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January 31, 2017

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 and the two anonymous referees for handling our manuscript during the review process.

The comments and suggestions from you and the two reviewers were extremely valuable and we are confident that the review process has substantially increased 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 in the Hydrology and Earth System Sciences Journal. Please do not hesitate to contact me if you have any questions.

Kind regards,

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Responses to Anonymous Referee #1

General comments: *In this contribution, Pereira and co-authors propose an update to the surface water structure of the Ecosystem Demography (ED2) model, throughout the implementation of a river routing scheme. The model was successfully applied in the Tapajós River Basin, a major tributary of the Amazon River. In general, the approach for model calibration/validation is standard and demonstrated a significant improvement between observed and simulated river discharge. In my opinion, although the results are easy to understand, the manuscript requires substantial scientific structuring and improvement if it is to be considered further. The model development itself is not a compelling motivation without a clear scientific question in the background. The paper should advance understanding of hydrological processes and report novel findings. Moreover, the discussion should be closely linked to the recent literature on topics related to large-scale (i) river routing model developments and (ii) inland waters importance. I included specific and technical comments in a separated PDF file as to improve this interesting paper.*

Please also note the supplement to this comment: http://www.hydrol-earth-syst-sci-discuss.net/hess-2016-114/hess-2016-114-RC1- supplement.pdf

Response: We thank the referee for his/her thoughts and extensive feedback on the manuscript. We wish to emphasize that this manuscript is not a research article, but rather a technical note. As described on the HESS website (http://www.hydrology-and-earth-system-sciences.net/about/manuscript_types.html): *"Technical notes report new developments, significant advances, and novel aspects of experimental and theoretical methods and techniques which are relevant for scientific investigations within the journal scope"*. Specifically, the purpose of this technical note is to describe and evaluate an integrated framework for capturing the variability of streamflow as a response of changes in land surface and climate change. It is not a new hydrological model, but rather strategic integration of an existing land surface model (ED2) with an existing hydrologic routing scheme (derived from MGB-IPH) suitable exploring the combined effects of climate and land cover change on patterns of river flow static land cover of the traditional hydrological models).

This integrated modeling framework was developed to explore the following research questions: (1) How do current and simulated climate and/or future forest cover affect water scarcity in closed-basin systems? (2) How can forest-dependent changes influence the water availability in large reservoirs? (3) What are the implications of those changes in the land use policy? In line with the referee's comment, we will revise the manuscript's introduction to clearly articulate the kinds of research questions that motivate the development of this new modeling framework.

Regarding the referee's comment that *"the discussion should be closely linked to the recent literature on topics related to large-scale (i) river routing model developments and (ii) inland waters importance"*, we agree that some recent studies were overlooked in the discussion. As per the referee's suggestion, we revised the discussion section to place the manuscript's findings in the context of recent research on river routing modeling developments and the importance of inland waters.

Supplement Comments:

1. Pg 1 L1: Text and language notes: "*Avoid the repetition of the same idea in the different parts of the text and the excessive use of adjectives (i.e. substantial, serious, unique, substantially, etc.)*"

Response: As per the referee's suggestion, we revised the text in order to avoid repetition of ideas and curb the excessive use of adjectives.

- Although, in general, the english is clear, consider final text edits by a native english.

Response: The manuscript's senior author is native English speaker and the manuscript was also proofread by another native English speaker. The revised manuscript was closely proof-read before resubmission.

2. Pg 1 L22: *This sentence is background...*

Response: As suggested, this sentence was deleted (See page 1 line 25).

3. Pg 2 L1: *Actually, the study showed that the river routing method improved the model river representation, when compared to a 'no river representation'...Isn't it obvious, or not?.*

Response: We believe that the statement "the integration of ED2 with the lateral routing scheme substantially improves the ability of the model to reproduce daily to decadal river flow dynamics …" is relevant because terrestrial biosphere models, which are being widely applied to examine the impacts of climate and land-use on the hydrology of the land surface, are typically "no river representation" models. While the referee is not surprised by the improved ability of ED2+R to predict patterns of runoff compared to ED2, in our opinion demonstrating and quantifying the extent of the improvement is important for justifying the need to develop integrated modeling frameworks such as ED2+R. In line with the referee's suggestion, we revised the sentence to include quantitative metric(s) regarding the magnitude of the improvement in flow predictions following incorporation of a horizontal routing scheme (See page 2 line 3-6).

Also, river routing methods exists in a long time. why is this result important, specially, when compared to other existing models, as you cited.

Response: as noted above, the purpose of this technical note is not the development of a river routing scheme, but rather the integration of a terrestrial biosphere model with a hydrological model. Although river routing schemes have widely been employed in hydrological models, in this technical note we incorporate a river routing scheme into a terrestrial biosphere model. The most important aspect of this paper is the incorporation of terrestrial ecosystem responses to climate, carbon dioxide, and land-use change as simulated by terrestrial biosphere models with hydrologic modeling. Incorporating these features improves the representation of the hydrological characteristics in basins characterized by large forest cover and/or high deforestation rate. In the revised manuscript we stressed the significance and novelty of this integrated modeling framework and the practical applications of this approach.

4. Pg 2 L8: Highlighted word: *"serious"*

Response: The sentence was rephrased (page 2 line 13).

5. Pg 2 L11-12: Deleted Text: *"(i.e., evapotranspiration, soil moisture, deep percolation, surface and sub-surface runoff)"*

Response: The requested text was deleted and the sentence revised in line with the referee's suggestion (page 2 line 16).

6. Pg 2 L15-17: Deleted Text: *"Terrestrial biosphere models can mechanistically represent the multiple interactions among land-surface energy balance, the hydrological cycle, and the carbon cycle that occur in terrestrial ecosystems". "You can finish the first paragraph with the following... Examples.."*

Response: This sentence was shortened as per the referee's suggestion (page 2 line 18).

7. Pg 2 L23: *This study focus on river routing... too much background information about the evolution of the vertical balance formulations, specially, when compared to literature of recent advances on large-scale river routing. Improve this aspect. For instance, see Cama-Flood from Yamazaki et al. 2011 and other developments since then. 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*

Response: A detailed description of the terrestrial biosphere model and its assumptions was requested by the Editor following the initial submission of the manuscript. However, we agree with the referee that recent advances on large-scale river routing are also relevant and can introduce further details about river routing in the revised manuscript, explicitly answering the question of why river routing modeling is important and needed, including the suggested Yazamaki et al. (2011) paper (page 3 line 3-6).

8. Pg 3 L1-5: Deleted Text: *"In this way, terrestrial biosphere models can estimate the temporal and spatial distribution of water resources across the simulated domain under changing climate and land cover conditions. The accurate computation of the vertical water balance, however, is only part of the process of estimation of river flows, which are vital data for water resource management (e.g. flood control, hydropower, irrigation)." You already talked about global issues in the first paragraph. I suggest you go further with the global scale issues.. focus...*

Response: As suggested, the above two sentences will be removed from the manuscript. Regarding the comment suggesting "we go further with global scale issues", we revised the sentence to provide further details about the kinds of analyses that can be conducted by integrating terrestrial biosphere models with river routing schemes (page 3 line 6-12).

9. Pg 3 L6-7: *This sentence "that could be compared with actual river gauge observations.." is weak. Despite "matching" modeled and observed data is needed during model development (i.e. calibration/validation) this is a weak motivation. You are developing a process-based model... of course you want a good performance, but why? Describe your motivation in this perspective.*

Response: In line with the referee's suggestion, the sentence was revised to better express the practical implications and motivations for incorporating a routing scheme. While the ability to evaluate the terrestrial biosphere model's predictions of runoff has value, we agree with the referee that the primary motivation is to conduct studies on the impacts of climate change and land-use on river flow that are useful and relevant for water managers and policy makers (page 3 line 12-15).

10. Pg 3 L10: *There is a good opportunity to improve the description of the river routing models used in these studies. This is important to situate the ED2+R approach in the "state-of-art" here and further in discussion section. What was your motivation to use Muskingum-Cunge routing scheme in and not other?*

Response: We opted for the Muskingum-Cunge method as the routing scheme in our modeling framework because this is an approach that has been well adopted for regional scale hydrological models like MGB, VIC, or SWAT, thus providing us the confidence that the flow routing scheme used would provide us computations comparable to these "state-of-the-art" watershed models. We revised the paragraph to improve the description of other routing models used in other studies and to explain our choice of the Muskingum-Cunge method for ED2+R (page 3 line 31 to page 4 line 2).

11. Pg 3 L15-23: *This paragraph has too many details and background on ED2. Also, there is too much emphasizes on model capabilities, which are not specially relevant in this study. For instance, I've found "ideally-suited" and "unique tool" and "successfully" .. this is too much.*

Response: As noted earlier (see response to comment 7 above), details and background about ED2 were requested by the Editor. The adjectives describing the model's capabilities are supported by the results of the studies cited in the manuscript and were designed to highlight the some of the capabilities of the ED2 terrestrial biosphere model. We revised the sentence to describe these capabilities in a more plain matter-of-fact manner (see Section 2).

12. Pg 3 L17-20: Deleted Text: *"One of the key benefits of ED2's formal approach to scaling vegetation dynamics is its ability to describe, in a physically consistent manner, the coupled water, carbon and energy dynamics of heterogeneous landscapes (Hurtt et al. 2013; Medvigy et al. 2009; Moorcroft et al. 2001)."* "This second sentence repeats the overall idea of the first sentence..."

Response: in the revised paper, the two sentences were merged as suggested (page 4 lines

18-19).

13. Pg 3 L20-23: Deleted Text: *"ED2's ability to incorporate sub-grid scale ecosystem heterogeneity arising from land-use change means that the model is ideally suited for investigating of how the combined impacts of changes in climate, atmospheric carbon dioxide concentrations, and land-cover are affecting terrestrial ecosystems." excessive details and model 'capabilities'*

Response: please see our response comment #11. The sentence was rephrased (page 4 lines 13-16).

14. Page 3 L24-29: *This is interesting, but what was this studies findings? How could a river routing scheme in ED2 fill any scientific gaps concerning this past studies? Did any these studies indicate the need for a river routing method?*

Response: the cited studies (Hurtt et al. 2002; Albani et al. 2006; Zhang et al. 2015; Knox et al. 2015; Swann et al. 2015) were not aimed at assessing hydrological implications of deforestation/climate change. Our study brings an additional capability to the range of scientific questions that have been investigated with the ED2 model. Specifically, the integration of ED2 with the Muskingum-Cunge river routing scheme provides a way to understand how historical changes and future projections of the impacts of climate change and deforestation may affect the Amazon's water resources. In addition, it is a first step towards a full two-way coupling of the routing scheme and ED2 that is likely to improve the ability to reproduce the hydrology of flooded ecosystems, a feature for simulation of Amazon tropical forest ecosystems, many of which experience significant seasonal inundation. These two points are already noted in the discussion section (see Section 6) and in the concluding remarks (see Section 7).

15. Pg 3 L29-31: Deleted text: *"ED2 is a unique tool to evaluate impacts from global and regional changes on ecosystem function, and therefore, it could provide critical information for hydrological studies."*

Response: Please see comments #7 and #11. We revised the sentence to better highlight the value of integrating a river routing scheme into ED2 (page 4 lines 29-32).

16. Pg 3 L32-33: *At the moment, the introduction indicates you implemented river routing mostly because ED2 didn't do it.. and that it could be useful.. ok..*

Your scientific question is not clear.. based on background literature. Why are you doing this study? Again, why do you want to improve the river routing?Why inland waters are important?

One reason: Cole et al. 2007 Ecosystems (2007) 10: 171–184 DOI:10.1007/s10021-006-9013-8

Why modeling and remote sensing are needed at large-scale? Some examples..

Alsdorf, D. E., E. Rodríguez, and D. P. Lettenmaier (2007), Measuring surface water from space, Rev. Geophys., 45, RG2002, doi:10.1029/2006RG000197.

Prigent et al. (2007) Global inundation dynamics inferred from multiple satellite observations, 1993–2000, J. Geophys. Res., 112, D12107, doi:10.1029/2006JD007847.

Response: As per comment 15 above, we revised the sentence to better highlight the value of integrating a river routing scheme into ED2, including the citations mentioned by the referee (page 4 l. 3 – page 5 l. 20).

17. Pg 4 L1: *How do you know this? Can you show this?*

Response: the point here is to highlight that our approach incorporates detailed land surface dynamics of the biosphere model into the hydrological analysis. Traditional hydrological models do not represent the dynamics of vegetation, which have very important implications for regional hydrological cycles. However, we are not proposing a comparison between the ED2+R and traditional hydrological models.

18. Pg 4 L5: *Why the interest in Tapajos? And why in Tapajós only.*

Response: The integrated ED2+R framework was developed as part of a research initiative examining how environmental change could affect the future of Brazil's electricity planning. The analysis focuses on the Tapajós river basin because it is planned to be home to a major portion of the planned hydropower expansion. In the revised paper, we added a more detailed description of the reasons why we are interested in the Tapajós (see section 4).

19. Pg 4 L9-12: *This paragraph is huge. Again, too much details on model structure and abilities.*

Response: please see comment #11. As suggested, the paragraph was shortened in the revised manuscript (page 5 l. 23-26).

20. Pg 4 L12-14: Deleted text: *"The resulting", "then", "a formal", "that accurately captures the resulting"* to reproduce...

Response: in the revised paper, this sentence was modified as suggested (page 5 l. 26-27).

21. Pg 4 L18-22: Deleted text: *"Generally, plant functional types are represented by: early successional trees (fast growing, low wood density, and water needy); mid-successional trees; late-successional trees (slow growing, shade tolerant, high wood density); and C4 grasses (comprising also pasture and agriculture) (Swann et al. 2015; Medvigy et al. 2009)."*

Response: As suggested, this sentence was deleted in the revised manuscript (page 5 l. 30).

22. Pg 4 L22-24: Deleted text: *"a series of", and "The size of the grid cell is"*

heterogeneity of what? specify.

Response: The heterogeneity being referred to here is the heterogeneity in ecosystem composition and structure within the climatological grid cells. The sentence was revised to clarify this point (page 6 l. 1).

23. Pg 4 L24: *describe the range either in degree, or in km.*

Response: As suggested the ranges was specified in terms of both degrees and km in the revised manuscript (page 6 l. 3).

24. Pg 4 L25-26 Deleted text: *"This characteristic of the ED2 model makes it suitable for a more realistic simulation of regions characterized by a mixture of natural and anthropogenically-modified landscapes."*

Response: As suggested, this sentence was deleted in the revised manuscript (page 6 l. 3).

25. Pg 4 L30-32 Deleted text: *"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."*

Response: This sentence is important for understanding how dynamic land cover transitions occur within the ED2 model. Since this is feature not typically incorporated in hydrological models we propose to retain this sentence in the manuscript.

26. Pg 5 L9: *Break a section here... call it 'ED2 hydrology module' or a name that suits you better.*

Response: As suggested, the text describing the hydrology was placed in a separate section in the revised manuscript (page 6 l. 21).

27. Pg 5 L14: *How is the soil/vegetation parameterization? ED2 uses a global scale dataset of soil, vegetation or it depends on application?*

Response: A description of the vegetation and soil parameterization of the ED2 model used in the study (a regional-scale parameterization used by Zhang *et al* 2015) was included section 2 of the revised manuscript. Moreover, as suggested by Referee #2, we added a table of parameters and inputs (see Section 2-page 6 l. 27-32, and Table 1-page 34)

28. Pg 5 L25: Deleted text: *"towards the basin outlet"*.

Response: in the revised paper, this sentence was deleted as suggested (page 7 l. 17).

29. Pg 5 L27-29: Deleted text: *"The original IPH-MGB model is composed of four different sub-models: soil water balance, evapotranspiration, intra-cell flow propagation, and inter-cell routing through the river network."*.
Include additional and more recent MGB-IPH studies, you can check a list for reading at (www.ufrgs.br/hge/publicacoes/).

It important to stress that although the typical application uses a Muskingum-Cunge approach for river routing, the new MGB-IPH already allows the use of hydrodynamic solution and floodplain coupling (i.e. local-inertial, Pontes et al. 2015). In the Amazon River Basin application (Paiva et al. 2013) a full hydrodynamic solution was also required to solve low slopes and floodplain inundation characteristic of this basin.

This MGB-IPH model improvements must also be described and could be taken into the discussion as well.. along with the other models.

PONTES et al. (2015) Modelagem hidrológica e hidráulica de grande escala com propagação inercial de vazões. Revista Brasileira de Recursos Hídricos, vol. 20, n. 4. 2015.

Response: We thank the reviewer for his/her suggestions regarding studies describing more recent MGB-IPH model developments. We revised this section and the discussion section to include the more recent MGB-IPH studies mentioned by the reviewer (page 7 l. 17-26).

30. Pg 5 L30: *It is enough to say the 'catchment and river routing methods' were utilized.*

Response: the sentence was shortened as suggested (page 7 l. 26).

31. Pg 6 L2-3: *groundwater or base reservoir? pick one. don't need any of the parenthesis.*

Response: the parentheses were removed as suggested (page 7 l. 30-31).

32. Pg 6 L6-7: *break the sentence at drainage network.*

Response: the sentence was rephrased (page 8 l. 1).

33. Pg 6 L7-13: *The DEM processing details are distracting and confusing at this point….Is this pre-processing or COTAT runs during simulation?*

Also, assuming you are not worried with floodplain terrain at the moment, the technique can be briefly explained with something like..

".. from a digital elevation model (Reed, 2003; Paz et al. 2006)"

Which DEM resolution are you using?

Response: The sentence was revised to make clear that the steps described here were all pre-processing steps (including the application of the COTAT algorithm), and that the horizontal resolution of the DEM is 90m (page 8 l. 2-4).

34. Pg 6 L14: *Muskingum-Cunge is a numerical scheme for the solution of the kinematic wave equation, which also accounts numerical diffusion to represent flow attenuation...*

Response: The sentence was revised as suggested by the Referee (p 8 l. 8-9).

35. Pg 6 L15: *river flow routing. What do you mean by river height?*

Response: we were referring to depth of the river cross-section. The sentence was revised to indicate this (page 8 l. 10).

36. Pg 6 L16-21: *This sentence is ok, but as it is about the model application in Tapajos, it should be described in the section 4.*

    You should describe better how would you parameterize at continental or global scale?

Response: The sentence describing the specification of the river morphology was moved to section 4 as suggested. To date, the ED2 biosphere model has been used for regional rather than continental-scale or global-scale studies (e.g. Zhang *et al*. 2015). Consequently, ED2+R is designed for simulations of river flows in specific catchments rather than global scale analyses.

37. Pg 6 L21-23: Deleted text: *"Later on, further studies successfully employed these statistical relationships to estimate river geometric parameters to carry out hydrodynamic simulations of the Amazon River system (Paiva et al., 2013; Paiva et al., 2011)."*

    This is not relevant for ED2+R method overview. Also, in Paiva et al. studies the authors derived their geomorphological relations, although the approach was similar to that of Coe et al.2008...

Response: We thank the reviewer for pointing out the distinction between the Paiva et al. and Coe et al studies. We revised this sentence to make clear that Paiva et al. (2011) developed their own statistical relationships based on Coe et al. (2008) (page 8 l. 17-18). The details about estimated river geometric parameters were requested by the Editor prior to the manuscript being sent out for review, and so we retained them here.

38. Pg 6 L30: *Change name for 'Study case: Tapajós river basin'*

Response: in the revised manuscript, this section was renamed as suggested (page 10 l. 13).

39. Pg 6 L31: *Please, provide an overview of the Tapajós basin, such as*

hydrological features (i.e. precipitation, land-use, etc.)

Response: As suggested, we added a more detailed description of the basin (land use, altitude, geology, slope, soil depth and texture etc., as well as a climate description such as rainfall, evaporation, temperature, seasonality etc.) in the revised manuscript (see page 10 l. 14 to page 11 l. 12 and Figure 3 page 29).

40. Pg 7 L1: *What is the grid/spatial discretization for hydrologic and river routing in this application? Which DEM was used?*

Response: ED2+R represents the simulation domain using grid cells of 0.5° resolution (~ 55 km). This was indicated in the legend of Figure 4b, but was also be included in the revised manuscript narrative (page 11 l. 9-10). The DEM used in the study is Shuttle Radar Topography Mission (SRTM)-derived DEM that has a spatial resolution of 3 arc-seconds for global coverage (~90 meters) (page 8 l. 3-4 and Table 1 – page 34).

41. Pg 7 L3: *Please provide more details on landuse and land cover*.

Response: as for comment 39 above, a detailed description of the basin was included in the manuscript (see page 10 l. 14 to page 11 l. 12 and Figure 3 page 29).

42. Pg 7 L6-8: Deleted text: *"Surface and subsurface runoff calculated for each cell with ED2 are connected with the three linear reservoirs of the routing scheme (Figure 2)"*
    this was described earlier.

Response: the sentence was deleted as suggested (page 11 l. 20).

43. Pg 7 L9: *put the "two-step procedure" in the end of the sentence*.

Response: the sentence was revised as suggested (page 11 l. 27-28).

44. Pg 7 L12-14*: It means the ED2 was calibrated against discharges? after that alfa [sic] and beta are fixed?*

    this partitioning, alfa [sic] and beta parameters must be described earlier in sections 3 or 4.

    In this way, this whole paragraph can be rewritten directly, as the calibration for alfa [sic], beta and CB, CI, CS are much similar.

    Also, tau, CB, CI and CS nomenclature is superposing, thus confusing. Use one or another and fix figures/text accordingly.

Response: In this technical note, we describe the calibration of the flow routing component of 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 can be found in Longo et al. (2014) and Zhang et al (2015). The flow routing component of ED2+R was calibrated against discharge measurements for all the sub-basins. The flow partitioning is fixed for all the sub-basins: the two parameters alpha and beta were calibrated first, then the residence time (tau) for the three reservoirs (CB, CI and CS). With a second iteration, we calibrated again the alpha and beta parameters (fixed for the entire basin), and again the three reservoirs (CB, CI and CS) for each of the sub-basins obtaining the results presented in this manuscript.
In the revised manuscript we incorporated the information presented in Annex B in section 4 and clarified these aspects (pages 11 and 12)

45. Pg 7 L15: *Explain, how did you set the alfa and beta intervals between 0 and 1?*

Response: The main point is that the biosphere model ED2 is organized in 2 reservoirs (surface and sub-surface), while the integrated model ED2+R is organized in three reservoirs (surface, intermediate, and base reservoirs). Alpha (ranging from 0 to 1 or 0% to 100%) represents the portion of ED2 surface runoff destined to the ED2+R surface reservoir. The remaining part (1-alpha) goes to the ED2+R intermediate reservoir. Beta represents a similar partitioning coefficient for the ED2 subsurface reservoir to the ED2+R intermediate and base reservoirs (page 11 l. 28 to page 12 l. 6).

46. Pg 7 L17-18: **highest?*

goodness-of-fit is often use to evaluate regression models or distribution models fitting..

while calibration is often based on minimization of objective functions.

Response: Goodness-of-fit is a general term used in statistics to describe the ability of a model to describe a set of observations; however as noted by the referee the best goodness-of-fit is often obtained through minimization of an objective function. To avoid confusion, the sentence was rephrased and we described in details the indexes used (see section 3 - pages 8 and 9).

47. Pg 7 L28-30: *Show detailed information (i.e. parameters, gages used, period, number of days filled, etc.) on this regression model for each gage where the interpolation was used.*

Calibration of the model using filled data with high correlation (r>0.85) can produce improved statistics. Isn't this affecting your results? Was the interpolation step really necessary and why?

Response: the interpolation of the gage observations was necessary to have continuous time series to calibrate the model. A table reporting information about time series and data filled was added in the revised manuscript (see Table 2 page 36).

48. Pg 8 L6-9: *Explain volume ratio statistic.*

The more recent Kling-Gupta efficiency metric (Gupta et al. 2009) overcomes some of the

Nash-Sutcliffe's flaws, please calculate it.

Gupta et al, 2009, Journal of Hydrology, doi:10.1016/j.jhydrol.2009.08.003

Response: We used the Nash-Sutcliffe Efficiency metric because is still widely used and generally viewed as an appropriate indicator of model fitness. That said, we thank referee for this suggestion and included the Kling-Gupta efficiency index, both in its 2009 and 2012 formulations (page 9 l. 11-25). Regarding the volume ratio statistic, it simply refers to the comparison of the total simulated vs. observed total water volume in the simulation period without consideration for the seasonal distribution of its flow. We added a detailed description in section 3 (page 9 l. 1- 4 – table 3 page 37).

49. Pg 8 L11: *You also have the opportunity to compare the results for*:

ED2 versus ED2+ catchment routing versus ED2+catchment+river routing

Response: The comparison suggested by the referee may provide an insightful intermediate set of modeling results; however, generating these results excluding river routing would require extensive modifications to the model code.

50. Pg 8 L12: *Focus on important numbers and features... some of interpretations could be better used in the discussion...*

Response: As suggested, this section was redrafted, moving all interpretation to the discussion section (seen section 5 – page 13-14).

51. Pg 8 L12: Deleted word: *"substantially"*

Response: The word was deleted as suggested (page 13 l. 17-18).

52. Pg 8 L14: *show time series for the seven basins.*

Results shown in Figure 5 can be summarized in a Table, which will also facilitate the reading of metric values.

Response: The time series for all seven sub-basins were included in Annex A (page 38). We disagree with the referee that Figure 5 (now figure 8), which shows the Observations versus predicted ED2 (non routed) and ED2+R time-series, can be adequately summarized in a table. We suspect however, that the referee may have intended to be referring to Figure 4, which displayed the calibration and validation results. Figure 4 was replaced with a table to facilitate the reading of metric values (Table 3-page 37).

53. Pg 8 L15: Deleted word: *"substantially"*

"goodness-of-fit" replace with "*model skill or model performance"*

Response: The sentence was revised in line with the reviewer's suggestion (page 13 l. 14-15).

54. Pg 8 L18: *what do you mean by reasonable* [sic] *well?*

<u>Response</u>: The statement "reasonably well" was clarified by including quantitative metrics of the model skill (page 13 l. 19-23).

55. Pg 8 L19: *what do you mean by water availability?*

Response: "water availability" here refers to quantity (in terms of volume) of water in the basin. This was added in parentheses afterwards (page 13 l. 18).

56. Pg 8 L19: Deleted text: *"the application of"*

<u>Response</u>: The above words was deleted, as suggested (page 13 l. 21).

57. *Pg 8 L20-21: so.. the routing scheme, improved the routing when compared to the model with no routing... and?*

<u>Response</u>: Please see our response to comment #3

58. Pg 8 L22: **higher?*

<u>Response</u>: the sentence was revised in order to clearly identify the quantitative metrics that were improved (page 13 l. 29-32).

59. Pg 8 L24: *reasonably well... what is this?*

<u>Response</u>: the sentence was revised in order to clarify the quantitative extent of the improvement (page 14 l. 3-5).

60. Pg 8 L24-25: *i can't see this result anywhere in figures or graphics..or anywhere..*

<u>Response</u>: The statements were supported by the data presented in Figure 4 (now replaced by Table 3). Specifically:

"*in the Upper Teles Pires and Upper Juruena, the model achieved the lowest NSE* (**this can be found among NSE statistics**), *and although water volumes are reproduced reasonably well* (**this can be found among Volume Ratio statistics**), *the seasonal variability is less accurate* (**this can be found among Correlation statistics**)." In the revised manuscript, the sentence was redrafted in order to better guide the reader through the relevant measures (page 13 l. 29 to page 14 l. 12).

61. Pg 8 L26-28: *I can't see this anywhere..*

<u>Response</u>: A table reporting information about time series and data filled was added in the revised manuscript and referred to here (please see our response comment #47 above) (Table 2 page 36).

62. Pg8 L29: *Explain FDCs briefly in methods*

Response: A description of the FDCs was added to the methods section as suggested (page 10 l. 7-11).

63. Pg8 L30: Deleted text: *"substantial improvement". at this point I know you are applying the routing scheme... use ED2 according ED2+R to avoid repetition*

Response: this sentence was redrafted as suggested (page 14 l. 13-15).

64. Pg 8/ L31: *"Excelent.." I can see the significant improvement... Use metrics, please.*

Response: As suggested, the verbal statement was justified by including explicit metrics alongside it (page 14 l. 15-19).

65. Pg 9 L2: *(Figure 6a, Figure 6b)*

Response: the wording was modified as suggested (page 14 l. 20-21).

66. Pg 9 L3: *What do you mean by general tendency?*

Response: The model overestimates the flow in the dry periods in both sub-basins. In the revised manuscript, this statement was revised to include explicit metrics that quantify the extent of the overestimation (page 14 l. 19-24).

67. *Pg 9 L4: (Figure 6c-6g)*

Response: the wording was modified as suggested (page 14 l. 25).

68. Pg 9 *L5: tend??*

Response: In the revised paper, this sentence was revised to include explicit metrics quantifying the extent of the over-estimation (page 14 l. 24-29).

69. Pg 9 L6: *what happens in figure 6g, where ED2+R don't seem to improve lowflows when compared to ED2?*

Response: Figure 6g (now Figure 9g) displayed the FDCs of the same time series presented in figure 5 (now figure 8).

In the revised manuscript, Figure 6g (now Figure 9g) was also mentioned in the last sentence "The overestimation 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 9g) the observations during the dry seasons of the period under consideration." (page 14 l. 25-29).

As we discussed in section 6, we believe this is likely due to the coarse resolution of the grid-cells, and interactions with deep groundwater. It is true that in the downstream part of the basin the model performs better and these issues are less evident; however, during the dry season the limitations of the model performance are also evident in the downstream part of the basin. This aspect was clearly stated in section 6 of the revised manuscript (page 15 l. 14-26).

70. Pg 9 L9: *What is a simple one-way routing scheme? Where did this come from?*

Response: We apologize for the mistake: the sentence should have stated "simple one-way integration". This means that the two components are not fully coupled: the biosphere model and the routing scheme are linked with a one-way integration. Therefore, the biosphere model underestimates the extent of the seasonally flooded ecosystems, a relevant aspect as mentioned in the reference the reviewer suggested for the introduction (Cole et al. 2007 Ecosystems (2007) 10: 171–184 DOI: 10.1007/s10021-006-9013-8). This is clarified in the discussion section, and again in the conclusion (page 15 l. 10-13 and from page 16 l. 31 to page 17 l. 8)

71. Pg9 L10-11: Deleted text: *"substantially"*, and *"the model's ability to reproduce daily water flows through a large river basin"*. Replace with: *"the performance of simulated daily discharges."*

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

72. Pg 9 L12-13: *Don't repeat literal results...*

Response: the sentence was deleted in line with the referee's suggestion (page 15 l. 4)

73. Pg 9 L 15-18: *I'm not sure, there are other things to consider like: Can you explain why this would deep groundwater interactions are important in the Tapajos basin? What's the role of river hydraulics? What is the importance of evapotranspiration in this basin? How does this affect the model ability to simulate local to global scales? Can't you calibrate or improve ED2 hydrology model parameterization to fix this? Isn't this asscoiated to the calibrated alfa and beta at the first step?*

Response: Analysis by Longo et al. (2014) showed that the ED2 model's evapotranspiration rates compare well to flux tower measurements. We also are confident that the parameters alpha and beta in the routing scheme are calibrated near-optimal values. We therefore believe it is likely that much of the residual error is arising from complexities associated with deep soils present in the headwaters of the Tapajos. In particular, the model application developed, soil layers are only represented to a depth of about 6 meters (Table 1 page 36), which might be too shallow to more realistically represent the conditions in the headwaters of the Tapajos. We revised the sentences to clarify these points (page 15 l. 18-26)

74. Pg9 L19-20: *greater marginal contribution? Do you mean baseflow to total flow? show this...*

Response: Surface flow accumulation is, by definition, lower in the headwaters. Therefore, in relative terms, the role of baseflow is more relevant in those portions of any catchment. This was clarified in the revised manuscript (page 15 l. 29-32)

75. Pg9 L21-22: *"masked by?" What do you mean by "larger rainfall-runoff contribution?" Are you trying to say the river storage is more important than the groundwater?!*

Response: as mentioned in the previous comment, in relative terms, the contribution from surface flow is larger in the downstream part of any catchment. This was clarified in the revised manuscript (page 15 l. 29 to page 16 l. 3).

76. Pg9 L23-25: *So what do you mean by this? Are these the only differences? What about the precipitation and climatological datasets, landuse vegetation? Moreover, how is the river parameterization x river routing method x model performance affected at this basin scale?*

Response: in our opinion, higher resolution climatological data, vegetation, and land use datasets, jointly with a finer resolution of the hydrological grid, would improve the performance of the model. In the revised manuscript, we better clarified these aspects (page 16 l. 3-16).

77. Pg9 L26: Deleted word: *"principal"*

better than what?

Response: As suggested, the word "principal" was deleted and the sentence was revised to make clear that the comparison is between ED2+R and the native ED2 formulation (page 16 l. 9-12).

78. Pg9 L27: *why are you repeating this idea?*

Response: the sentence was revised as suggested (page 16 l. 12).

79. Pg9 L28: *what is: local and regional scale? Also, it was said before that the ED2+R showed limitations to simulate some groundwater processes in headwaters... Is ED2+R really prepared to run at global scale? What about the computational effort to run the ED2+R in comparison to ED2? What about its ability represent more complex river systems (i.e. floodplains, backwater effects)?*

Response: As noted above (see our response to comment #36), the current ED2+R formulation is not designed to conduct global scale simulations. It does, however, incorporate ecosystem responses to global environmental change drivers such as anthropogenic climate change, increasing levels of atmospheric carbon dioxide, and changes in land cover. The current ED2+R formulation is not designed to simulate more complex and detailed hydrological dynamics such as backwater effects. This was also noted in the revised manuscript (page 16 l. 8-9).

80. Pg9 L32: *What are the current limitations? Where is ED2+R when compared to*

other more sophisticated models?

Response: The limitations of the ED2+R are discussed in the concluding section (Page 16, lines 29 to page 17 l. 12)

81. Pg 10 L 3-9: Deleted text: *"Biosphere models are excellent tools to study hydrological dynamics under climate and land use/land cover changing conditions. These models are usually set to simulate long periods in large regions, usually at global or continental scales. Their ability in reconstructing the water balance at relatively fine geographical and temporal resolution, taking into consideration global environmental changes makes them powerful instruments for hydrological simulations. In order to translate the results of the land surface simulation in terms of river flows, the simulated results need to be processed using a hydrological routing scheme."*

This is background...

Response: As suggested, the above text was deleted in the revised manuscript (page 16 l. 24).

82. Pg 10 L15-17: *"were linked to the relatively resolution of the model and the rough representation of groundwater flow typical of this kind of models."*

see comment in discussion..

Response: please see our responses to comments #69 and #73 above.

83. Pg 10 L18: *"one-way integration"*

what so you mean by this? and why is this relevant?

Response: please see our response to comment #70 above.

84. Pg 10 L20: *"flooded ecosystems"*

not quite... muskingum-cunge is not really appropriate for floodplain dynamics, especially in large tropical floodplains.

also, what do you mean by flooded ecosystems?

Response: please see our response to comment #70 above. In this first attempt to integrate ED2 and the river routing scheme, our goal was to improve ED2's ability to predict the streamflow. The feedbacks from the river routing scheme to the ED2 can now determine the grid cells across the domain that are likely to be saturated (near the river paths, for example). For example ED2 can potentially use this information to reduce the growth (or increase the mortality rates) of plants that are more sensitive to inundation (page 17 l. 7-12)

85. Pg 10 L20: *could be? Isn't it?*

Response: the wording was changed as suggested (page 17 l. 2).

86. Pg 10 L27: *Annex A: I don't think this section is needed.*

Response: Annex A was deleted from the revised manuscript as suggested (a new Annex A was included to present the time series of all the subbasins as requested in comment #52 – Page 38)

87. Pg 11 L24: *The only criteria here was the ENS?*

This is confusing:

1.Did you calibrate the ED2 (without +R)first?

2. Do you calibrate alfa, beta with ED2+R or ED2 only?

Explain clearly.

Response: Please see our response to comment #44 above.

88. Pg 11 L29: *"almost completely?" "uninfluential?"*

Response: In our analysis we did not consider the first 5 years of simulation (1970-1975), and calibrated the model using the data for the period 1976-1992 (figure 5). As a result of this long model spin-up, the setting of the initial conditions of groundwater, especially in the upstream part of the basin, are almost negligible (figure B.2). To clarify this point, the sentence "Changes in initial groundwater contributions in the downstream part of the basin are almost completely uninfluential" was rephrased (page 12 l. 27-29)

89. Pg 12 L1: *Figure B.3*

How did you set the range of variation of each parameter?

Does the final parameters have a reasonable physical meaning?

Response: The final parameters have a reasonable physical meaning given the large area of the grid cells. The range of variation was determined maximizing the calibration results.

90. Pg 19 L9: *In the figure caption, erase text in parenthesis*

Response: The text in parentheses was removed as suggested (p 28 l. 9-13)

91. Pg 21 L1: *Figure 4: a table would do it.. i think it is hard to read the values.*

Response: As noted earlier (see response to comment #52), the figure was replaced with a corresponding table as suggested (Table 3 page 37)

Responses to Anonymous Referee #2

General comments:
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. The model was applied to the Tapajós River Basin. While the model shows improvements, the approach is not particularly novel and I believe that the value of the paper could be improved by providing more detail on the input parameters and variables used in the model. By considering the input parameters, the discussion could be improved by describing them in light of understanding the hydrological processes in the Basin and therefore improve the interpretation of the results. In its present form, the results only really illustrate that the model improved the simulation and gives little hydrological interpretation as to why. I think the introduction could be improved by giving a brief review of the significance of river-routing routines in hydrological modeling as well as what the "state-of-the-art" is in terms of large scale river basin model development.

Response: We thank the referee for the constructive comments and feedback on the manuscript.

General comment 1: "*By considering the input parameters, the discussion could be improved by describing them in light of understanding the hydrological processes in the Basin and therefore improve the interpretation of the results. In its present form, the results only really illustrate that the model improved the simulation and gives little hydrological interpretation as to why*."

Response: We improved the presentation of the input parameters and variables used in the model, and to explained their practical implications for the hydrological process. As suggested in the Referee 2's subsequent specific comments, Annex B was incorporated in section 4 and Annex A eliminated (this was also suggested by Referee 1).

We focused more on the interpretation, filling the gaps related to the comment "*the results only really illustrate that the model improved the simulation and gives little hydrological interpretation as to why*" (See section 6)

General comment: 2: "*I think the introduction could be improved by giving a brief review of the significance of river-routing routines in hydrological modeling as well as what the "state-of-the-art" is in terms of large scale river basin model development*."
Response: We revised and expand the description of the river routing routines and their significance in hydrological modeling and clarified what is the current state-of-the-art in large scale river basin model development (See section 1).

Specific Comments:

Response: As suggested, we added a more detailed description of the basin (land use, altitude, geology, slope, soil depth and texture etc., as well as a climate description such as rainfall, evaporation, temperature, seasonality etc.) and stress more the reasons why we are interested in the Tapajós (see page 10 l. 14 to page 11 l. 12 and Figure 3 page 29).

8. Pg 7 L13 *what are parameters α and β? what is there range (i.e. 1-10 or 1-100 etc).*

Response: As previously described in the annex B, "…*the calibration process has two steps, as highlighted in Figure 2. The first step is the partitioning of the flows from the two reservoirs of the ED2 biosphere model to the three reservoirs of the ED2+R routed biosphere model"*.
The main point is that the biosphere model ED2 is organized in 2 reservoirs (surface and sub-surface), while the integrated model ED2+R is organized in three reservoirs (surface, intermediate, and base reservoirs). Alpha (ranging from 0 to 1 or 0% to 100%) represents the portion of ED2 surface runoff destined to the ED2+R surface reservoir. The remaining part (1-alpha) goes to the ED2+R intermediate reservoir. Beta represents a similar partitioning coefficient for the ED2 subsurface reservoir to the ED2+R intermediate and base reservoirs.

In the revised paper, we moved the annex B in section 4 and add a better description of the alpha and beta parameters (See pages 11 and 12)

9. Pg 7 L15 *change the word "was" to "were"*

Response: the above grammatical error was corrected (page 12 l. 10)

10. Pg 7 L20 *this is the first time parameters CS, CI and CB are referred to, by no description of what they are is given. The first time they are described is in Annex B.*

Response: In the revised paper, we moved the annex B in section 4 and redrafted the parameters description in order to give appropriate information when introducing the CS, CI and CB parameters (See pages 11 and 12).

11. Pg 8 L18 *Avoid vague terms like "reasonably well". Try and quantify such statements.*

Response: We revised the above sentence in order to provide detailed quantification of the improvements in model performance (page 13 l. 19-21). In general, all section 5 was redrafted quantifying each statement with appropriate metrics (pages 13 and 14)

12. Pg 8 L 31 *As above, avoid vague terms such as "excellent match". Quantify what makes this and excellent match.*

Response: As per response #11 above, we revised the above sentence in order to provide detailed quantification of the improvements in model performance (page 13 l. 26-29).

13. Pg 9 L 17 *How much of an impact does deep groundwater have on the streamflow and therefore on the routing routine? This could be determined by doing a sensitivity analysis of CS, CI and CB.*

Response: We agree with the referee that such analysis is important, and that is what we intended to present in the comparison of Cs, Ci, and Cb presented in Fig. B.3 (now figure 7). As mentioned above, in the revised manuscript Annex B was incorporated in section 4. Doing this, we gave more relevance to the findings presented in figure B.3 (See also page 15 l. 26-32).

14. Pg 9 L26 &27 *What makes the ED2+R models principal advantage its ability to predict the sensitivity to global environmental change? This statements needs to be substantiated and once again, the input parameters need to be described. For example, is the model able to simulated changes in transpiration due to increases in CO2 which has a knock-on effect on streamflow.*

Response: The principal advantage is ED2+R's ability to predict how the integrated responses of terrestrial ecosystems to changes in climate forcing, increasing atmospheric carbon dioxide concentrations and land-use change will affect streamflow. We revised this sentence to make this point more clear (page 16 l. 9-21).

Please, see also page 4 l. 22-32 "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 of ED2 as a tool able to assess impacts from global and regional changes on ecosystem function, and built the basis for a possible development of an integrated tool aimed at analyzing hydrological implications."

15. Pg 9 L27-29 The sentence "As mentioned. . ...modelling framework." Is repetition. Therefore, this could be deleted.

Response: in the revised paper, this sentence was deleted as suggested .

16. Pg 10 L3-9 *This sentence does not form part of a conclusion, but is merely a repeat of what is said in the introduction. Therefore, this could be deleted and the conclusion begin from ". . .In this Technical Note. . ."*

Response: in the revised paper, this sentence was revised as suggested (page 16 l. 12).

Specific technical corrections are listed below:

1. Pg 3 L22 *Remove the word "of" after . . .investigating of how. . .*

Response: The sentence was modified as suggested (page 4 l. 21).

2. Pg 4 L23 *What is the word heterogeneity referring to? Is it the landuse, rainfall, soils etc.?*

Response: The heterogeneity being referred to here is the heterogeneity in ecosystem composition and structure within the climatological grid cells. The sentence was revised to clarify this point (page 6 l. 1).

3. Pg 4 Sect. 2 *As mentioned earlier, I believe a brief description of the model parameters and variables would be useful. This would add value to the paper so that the results could be reproduced by other researchers. In the papers present form, the reader would certainly not be able to reproduce the results. The parameters/variables used could be presented in a table format.*

Response: As suggested, a table summarizing the main hydrological parameters was added into the manuscript to enable the results to be reproduced by other researchers (Table 1 page 34). Moreover, a more detailed description of parameters and inputs was provided in section 2

4. *Pg 5 L26 the IPH-MGB model routing routine forms the foundation for the ED2+R model. This needs to be briefly expanded on and mentioned in the Introduction of the paper.*

Response: As suggested, a more detailed description of the MGB-IPH routing scheme used was added (page 7 l. 15-24).

5. Pg 5 L27 *move the word "used" in front of the word "extensively" (i.e. ...used extensively. . . rather than extensively used.)*

Response: This sentence was modified as suggested (page 7 l. 19).

6. Pg 6 L9 *I don't think Annex A is required in this paper. Therefore, the reference to Annex A can be removed.*

Response: This Annex was deleted as suggested.

7. Pg 6 Sect 4. *The catchment characteristics need to be described. For example, what is the landuse, altitude, geology, slope, soil depth and texture etc., as well as a climate description such as rainfall, evaporation temperature, seasonality etc.*

17. Pg 10 Sect 7. *As mentioned previously, without some description of the model parameters and inputs, it is difficult to draw hydrological conclusions when there is no transparency as to what has been input into the model. If the input parameters are known, then better conclusions can be drawn as to whether it is the input data that requires attention rather than the parametrisation of another routine, which in this case is the river-routing routine.*

<u>Response:</u> We hope that this concern was addressed once the table with the hydrological parameters and inputs are incorporated (see response 3 above and table 1-page 34).

18. Pg 11 Annex B *I think Annex B should be incorporated into the paper rather than as a separate Annex. A chapter on the calibration of the model is important.*

<u>Response:</u> Annex B that described the model calibration was moved into section 4 of the main text as suggested (see section 4 – pages 11-12).

Technical Note: A hydrological routing scheme for the Ecosystem Demography model (ED2+R)

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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 ~~using a hydrological transport scheme~~. In this Technical Note, we describe the integration of the Ecosystem Demography (ED2) model with a hydrological routing scheme. ~~ED2 is a terrestrial biosphere model capable of incorporating sub-grid scale ecosystem heterogeneity arising from land use change, making it ideally suited for investigating combined impacts of changes in climate, atmospheric carbon dioxide concentrations, and land-cover on the water cycle~~ The ~~P~~purpose of

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the study was to create a tool capable ~~to~~of incorporat~~e~~ing the terrestrial ecosystem responses to climate, carbon dioxide, and land-use change –as –simulated ~~by~~with terrestrial biosphere models– ~~with~~to hydrological ~~modeling~~predictions. The resulting ED2+R model calculates the lateral ~~propagation~~ 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 ~~large~~ 476,674 km^2 river basin in southeastern Amazonia, Brazil. The results showed that the integration of ED2 with the lateral routing scheme ~~substantially improves the ability of the model to reproduce~~~~allows~~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' ~~typical of~~common among ~~traditional~~ 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 ~~serious~~ 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 ~~(i.e., evapotranspiration, soil moisture, deep percolation, surface and sub-surface runoff)~~ 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 can mechanistically represent the multiple interactions among land-surface energy balance, the hydrological cycle, and the carbon cycle that occur in terrestrial ecosystems. Examples of t~~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).

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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 ~~better~~ representation of the interactions between evapotranspiration, soil moisture and runoff (Clark et al. 2015).

~~From~~To couple the calculation of the one-dimensional water balance to the estimation of ~~the highly detailed~~daily river flow ~~propagations~~, there is the need to simulate multiple hydrological dynamics involved in the lateral flow propagation through the landscape, including the most complex hydraulic features of floodplains, lakes, and wetlands (Yamazaki et al. 2011). The first step ~~for~~towards ~~the~~ represent~~at~~i~~o~~ng ~~of~~ the finer scale hydrodynamic processes~~, and to~~ responsible for patterns in ~~obtain the estimation of simulated hydrographs highly correlated In this way, terrestrial biosphere models can estimate the temporal and spatial distribution of water resources across the simulated domain under changing climate and land cover conditions. The accurate computation of the vertical water balance, however, is only part of the process of estimation of river flows, which are vital data for water resource management (e.g. flood control, hydropower, irrigation). To calculate river flows from a land surface model that could be compared with actual~~ river gauge observations, is to ~~it is needed to dynamically route the calculated one-dimensional water balance, water runoff must be routed through the studied landscape,~~ consider~~ing~~ the topographic and geomorphological features that control water flow (Arora et al. 1999). The coarse spatial resolution of ~~the~~ regional land surface models, due to computational constraints, does not allow to properly simulate complex hydrological dynamics determined by ~~the very~~ 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 f~~on the dynamics of the regional scale river regimes with implication fo~~r ~~operational~~flood/drought forecasting, water resources planning and management, and infrastructur~~al~~e development (Andersson et al. 2015). Consequently, several terrestrial

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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 ~~Later~~ used after ~~on, Oki et al. (2001) used JULES/TRIP~~ 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, ~~(Oki et al. 2001; Oki et al. 1999); LPJ with the routing scheme described in Rost et al. (2008);~~ 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. ~~CLM with the Variable Infiltration Capacity's river routing model (Liang et al. 1994);~~ 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 ~~MPI-JSBACH with the Hydrological Discharge (MPI-HD) model~~ (Hagemann and Gates 2001; Hagemann and Dumenil 1997)~~; and IBIS with the river transport model THMB (Coe et al. 2008)~~. Several routing schemes have been designed over time, ~~among the others~~including: normal depth, modified pulse, simple Muskingum, and Muskingum Cunge (USACE 1991). In particular, the semi-distributed kinematic wave routing Muskingum Cunge method has been ~~particularly appreciat~~recognized~~ed~~ 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 ~~the influence of land use on~~ regional patterns of rainfall and biosphere temperature (~~Pearson et al. 2013; Bahn et al. 2014; Ostberg et al. 2015; Bahn et al. 2014; Pearson et al. 2013; Bahn et al. 2014;)~~ 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 ~~contemporary s~~satellite~~-based~~ information and ~~historical~~ 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. However, these modeling frameworks tend to assume

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global and regional changes in the biosphere as 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.

~~Similar to the models mentioned above, the~~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)~~. One of the key benefits of ED2's formal approach to scaling vegetation dynamics is its ability~~ to describe~~, in a physically consistent manner,~~ 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 ~~means that~~makes the model ~~is ideally~~ suited for investigating ~~of~~ how the combined impacts of changes in climate, atmospheric carbon dioxide concentrations, and land-cover ~~are~~ affect~~ing~~ 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 of ED2 ~~is a unique~~as a tool able to ~~evaluate~~ assess impacts from global and regional changes on ecosystem function, and ~~therefore, it could provide critical information~~ built the basis for a possible development of an integrated tool aimed at ~~for~~analyzing hydrological ~~studies~~implications. In this technical note, we describe the integration of ED2 with a ~~flow~~ hydrological routing scheme. The ~~flow~~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 daily river flows through a large river basin. The advantage of the proposed model is the ability to ~~better~~ predict the sensitivity of river flows to

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global and regional environmental changes as climate and land~~-~~use changes.~~,~~ The new product combines~~ing~~ the advantages of biosphere and hydrological models, bringing together global, regional, and local scale hydrological dynamics in a single model~~l~~ing framework. The resulting model is intended to be used as computational tool to explore the following research questions:

(1) How do current and ~~simulated~~ future climate and ~~/or future~~ land ~~use~~cover affect water ~~scarcity~~availability in ~~closed basin~~river systems?

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

(3) What are the implications of those changes for management of ~~the~~ water and land resources~~ and land use management~~?

Th~~is~~ese research questions are in line with ~~the~~key problems ~~arisen~~raised ~~elsewhere~~ in the literature, ~~and~~ focus~~ed~~ing on the importance of large scale modelling and remote sensing to fill ~~the~~ knowledge gaps ~~related to~~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 ~~using~~ as a function of climate and soil properties~~.~~ ~~It is unique amongst terrestrial biosphere models because,~~. ~~r~~Rather than using a conventional “ecosystem as big-leaf” assumption, ED2 is formulated at the scale of functional and age groups of ~~individual~~ plants. ~~The resulting ecosystem~~Ecosystem-scale dynamics and fluxes are ~~then~~ calculated through ~~a formal~~ a scaling procedure ~~that accurately captures~~to reproduce ~~the resulting~~ 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). ~~Generally, plant functional types are represented by: early successional trees (fast growing, low wood density, and water-needy); mid successional trees; late successional trees (slow growing, shade tolerant, high wood density); and C4 grasses (comprising also pasture and agriculture) (Swann et al. 2015;~~

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~~Medvigy et al. 2009). Each grid cell is subdivided into~~The ~~a series of~~ dynamic tiles ~~that~~ represent the sub-grid scale heterogeneity in ecosystem composition within each cell. Grid cell size is~~.~~ ~~The size of the grid cell is~~ determined by the resolution of meteorological forcing and soil characteristics data, typically from 1 to 0.001 degrees ~~to~~(~ 110 to 1 km). ~~This characteristic of the ED2 model makes it suitable for a more realistic simulation of regions characterized by a mixture of natural and anthropogenically modified landscapes.~~ 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 ~~F~~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 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).

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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 ~~transportation~~movement of water over land in hydrology models for large river basins. ~~as~~In this way, ~~their~~ the prediction performance of models can be evaluated ~~with good accuracy~~ 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).

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 ~~towards the basin outlet~~. The ~~flow~~ hydrological routing scheme chosen was adapted from the original formulation of the ~~IPH~~ MGB-IPH, a rainfall-runoff model that has been used extensively ~~used~~ 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 ~~IPH~~ 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~~ only the ~~the latter two sub-models were utilized as the processes accounted for by the first two are estimated with ED2~~catchment and river routing methods were utilized. The resulting ED2+R model computes the daily total volume of water passing through any given

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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 ~~(surface reservoir)~~, interflow ~~(intermediate reservoir)~~ and groundwater flow ~~(base reservoir)~~ (Figure 2). The reservoirs are used to determine the contribution and attenuation of river flow by different soil layers, characterized by different ~~propagation~~ routing times. The sum of overland flow, interflow, and groundwater flow is then moved from each grid cell into the drainage network, ~~that was~~ ~~computed~~designed in the pre-processing phase using data from a digital elevation model (DEM) ~~-SRTM,~~from the Shuttle Radar Topography Mission at a 90-~~-~~meter~~s~~ resolution~~)~~ ~~using~~ and the ~~COTAT (~~Cell Outlet Tracing with an Area Threshold~~)~~ algorithm (COTAT) (~~(~~Reed 2003)~~ and is enhanced with a parameter that accurately assigns flow directions to DEM grid cells over regions with meandering rivers (Annex A)~~. Each DEM grid cell therefore becomes part of a flow path, which then accumulates water to a final downstream drainage network outlet ~~(Figure 3 – Panel b)~~. 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 ~~solves~~ adopts the Muskingum-Cunge ~~equation~~ numerical scheme ~~of flow routing~~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, ~~height~~ 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). ~~Later on,~~ ~~f~~Further studies ~~-~~successfully ~~employed~~ derived~~these~~ ~~statistical~~ geomorphological relations~~hips~~ to estimate river geometric parameters ~~to~~ and carry out hydrodynamic simulations of the Amazon River system using a similar approach (Paiva et al., 2013; Paiva et al., 2011) ~~(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 subbasin level as delineated ~~considering~~ 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:

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

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:

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

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

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

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; 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).

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

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

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.

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 ≥ 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). FDCs ~~is~~are a cumulate frequency plots that show~~s~~ 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.

4 ~~Parameterization and evaluation for the~~ Case Study: Tapajós river basin ~~application~~

We parameterized and evaluated the ED2+R formulation for the Tapajós River Basin, ~~one of~~ the fifth largest ~~tributaries~~ tributary of the Amazon. It drains an area of 476,674 km^2 in ~~the~~ southeastern Amazonia, ~~between~~within the Brazilian states of Mato Grosso, Pará and Amazonas. ~~M~~The main rivers in the basin are the Tapajós (with a length ~~above~~greater than 1,800 km ~~length~~ and average discharge of 11,800 m^3 s^{-1} ~~average discharge~~), Juruena (~~about~~length of approximately 1,000 km and discharge of 4,700 m^3 s^{-1}) , and Teles Pires (also known with the name Sao Manoel, about 1,600 km long and average discharge of 3,700 m^3 s^{-1}). The river system flows northwards ~~in the basin~~, with terrain~~an~~ elevation ranging from ~~the~~

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about 800 meters above sea level in the southern part, to a few meters above sea level in its confluence with the Amazon river (ANA, 2011). The basin ecosystems are mainly represented by tropical evergreen rainforest~~ biomes~~s in the northern part (in the states of Amazonas and Pará), and Cerrado dry vegetation in the south (Mato Grosso). Precipitation~~s~~ range 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; ~~between the~~total precipitation in the wet season (September to May) ~~where precipitation~~ could be as high as 400 mm month^{-1} in the most tropical areas, ~~and~~whereas in the dry season (June to August), ~~where~~ precipitation is close to zero in the Cerrado ~~area,~~ and as low as 50 mm month^{-1} in the wetter areas (Mohor et al., 2015). ~~Given~~As a result of the large rainfall seasonal variability, ~~also the~~ river flows are also extremely variable: the ~~Tapajós river historical~~ mean monthly ~~records~~ flow of the Tapajós river range between about 2,300 and 28,600 m^3 s^{-1} ~~(Arias et al. under review)~~according to the historical records used for the calibration of our 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 ~~the~~ recent decades. As estimated from the land-use/land-cover dataset set used in this study (Hurtt et al. 2006), ~~:~~ in the late 200~~8~~0s~~,~~ only about 56% of the basin (270,000 km^2) was covered by the original vegetation ~~(Arias et al. under review)~~cover. Large parts of the basin laying in the territory of Mato Grosso, w~~as~~ere 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 ~~for~~by natural parks ~~ecological~~ or ~~social reasons (i.e.,~~ indigenous ~~population living in the forest)~~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 ~~can refer~~ to Arias et al. and Farinosi et al. (under review).

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

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dataset has a 3-hour temporal resolution, which was downscaled to an hourly resolution, as described in Zhang et al. (2015). ~~Surface and subsurface runoff calculated for each cell with ED2 are connected with the three linear reservoirs of the routing scheme (Figure 2).~~ 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 ~~through a two-step procedure~~ 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 subbasins (overland, intermediate, and groundwater flows – *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 (>30). 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).

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In the second step, the residence times (τ) of flow within the ED2+R reservoirs of each grid cell in the domain were calibrated (*CS*, *CI*, and *CB* in Figure 2). The calibration procedure characterizing the second step is similar to the previous one but in this case the calibration is repeated for each subbasin sequentially; the calibration process was conducted from the furthest upstream subbasins – headwaters – to the final outlet of the basin (Anderson 2002). The model was run multiple times (between 30 and 50 per subbasin) 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 subbasins, and to select the combination that best approaches the historical observations. Figure 6 shows how the model is sensitive to marginal variation in initial conditions of baseflow, particularly in the upstream section (i.e. UTP - Upper Teles Pires, UJ – Upper Juruena, and LTP – Lower Teles Pires). ~~Due to the five year spin-up period, c~~Changes in initial groundwater were controlled by the initialization five year period, thus contributions ~~in~~to the downstream part of the basin had minimal impact (i.e. UT and LT - Upper and Lower Tapajós).

Figure 7 describes ~~instead~~ the calibration of the residence time for each of the subbasins. The different combinations of the values assigned to the parameters *CS*, *CI*, and *CB* significantly ~~impa~~affect the overall goodness-of-fit of the river flow simulations (NSE indicator). The calibration process was conducted from the furthest upstream subbasins – 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).

~~Missing observations in the river flow records were filled via linear spatial and temporal interpolation between the series in neighboring gauge stations (Equation 1):~~

$$\cancel{Obs_y(t) = K + \beta_1 \cdot Obs_z(t) + \beta_2 \cdot Obs_q(t) + \beta_3 \cdot Obs_y(t-365) + \beta_4 \cdot Obs_y(t+365)} \quad \cancel{(1)}$$

~~Where *z*, *y*, and *q* are three gauge stations with timeseries highly correlated (Pearson's r ≥ 0.85), and *t* expresses time in days. The estimated β coefficients were used for the estimation of the missing observations in the site *y*. For further details on the calibration procedure, see Appendix B.~~

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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 ~~substantially~~ increases the ability of the model to ~~accurately~~ 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 ~~substantially~~ improved the ~~goodness-of-fit~~model's performance between simulated and observed values with respect to all ~~three~~ the four measures selected ~~,~~ (Nash-Sutcliffe (NSE), ~~(Figure 4, panel a),~~ Kling Gupta (KGE), Pearson's R correlation ~~coefficient (panel b in Figure 4~~), and volume ratio) (Table 3~~panel c in Figure 4~~). Both routed (ED2+R) and non-routed (ED2) simulation results manage to reproduce ~~reasonably well~~ 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)~~. (panel c in Figure 4); however, the application of t~~The routing scheme improves the ability of the model to reproduce the spatio-temporal ~~propagation~~ 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 c~~orrela~~alibration and 0.86 for the validation period. The performance of the presented tool is evident also analyzing ~~the cumulative distribution~~FDCs ~~of the discharge~~ (~~panels a and b in , and~~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 ~~higher~~ 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~~ In the Upper Teles Pires and Upper Juruena, the model achieved the lowest NSE (0.28 and 0.29 respectively in the

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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~~ Although water volumes are correctly reproduced in both the sub-basins ~~reasonably well~~ (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 ~~values~~ indices ~~increased substantially~~are closer to the optimal value in the central and lower part of the basin~~, namely,~~ 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 ~~and Figure 6~~). ~~The Jamanxim basin results, especially during the validation period, are affected by the very short and fragmented observation time series.~~

F~~low duration curve~~DCs, representing the probability of the flow values to exceed a specific ~~value~~discharge, highlight the ~~substantial improvement~~ ~~impact~~positive effect ~~-~~of the application of the routing scheme ~~of~~in ~~the model~~ED2+R across the entire range of flow variability ~~results after applying the routing scheme~~ (Figure 9). The simulated ~~flow duration curve~~FDCs follow the same shape ~~show an~~ ~~excellent~~ ~~match to~~ of the ~~observations~~ observed ones in the furthest upstream sub-basins, especially in the cases of the Upper Juruena and Upper Teles Pires, ~~. This~~ impl~~ies~~ying that the routing scheme is effective in ~~keep~~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 (~~respectively~~ 1,030-2,400 and 302–2,767 m^3 sec^{-1}, respectively). This is especially true for ~~in~~ the lowest flows, where the error between simulated and observed curves is lower than 15% ~~of the observed values~~ (~~panels a and b in~~ Figure 9 a-b, Figure A.1). ~~For~~ Regarding the intermediate subbasins~~downstream subbasins~~, Lower Juruena and Lower Teles Pires, flood duration curves show ~~a general tendency~~ ~~how~~that the model ~~of~~ overestimates~~ing~~ the lowest values of the distribution~~,~~ up ~~to~~by ~~a magnitude quantifiable in~~ approximately 30% of the observed values ~~-~~(flow equaled or exceeded 60 to 100% of the time in ~~panels c to g in~~ Figure 9 c–d). Similar overestimation of the model could be noticed in the furthest downstream subbasins, Upper and Lower Tapajós (Figure 9 e–g). ~~This~~ The overestimation of the lower discharge values highlighted in Figure 9g, is also evident in the multiyear hydrograph (Figure 8), which shows ~~that~~ that~~how~~ the ED2+R ~~tend~~ simulation results ~~to~~ overestimate (by about 40%

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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 ~~4-6~~ 8 - 9 show, the one-way integration of ED2 with a ~~a simple one-way~~ routing scheme ~~substantially~~ increases the ~~model's ability to reproduce daily water flows through a large river basin~~performance of simulated daily discharges. ~~The results highlight the ability of the ED2+R model to more accurately capture the hydrological dynamics in the study domain in terms of both volumes (Figure 6) and seasonality of river flows (Figure 5).~~ 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 ~~the~~ applications ~~to~~in the tropic~~al regions~~s, 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).

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 ~~concur in determining~~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~~T~~ this is due to ~~both~~ the relatively coarse spatial resolution of the model in combination with the limitations typical of most land surface models in capturing the interactions with ~~the~~ 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

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Commented [FF75]: Add rely to CMT 73 DONE OK 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 of the groundwater flow: as shown in Figure 7, in fact, especially in the headwaters, even small variations in the CB parameter largely 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 ~~part of the~~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 subbasins. 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 ~~more sophisticated~~ 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 ~~principal~~ advantage of the ED2+R model is the ability to ~~better predict~~ study the sensitivity of the river flows to global and regional ~~environmental~~ 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~~. As mentioned earlier, ED2+R combines the advantages of biosphere and hydrological models, bringing together global, regional, and local scale hydrological dynamics in a single modelling framework~~. 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 providing more detailed hydrological processes. ~~This~~ 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: chang~~es~~ing 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~~al~~ system.

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7 Conclusions

~~Biosphere models are excellent tools to study hydrological dynamics under climate and land use/land cover changing conditions. These models are usually set to simulate long periods in large regions, usually at global or continental scales. Their ability in reconstructing the water balance at relatively fine geographical and temporal resolution, taking into consideration global environmental changes makes them powerful instruments for hydrological simulations. In order to translate the results of the land surface simulation in terms of river flows, the simulated results need to be processed using a hydrological routing scheme.~~ 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 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 ~~substantially~~ 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 groundwater flow typical of this kind 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 ~~that could be extremely important especially~~ 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

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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.

~~Annex A – COTAT algorithm~~

~~Cell outlet tracing with an area threshold (COTAT) algorithm (retrieved from Reed et al. 2003):~~

~~„*The basic rules for the COTAT algorithm are defined here:*~~

~~*1. Identify an outlet pixel in each coarse-resolution cell. The outlet pixel drains the largest cumulative area of any pixel in that cell.*~~

~~*2. For each cell, trace downstream, from its outlet pixel, along the flow path defined by the high-resolution flow directions.*~~

~~*3. For each subsequent outlet pixel reached, determine its total drainage area and subtract the drainage area of the starting outlet pixel.*~~

~~*Case 1: If this difference is greater than a user specified area threshold, stop tracing.*~~

~~*Case 2: Otherwise, continue tracing to subsequent outlets until either the area threshold is exceeded or until the edge of the high-resolution grid is reached.*~~

~~*4. Assign the flow direction of the starting cell toward the neighboring cell with the farthest outlet along the trace defined in steps 2 and 3" (from Reed et al. 2003 – Section 3. Methodology, page 2)*~~

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~~Annex B – Calibration of the ED2+R model for the Tapajós River Basin~~

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~~In this annex, we present the calibration of the ED2+R model for the Tapajós river basin. The calibration process has two steps, as highlighted in Figure 2. The first step is the partitioning of the flows from the two reservoirs of the ED2 biosphere model to the three reservoirs of the ED2+R routed biosphere model. The second step regards the adjustment of the residence times of the water flows in the three reservoirs for each of the grid cells in each of the subbasins (overland, intermediate, and groundwater flows – CS, CI, CB in Figure 2). Figure B.1 shows the different combinations of the α and β parameters introduced in Figure 2. The color bar indicates the Nash-Sutcliffe indicator (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 B.1) lies in one of the optimal combination areas (NSE ~ 0.8).~~

~~The second step of calibration is represented by the adjustment of residence time of the overland, intermediate, and groundwater flows (CS, CI, and CB in Figure 2). Figure B.2 shows how the model is sensitive to marginal variation in initial 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 groundwater contributions in the downstream part of the basin are almost completely uninfluential for the overall representation of the river flows (i.e. UT and LT - Upper and Lower Tapajós).~~

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~~Figure B.3 describes instead the calibration of the residence time for each of the subbasins. The different combinations of the values assigned to the parameters CS, CI, and CB significantly impact the overall goodness-of-fit of the river flow simulations (NSE indicator). The calibration process was conducted from the furthest upstream subbasins – 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 B.3).~~

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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.

Acknowledgements

This work was conducted while F. F. Pereira, F. Farinosi, E. Lee, and M. E. Arias were Giorgio Ruffolo Fellows in the Sustainability Science Program at Harvard University. F. Farinosi was also funded through a doctoral scholarship by Ca' Foscari University of Venice. Support from Italy's Ministry for Environment, Land and Sea is gratefully acknowledged. We would like to thank Marcos Longo for letting us use one of his figures, and Angela Livino for the useful comments. The authors would like to dedicate this study to the late Professor John Briscoe (1948 - 2014), who envisioned and co-led the Amazon Initiative of Harvard's Sustainability

Science Program. We are grateful to the Editor, Professor Graham Jewitt, and to the two Anonymous Referees for the valuable comments received during the review process.

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Figures

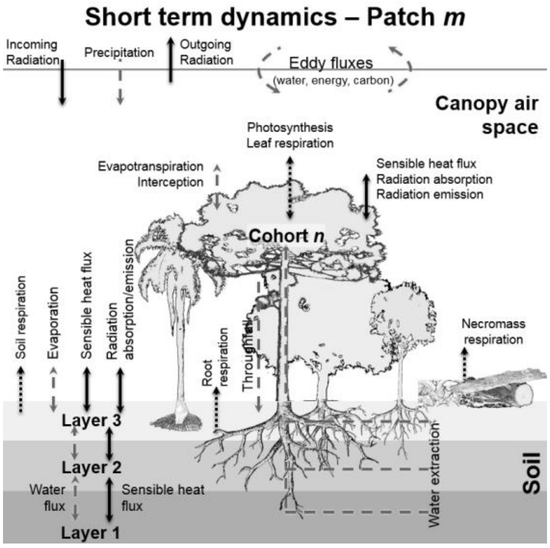

Figure 1. Schematic of the enthalpy fluxes (all arrows) and water fluxes (all but solid black arrows) that are solved in ED2. The schematic is based on Walko et al. (2000); and Medvigy et al. (2009). (Courtesy of Marcos Longo).

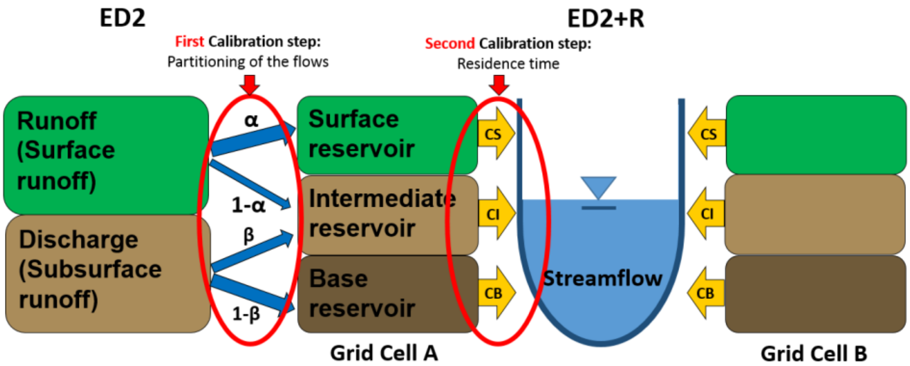

Figure 2. Schematic representation of the connection between the terrestrial biosphere model and the hydrological routing scheme. Calibrating parameters circled in red~~ (Figure B.1 and Figure B.3)~~. The reservoirs are used to determine the contribution of streamflow that comes from overland flow~~ (surface reservoir)~~, interflow ~~(intermediate reservoir)~~ and groundwater flow ~~(base reservoir)~~. The daily sum of these three reservoirs is then moved from each grid cell into the drainage network.

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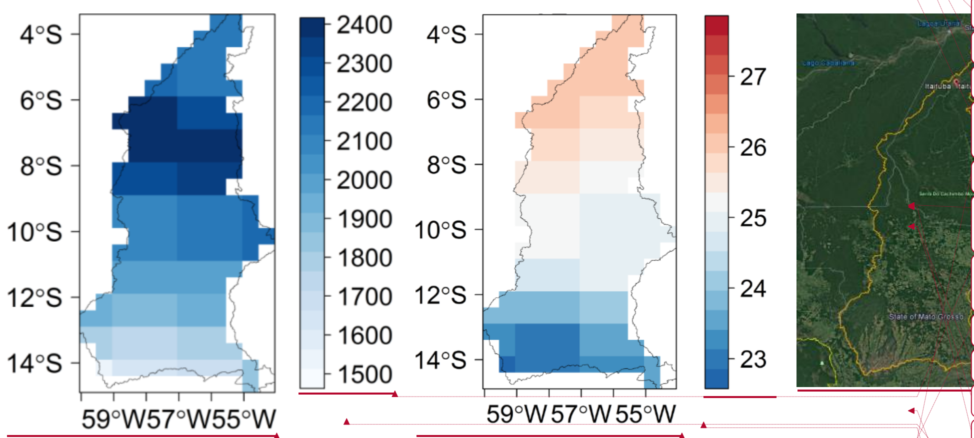
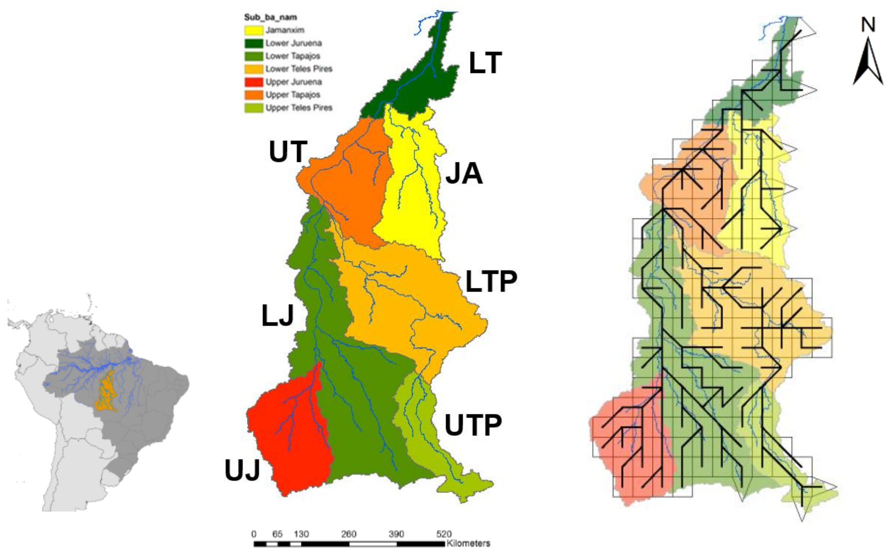
Average yearly precipitation (mm year^-1^) **Average temperature (°C)**



(a) (b) (c)

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 the Tapajós river basin. Source: Google Earth Pro.



(a) (b)

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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.

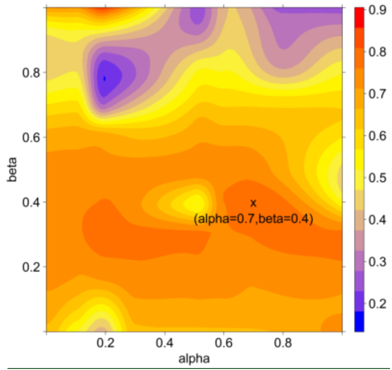

Figure 5. ~~Figure B.1.~~ Calibration of flow partitioning (parameters alpha and beta in Figure 2) between the ED2 and the ED2+R reservoirs. Color bar indicates the NSE values of the simulated versus the observed river flow values (0 very different, 1 very similar)

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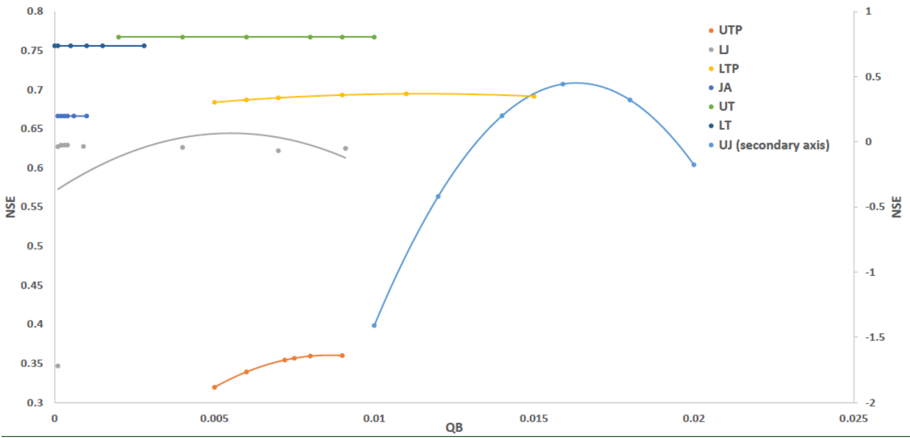

Figure 6. Initial conditions of baseflow sensitivity for different ED2+R subbasins in the domain. Upper Juruena (UJ); Upper Teles Pires (UTP); Lower Juruena (LJ); Lower Teles Pires (LTP); Upper Tapajós (UT); Jamanxim (JA); and Lower Tapajós (LT).

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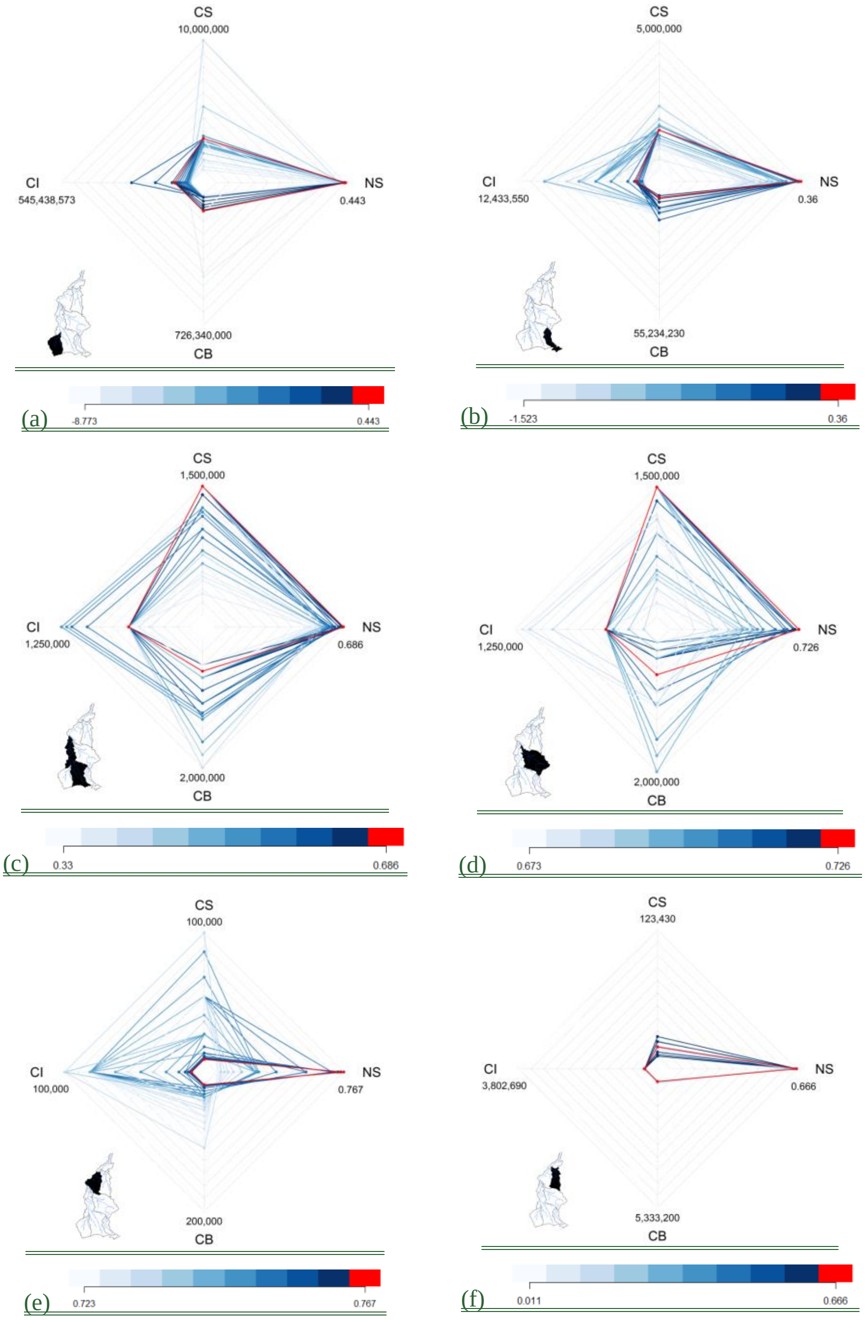
~~Figure B.2. Initial conditions of baseflow sensitivity for different ED2+R subbasins in the domain. Upper Juruena (UJ); Upper Teles Pires (UTP); Lower Juruena (LJ); Lower Teles Pires (LTP); Upper Tapajós (UT); Jamanxim (JA); and Lower Tapajós (LT).~~



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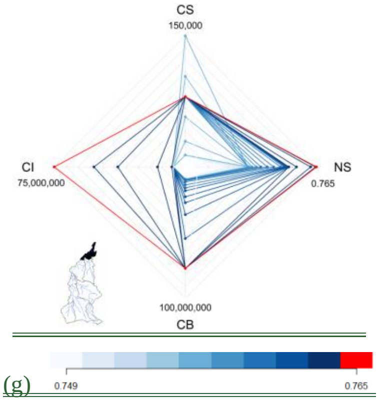

(g)

Figure 7. ~~Figure B.3.~~ Calibration of the residence times (τ) of the flow within the ED2+R reservoirs of different grid cells in the domain. Overland, intermediate and groundwater flows are indicated respectively by CS, CI, and CB (Figure 2). In red the chosen combination. (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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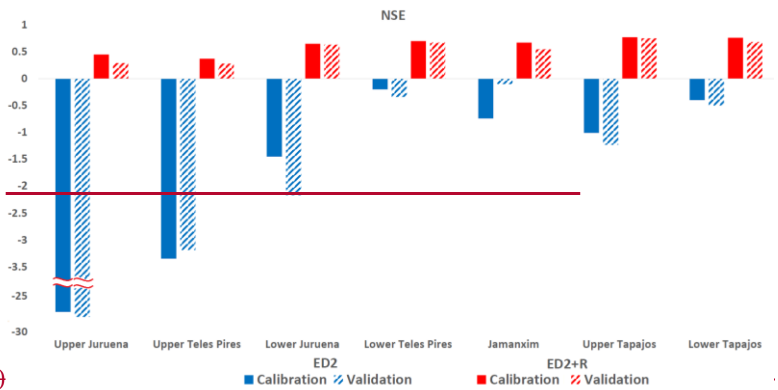

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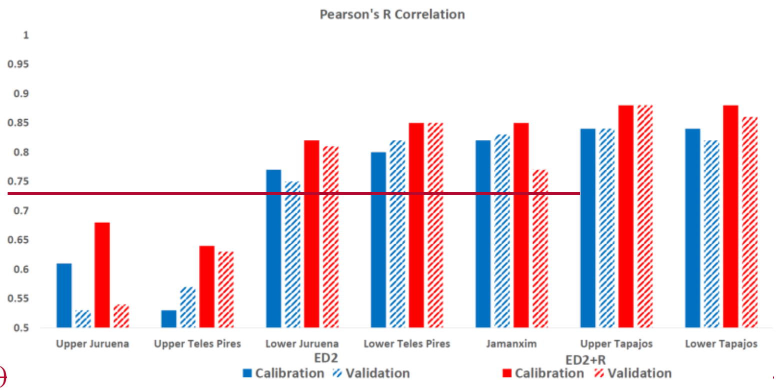

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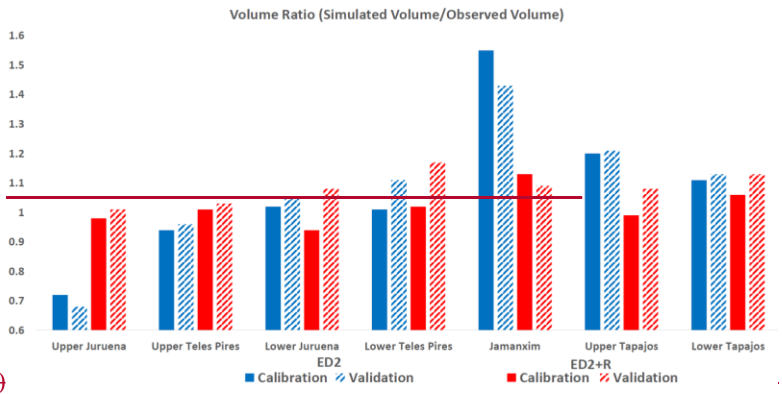


~~(c)~~

~~Figure 4. Calibration and validation results. (a) Nash-Sutcliffe, (b) Pearson's R, and (c) volume ratio, optimal values = 1; in red ED2+R results, in blue ED2. Filled bars corresponds to calibration period, shaded bars for validation period.~~

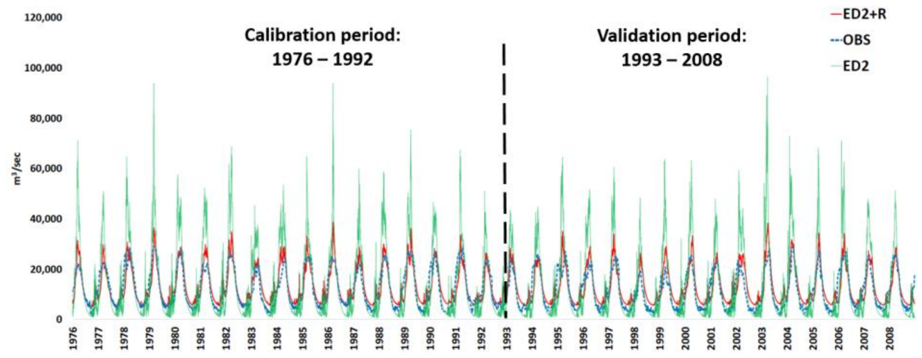


Figure 8. Calibration and validation of the river flow (m^3/sec) at Itaituba (farthest downstream river gauge – Lower Tapajós sub-basin). ED2 output (green line), ED2+R (red line), and Observations (blue dotted line). The dotted black line splits the calibration and validation periods. Similar comparison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

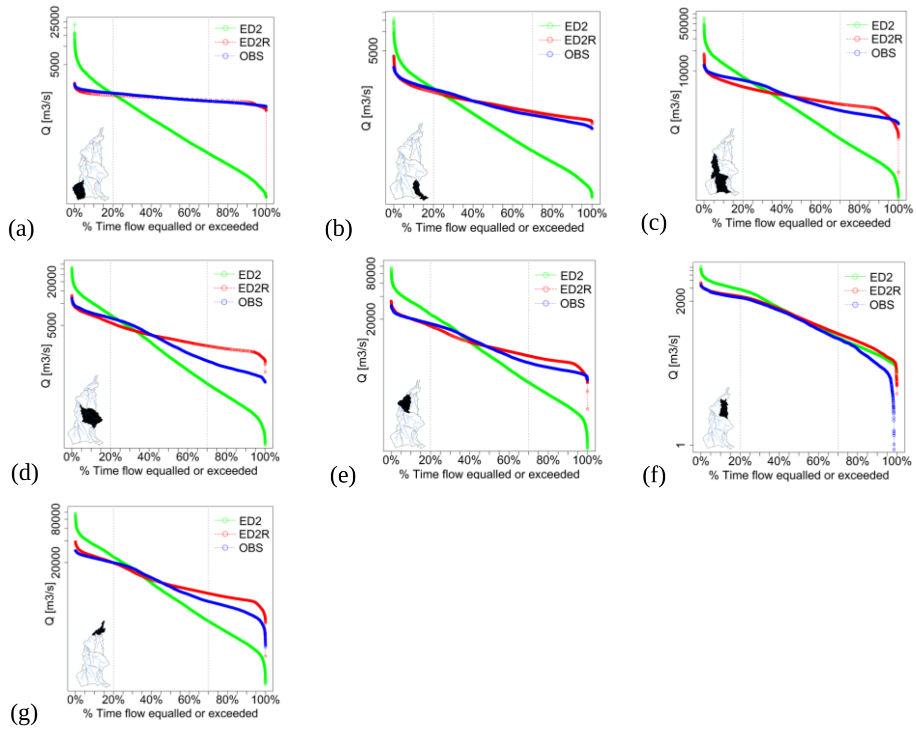
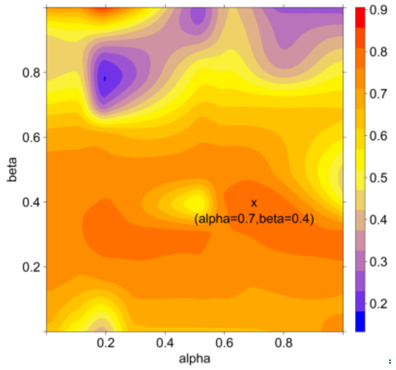


Figure 9. Flow duration curves (percentage of time that flow – m^3/s – is likely to equal or exceed determined thresholds) of observed values (blue), ED2 outputs (green), ED2+R (red) at the outlet of the seven sub-basins. (a) Upper Juruena (UJ); (b) Upper Teles Pires (UTP); (c) Lower

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

Tables



~~Figure B.1. Calibration of flow partitioning (parameters alpha and beta in 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)~~

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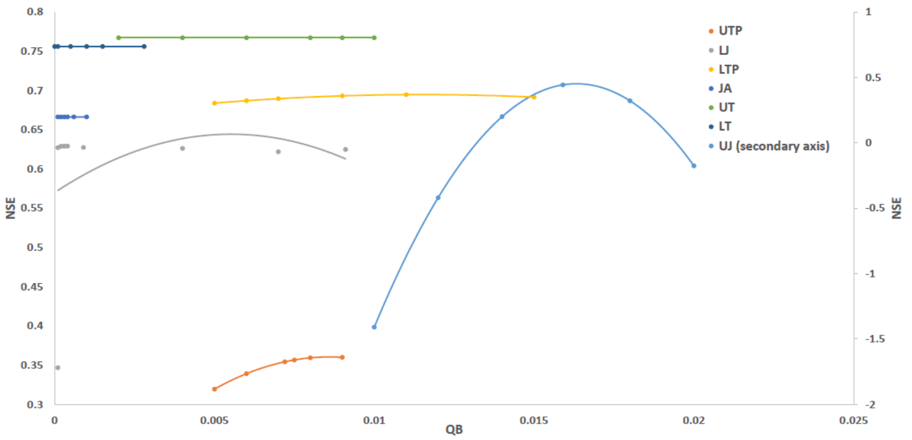

~~Figure B.2. Initial conditions of baseflow sensitivity for different ED2+R subbasins in the domain. Upper Juruena (UJ); Upper Teles Pires (UTP); Lower Juruena (LJ); Lower Teles Pires (LTP); Upper Tapajós (UT); Jamanxim (JA); and Lower Tapajós (LT).~~

Table 1. ED2+R parameters (based on Zhang et al., 2015; Longo et al., 2014; Knox et al., 2012)

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	$kg_w m_{leaf+wood}^{-2}$
Residual stomatal conductance	10,000	$\mu mol\ m^{-2} s^{-1}$
Leaf-level water stress parameter	0.016	$mol_{H_2O}\ mol_{Air}^{-1}$
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 Overland (CS), intermediate (CI), and 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 ~~Tapajos~~Tapajós (75; 75,000; 75,000) Lower ~~Tapajos~~Tapajós (75; 75,000; 75,000)	*x1 '000 ~~h~~ (***)*
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 ~~Tapajos~~Tapajós (0.0080) Lower ~~Tapajos~~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. ~~The magnitude of the residence time parameters is influenced by the size of the grid-cell~~

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~~Figure B.3. Calibration of the residence times (τ) of the flow within the ED2+R reservoirs of different grid cells in the domain. Overland, intermediate and groundwater flows are indicated respectively by CS, CI, and CB (Figure 2). In red the chosen combination. (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).~~

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 ~~1~~7	Original number of daily gauge records (number of daily observations)	Gap filling station 1 – **q** in Equation ~~1~~7 – [correlation with **z**]	Gap filling station 2 – **y** in Equation ~~1~~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 Sao Manuel [0.89]	11,688
Lower Teles Pires	Tres Marias	8,682	Barra do Sao Manuel [0.98]	Santa Rosa [0.98]	10,640
Lower Juruena	Foz do Juruena	2,074	Barra do Sao Manuel [0.98]	Jatoba [0.97]	11,447
Upper Tapajós	Jatoba	10,218	Fortaleza [0.99]	Barra do Sao Manuel [0.98]	11,517
Lower Tapajós	Itaituba	5,789	Fortaleza [0.99]	Jatoba [0.98]	11,688

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Table 3. Calibration and validation results. ~~(a)~~ Nash-Sutcliffe Efficiency, ~~(b)~~Kling Gupta (2009 and 2012 methods), Pearson's R correlation, and ~~(c)~~ volume ratio~~, . optimal~~ Optimal values = 1 (statistics where calculated using the R package hydroGOF - Zambrano-Bigiarini 2014)~~; in red ED2+R results, in blue ED2. Filled bars corresponds to calibration period, shaded bars for validation period~~.

Sub-basin	Calibration period (1976-1992)								Validation period (1993-2008)							
	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 ~~Tapajos~~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 ~~Tapajos~~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

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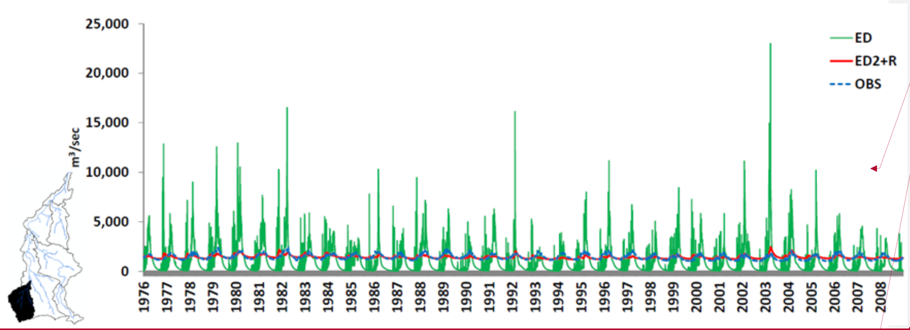
Annex A



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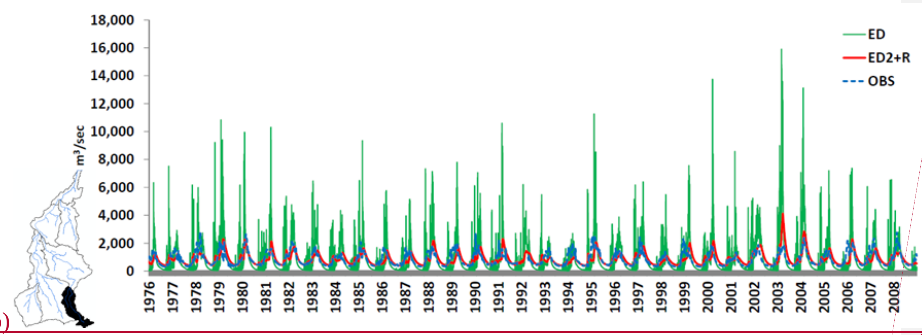

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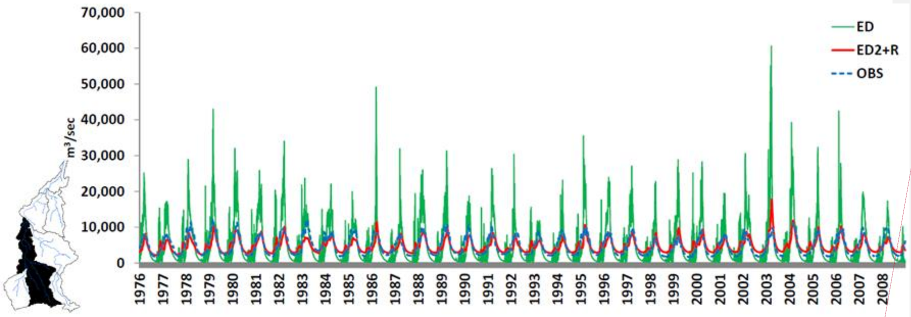

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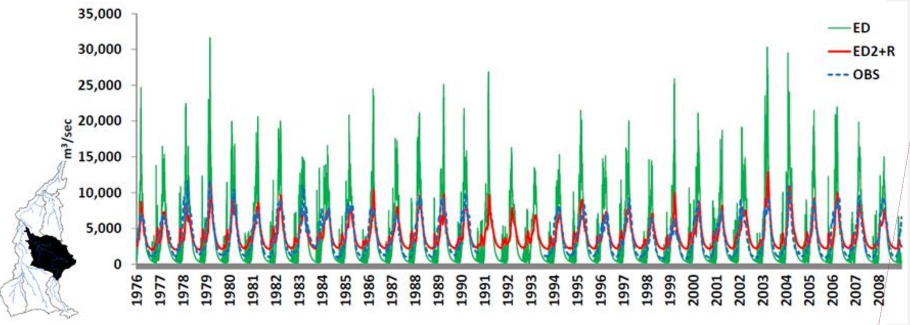

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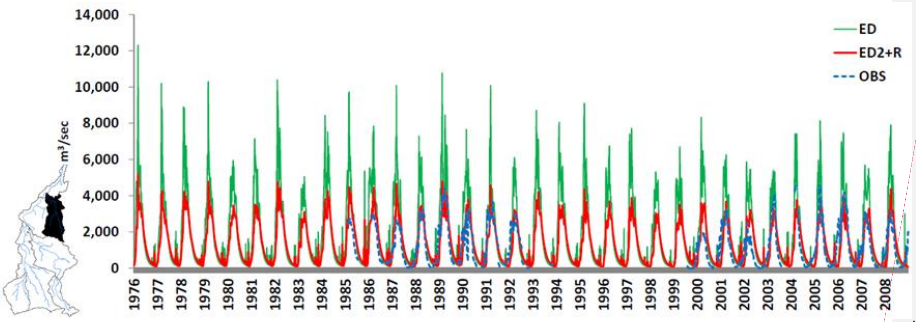

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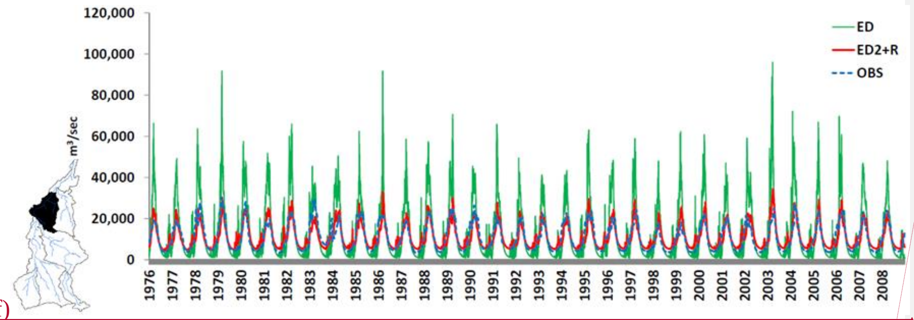

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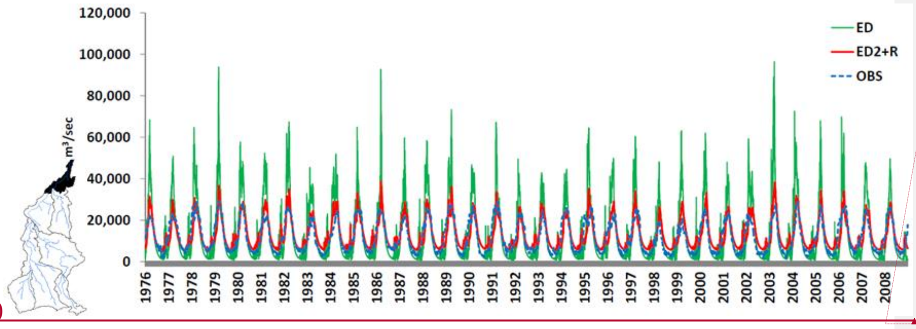
(g) 

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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).