a more detailed description of the basin's physical characteristics and historical analysis of trends in deforestation, precipitation and discharge, we refer the reader to Arias et al. and Farinosi et al. (under review).

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For calibration purposes the basin was divided into seven sub-basins, each of them with a corresponding gauge for which historical daily river flow observations were available (Figure 4a). The domain was gridded with a spatial resolution of 0.5° by 0.5°, roughly corresponding to 55 km by 55 km. Simulations were carried out for the period 1970-2008. The ED2 model was forced using reconstructed climate (Sheffield et al. 2006) and land use/land cover data (Hurtt et al. 2006; Soares-Filho et al. 2006) at 1-degree spatial resolution. The original meteorological dataset has a 3-hour temporal resolution, which was downscaled to an hourly resolution, as described in Zhang et al. (2015). In this technical note, we describe the calibration of the flow routing component of the ED2+R. The parameterization of the ED2 terrestrial biosphere model was developed and evaluated independently using eddy-flux tower observations of carbon, water, and energy fluxes and forest inventory observations of above-ground biomass dynamics. Further details are available elsewhere (Zhang et al. 2015, Longo 2014).

ED2+R Model Calibration: The ED2+R model was manually calibrated using gauge observations (HYBAM and ANA) spanning a period of 17 years, from 1976 to 1992 (the period 1970-1975 was not considered in order to avoid simulation initiation effects) through a two-step procedure, as highlighted in Figure 2. The first step is the partitioning of the flows from the two reservoirs (surface and sub-surface) of the ED2 biosphere model to the three reservoirs (surface, intermediate, base) of the ED2+R routed biosphere model (parameters α and β in Figure 2). In particular, α (ranging from 0 to 1, or from 0% to 100%) represents the share of ED2 surface runoff allocated to the ED2+R surface reservoir. The remaining part $(1-\alpha)$ is allocated to the ED2+R intermediate reservoir. β represents a similar partitioning coefficient for the ED2 sub-surface reservoir to the ED2+R intermediate and base reservoirs. The second step relates to the adjustment of the residence times of the water flows in the three reservoirs for each of the grid cells in each of the sub-basins (overland, intermediate, and subsurface water ~~groundwater~~ flows – represented by the adjustment parameters *CS*, *CI*, *CB* in Figure 2).

In the first step, following the methodology described by Anderson (2002), the sensitivity of the α and β parameters was tested by running the model multiple times (~~~>~~3~~0~~5). For each run, the Nash-Sutcliffe indicator (NSE) (Nash & Sutcliffe 1970) was quantified comparing the results of the simulation to historical flow observations. The combinations of the α and β parameters characterized by the largest NSE were selected. Parameters α and β were assumed to be uniform for the whole basin. Figure 5 shows the different combinations of the α and β parameters introduced in Figure 2. The color bar indicates the NSE resulting from the comparison between the simulated and observed river flow values obtained using different combinations of the parameters α (x axis) and β (y axis). The chosen combination (indicated by an x in Figure 5) lies in one of the optimal combination areas (NSE ~ 0.8).

In the second step, the residence times (τ) of flow within the ED2+R reservoirs of each grid cell in the domain were calibrated through the adjustment of the non-dimensional parameters (*CS*, *CI*, and *CB* in Figure 2) used to correct the Kirpich formula for time of concentration (as explained in Collischonn et al. 2007). The calibration procedure characterizing the second step is similar to the previous one but in this case the calibration is repeated for each sub-basin sequentially~~;~~. ~~the~~ The calibration process was conducted from the furthest upstream sub-basins – headwaters – to the final outlet of the basin (Anderson 2002). The model was run multiple times (between 30 and 50 per sub-basin) with different combinations of the three parameters (*CS*, *CI*, and *CB* in Figure 2); for each run, the goodness-of-fit was quantified. This allowed us to design a sensitivity curve of the model to different combinations of the three parameters for each of the seven sub-basins, and to select the combination that best approaches the historical observations. Figure 6 shows how the model is sensitive to marginal variation in initial

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conditions of baseflow, particularly in the upstream section (i.e. UTP - Upper Teles Pires, UJ – Upper Juruena, and LTP – Lower Teles Pires). Changes in initial subsurface water ~~groundwater~~ were controlled by the initialization five year period, thus contributions to the downstream part of the basin had minimal impact (i.e. UT and LT - Upper and Lower Tapajós).

Figure 7 describes the calibration of the residence time adjustment parameters for each of the sub-basins, as well as an approximate calculation of the corresponding time of concentration for each of the reservoirs in the cell. The different combinations of the values assigned to the parameters *CS*, *CI*, and *CB* significantly affect the overall goodness-of-fit of the river flow simulations (NSE indicator). The calibration process was conducted from the furthest upstream sub-basins – headwaters – (UTP – Upper Teles Pires, UJ – Upper Juruena, and JA – Jamanxim) to the final outlet of the basin (LT – Lower Tapajós). The different combinations are marked with the corresponding NSE value; the optimal combination is marked in red (Figure 7).

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The period 1993-2008 was used for model evaluation. Comparison between observations and simulated flows (goodness-of-fit) were carried out using Pearson's R correlation coefficient (Pearson 1895), volume ratio (VR), the Nash-Sutcliffe Efficiency (NSE) coefficient (Nash & Sutcliffe 1970), and the Kling Gupta Efficiency (KGE) index (Kling et al. 2012; Gupta et al. 2009) (Table 3).

5 Results

The integration of the routing scheme with ED2 increases the ability of the model to reproduce the observed temporal variations in river flows at the basin outlet (Figure 8). This statement applies to all of the sub-basins, as the application of the routing scheme improved the model's performance between simulated and observed values with respect to all the four measures selected (Nash-Sutcliffe (NSE), Kling Gupta (KGE), Pearson's R correlation , and volume ratio) (Table 3). Both routed (ED2+R) and non-routed (ED2) simulation results manage to reproduce the observed water availability (quantity of water available) in the basin in terms of volume. The volume ratio at the furthest downstream sub-basin (Lower Tapajós), in fact, ranges around the optimal value for both validation and calibration periods (ED2 1.11-1.13, ED2+R 1.06-1.13). The routing scheme improves the ability of the model to reproduce the spatio-temporal distribution of water flows across the basin: both the NSE and the KGE indexes reached values ranging between 0.76 and 0.86 in the calibration, and 0.68-0.80 in the validation period (Table 3). Also, the correlation values confirm the results of the other indexes, reaching

0.88 for the calibration and 0.86 for the validation period. The performance of the presented tool is evident also analyzing FDCs (Figure 9 a - g). The adoption of the river routing scheme allows a more realistic representations of the high discharge values (flow equaled or exceeded 0 to 20/30% of the time), and low discharge values (flow equaled or exceeded 60 to 100% of the time) in all the sections of the basin (Figure 9). The model's performance in simulating river flows is generally more robust in the downstream sub-basins (NSE 0.68-0.77, and KGE 0.76-0.84 in the Upper and Lower Tapajós) and poorer in the headwaters (NSE 0.28-0.45, and KGE 0.38-0.61 in the Upper Juruena and Upper Teles Pires). In the Upper Teles Pires and Upper Juruena, the model achieved the lowest NSE (0.28 and 0.29 respectively in the calibration, and 0.37 and 0.45 in the validation period), and KGE values (0.61 and 0.50 calibration, and 0.63 and 0.38 validation). Although water volumes are correctly reproduced in both the sub-basins (VR between 1.01 and 0.98 in the calibration, and 1.03 and 1.01 in the validation period), the seasonal variability is less accurate (correlation 0.64-0.68, and 0.63-0.54). The KGE, NSE and correlation indices are closer to the optimal value in the central and lower part of the basin, in particular in the Lower Juruena (calibration - NSE 0.65, KGE 0.64, correlation 0.82; validation - NSE 0.63, KGE 0.67, correlation 0.81), Lower Teles Pires (calibration - NSE 0.71, KGE 0.67, correlation 0.85; validation - NSE 0.67, KGE 0.60, correlation 0.85), Upper Tapajós (calibration - NSE 0.77, KGE 0.82, correlation 0.88; validation - NSE 0.75, KGE 0.81, correlation 0.88), and Lower Tapajós (calibration - NSE 0.76, KGE 0.83, correlation 0.88; validation - NSE 0.68, KGE 0.76, correlation 0.82) (Table 3).

FDCs, representing the probability of the flow values to exceed a specific discharge, highlight the positive effect of the application of the routing scheme in ED2+R across the entire range of flow variability (Figure 9). The simulated FDCs follow the same shape of the observed ones in the furthest upstream sub-basins, especially in the cases of the Upper Juruena and Upper Teles Pires, implying that the routing scheme is effective in maintaining the simulated discharge range (Upper Juruena 1,200-2,480 m^3 sec^{-1}, Upper Teles Pires 393-4,130 m^3 sec^{-1}) in line with the observations (1,030-2,400 and 302–2,767 m^3 sec^{-1}, respectively). This is especially true for the lowest flows, where the error between simulated and observed curves is lower than 15% (Figure 9 a-b, Figure A.1). Regarding the intermediate sub-basins, Lower Juruena and Lower Teles Pires, flood duration curves show that the model overestimates the lowest values of the distribution ~~up~~ by approximately 30% of the observed values (flow equaled or exceeded 60 to 100% of the time in Figure 9 c–d). Similar overestimation of the model could be noticed in the furthest downstream sub-basins, Upper and Lower Tapajós (Figure 9 e–g). The overestimation

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of the lower discharge values highlighted in Figure 9g, is also evident in the multiyear hydrograph (Figure 8), which shows that the ED2+R simulation results overestimate (by about 40% on average in the discharge values included in the range 60 to 100% in Figure 9 g) the observations during the dry seasons of the period under consideration.

6 Discussion

As the results in Table 3 and Figures 8 - 9 show, the one-way integration of ED2 with a routing scheme ~~increases~~ improves the performance of simulated daily discharges. Although this could appear obvious from a hydrological modeling perspective, the significance of this study lies in the fact that terrestrial biosphere models, which are widely applied to examine the impacts of climate and land use on the hydrology of the land surface, are typically "no river representation" models. The incorporation of ecosystem responses to climate, carbon dioxide, and land-use changes simulated by terrestrial biosphere models with hydrological modeling improves the representation of the hydrological characteristics of basins characterized by large forest cover and/or large deforestation rates. In applications in the tropics, the one-way integration of the terrestrial biosphere model and the routing scheme (i.e. the two tools are not fully coupled) could lead to a partially inaccurate representation of the seasonally flooded ecosystems, a relevant aspect as documented in the literature (Cole et al. 2007).

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As seen in Figure 9, the performance of the model in simulating river flows in the basin is generally higher in the downstream sub-basins and poorer in the headwaters. Several factors are likely to cause this issue, both from the simulation of the hydrological dynamics in ED2, the flow partitioning (α and β parameters), and the basin hydraulic characteristics in ED2+R. The accurate calibration of the biosphere model with flux tower observations (Zhang et al. 2015; Longo et al. 2014) and the optimization of the flow partitioning, make us believe that this is due to the relatively coarse spatial resolution of the model in combination with the limitations typical of most land surface models in capturing the interactions with deep groundwater (Lobligeois et al. 2014; Zulkafli et al. 2013; Smith et al. 2004). We believe that the error is arising from the complexities associated with deep soils present in the headwaters of the Tapajós basin. In particular, in the model application developed, soil layers are represented to a depth of 6 meters (Table 1), which might be too shallow to ~~more~~ realistically represent the conditions in the headwaters of the basin. The importance of groundwater is also evident from the calibration of the residence time parameter of the subsurface water ~~groundwater~~ flow: as

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shown in Figure 7, in fact, especially in the headwaters, even small variations in the CB parameter ~~largely~~ greatly affect the model performance (specifically quantified with NSE in Figure 7). The combined effect of groundwater interactions and spatial resolution is more evident in the upstream sub-basins because of the greater marginal contribution of baseflow in these areas. Surface flow accumulation, in fact, is lower in the headwaters. Therefore, in relative terms, the role of baseflow is more relevant in this portion of any basin. Further downstream, the effect of groundwater interactions and spatial resolution is, at least in part, masked by the larger rainfall-runoff contribution and the overall flow accumulation from the upstream sub-basins. Other recent hydrological simulations of the Tapajós have obtained higher accuracy (e.g. Mohor et al. 2015; Collischonn et al. 2008; Coe et al. 2008); however, these simulations were set up discretizing the basin into a finer spatial resolution grid (9 to 20 km versus ~ 55 km grid cells) and using hydrological tools able to reproduce highly detailed hydrodynamic characteristics of complex river systems (i.e. floodplain, lakes, wetlands, backwater effects) that are out of the scope of the tool presented in this study. The advantage of the ED2+R model is the ability to study the sensitivity of the river flows to global and regional changes as computed by traditional terrestrial biosphere models, but adding a more detailed hydrological feature with respect to a very simplistic- of no-river representation. The coarse spatial resolution of the global datasets used as input for ED2+R is, however, a limiting factor. Higher resolution climatological data, vegetation, and land use datasets, while allowing a finer resolution of the hydrological grid, are expected to improve the performance of the model by providing more detailed hydrological processes. On the other hand, a finer spatial resolution of the hydrological grid would also require a more detailed representation of the subsurface water in the model. In general, the tool can be used to study how different hydrological systems are being affected by changes in climate forcing and changes in ecosystem composition and structure arising from the combination of: changing climate, rising atmospheric carbon dioxide, and land-use transformation. Additionally, ED2+R could potentially bridge one of the missing gaps for diagnosing and assessing feedbacks between atmosphere and biosphere with inland surface waters being represented as a dynamic system.

7 Conclusion

In this Technical Note, we present the integration of the terrestrial biosphere model Ecosystem Demography 2 (ED2) with the Muskingum-Cunge routing scheme. We tested the integrated

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model (ED2+R) in the Tapajós river basin, a large tributary of the Amazon in Brazil, for the period 1970-2008. The results showed that the integration of a biosphere model with a routing scheme improves the ability of the land surface simulation to reproduce the hydrological and river flow dynamics at the basin scale. The main limitations highlighted in this case study were linked to the relatively coarse spatial resolution of the model and the rough representation of subsurface water ~~groundwater~~ flow typical of this kinds of models. Moreover, the terrestrial biosphere model ED2 and the routing scheme are presented here in a one-way integration. The full coupling of the routing scheme and ED2 could further improve the ability to reproduce the water balance considering flooded ecosystems, a relevant feature in the simulation of environments like the tropical forest, where local evapotranspiration plays a primary role in the specific ecosystem's dynamics. In this first integration, our goal was to give the possibility to the terrestrial biosphere model to reproduce river flows through a routing scheme. With a fully coupled (i.e. two-way) integration, the model would be able to determine the grid cells that are likely to be saturated and use this information for the modeling of the ecosystem's dynamics. For instance, this could determine the increase of the mortality rate of plants that are sensitive to inundation. An additional limitation of the model, could be identified in its inability to reproduce highly detailed hydrological dynamics of complex river systems (as for instance, floodplain hydraulic features, or backwater effects), however, such a detailed hydrological complexity was out of the scope of this study. Future efforts will be oriented towards the resolution of the highlighted limitations and current research is focusing on the application of ED2+R on understanding historical changes and future projections of the impacts of climate change and deforestation on the Amazon's water resources.

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Author's contribution

F. Pereira, P. Moorcroft and J. Briscoe designed the study; F. Pereira developed the ED2+R model code; F. Farinosi, M. Arias, and E. Lee calibrated the model and carried out the analysis; F. Farinosi, M. Arias and P. Moorcroft wrote the paper.

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Figures

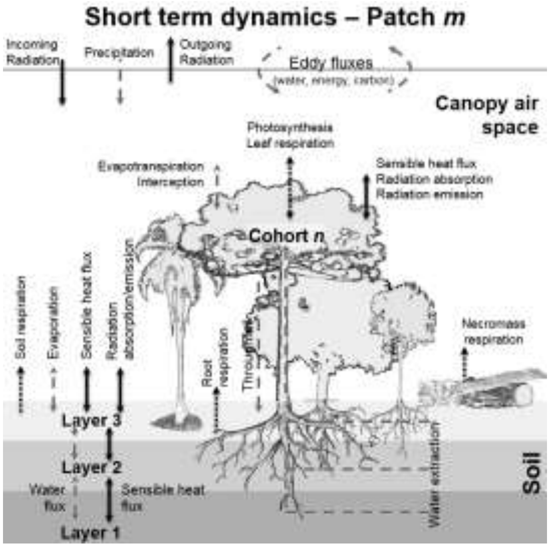
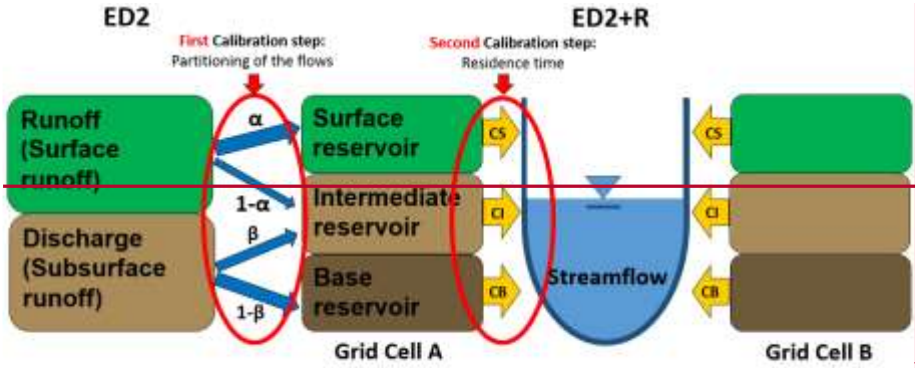


Figure 1. Schematic of the enthalpy fluxes (all arrows) and water fluxes (all but solid black arrows) that are solved in ED2. The schematic is based on Walko et al. (2000); and Medvigy et al. (2009). (Courtesy of Marcos Longo).



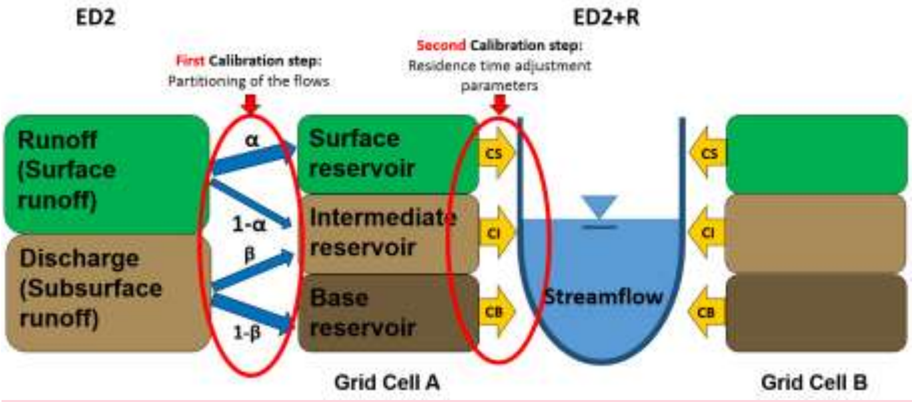


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Figure 2. Schematic representation of the connection between the terrestrial biosphere model and the hydrological routing scheme. Calibrating parameters circled in red. The reservoirs are used to determine the contribution of streamflow that comes from overland flow, interflow and groundwater flow. The daily sum of these three reservoirs is then moved from each grid cell into the drainage network.

Average yearly precipitation (mm year^{-1})	**Average temperature (°C)**

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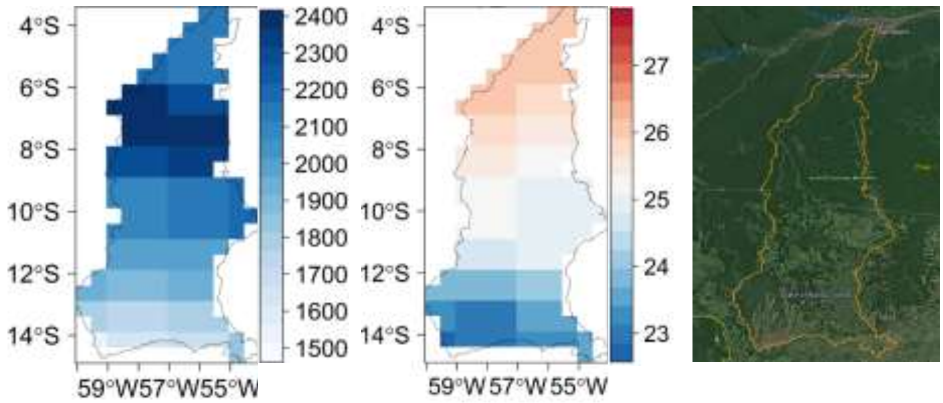

(a) (b) (c)

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Figure 3. Average precipitation (a) and temperature (b) in the Tapajós river basin (1986 - 2005). Redrafted from Farinosi et al. (under review). (c) ~~Land use in~~Aerial imagery the Tapajós river basin illustrating land cover diversity in the catchment. Source: Google Earth Pro.

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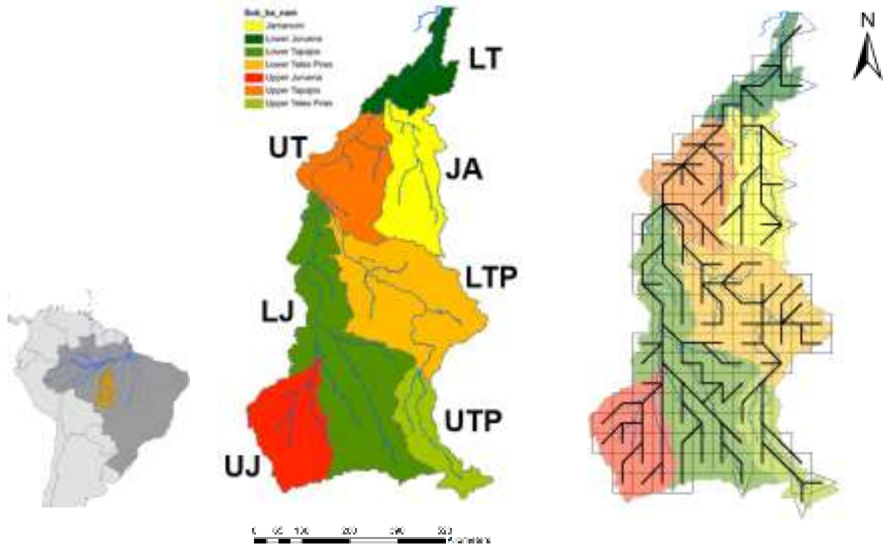


(a) (b)

Figure 4. (a) Organization of the Tapajós basin into seven sub-basins: Upper Juruena (UJ); Lower Juruena (LJ); Upper Teles Pires (UTP); Lower Teles Pires (LTP); Jamanxim (JA); Upper Tapajós (UT); and Lower Tapajós (LT). (b) ED2+R represents the domain in grid cells with 0.5° resolution (~ 55 km). The black segments indicate flow accumulation network.

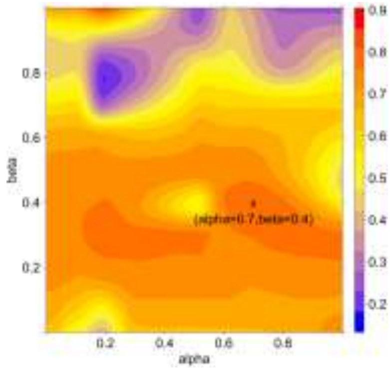
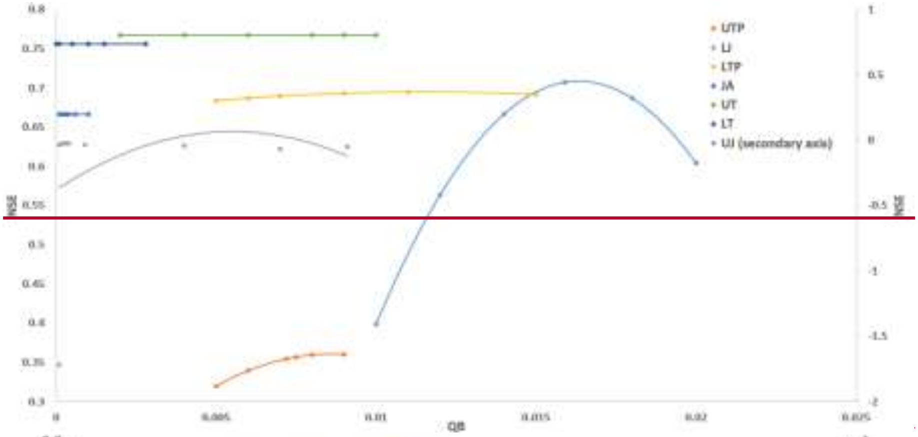


Figure 5. Calibration of flow partitioning (parameters alpha and beta in Figure 2~~Figure 2~~) between the ED2 and the ED2+R reservoirs. Color bar indicates the NSE values of the simulated versus the observed river flow values (0 very different, 1 very similar)



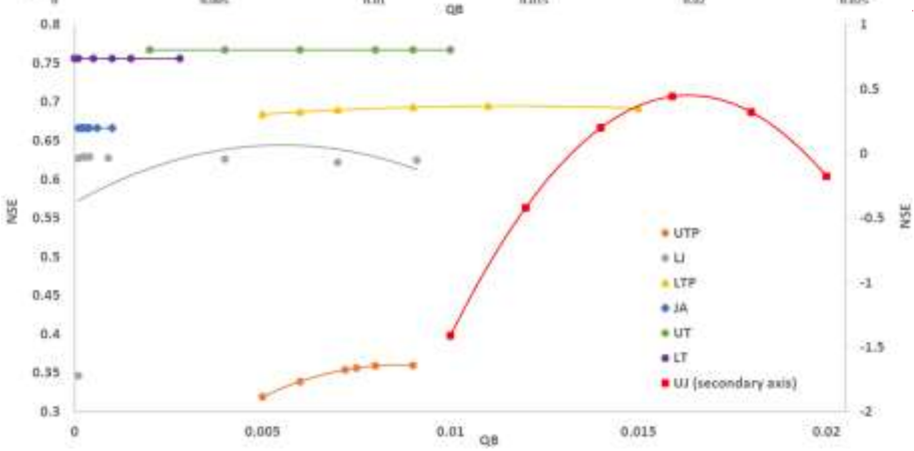


Figure 6. Model sensitivity to the ~~i~~Initial conditions of baseflow ~~sensitivity~~ (QB) for the different ED2+R sub-basins in the domain~~.~~: Upper Juruena (UJ); Upper Teles Pires (UTP); Lower Juruena (LJ); Lower Teles Pires (LTP); Upper Tapajós (UT); Jamanxim (JA); and Lower Tapajós (LT).

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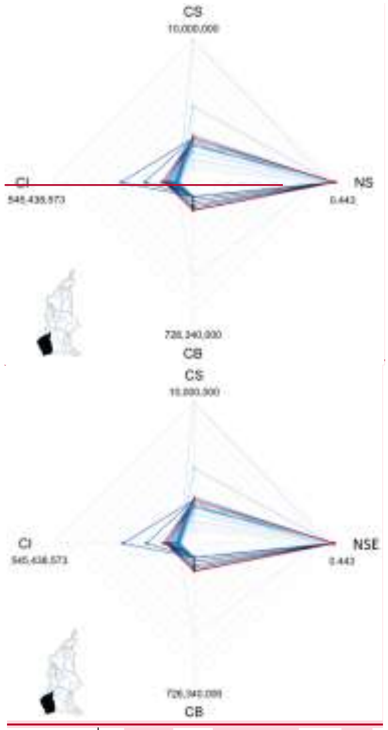
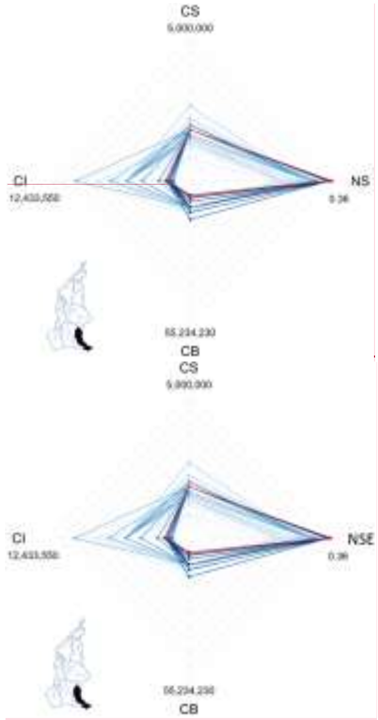
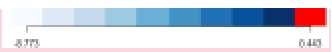




	Surface	Intermediate	Base
Appr. time of concentration (days)	11.00	13.45	13.64

	Surface	Intermediate	Base
Appr. time of concentration (days)	10.45	10.52	10.79

(a)



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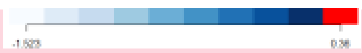

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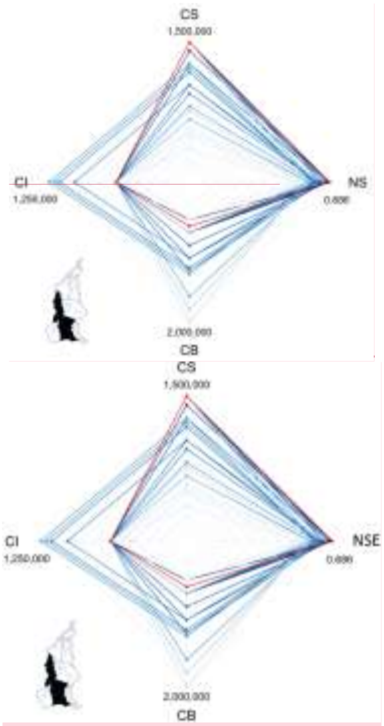
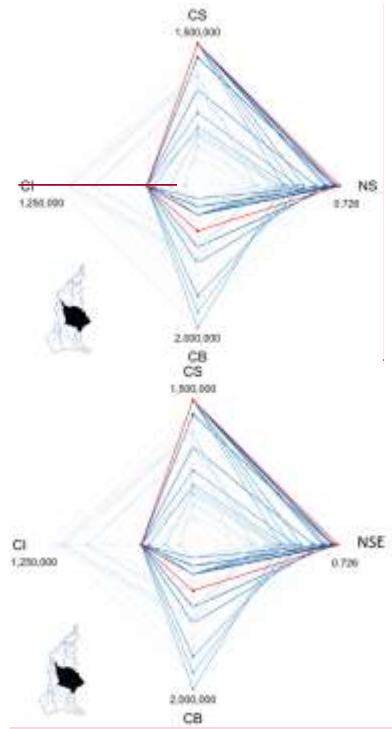
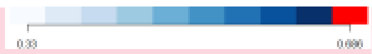




	Surface	Intermediate	Base
Appr. time of concentration (days)	9.33	8.73	8.61

	Surface	Intermediate	Base
Appr. time of concentration (days)	11.34	10.67	10.84



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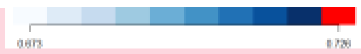

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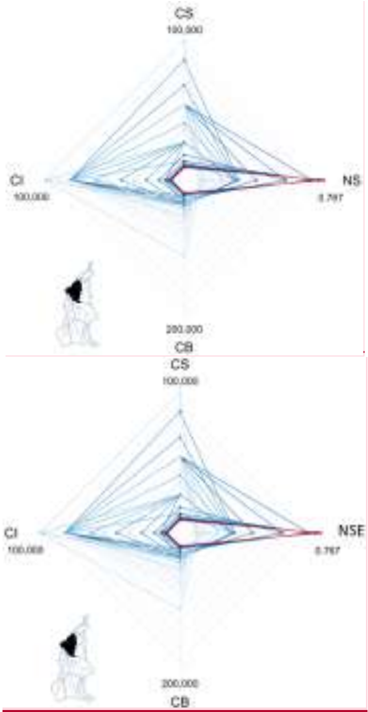
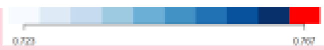
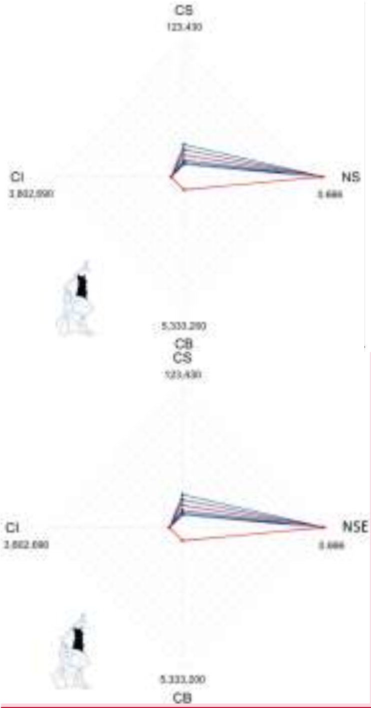
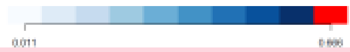


	Surface	Intermediate	Base
Appr. time of concentration (days)	7.88	12.73	12.73

(e) 



	Surface	Intermediate	Base
Appr. time of concentration (days)	6.72	6.72	6.80

(f) 

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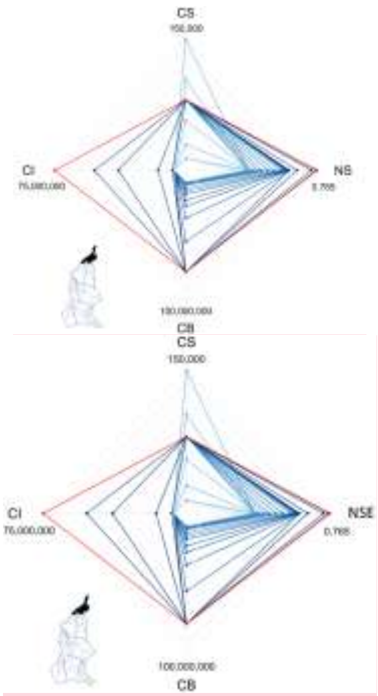


	Surface	Intermediate	Base
Appr. time of concentration (days)	9.18	14.82	14.82

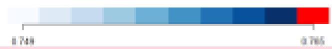
(g) 

Figure 7. Calibration of the residence times (τ) of the flow within the ED2+R reservoirs of different grid cells in the domain through the adjustment of the non-dimensional C parameters. Overland, intermediate and subsurface water ~~groundwater~~ flows are ~~indicated~~ calibrated respectively ~~by~~through the adjustment parameters CS, CI, and CB (Figure 2~~Figure 2~~). The color bars refer to the model performance (Nash-Sutcliffe Efficiency NSE) of the specific parameter combination in the specific sub-basin. In red the chosen combinations. At the bottom of each graph, a table providing the corresponding approximate average time of concentration (in days) for the cells in the sub-basin. (a) Upper Juruena (UJ); (b) Upper Teles Pires (UTP); (c) Lower Juruena (LJ); (d) Lower Teles Pires (LTP); (e) Upper Tapajós (UT); (f) Jamanxim (JA); and (g) Lower Tapajós (LT).

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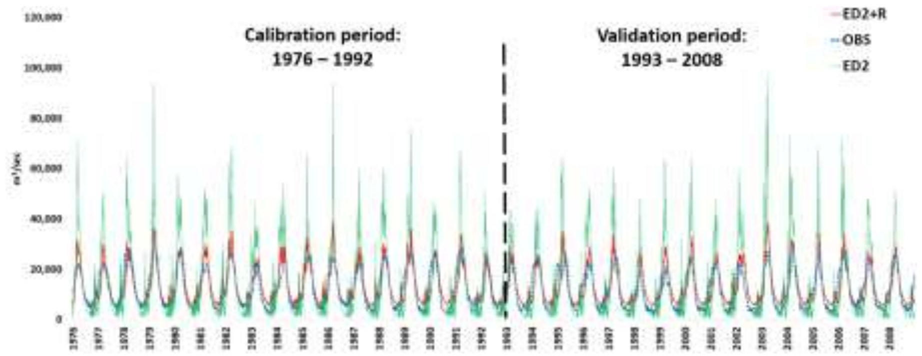

Figure 8. Calibration and validation of the river flow (m^3/sec) at Itaituba (farthest downstream river gauge – Lower Tapajós sub-basin). ED2 output (green line), ED2+R (red line), and Observations (blue dotted line). The dotted black line splits the calibration and validation periods. Similar comparison for each of the 7 sub-basins is available in Annex A.

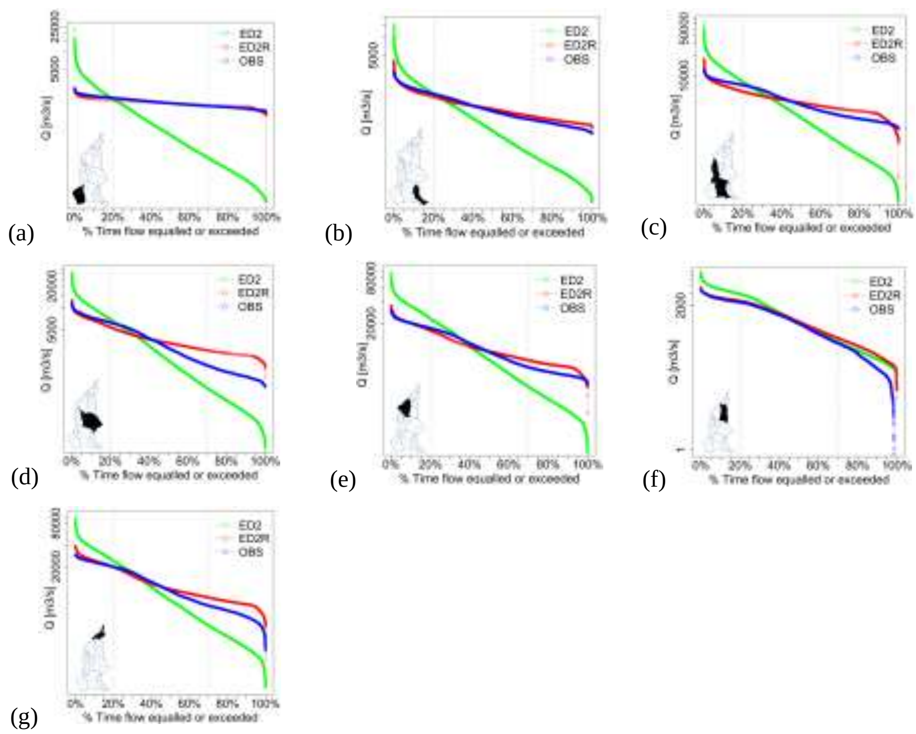

Figure 9. Flow duration curves (percentage of time that flow – m^3/s – is likely to equal or exceed determined thresholds) of observed values (blue), ED2 outputs (green), ED2+R (red) at the outlet of the seven sub-basins. (a) Upper Juruena (UJ); (b) Upper Teles Pires (UTP); (c) Lower

Juruena (LJ); (d) Lower Teles Pires (LTP); (e) Upper Tapajós (UT); (f) Jamanxim (JA); and (g) Lower Tapajós (LT).

Tables

Table 1. ED2+R calibrated parameters (based on Zhang et al., 2015; Longo et al., 2014; Knox et al., 2012). Additional information about ED2 parameter calibration for the Amazon basin are available in Zhang et al. (2015) and Longo et al (2014).

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Input	**Source**	
Meteorological forcing	Sheffield et al. (2006)	
Land use	Hurtts et al. (2006)	
Topography (DEM)	SRTM, Shuttle Radar Topography Mission 90 mt resolution	
Soil data	Quesada et al. (2010) -IGBP-DIS global soil data (Global Soil Data Task 2014)	
Geomorphological relations	Coe et al. (2008)	
Streamflow observations	HYBAM - ANA	
Carbon dioxide concentration	378 ppm	
Process	**Method**	
Integration scheme	4th order Runge-Kutta method	
Energy and water cycles	Knox (2012) and Longo (2014)	
Temperature-dependent function for photosynthesis	Q_{10} function	
Canopy radiation scheme	Two-stream model	
Allometry for height	Based on Poorter et al. (2006)	
Allometry for above-ground biomass	Based on Eqn. (2) of Baker et al. (2004)	
Allometry for leaf biomass	Based on Cole & Ewel (2006) and Calvo-Alvarado et al. (2008)	
Parameter	**Value**	**Units**
Biophysics time step	600	s
Number of soil layers	16	-
Depth of the deepest soil layer	6	m
Depth of the shallowest soil layer	0.02	m
Cohort water holding capacity	0.11	$kg_w m^{-2}_{leaf+wood}$
Residual stomatal conductance	10,000	$\mu mol\ m^{-2} s^{-1}$
Leaf-level water stress parameter	0.016	$mol_{H_2O}\ mol^{-1}_{Air}$
Oxygenase/carboxylase ratio at 15ºC	4000	-
Power base for oxygenase/carboxylase ratio	0.57	-
Power base for carboxylation rate	2.4	-
Power base for dark respiration rate	2.4	-
Environmentally-determined parameters	**Value**	**Units**
Weight factor for stress due to light	1.0	-
Maximum environmentally-determined mortality rate	5.0	yr^{-1}
Steepness of logistic curve	10.0	-
Band-dependent radiation parameters (*)	**Value**	**Units**
Dry soil reflectance	(0.20; 0.31; 0.02)	-
Wet soil reflectance	(0.10; 0.20; 0.02)	-
Leaf transmittance	(0.05; 0.20; 0.00)	-
Leaf reflectance (grasses)	(0.10; 0.40; 0.04)	-
Leaf reflectance (trees)	(0.10; 0.40; 0.05)	-
Wood transmittance	(0.05; 0.20; 0.00)	-
Wood reflectance (trees)	(0.05; 0.20; 0.10)	-
Plant Functional Type PFT-dependent parameters (**)	**Value**	**Units**
Leaf orientation factor	(0.10; 0.10; 0.10)	-

Leaf clumping factor	(0.80; 0.80; 0.80)	-
Leaf characteristic size	(0.10; 0.10; 0.10)	*m*
Max. carboxylation rate at 15ºC	(18.75; 12.50; 6.25)	$\mu mol_C\, m_{leaf}^{-2} s^{-1}$
Dark respiration rate at 15ºC	(0.272; 0.181; 0.091)	$\mu mol_C\, m_{leaf}^{-2} s^{-1}$
Quantum yield	(0.080; 0.080; 0.080)	-
Slope parameter for stomatal conductance	(9.0; 9.0; 9.0)	-
Fine root conductance parameter	(600; 600; 600)	$m^2 kg_{C_{root}}^{-1} yr^{-1}$
River Routing Parameters (Section 4)	**Value**	**Units**
Grid-cell size (Figure 4)	0.5x0.5	*degrees*
Flow partitioning parameters (α; β) (Figure 5)	(0.70; 0.40)	-
Residence time adjustment parameters, respectively referring to ~~O~~overland (CS), intermediate (CI), and subsurface water ~~groundwater~~ flows (CB) (Figure 7) (CS; CI; CB)	Upper Juruena (2,600; 70,000; 90,000) Upper Teles Pires (1,600; 1,750; 2,500) Lower Juruena (1,500; 600; 500) Lower Teles Pires (1,500; 650; 800) Jamanxim (10; 10; 11) Upper Tapajós (75; 75,000; 75,000) Lower Tapajós (75; 75,000; 75,000)	*x1‘000 (***)*
Initial conditions of the baseflow (Figure 6)	Upper Juruena (0.0159) Upper Teles Pires (0.009) Lower Juruena (0.0004) Lower Teles Pires (0.011) Jamanxim (0.0001) Upper Tapajós (0.0080) Lower Tapajós (0.0005)	$m^3 km^2$

(*) Radiation-dependent parameters are given in the format (xPAR; xNIR; xTIR) corresponding to values for photosynthetically active, near infrared and thermal infrared, respectively.
(**) PFT-dependent parameters are given in the format (xETR; xMTR; xLTR) corresponding to the values for early-, mid-, and late-successional cohorts, respectively.
(***)The residence time parameters are dimensionless and used to correct the Kirpich formula for time of concentration as explained in Collischonn et al. (2007). Their magnitude is influenced by the size of the grid-cell and its topography.

Commented [FF45]: REF4_CMT9 and REF4_CMT21

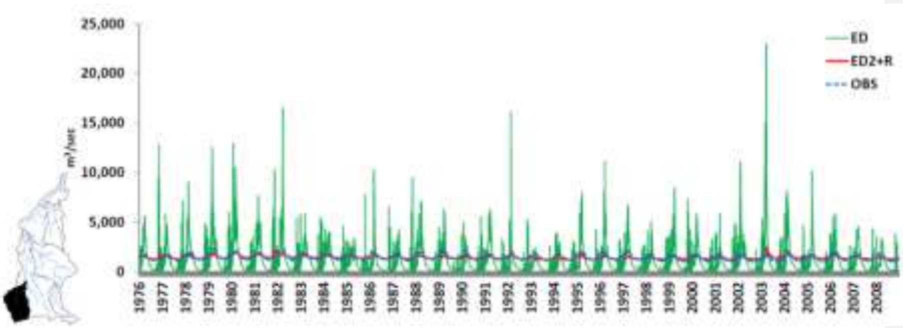
Table 2. Statistics about the gauge information filling procedure (correlation with the station to be filled, number of original observations, filled number of observations).

Sub-basin name	Main river gauge station - **z** in Equation 7	Original number of daily gauge records (number of daily observations)	Gap filling station 1 – **q** in Equation 7 – [correlation with **z]**	Gap filling station 2 – **y** in Equation 7 – [correlationwith **z]**	Number of daily records after filling procedure (number of daily observations)
Jamanxin	Jamanxim	1,928	Jardim do Ouro [0.97]	Novo Progresso [0.96]	5,382
Upper Teles Pires	Cachoeirão	10,356	Teles Pires [0.91]	Indeco [0.94]	11,524
Upper Juruena	Fontanilhas	10,469	Foz do Juruena [0.94]	Barra do Sã~~a~~o Manuel [0.89]	11,688
Lower Teles Pires	Tres Marias	8,682	Barra do Sã~~a~~o Manuel [0.98]	Santa Rosa [0.98]	10,640
Lower Juruena	Foz do Juruena	2,074	Barra do Sã~~a~~o Manuel [0.98]	Jatoba [0.97]	11,447
Upper Tapajós	Jatoba	10,218	Fortaleza [0.99]	Barra do Sã~~a~~o Manuel [0.98]	11,517
Lower Tapajós	Itaituba	5,789	Fortaleza [0.99]	Jatoba [0.98]	11,688

Table 3. Calibration and validation results. Nash-Sutcliffe Efficiency, Kling Gupta (2009 and 2012 methods), Pearson's R correlation, and volume ratio. Optimal values = 1 (statistics where calculated using the R package hydroGOF - Zambrano-Bigiarini 2014).

	Calibration period (1976-1992)								**Validation period (1993-2008)**							
Sub-basin	**Nash-Sutcliffe**		**Kling-Gupta [method 2009] {method 2012}**		**Pearson's R Correlation**		**Volume Ratio Vol sim/Vol Obs**		**Nash-Sutcliffe**		**Kling-Gupta [method 2009] {method 2012}**		**Pearson's R Correlation**		**Volume Ratio Vol sim/Vol Obs**	
	ED vs OBS	**ED2+R vs OBS**	**ED vs OBS**	**ED2+R vs OBS**	**ED vs OBS**	**ED2+R vs OBS**	**ED vs OBS**	**ED2+R vs OBS**	**ED vs OBS**	**ED2+R vs OBS**	**ED vs OBS**	**ED2+R vs OBS**	**ED vs OBS**	**ED2+R vs OBS**	**ED vs OBS**	**ED2+R vs OBS**
Upper Juruena	-26.88	0.45	[-3.60] {-5.75}	[0.50] {0.51}	0.61	0.68	0.72	0.98	-27.47	0.29	[-3.54] {-6.10}	[0.39] {0.38}	0.53	0.54	0.68	1.01
Upper Teles Pires	-3.35	0.37	[-0.51] {-0.64}	[0.61] {0.61}	0.53	0.64	0.94	1.01	-3.19	0.28	[-0.51] {-0.59}	[0.63] {0.63}	0.57	0.63	0.96	1.03
Lower Juruena	-1.45	0.65	[-0.23] {-0.18}	[0.64] {0.67}	0.77	0.82	1.02	0.94	-2.17	0.63	[-0.43] {-0.30}	[0.72] {0.67}	0.75	0.81	1.05	1.08
Lower Teles Pires	-0.20	0.71	[0.25] {0.27}	[0.68] {0.67}	0.80	0.85	1.01	1.02	-0.34	0.67	[0.17] {0.34}	[0.69] {0.60}	0.82	0.85	1.11	1.17
Jamanxim	-0.74	0.67	[0.01] {0.39}	[0.79] {0.78}	0.82	0.85	1.55	1.13	-0.10	0.55	[0.23] {0.52}	[0.75] {0.73}	0.83	0.77	1.43	1.09
Upper Tapajós	-1.01	0.77	[-0.13] {0.21}	[0.82] {0.83}	0.84	0.88	1.20	0.99	-1.23	0.75	[-0.22] {0.16}	[0.84] {0.81}	0.84	0.88	1.21	1.08
Lower Tapajós	-0.40	0.76	[-0.09] {0.28}	[0.86] {0.83}	0.84	0.88	1.11	1.06	-0.50	0.68	[0.09] {0.29}	[0.80] {0.76}	0.82	0.86	1.13	1.13

Annex A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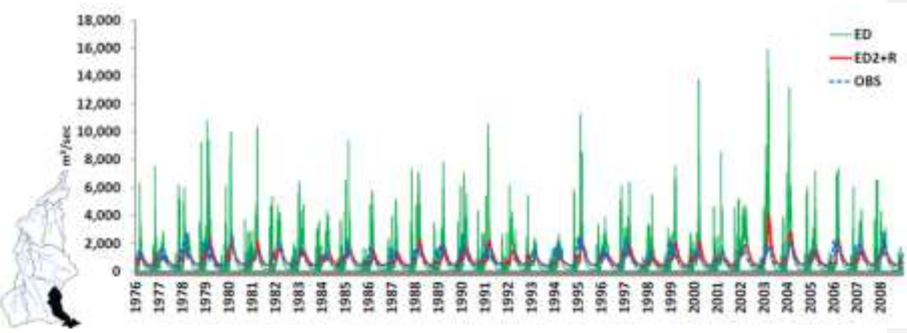
20,000
15,000
10,000
5,000
0
m³/sec
ED
ED2+R
OBS

(a)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12,000
10,000
8,000
6,000
4,000
2,000
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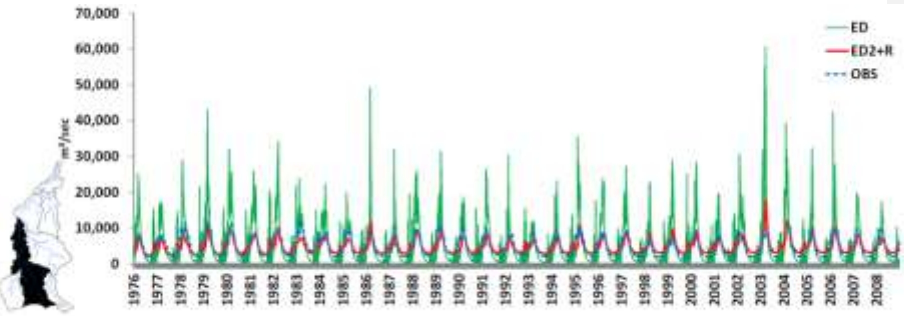
m³/sec
ED
ED2+R
OBS

(b)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10,000
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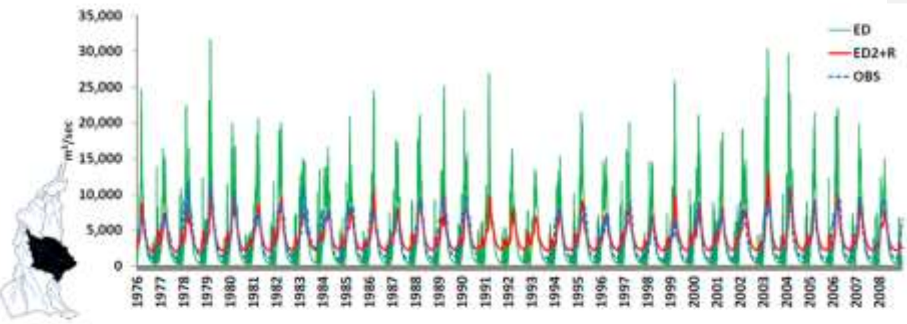
m³/sec
ED
ED2+R
OBS

(c)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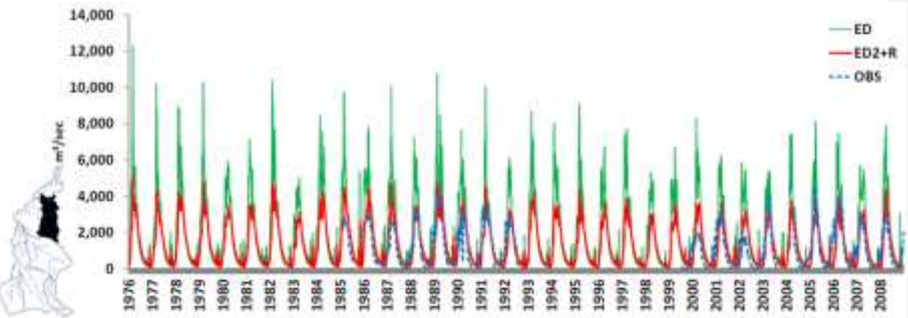
10,000
5,000
0
m³/sec
ED
ED2+R
OBS
1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008
(d)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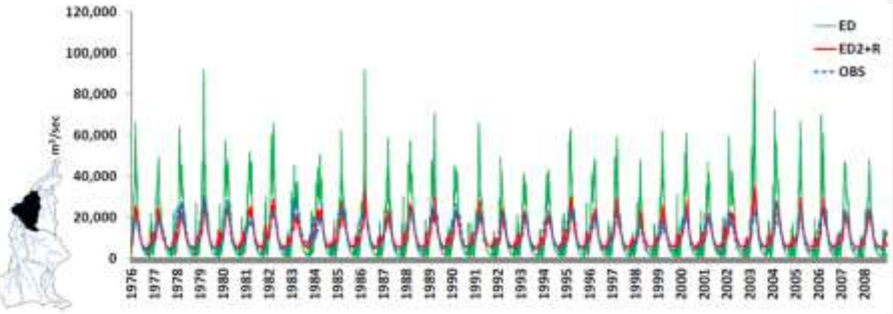
m³/sec
ED
ED2+R
OBS
1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008
(e)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100,000
80,000
60,000
40,000
20,000
0
m³/sec
ED
ED2+R
OBS
1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008
(f)

(g)

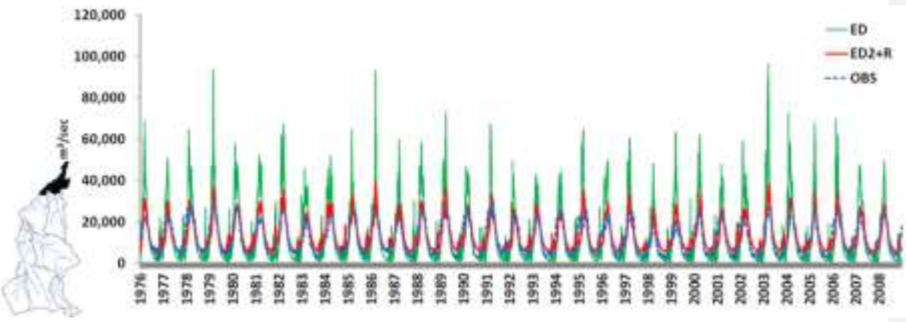

Figure A1. Time series of river flow (m3/sec) at the outlet of each sub-basins. ED2 output (green line), ED2+R (red line), and Observations (blue dotted line). (a) Upper Juruena (UJ); (b) Upper Teles Pires (UTP); (c) Lower Juruena (LJ); (d) Lower Teles Pires (LTP); (e) Jamanxim (JA); (f) Upper Tapajós (UT); and (g) Lower Tapajós (LT).

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