Editor Decision: Reconsider after major revisions (further review by Editor and Referees) (29 Jul 2017) by Hilary McMillan

Comments to the Author:

The three referees of this manuscript have provided detailed reviews, and I encourage the authors to submit a revision of the manuscript that addresses each point. I will request the referees to review the revised paper.

To these three reviews, I add my review as Associate Editor. This paper describes a substantive piece of modelling work to describe existing v. naturalised flows in a large basin with multiple and complex reservoirs. The results of this modelling can then be used to analyse the impacts of the reservoirs on drought flows. The impacts of reservoirs on droughts, good or bad, is a topic of current interest in the hydrologic community, and this paper has the potential to contribute to the debate.

However, the existing paper is on the borderline of acceptability for HESS, as it describes a case study using existing models, and does not contribute to the development of new techniques or theory. In order to overcome this deficiency, I urge the authors during their major revision, to develop the results and discussion section such that it is clear that the paper contributes to the wider understanding of the impacts of reservoirs on droughts. The paper should clearly articulate the major findings in terms of what controls reservoir impacts on droughts (using the multiple reservoirs and multiple years in this study). The authors then need to consider, using additional data on other reservoirs if necessary, how these findings would apply to other watersheds. Would other systems likely behave the same way? Which other parts of the world could see similar effects? Are there any aspects of these systems that are unique and not likely to be replicated elsewhere? It would also be relevant to see a discussion of the effects of these changes on water users in the study watersheds. I will review the revised paper to determine whether the authors have been successful in making this important link to current understanding of hydrologic systems.

Answer:

Dear Prof. McMillan,

Thank you for your comments which we appreciate!

We have now included sections about reservoir effects on droughts in the region in the results section (4.3, 4.4 and 4.5) and discuss impacts of reservoir operation on droughts (5.5 and 5.6) and our findings in a wider context. Furthermore, we explain to which extent our findings are comparable and transferable to other catchments in section (5.3 and 5.4). Finally, we also addressed in the discussion section (5.6) the effect of such changes on water users in the study watersheds.

In the introduction we illustrated the effects of hydrological droughts on the water uses - as the severe impacts of salt water intrusion on drinking water supply and on irrigated agriculture. Water related challenges and stakeholder needs are also described in several chapters of the Springer Book: Land Use and Climate Change Interactions in Central Vietnam: LUCCi, Nauditt, A., and Ribbe, L. (Eds.), Water Resources Management and Development, Springer Book Series: Water Resources and Development, ISBN 978-981-10-2623-2. Other potential human impacts on hydrological drought were discussed in: Nauditt, A., Firoz, A., Viet, T. Q., Fink, M., Stolpe, H., and Ribbe, L.: *Hydrological drought risk assessment in an anthropogenically impacted tropical catchment*.

To our knowledge, such a distributed hydrological model as J2000 had never been used in such a data scarce tropical environment. We think that linking the physically based model with a reservoir operation model is an innovative approach to assess such a complex tropical river system with a large number of recently built operating hydropower reservoirs and a basin transfer. Especially in combination with the hydrological drought analysis it represents an innovative integrated assessment framework for drought risk assessment which can be applied in data scarce and anthropogenically modified catchments worldwide also suitable for snowmelt driven environments or any other climate.

Yours sincerely, ABM. Firoz on behalf of all the authors

We thank Reviewer # 1 for the constructive feedback to our manuscript and the helpful comments which help to further improve the presentation of our findings. In the following sections, for our responses we use blue font while for reviewer's comments we use black italic font.

Response to Reviewer #1 Comment

Authors estimate reservoir impacts on hydrological drought using a catchment hydrological model combining with reservoir routing approach in a tropical river basin in Central Vietnam. The topic is interesting as it gives how extent of the reservoir operation affects seasonal variation of streamflow and thus drought occurrence in the extremely uneven distributed precipitation region. The used approaches are able to quantify the reservoir effects on streamflow. However, some conclusions need to further illustration.

(1) Generally, the construction of reservoirs is to reduce the drought by smoothing streamflow variations (increase water release in the dry season and decrease the release in the flood season). However, it could shift the drought occurrence (e.g. Fig. 9). So I don't agree with authors' conclusions "we found a stronger hydrological drought risk for the anthropogenically impacted reconstructed streamflow".

We regret that our argumentation has not been clearly formulated. The purpose of our study was to assess the impacts of hydropower operation and other human alterations of the hydrological system on downstream discharge. You are right and the quantified decreases in streamflow under human influence for the historical observed period do not imply a "risk" per se. However, hydropower generation at the Dak MI 4 reservoir implies a diversion from Vu Gia to Thu Bon and therefore it reduces the discharge in Vu Gia at Than My and Ai Nghia stations under hydropower operation ("reconstructed" streamflow). For the Thu Bon an increase in discharge was observed.

We now reformulated the concluding sentence: In accordance with the reports from local stakeholders, we found a stronger hydrological drought risk for the Vu Gia river supplying water to the City of Da Nang and large irrigation systems especially in the dry season. Vu Gia river experiences the most adverse effects in terms of number of drought days compared to its natural condition, with an increase of 37 % and 17 % at Thanh My and Ai Nghia station respectively.

(2) In the study region, one of the main effect on streamflow in the two streams is the water division from VuGia to Thu Bon. The division increases streamflow at Nong Son station and decreases streamflow at Thanh My station (Fig 7 A and 8a). So I am very interested how this water division influence drought occurrences at two streams in addition to reservoir operations. Authors need to give clear illustrations.

The diversion of the river from Vu Gia to Thu Bon at the upper part is mainly due to the construction of Dak Mi 4 dam. Although the Dam is built on the Vu Gia river, but its turbines are located at the Thu Bon catchment, therefore, any release of Dak Mi 4 through the turbine is discharged to the Thu Bon river. This lead to the increase of the discharge towards the Thu Bon river. Therefore, any changes of the water from Vu Gia to Thu Bon is always associates with the reservoir operation, which in our case is the reconstructed streamflow.

In order to assess the drought risk, we have presented Figure 9, which shows how the number of drought days changed due to the diversion and the reservoir operation. However, we failed to properly illustrate this. Therefore, we have added one more table in the discussion section, Table 4. The results reveal that Thanh My and Ai Nghia station experienced 37.08 % and 27.20 % more drought days, while Nong Son and Giao Thuy station had a reduction in drought days of 17.17 % and 30.43 % respectively. We also found that there is a strong seasonal variation in in hydrological drought. For example, in the dry season, the streamflow is reduced almost 45 % for Thanh My, however, for Ai Nghia, this reduction is only 7.9 %. This phenomenon is mainly because of other hydropower e.g., A Vuong, Song Bung 4,5,6 and Song Con release water during the dry season for producing energy which is located other side of the Thanh My station, but contributing the flow at the Ai Nghia station. The detailed explanation will be incorporated in the revised manuscript in Section 5.1

		Nong Son	Giao Thuy	Thanh My	Ai Nghia
a) Drought duration (%)		-17.17	-30.43	37.08	27.20
b) Changes of flow (%)					
	Ann	19.46	10.09	-37.82	-17.41
	Dry	43.3	27.23	-44.67	-7.91
	Wet	10.84	3.61	-35.03	-21.10
c) Changes of flow (in m^3s^{-1})					
	Ann	51.52	38.32	-51.66	-52.14
	Dry	45.65	42.51	-26.43	-9.97
	Wet	63.25	29.93	-102.12	-136.47

Table. 4. Impact of human alterations on drought intensity and changes of flow in the VGTB for the period 1980-2013 on an annual and seasonal scale. a) Drought duration is calculated based on percentage changes of the number of drought days from naturalized conditions to reconstructed conditions (Fig 9). b) Changes of flow (%), are calculated based on the percentage changes of the mean flow between the Naturalized and Reconstructed streamflow for the corresponding time frame. c) The changes of flow are calculated based on mean differences of reconstructed streamflow from the naturalized mean flow. Positive values indicate increasing flow or less drought intensity compared to the naturalized discharge values.

(3) Authors only described "the reservoir should release a minimum of 25 m^3s^{-1} water from the reservoir to the Vu Gia river (MOIT, 2011) (Page 9). How much the division amount between the two streams was used in the study?

According to our observations (2011-2013), only a maximum of 12.5 m^3s^{-1} is released to Vu Gia. We therefore used the actual diverted amount in this study.

(4) The whole study is focused on the reservoir operation including water division influence on drought. So I suggest that the topic should change to be "reservoir impacts on hydrological drought: : :.". Human impacts are too broad as authors don't quantify other human influences, such as land use and land cover.

Thank you very much for your observation and suggestions which we duly appreciate. However, we kindly ask you to leave it as "human impacts" than "reservoir impacts" given that the installation of reservoir is a human built infrastructure to serve solely human purposes such as energy generation and flood protection. Consequently, we demonstrated how such an infrastructure can influence hydrological drought. We agree that human dimension is too broad; however, it is used more as a metaphorical dimension of human activities.

(5) So in introduction, descriptions of the previous studies on modeling approaches for quantifying human activities on hydrology should be focused on mostly reservoir operations and regional water division.

We appreciate this comment. During our research, we evaluated previous studies regarding the possibilities to assess hydrological drought in dependence of a diversity of anthropogenic alterations. We therefore presented a comprehensive state of the art dealing with modelling and statistical approaches to assess hydrological drought. As we kindly ask you to keep it as "human impacts", therefore, we would not modified significantly the introduction section. However, we have incorporated more studies related to reservoir operation and regional water division in our introductory section in the revised manuscript.

(6) rainfall-runoff model J2000 should be calibrated and validated by using observed streamflow discharge before reservoir operation.

Thank you for this comment and we apologize that our explanations have not been clear. The J2000 model was calibrated and validated using observed streamflow before hydropower came into operation in 2009. The model was then used to simulate naturalised discharge.
In section 3.1, we changed the sentence: The J2000 model was calibrated and validated for the gauging station Nong Son for the period of 1996-2005 (Calibration and validation), an undisturbed period before the reservoirs were constructed in 2009.

(7) Line 20 on Page 11: "The flow during the rainy season decreased by -2 to -38%" refers to which stream?

Please apologize for not making this clear: here we summed the flow of Ai Nghia and Giao Thuy stations to provide an overview about the overall water availability at basin scale as shown in Fig 7b.
We changed the sentence:
The water availability in the entire basin during the wet season decreased by -2 to -38 % (Fig. 7b).

(8) In discussion, it is not necessary to describe generally known uncertainty of the modelling. Authors can discuss uncertainty in lack of more observation data in sub-basins, e.g. calibrated parameters from one sub-basin (station) used for other sub-basins.

Thank you for the remarks. We agree that a description of potential uncertainty analyses is not very helpful. Our intension was to discuss potential analyses which could be carried out in a further step. Now, we have included the uncertainty analysis graph for the J2000 hydrological model as a supplementary information in the paper and include parameter estimation as well (please see our detailed response to Reviewer #3 about uncertainty and parameter estimation). In addition to this, Reviewer # 2 also raised the question about the uncertainty part (4.2 and 4.3). We therefore decided to merge and shorten sections 4.2 and 4.3.

(9) Conclusion should be revised to focus on how extent of the reservoir operation affects seasonal variation of streamflow and thus drought occurrence in the extremely uneven distributed precipitation region.

We have revised the conclusion focusing on how the human modified system impacted seasonal variation of streamflow and drought occurrence as suggested. However, a more detail description of this impact will be incorporated in section 5 as well as in the conclusion at section 6.

Response to Reviewer #2

We thank Reviewer # 2 for the profound evaluation of the paper and the helpful comments, which will further improve this paper. We are confident to adequately address each comment and our reply describing the planned revisions of the manuscript are highlighted in blue normal font, while the reviewer's comments are in *italic font*.

The paper implemented a number of models and assessment method to quantify and highlight the role of reservoirs in the upper part of the change in hydrological drought in downstream of Vu Gia Thu Bon river basin (VGTB), in central Vietnam. By comparing the naturalized and reconstructed data at four discharge stations, a significant consequence of reservoir operation was found in different time scales. Not only duration and frequency, but also the severity of drought was considered with use of threshold approach. This makes the paper completely compatible with the third scoop of HESS, which aim to investigate the influence of human activity to some particular aspects including droughts. Although considering the natural- and impounded-flow has been widely used, but the successful simulation and combination of a rainfall-runoff model and a reservoir modelling based a good foundation for further study facing with the poor data observation.

We thank you so much for the recognition of our work and related effort.

1. ***General Comments:***

The abstract does summarize from context to method and major outcomes of the study. However, it could be more precise if the author either remove or better express the third sentence in the second paragraph without mentioning the local stakeholders.

We agree with you that the formulation is too weak for an abstract. We reformulated the sentence also responding to reviewer # 1:

"We found a stronger hydrological drought risk for the Vu Gia river supplying water to the City of Da Nang and large irrigation systems especially in the dry season."

The introduction provides a good summarized background of the topic, so that the reader can quickly obtain the wide range of application for this issue. A certain number of former researched are mentioned to strengthen the objectives. However, it would be worth if the author reveals other works in which (fully or partly) implemented the same methodologies. The objectives are clearly stated in line 17 – 26 (page 3) with a main goal and four mini-ones.

We thank you very much for the comment. Although we have not found any publication in the literature which fully follows our methodologies, there are some, which partially do which we have incorporated in the introduction section. We have incorporated the work of López-Moreno et al., (2014); Wagner et al. (20017) and Wada et al. (2013).

The study area is fully characterized in part 1.1 to help the reader, who are not familiar with tropical climate, catch the major identities. The status of observation data, hydropower plants *and reservoirs are described in section 2.1, and are very essential to understand the circumstances in VGTB. Besides the spelling mistakes (see specific comments section), a redundancy of information is found in two parts. The author may wish to combine 1.1 and 2.1 (as suggested above) to avoid double explanation about hydrological gauges*.

Thank you for this constructive suggestion to shorten and merge the two sections. We agreed that the repeating information is unnecessary. As per suggestion, we have merged section 1.1 under Section 2.1 and shortened the text. We furthermore included a method section as separate section 3.

Moreover, a few points need better coherence, for example: The author offers no explanation of why he chooses data set for his calculation in the period 1980–2013, whilst the discharge data available since 1976 (page 4, line 23).

Please apologize for not making this clear. The temperature data, which is needed for J2000 calibration, does start in 1980. Therefore, we could not use earlier data from other variables. We included an explanation in section 2.2.

Quang Hue channel (page 5, line 15) actually diverts water from Vu Gia to Thu Bon in flood season only, thus, the author could obviously avoid this connection by explaining that this work considers the drought season, rather than assume that "Ai Nghia locate upstream of the diversion of the Quang Hue…" (line 16).

Generally, the Quang Hue Channel in VGTB has diverted water from Vu Gia to Thu Bon all over the years, but the diversion varies between the seasons. For example, during the summer or dry season, sometimes it diverts 20% of its water while in the flood season this amount increases significantly. Please see the reference document (ICEM, 2008: PP 105). Furthermore, in the supplementary document (S1), we have included the diversion rate. Therefore, we have chosen a proxy location of Ai Nghia, to calculate the impact. In the revised text version, we will explain this diversion in detail to avoid misunderstanding. For this, we have added a new section 2.21. Data uncertainties, which explained in more detail of this issues.

The definition of "Flood season" and "Dry season" mentioned in page 6 (line 4) may need a source. Otherwise, the current operation rule in VGTB defines them differently (please refer Decision 1537/QD-TTg released on 07/09/2015, Decision of Inter-reservoir operation rule in VGTB).

Thanks for the suggestion. We have incorporated the references from the technical documents for Dak Mi 4, A Vuong hydropower operations rules. (MOIT, 2011 & 2012)

Table 1 mentioned in this part is expected to use the up-to-date statistic. Since they were listed in 2008, the year of operation is not matched completely. Dak Mi4, for example, is said to start operating in 2011, but the actual activation was in 2012 which also mentioned in the results part and figure 5 later on.

Thanks for the remark about the table. Actually, A Vuong reservoir start its operation from September 2008 and Dak Mi 4 reservoir from September 2011. However, we have only data from January 2009 and January 2012 for A Vuong and Dak Mi4 respectively, therefore we mentioned this in the result section. We now included in Section 2.3 the following sentences-

“Please note that, A Vuong start its operation in September 2008 and Dak Mi4 reservoir start its operation from September 2011 (Table-1).”

The Dak Mi 4B actually does not play important role in this work. It is not mentioned in the body of the paper, except in page 5, line 21. The author may wish to explain why it disappears in the paper, because Dak Mi 4 reflects to both Dak Mi 4A&B or only Dak Mi 4A.

Dak Mi 4B is a runoff hydropower plant, i.e., it does not have any storage functionality but uses the turbine discharge water of Dak Mi 4A to generate energy and release to Thu Bon river. Hence, we have not accounted this for model evaluation. However, as for the other hydropower reservoirs, we considered its operation in the integrated model. We will explain this in the revised manuscript.

The method part spreads in almost two pages which give general description about JAMS/J2000 HRU, HEC-ResSim, combined modeling and Hydrological Drought Assessment.

We thank Reviewer for the encouraging feedback.

Besides the suggestion for re-order the sub-sections (see major comments), this part could be a bit improved if:

The performance of efficiency statistics for the J2000 is mentioned here and also provide the “significance level” if possible, rather than explain them in the result part (page 9, line 2–7). As a reader, I may question how is the goodness of E2, R2…. which are shown in Table 2 and 3?

Thank you for your constructive comment. We agree to bring this into the method section 3.1. The efficiency statistics and the evaluation scale was explained.

the sub-section 2.2.4 is shortened and the reason of choosing tc = 3 days, or zc = 10 % is given. Since they are not presented in the result part, a question of whether the equations and its components are really needed to write in details?

Thank you for the suggestion. We agree with the reviewer that the sub-section 2.2.4 should be shortened and that the equations need to be deleted. We intend to shorten the text by e.g., deleting the equations and associate extra text to explain this and considering the text by addressing key points how the threshold method is applied here. In the revised text we have explained why we have chosen different values for selecting the threshold level as well as the pooling process and minimum days of drought as well.

D-3: the definition of “hydrological year” (page 8, line 7) may be required to make the reader not confuse with the one “water year” which start at beginning of flood season. In line 11–12, it is defined as “the starting of the wet season”, but in the line 11–12 (page 4), the rainy season last from September to December. The author may wish to either better distinguish them or unify one term (if they are same)

We want to thank Reviewer # 2 for these valuable comments. First, the definition “hydrological year” has been clarified in the text and we apologize for the mistake in the original manuscript. We defined that the hydrological year starts when the streams, channels or rivers are receiving water after the dry season. In VGTB, August can be referred to as the starting month, because from this month on the flow is starting to increase from its preceding month (Fig. 2). Therefore, we have defined beginning of August is the start of our hydrological year. Secondly, when considering the seasonality, September to end of December is considered as flood season and the dry season lasts from January to August. This argument has been addressed and included in the revised manuscript .

If the using of data set in each model is explained in this part, rather than in results. (also done in line) and the changes were made.

Thanks for the suggestion. We understand that the using of the data set in each model should be explained in the method part. The proposed changes have been implemented in the revised manuscript

The results are in an appropriate presenting, which follow sequentially the methodologies. The good point of this part is the way to deal with the data shortage, which is very common in this catchment, and they way to have long-term impact of reservoirs. I think this is very good approach. The amount of result is sufficient to the interpretation as well as compatible to the given objective. However, some sentences in this part are seen that should belong to the method- or discussion section. For instance, the explanation of how using data for model or the number of reservoirs in simulation may be better located in methodology, or the line 28–33 (page 9) should belong to discussion, and so on. There are few comments for this part as below:

Thanks for these remarks and the appreciation. We fully agree with the modification proposed by the Reviewer regarding reorientation of the results into the method or discussion section. The uses of data in the model have shifted into the methodology section, for example, we have removed old section 3.1 J2000 Hydrological model calibration to simulate reservoir inflow and naturalized discharge and merged this into method section (new) 3.1. Jams/J200 HRU based Rainfall- Runoff model

The author used data for J2000 HRU is from 1996–2005 to obtain the parameters but do not explain why that period but no former or later one.

Thank you for this comment and we apologize that our explanations have not been clear. We have chosen this time frame because we used the observed streamflow before hydropower came into operation. In section 3.1, we changed the sentence: “The J2000 model was calibrated and validated for the gauging station Nong Son for the period of 1996-2005which was an undisturbed period before the reservoirs were constructed in 2009.

The Reservoir Modelling is taken for four out of eight reservoirs, but results of Song Con 2 is missing in this part, although it is shown in Fig.5

We appreciate the Reviewer comment on Song Con 2 hydropower. This has now been addressed adequately and was adopted into the revised manuscript

E-3: The value of E2, R_2… in Table 3 may need further explanation in terms of calculation or comparison.

Thanks for the suggestion. We have included the explanation in the results section of the hydropower modelling

The paper has a very long and detail discussion with three main questions, from the applicability of the off-line coupling model to the potential uncertainties it may occur. Two limitations are discussed in this section, that makes the paper have a comprehensive view. However, it seems to me that the section 4.2 and 4.3 are more related to the technical issue, about the appropriateness of this linkage to the same issue, rather than the understanding of changes quantified. Since the title and the objective stress on quantifying human impacts on hydrological drought, I expect this will be the major part of discussion. The current argument would be helpful in a paper, which focus more on the linkage. Besides, no figure or table was mentioned in the discussion part, this would raise the question to the reader that how related the results and the aim of paper are. As pointed out above, there is some writing in results presenting discussion, thus, I think the author may wish to restructure them to make the discussion section more relevant to the objective. For example, Figure 7, 8, 9 contains the most important results to the given goal, thus, they should be discussed in this part. In addition, I would suggest to reduce section 4.2 and 4.3 if the paper is required to be shortened.

Thank you for this valuable suggestion. We agree that there is a lack of discussion about the key points of the paper. We therefore have changed it by including a new section 4.1 on "Quantifying human impacts" discussing the key results with reference to the figures 6 to 9. In addition to this, we have included Table 4, "Impact of human alterations on drought intensity and changes of flow in the VGTB for the period from 1980- 2013 on an annual and seasonal scale".

		Nong Son	Giao Thuy	Thanh My	Ai Nghia
a) Drought duration (%)		-17.17	-30.43	37.08	27.20
b) Changes of flow (%)					
	Ann	19.46	10.09	-37.82	-17.41
	Dry	43.3	27.23	-44.67	-7.91
	Wet	10.84	3.61	-35.03	-21.10
c) Changes of flow (in m^3s^{-1})					
	Ann	51.52	38.32	-51.66	-52.14
	Dry	45.65	42.51	-26.43	-9.97
	Wet	63.25	29.93	-102.12	-136.47

Table. 4. Impact of human alterations on drought intensity and changes of flow in the VGTB for the period 1980-2013 on an annual and seasonal scale. a) Drought duration is calculated based on percentage changes of the number of drought days from naturalized condition to reconstructed condition (Fig 9). b) Changes of flow (%), are calculated based on the percentage changes of the mean flow between the Naturalized and Reconstructed streamflow for the corresponding time frame. c) The changes of flow are calculated based on mean differences of reconstructed streamflow from the naturalized mean flow. The positive value indicates increasing flow or drought intensity in relation to the naturalized condition.

As of Reviewer # 1, questions about the applicability of the section 4.2 and 4.3 in this research, therefore we have agreed to shorten this.

The first two sentences of the conclusion are more likely suitable for introduction rather than in conclusion. The first paragraph re-shows the methods and they are quite general, thus, it might be redundant in my view. In this step, the author may wish to relate the methods and the principal findings to help the reader have the substantial closure. I do not think that mentioning to "the reports from local stakeholders" is needed in this section, it could be better to relate to the discussion. The uncertainties expressed here in five lines making the conclusion less concise. The last paragraph shows clearly outcomes of this paper.

We agree that repeated introductory sentences are redundant in the conclusion. We tried to follow the general guidelines how to write a conclusion by summarizing the key issues of the paper.

We now shortened these introductory sentences and also the ones referring to a potential uncertainty analysis. The updated conclusion will be included in the revised manuscript.

The literature cited is relevant to the study. I suggest to unify the order of team papers chronologically before alphabetically as guided by HESS. Furthermore, the author could also reduce the references list by choosing the ones that used for the discussion later on.

Thanks for the suggestions, we will follow the reference guideline of HESS. Please allow us to keep the references used for the introduction as we would like to deliver a general state of the art on how human impacts on discharge can be quantified in the scope of this paper.

2. **Major Comments-**

Regarding to the structure: I recommend reordering a few parts. In detail, the section 1 (introduction) had sub-section 1.1, but the other 1.2 could not be found. Furthermore, since the introduction is expected to provide the literature and objectives only, the author may wish to group sub-section 1.1 and 2.1 in section 2. The methodology could either combine with the data or be a separated section. In case, the author wish to keep them as ordered, the sub-section 1.1 could join as a part of section 2.1. The results section is well presented the introduced methods consecutively, except sub-section 3.3 and 2.1.1. The author may wish to switch part 2.1.1 for 2.1.3 to make the reader easier to follow the next section. I also suggest to re-locate some parts in results (as presented above) to help the reader find easier to follow.

We thank Reviewer #2 for the constructive feedback. We have taken them into consideration and agree to combine the sub-section 1.1 and 2.1 in section 2. Based on your suggestions, we have reorganized the paper as follows: 1. Introduction, 2. Data and Study Area, 3. Methods, 4. Results, 5. Discussion and 6. Conclusion. We have further considered to relocate some of the results in the discussion section.

Because the author mentions in both the title and the objective that to quantify the human impacts on hydrological drought using a combined modeling approach, I expected that the impact quantified and off-line coupling are both discussed, and the former one is likely the major theme. However, in the current paper, little mention of this impact (quantity and reason) is made in the *discussion. I recommend strengthening the discussion by linking to the results (figures and tables) and making it more relevant to the objective.*

Thank you for this valuable suggestion. As previously mentioned, we have updated the discussion by including new sections 5.1, 5.2, 5.3, 5.4, and 5.5. In addition to this, we have included Table. 4, "Impact of human alterations on drought intensity and changes of flow in the VGTB for the period from 1980 - 2013 on an annual and seasonal scale".

I recommend shortening the section 1.1, 2.1, 4.2 and 4.3 as explained above, to make the paper more concise.

As explained earlier, we have merged section 1.1 and 2.1 under section 2, and 4.2 and 4.3 is shortened and merged into one section

3. ***Specific comments***

The paper is written in a good expression of English. I have no objection about this issue. However, there are still some minor remarks given:

1. *Page 2, line 10 and 11: the double hyphens need to make sure as being necessary.*

We have changed this accordingly.

2. *Page 2, line 23, a comma is missing after the blanket*

We have accepted your comment and changes were made accordingly.

3. *Page 2, line 29: "runoff" not "run-off "*

Ans- Thanks for the comment, change was made accordingly.

4. *Page 2, line 33: Wang and Hejazi (2011) not (Wang and Hejazi, 2011)*

Ans- Thanks for the comment, change was made accordingly.

5. *Page 6, line 16: a double space found between "model" and "was"; line 28: "it is" not "It is"*

Ans- Thanks for the comment, changes were made accordingly.

6. *Page 9, line 1: data were not datawere*

Ans- Thanks for the comment, we have changed this accordingly.

7. *Page 10, line 18: E2 = 0.74 or logE2 = 0.74*

Ans- Thanks for the remarks, It will be loge2 = 0.74, and the correction was made.

8. *Page 11, line 15: Thanh My not Ai Nghia*

Ans- Thanks for the comment, we have corrected it as Thanh My.

9. *Page 11, line 17: Fig. 7b not Fig. 7B*

Ans- Thanks for the comment, we have changed it as Fig. 7b.

10. *Page 26, figure 2: Giao Thuy not Giao Thu*

Ans- Thanks for the comment, We have changed as Giao Thuy.

11. *The format should be unified. For example, many paragraphs in page 1, 13, 14, 15 and 16 have left alignment.*

Ans- We have corrected the formatting for the mentioned pages.

The paper basically follows the manuscript composition guideline (given by HESS) in terms of mathematical requirements. There are however some typical errors found in the manuscript:

a) *Coordinates: in page 4, line 1, coordinates of VGTB ("6o 55'–14o 55' N" not "6^{o} 55'–14 ^{o}55' N").*

Ans: Thanks for the comments, we have corrected this as suggested.

b) *page 4 and the rest of the paper: spaces must be included between number and unit, e.g. 47 % not 47%.*

Ans: Thanks for the comment, we have corrected all the number and units, as suggested in the text.

c) *page 4, line 3: km2 not km^{2}*

Ans- Thanks for the comment. We have changed it accordingly.

d) *page 4, line 9: tons-ha or tons ha^{-1}*

Ans- Thanks for the comment. We have changed it accordingly.

e) *Numbers: neither dots nor commas are permitted as group separators, except that the number start with the ten-thousand digit (given by HESS). Thus, 2598 not 2,598 (page 4, line 6) and so on.*

Ans: Thanks for the comment, we have corrected all the numbers as suggested.

f) *Using of hyphens (-) and en dashes (–) are quite often confused. In most cases in this paper, hyphen is used as en dash and it should be better distinguished. For example: 65-80% (page 4, line 13) should be written as 65–80 %, and so on. Please refer guideline (given by HESS) to make them correct.*

Ans: Thanks for the remarks and observations. We have changed hyphens (-) to en dashes (-) as suggested.

Figure and Tables:

g) *Figure 7 presents the percentages of changes but did not explain how this value is calculated*

Ans- Thanks for the comment. We agreed that it needs a bit more explanation in addition what we have explained in the text. So the correction we have made as follows:

The percentage of changes of flow is calculated based on the percentage changes of the mean flow between the Naturalized and Reconstructed streamflow for the corresponding time frame. We have incorporated this in to the Figure 7a.

h) *Figure 9: Giao Thuy not Giao Thyu*

Ans- Thanks for the correction. We have changed this as Giao Thuy

Abbreviation of:

a) *figures should be unified: e.g. Figure 5 (page 10, line 22) or Fig. 5 (page 9, line 24, 28)*

Ans: Thanks for the suggestions. We have changed it as Fig. 5 and the guideline has followed for the rest of the manuscript.

b) *letter should be first introduced. For example, MAM and JJA (page 12, line 3) are understood that March-April-May or June-July-August, but it could make confusing to the reader when first read them.*

Ans: Thanks for the remarks. We have introduced to the abbreviated letters in the revised manuscript.

Overall, I think the off-line coupling results are considered that novel enough for publication in HESS scope. This is extremely helpful in terms of transferability to the similar river basin dealing with data shortage or poor observation network as Vietnam. However, since the linkage approach is getting more common nowadays, the paper may expect to prove some more related studies to make sure that this work more original. By the stage of publication, all the comments on this manuscript obviously need to make clear.

We thank you so much for the recognition of our work. To address your suggestions, we have included some more recent literature, showing the coupling approach to evaluate the reservoir impact on the streamflow changes. However, there is no literature which exactly follows our approach. Below is the list of the new references that we incorporated into the revised manuscript.

López-Moreno, J. I., Vicente-Serrano, S. M., Beguería, S., García-Ruiz, J. M., Portela, M. M., and Almeida, A. B.: Dam effects on droughts magnitude and duration in a transboundary basin: The Lower River Tagus, Spain and Portugal, Water Resour. Res., 45, 6, doi:10.1029/2008WR007198, 2009.

Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H., and Birk, S.: Impacts of climate change on stream flow and hydro power generation in the Alpine region, Environ Earth Sci, 76, 33, doi:10.1007/s12665-016-6318-6, 2017.

Wada, Y., van Beek, L. P. H., Wanders, N., and Bierkens, M. F. P.: Human water consumption intensifies hydrological drought worldwide, Environ. Res. Lett., 8, 34036, doi:10.1088/1748-9326/8/3/034036, 2013.

Other references

ICEM: Strategic Environmental Assessment of the Quang Nam Province Hydropower Plan for the Vu Gia-Thu Bon River Basin, Prepared for the ADB, MONRE, MOITT & EVN, Hanoi, Viet Nam, 205 pp., 2008.

MOIT: Decision Number 6801/QD-BCT, Decision on Dak Mi 4 Reservoir Operation, Ministry of Investment and Trade, Socialist Republic of Vietnam, Hanoi, Viet Nam, 2011

MOIT: Decision Number 1997/QD-BCT, Decision on A Vuong Reservoir Operation, Ministry of Investment and Trade, Socialist Republic of Vietnam, Hanoi, Viet Nam, 2012

Response to Reviewer # 3

We thank Reviewer # 3 for the detailed evaluation of the paper and the helpful comments, which will further improve this paper. We are confident to adequately address each comment and our reply are highlighted in blue normal font, while the reviewer's comments are in *italic font*.

General comments

This study presents an interesting investigation regarding the human impacts on river discharges and hydrologic droughts risks. To this end, a robust modelling approach was adopted, allowing the authors to assess the changes in streamflow caused by the construction of several reservoirs in the study area. The contribution of this paper, although relevant, is limited by a number of factors that, if addressed, could reveal a greater potential provided by the data.

Thank you for your appreciation of our effort. We have addressed all of your comments in our revised manuscript.

From my perspective as a non-native English speaker, the manuscript is well written but the ideas need to be better presented. For instance, the reader leaves the Methods section unaware of relevant information (model parameter, model calibration, etc) and is surprised with them in the Results section.

Answer: Thank you for this suggestion! We will include more information about the model parameters, calibration procedure in the method section. We have reorganized the Data and Methods section as follows: instead of presenting the Data and Methods in one section, we have separated them: 2. Data, 3. Methods. A detailed description about the hydrological model has been included in the Methods section which incorporates the calibration procedure, the parameter estimation and model efficiency statistics. In addition to this, a detailed explanation of the model can be found in Fink et al. (2013) and Nepal et al. (2014).

Although the general idea is crystal clear to me (to assess the hydrologic impacts due to the construction of dams), the means of doing so need to be clearer. Because the paper relies on three different time series (observations, naturalized and reconstructed discharges), the reader needs to understand how each one will contribute to the analysis. This could be better explained in Data and Methods, as indicated in the list in Specific Comments. Another issue is that it is not clear in Data and Methods if the naturalized discharge refers to the undisturbed discharge from 1980 until the construction of the dams or is a simulated data. There might not be enough time to address all suggestions, but there are some points that require more attention.

Answer: We appreciate the comments. The definition of "naturalised" and "reconstructed" discharges were described in method section 2.2.1 (p 6, line 14 – 24). For our drought risk assessment, we simulated the "naturalised" and "reconstructed" discharge to be able to evaluate the changes of streamflow due to reservoir construction. These simulated time series were calibrated against the observed period. The naturalized discharge is the output from the J2000 hydrological model, which simulates discharge for pristine conditions without the intervention of the reservoirs, while the "reconstructed" discharge is the output of the reservoir simulation model, that accounts for the hydropower operation influences in the streamflow for the same time from 1980 – 2013. In our analysis, observed data – referred to as the measured discharge data at the stations are only used for the calibration and the evaluation of the simulated results.

Specific Comments

Introduction

P4, L12: I believe this sentence is incomplete or "is" should replace "however". Please check that.

We have changes the sentence accordingly, “The climate in the VGTB basin is characterized by a strong rainy season lasting from September to December.”

P4, L13-14: Those ranges are not clear. Almost 65 or 80 %? 70 or 85 %? Is the word “respectively” missing somewhere in this sentence? If you want to specify the range, I do not think this is the best way to do that. Please rephrase.

Thank you for the suggestion. We have rephrased the sentences as follows:

Rainfall during the wet season accounts for 65-80 % of the total annual rainfall, with 40-50 % of the annual rainfall occurring in October and November, and this high rainfall regularly causes severe floods (Souvignet et al., 2013).

P4, L14: I believe a “.” is missing at the end of this sentence.

We have corrected it and put a “.”.

P4, L15-16: How often, e.g. n times in the past y year: : :? Is this statement based on the author’s experience or it is possible to cite someone who verified this information?

Thanks for the comment. We have changed the sentences as suggested.

“The extended dry season lasts from January to August and is frequently accompanied by droughts (e.g., in year 1982, 1983, 1988, 1990, 1998, 2005, 2012 and 2013)” Nauditt et al.,2017

P4, L16: Please either replace “month” by “period” or “is the driest month” by “are the driest months”.

The sentence is corrected as suggested.

“February to April considered as the driest month, accounting for only 3-5 % of the total annual rainfall, resulting in severe water shortages and problems with saline intrusion at the coast (Souvignet et al., 2013)”

Data & Methods

P5, L4: Are these records available online? If so, please provide an address and indicate when it was last accessed.

Answer: Sorry for not making this clear. These data are not freely available and were bought them in the scope of a BMBF funded research project (www.lucci-vietnam.info). We now included a sentence in the data section about this as well as the missing acknowledgements.

P5, L5: The map in Fig. 1 shows only 12 rain gauges but here it is said that 16 were considered. Please indicate the remaining gauges on the map.

Thank you for this hint. We have updated the map (see below), which shows the location of 17 rain gauge stations and the text has been corrected in the manuscript.

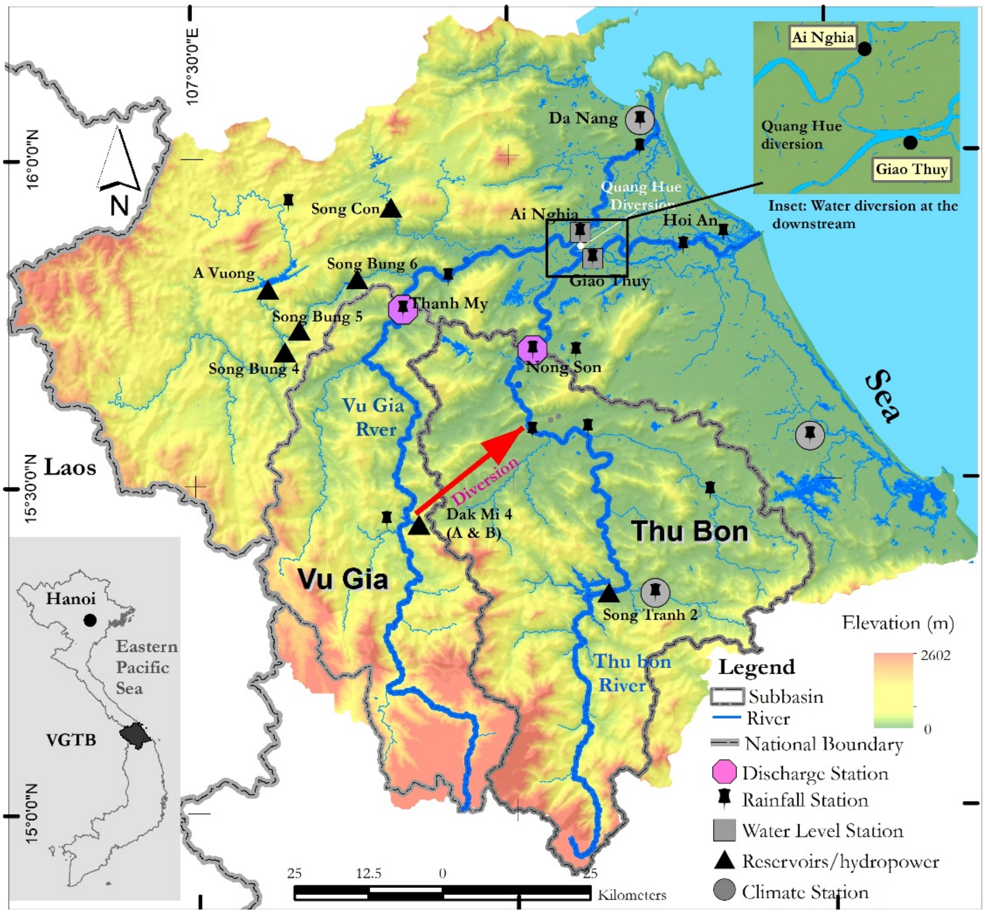


Figure-1: Map of the Study Area

P5, L15: What is the impact of such assumption?

Answer: We agree with the reviewer that this was not clearly explained. The flow diverted through the Quang Hue channel is strongly dependent on tidal changes and seasonal variation in streamflow of both Thu Bon and Vu Gia. Also, the impact is minor compared to the reservoir operation generated discharge from the tributaries. We did not incorporate the dynamics of the channel as there are no daily data on diversion flow. Our results also show that the contribution from tributaries to Vu Gia downstream of Thanh My are more relevant for the discharge at Ai Nghia. We included such an explanation to make this clear.

We now incorporated a new section 2.2.1. Data uncertainties and explained this issues in more detail

P7, L3: J2000 needs data on "land use, soil, geology, ….:" It is not mentioned how these information were acquired. Model parameter description was completely overlooked.

Answer: Thank you for your comment on the data issues for the J2000 model. We have not mentioned this in the original text as the data used for the J2000 model were described in Fink et al., 2013.

Soils: Soil map (1:100,000) (National Institute of Agriculture Planning and Protection, 2005) + 150 soil profile descriptions in the catchment to derive soil-model parameters for the various soil classes described in the map. Geology map (1:100,000) (Department of Geology and Minerals of Vietnam, Hanoi, 1997). Land-cover classification of Landsat images for the year 2010 (Avitabile et al,. 2016). The digital elevation model (DEM) was derived from contour lines and points from a digital map (scale 1:50,000) using the topography to-raster algorithm of ArcGIS. The resulted DEM had a resolution (cell size) of 25 m.

The following text has been incorporated-

A detailed description of the spatial (e.g., soil, vegetation, digital elevation model, land use and geology) and hydro-climatic data used for hydrological model was described in Fink et al., (2013, p 1828).

Model parameters and calibration procedure were not presented as the focus of this article was mainly to show the drought risk assessment based on the coupled modelling approach. These are described in Fink et al., (2013) and Nepal et al., (2014) and can also be found under http://jams.uni-jena.de/documentation/. However, we will include the parameter estimation values as supplementary material in the revised manuscript.

Table 1: Parameters selected for the model calibration (other parameters of the model were left to default values during calibration)

Calibrated parameters	**Short description**	**calibrated Value**	**Range**
soilMaxDPS	Maximum depression storage capacity	2	1.0 - 5
soilMaxInfSummer	Maximum infiltration in summer	40	1 -200
soilMaxInfWinter	Maximum infiltration in winter	100	1 -200
soilDistMPSLPS	MPS/LPS distribution coefficient	0.68	0 - 1
soilDiffMPSLPS	MPS/LPS diffusion coefficient	0.4	0 - 1
soilConcRD1	Recession coefficient for overland flow	1.2	1.0 -3.0
soilConcRD2	Recession coefficient for interflow	3.5	2.0 - 10
soilPolRed	Potential reduction coeffiecient for aET computation	3	1.0 - 10
soilMaxPerc	Maximum percolation rate	20	1.0 - 20
gwRG1Fact	Adaptation of the fast groundwater outflow	1	0.1 - 10
gwRG2Fact	Adaptation of the baseflow	0.4	0.1 - 10
gwRG1RG2dist	RG1-RG2 distribution coefficient	0.5	0 - 1
flowRouteTA	River routing coefficient	10	1 -100

The parameters that were calibrated are affecting three domains of the model. The most important ones are governing the simulation of the soil processes. The soilMaxDPS governs how much water can be hold back on the soil surface before surface runoff occurs. The soilMaxInfSummer and soilMaxInfWinter are there to influence the maximum infiltration in the dry and rainy season. The soil characteristics in the model are described by a dual porosity approach were the large pores (excess water) and the medium pores (usable field capacity) are represented in two different storages (MPS and LPS). The parameter soilDistMPSLPS is influencing the distribution of infiltrated water between LPS and MPS. SoilDiffMPSLPS affecting the diffusion from LPS to MPS. The recession coefficients soilConcRD1, soilConcRD2 are influencing the travel time of the runoff components surface runoff and interflow. The reduction of actual evapotranspiration (actET) to potential evapotranspiration (potET) is influenced by the soilPolRed which is a shape parameter for the actET, potET function according to the actual soil moisture conditions. The Groundwater runoff components (fast groundwater and base flow) influence the two recession adaption coefficients gwRG1Fact and gwRG2Fact. The distribution between these two components is influenced by the gwRG1RG2dist distribution coefficient. The recession in the river network is affecting the simulated recession in the river network.

Results

Although I appreciate straightforward analysis, section 3.1 is rather simplistic. Model calibration should not be done based only on statistics (R2, Nash, etc: : :). I would like to see a plot comparing simulated and observed discharges and a sensitivity analysis.

Answer: Thank you for this suggestion. Due to the high number of figures presented in the paper we could not show the hydrograph simulation performance. We therefore include the following figures to this response:

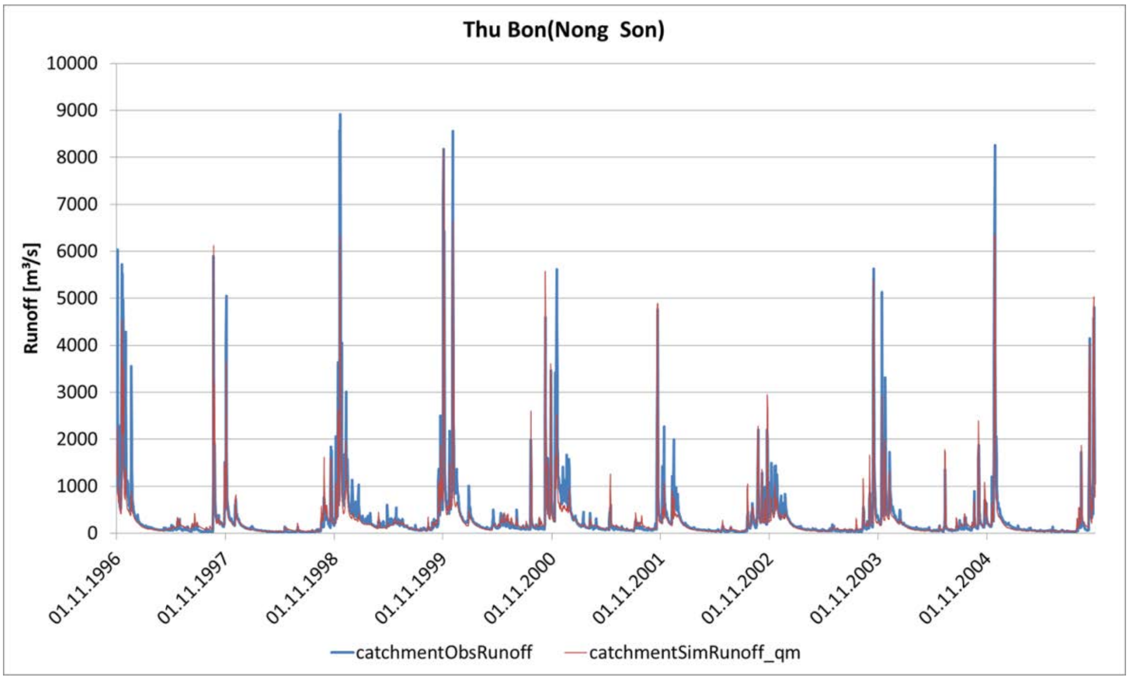


Figure 2: Hydrograph simulation compared to observed discharge (1996-2005) for the Thu Bon river (Nong Son station)

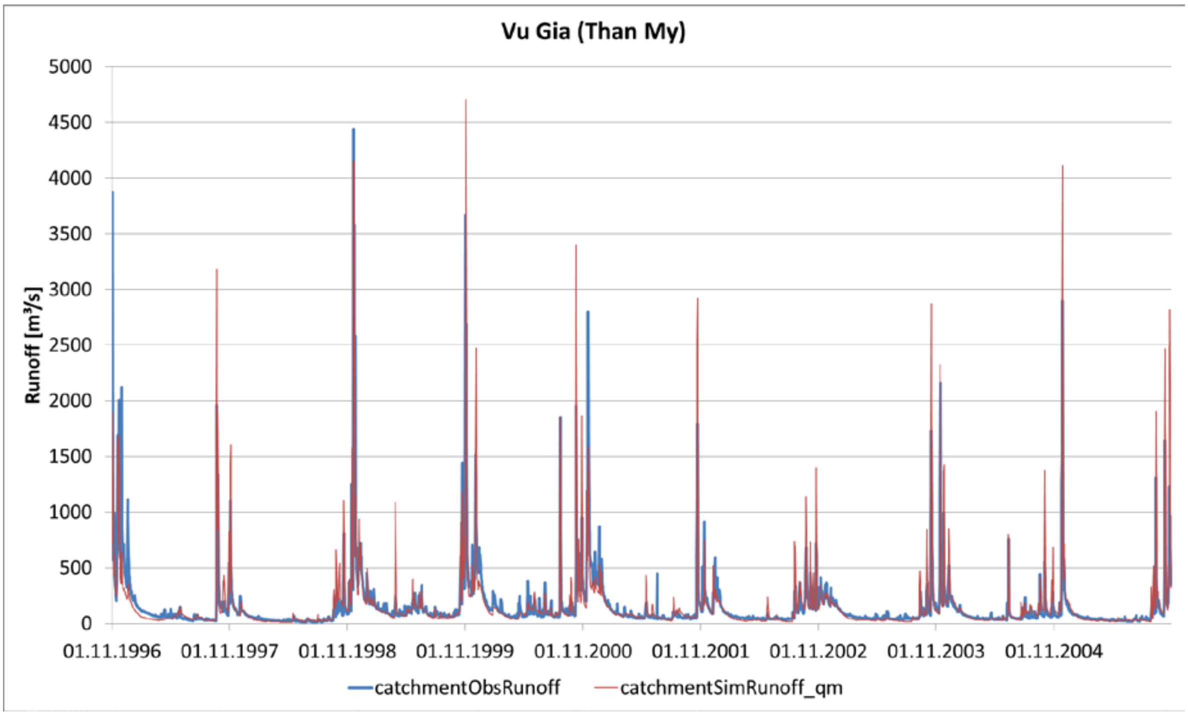


Figure 3: Hydrograph simulation compared to observed discharge (1996-2005) for the Vu Gia river at Thanh My station. Also please refer to Fink et al (2013).

Sensitivity Analysis of the calibrated parameters

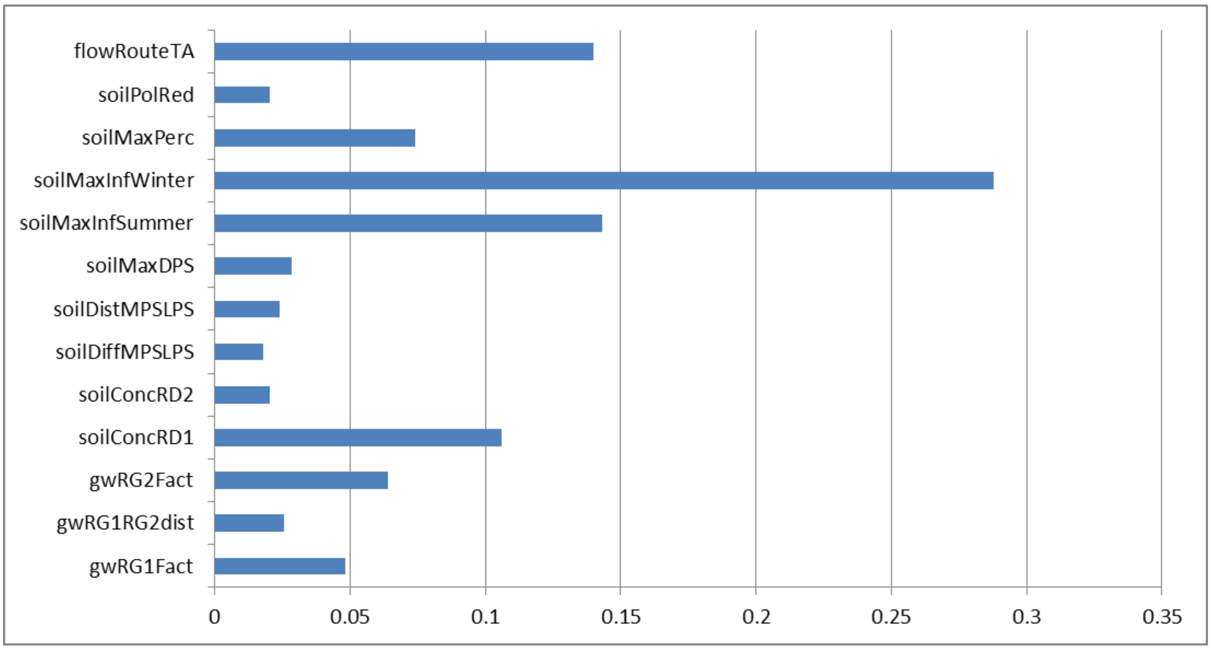


Figure 4: Sensitivity of calibrated parameters for the Thu Bon catchment (gauge Nong Son) with the Nash–Sutcliffe efficiency criterion.

Based on 1000 Monte-Carlo simulation we estimated the sensitivity of the parameters used for calibration. The method performed for this sensitivity analyses is the “regional sensitivity analysis” (RSA) (Hornberger and Spear, 1981) utilizing the Nash–Sutcliffe efficiency criterion. This method estimates the impact of a parameter and its interactions with model outputs (Nepal et al. 2012). The results in Figure 1 shows the importance of the different calibrated parameters for the simulated runoff according to the Nash–Sutcliffe efficiency criterion. This example shows that the parameters with the highest sensitivity (infiltration parameters, surface runoff coefficient and river runoff coefficient) are parameters which have their main influence on quick runoff components and peak flow. In contrast to that, the parameters which affect the overall water balance are less important (e.g. SoilDiffMPSLPS, SoilDistMPSLPS, soilPolRed). One reason is the use of the Nash–Sutcliffe efficiency with is focusing on the high flows, another the extreme water surplus in the rainy season where the evapotranspiration plays only a minor role.

Item 3.2 What are the results in the 1st paragraph? I suggest moving the proper parts to Methods and leave only the information that concerns the reservoir modelling process.

Answer: thank you for this suggestion. We agree that this part belongs to the Methods section and shifted it to in the method section.

I’m not comfortable with using the Q simulated by J2000 as reference just because “there are no gauging stations at Ai Nghia and Giao Thuy”. First, if what you have at Ai Nghia and Giao Thuy are water level stations that could not be used to derive river discharge estimates because of tidal effect, how is the tidal effect accounted for in your J2000 model? If it hasn’t been considered, how does that decision affect your analysis or it doesn’t affect at all? Also, how far upstream the tidal has some influence?

Answer: Thank you for these comments. The data of Ai Nghia and Giao Thuy stations show the following key constraints:

1. Ai Nghia station is subject to flooding during the rainy season, therefore, discharge during the rainy season cannot be used with the given rating curve.
2. The Giao Thuy station is influenced by tidal waves (although it is located 38 km upstream from the sea), therefore the water level data of Giao Thuy station cannot be accurately presented by a rating curve.
3. The most important constraint is the dynamic water diversion. As explained previously, there is no control mechanism which measures the exact amount of water diverted from Vu Gia to Thu Bon through Quang Hue channel. It is therefore difficult to predict how much water is

diverted without long term measurements. This leads to an increased uncertainty in the water level data.

We agree that the model cannot consider hourly tidal effects. Our purpose was to assess drought risk at this point in dependence of upstream climatic, human and catchment related circumstances. We assessed water availability at the daily, monthly, seasonal and yearly timescale for the irrigation system entrance. Therefore, hourly tidal information will not affect the results of this study.

Second, I don't agree the J2000 produced "robust" results without at least seeing a Qsim vs Qobs plot. It is comprehensible that observational data availability is often an issue and, sometimes, we need to appeal to simulated data. However, the authors need to discuss the potential implications of this choice.

Answer: we agree with your suggestion and incorporated a section on uncertainties related to these simulations in the discussion. Below (in the Discussion section) you find a Qsim versus Qobs plot including an uncertainty band.

P9, L25: specify that these "very good agreement" refers to A Vuong reservoir.

Answer: thank you for this hint. We have included the name of A Vuong.

Section 3.3: Again, some information do not belong to Results. From my point of view, only the lines after L17 report results per se.

Answer: thank you for this suggestion. We agree that this part also belongs to the Methods section and shortened and shifted it to methods section.

P10, L26-27: This is the first time it is mentioned that the reconstructed streamflow was compared against observations. This should be explained in Methods.

We agree with you and explained this in the method sections.

P10, L27-28: This is the first time it is mentioned to which period corresponds the reconstructed streamflow (RS). Up to this point, it seemed that the RS was for the early 2010s.

Answer: We agree with the reviewer, we did not explain in the methods section that the models were calibrated against the observed daily streamflow available for the years 1980 to 2013. As the reservoirs were constructed after 2009, we needed to use the "pristine" streamflow to calibrate J2000 and the reservoir impacted streamflow after 2009 to calibrate HEC RESSIM. We have incorporated this explanation to the Methods section.

Discussion

The authors recognize the uncertainties that need to be addressed but provides only a qualitative overview about them. It would be enlightening to know how those uncertainties affect the results. Perhaps less important (or greater) hydrologic changes would be found. These possibilities should at least be mentioned.

Answer: We agree with your comment and we now mentioned this in the discussion. Fink did an uncertainty analysis with the Nong Son data using 1000 model runs. Figure 5 shows the 5 % best simulations in the grey shaded area; the blue line indicates the measurements. The blue line represents the observed discharge and moves within the uncertainty band which is an indicator for a robust modelling. The graph shows the largest uncertainty during high flows and the recession phases.

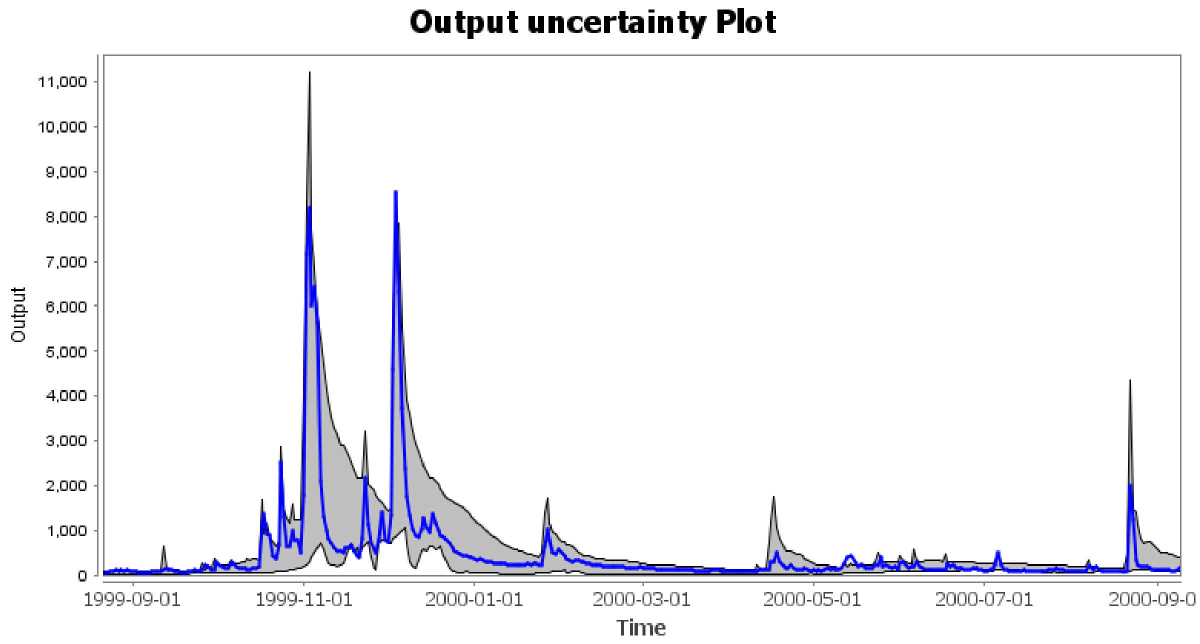


Figure 5: 5 % best simulations (range grey shaded) versus observed discharge (blue line) at Nong Son.

Section 4.2 - The authors claim that the limited rainfall data are related to the difficult access to the basin headwaters where there is no rain gauges. I wonder what could be learned from remotely sensed precipitation. Would such estimates bring more uncertainties than the regionalization methodology adopted by J2000?

Answer: Thank you for this suggestion. Yes indeed in some cases satellite based rainfall estimates do perform better in closing the water balance than observed data. Since we wanted to analyse long term effects we needed longer time series as the station data which were available from 1980 till 2013In the scope of this study we have not considered satellite based rainfall estimation products as they are only available for shorter periods (Zambrano-Bigiarini et al., 2017).

P14, L1: Please cite some examples to support this claim.

…..R2 of the regression line is used to determine if the relation between the rain and the altitude is strong enough to be used for the modelling. A threshold value of R2 of 0.75 is typically used for this decision (Krause 2001, Nepal 2012, Biskop 2016).

P14, L33: This sentence should be in Methods.

Answer: Thanks for the comment, we shifted it to the Methods section.

Conclusion

This section should be more elaborated, showing what was learned and concluded regarding each goal listed in the Introduction. The authors could also consider renaming it to Summary (and Conclusion) as most of it is not really conclusion but a summary of the results.

The authors were too cautious in concluding the main point of this study, which is to provide evidence about the positive/negative impacts of the dams on hydrologic droughts in the study area. This should be explicitly stated here.

Answer: We agree that the conclusion is not containing the key findings in terms of the objectives. We updated the conclusion accordingly in the revised manuscript.

Technical Corrections

There are several problems regarding the citations. For instance, in Page 2, Line 22, it should read “Räsänen et al. (2012) quantified” instead of “(Räsänen et al., 2012) quantified”. Similar issues are found throughout the manuscript:

-P2, L24

We have corrected it as “Räsänen et al. (2012) quantified”

- P2, L32

we have corrected it as “Wang and Hejazi (2011)”

- P3, L20

We have deleted extra “(” in the text

- P4, L10: extra “(”

We have deleted extra “(” in the text

- P4, L13: extra “.”

We have deleted extra “.” in the text

- P12, L26

We have corrected it as “Adam et al. (2007)”

- P13, L3

We have corrected it as “Nauditt et al. (2017)”

- P13, L18

We have corrected it as “are described e.g. in Walker et al. (2003); Refsgaard et al. (2007); Beven and Binley (1992).”

- P13, L30

We have corrected it as “Krause (2002)”

- P14, L14

We have corrected it as “Mateus and Tullos (2016)”

-P15, L4

We have corrected it as “by Nepal et al. (2014)”

References:

Avitabile, V., Schultz, M., Herold, N., Bruin, S. de, Pratihast, A. K., Manh, C. P., Quang, H. V., and Herold, M.: Carbon emissions from land cover change in Central Vietnam, Carbon Management, 7, 333–346, doi:10.1080/17583004.2016.1254009, 2016.

Biskop S.: Advancing the understanding of hydro-climatic controls on water balance and lake-level variability in the Tibetan Plateau - Hydrological modeling in data-scarce lake basins integrating multi-source data. PhD Thesis, Friedrich Schiller University of Jena, 2016.

Fink, M., Fischer, N., Führer, N., Firoz, A., Viet, T., Laux, P., and Flügel, W.-A.: Distributive hydrological modeling of a monsoon dominated river system in central Vietnam, in: MODSIM2013, 20th International Congress on Modelling and Simulation, Piantadosi, J., Anderssen, R., and Boland, J. (Eds.), MODSIM2013, 20th International Congress on Modelling and Simulation, Sydney, Australia, 1826–1832, 2013.

Hornberger GM, Spear RC.: An approach to the preliminary analysis of environmental systems. Journal of Environmental Management12:7–18, 1981.

Krause P.: Das hydrologische Modellsystem J2000: Beschreibung und Anwendung in grossen Flusseinzugsgebieten. Schriften des Forschungszentrum Jülich. Reihe Umwelt/Environment; Band 29, 2001.

Nauditt, A., Firoz, A., Viet, T. Q., Fink, M., Stolpe, H., and Ribbe, L.: Hydrological drought risk assessment in an anthropogenically impacted tropical catchment, in: Land Use and Climate Change Interactions in Central Vietnam: LUCCi, Nauditt, A., and Ribbe, L. (Eds.), Water Resources Management and Development, Springer Book Series, 2017.

Nepal S.: Evaluating upstream–downstream linkages of hydrological dynamics in the Himalayan region. PhD Thesis, Friedrich Schiller University of Jena, 2012.

Nepal, S., Krause, P., Flügel, W.-A., Fink, M., and Fischer, C.: Understanding the hydrological system dynamics of a glaciated alpine catchment in the Himalayan region using the J2000 hydrological model, Hydrol. Process., 28, 1329–1344, doi:10.1002/hyp.9627, 2014.

Souvignet, M., Laux, P., Freer, J., Cloke, H., Thinh, D. Q., Thuc, T., Cullmann, J., Nauditt, A., Flügel, W.-A., Kunstmann, H., and Ribbe, L.: Recent climatic trends and linkages to river discharge in Central Vietnam, Hydrol. Process., 28, 1587–1601, doi:10.1002/hyp.9693, 2013.

Zambrano-Bigiarini, M., Nauditt, A., Birkel, C., Verbist, K., and Ribbe, L.: Temporal and spatial evaluation of satellite-based rainfall estimates across the complex topographical and climatic gradients of Chile, Hydrol. Earth Syst. Sci., 21, 1295–1320, doi:10.5194/hess-21-1295-2017, 2017.

Quantifying human impacts on hydrological drought using a combined modelling approach in a tropical river basin in Central Vietnam

A.B.M Firoz[1]; Alexandra Nauditt[1;] Manfred Fink[2] and Lars Ribbe[1]

[1] Institute for Technology and Resources Management in the Tropics and Subtropics (ITT), TH Köln, Cologne, 50679, Germany,

[2] Chair of Geographic Information ScienceInstitute for Geoinformatics, Department of Geography, Friedrich-Schiller-University Jena, 07743, Germany

Correspondence to: A.B.M Firoz (abm.firoz@th-koeln.de)

Abstract. Hydrological droughts are one of the most damaging disasters in terms of economic loss in Central Vietnam and other regions of South East Asia severely affecting agricultural production and drinking water supply. Their increasing frequency and severity can be attributed to extended dry spells and increasing water abstractions for e.g. irrigation and hydropower development to meet the demand of dynamic socioeconomic development. Based on hydro-climatic data for the period from 1980 to 2013 and reservoir operation data, the impacts of recent hydropower development and other alterations of the hydrological network on downstream streamflow and drought risk were assessed for a mesoscale basin of steep topography in Central Vietnam, the Vu Gia Thu Bon (VGTB) river basin. The Just Another Modelling System (JAMS) /J2000 was calibrated for the VGTB river basin to simulate reservoir inflow and the naturalized discharge time series for the downstream gauging stations. The HEC-ResSim reservoir operation model simulated reservoir outflow from eight major hydropower stations as well as the reconstructed streamflow for the main river branches Vu Gia and Thu Bon. Drought duration, severity and frequency was analysed for different time scales for the naturalized and reconstructed streamflow by applying the daily varying threshold method.

Efficiency statistics for both models show good results. A strong impact of reservoir operation on downstream discharge at the daily, monthly, seasonal and annual scale was detected for four discharge stations relevant for downstream water allocation. In accordance with the reports from local stakeholders, we found a stronger hydrological drought risk for the anthropogenically impacted reconstructed for the Vu Gia river supplying water to the City of Da Nang and large irrigation systems especially in the dry seasonstreamflow. We conclude that the calibrated model setup provides a valuable tool to quantify the different origins of drought to support cross-sectorial water management and planning in a suitable way to be transferred to similar river basins.

1 Introduction

River basins and their hydrological systems play a key role in providing freshwater to downstream deltaic systems, for irrigation and domestic water supply and to regulate salt water intrusion (Ribbe et al., 2017). The patterns of timing and magnitude of streamflow essentially depend on climatic variables such as precipitation (Zhang et al., 2007; Min et al., 2011; Souvignet et al., 2013; Min et al., 2011; Zhang et al., 2007; Ahn and Merwade, 2014), temperature and the resulting altered evapotranspiration rates (Ahn and Merwade, 2014; Santer et al., 2011; Trenberth, 2011; Vörösmarty et al., 2000; Santer et al., 2011; Trenberth, 2011; Ahn and Merwade, 2014), as well as on the modification of the hydrological systems by humans introducing water infrastructure such as reservoirs and damming, inter-basin water transfers and construction of weirs. Further important influences on the water dynamics is anthropogenic water consumption for irrigated agriculture, industrial and domestic water supply (Zhou et al., 2012; Patterson et al., 2013; Ahn and Merwade, 2014; Hu et al., 2015; Wang et al., 2015; Zhou et al., 2012; Lauri et al., 2012; Rossi et al., 2009; McClelland, 2004).

Hydrological droughts are becoming more frequent disasters worldwide which can also be attributed to both hydro-climatic and anthropogenic changes (AghaKouchak et al., 2015; van Loon et al., 2016; AghaKouchak et al., 2015; van Lanen et al., 2016). Regional studies show that larger changes in streamflow have been observed in anthropogenically modified river basins, in particular those altered by hydropower development and operation, than in hydrological systems which are only affected by climate variability and change in anthropogenically modified river basins – in particular those altered by hydropower development and operation – larger changes in streamflow have been observed than in hydrological systems which are only affected by climate variability and change (Arrigoni et al., 2010; Ahn and Merwade, 2014; Arrigoni et al., 2010; Tang et al., 2014). Such alterations of the hydrological system often negatively affect downstream discharge patterns and communities dependent on the provision of freshwater for irrigation and domestic water supply (Rossi et al., 2009; Zhou et al., 2012; Rossi et al., 2009; Song et al., 2015). Therefore, seasonal impacts of reservoir operation on low flow patterns and trends need to be quantified in order to separate them from natural drought propagation and to inform downstream water users to properly manage water supply for irrigation, industry and domestic water supply.

The effects of reservoir operation on streamflow have been assessed for instance in the Lena, Yenisei and Ob' river basins of the arctic Eurasian river system, on a seasonal and annual basis revealing that reservoir operation accounts for most of the seasonal changes in the three river basins, ranging from 60 % to 100 % particularly in winter and early spring. Reservoir operation was found to have little effect on annual trends (Ye et al., 2003; Adam et al., 2007; Ye et al., 2003, 2003; Adam and Lettenmaier, 2008). (Räsänen et al., (2012) quantified hydrological changes in the upper Mekong basin due to hydropower operation in China, which showed that discharge increased by 34–155 % from December to May and decreased by 29 - 36 % from July to September. showing an increased December May discharge by 34 155 % and a decreased July September discharge by 29 36 %. Impacts of the worldwide largest Three Gorges reservoir constructed in 2003 were quantified by (Zhang et al., 2015) who assessed streamflow at three outlets on the south bank of Yangtze tributary Jingjiang River providing evidence that the reservoir impacts were largely responsible for major droughts downstreamThe impacts on streamflow of the Three

Gorges Reservoir were quantified by Zhang et al. (2015), who assessed streamflow at three outlets on the south bank of the Jingjiang River (a Yangtze tributary), providing evidence that the reservoir impacts were largely responsible for major droughts downstream..

Positive impacts of reservoir operation on downstream hydrological regimes for example have been reported for Chinese catchments (Song et al., 2015), suggesting a decreasing frequency of flood events in the Sanchahe River Basin , China and by (Tang et al., (2014), who showed an increasing surface run-off during the dry season at the upper Mekong/Lancang River in China.

Various approaches have been used to quantify and separate anthropogenic and climate change impacts on streamflow. Most commonly used approaches, are streamflow time series analyses looking at seasonal and frequency patterns to assess impacts of human alterations on discharge. (Wang and Hejazi, (2011) used Budyko curves (Budyko, 1974), to detect human induced changes in streamflow investigating their deviation from the initial relationships between mean annual precipitation, evaporation and potential evaporation as defined by the Budyko curves. Double mass curves (DMCs) are applied to compare the cumulative distribution of precipitation and discharge time series before and after human alterations (Wang et al., 2015) as well linear regression to establish the relationship between discharge and different climatic variables (Sharon A. Johnson et al., 1991; Wang et al., 2012; Sharon A. Johnson et al., 1991; Hu et al., 2015). However, although such relatively simple statistical analyses of hydro-climatic time series might give a first insight in system behaviour; they might not capture the non-linear nature of hydrological systems.

In fewerSeveral studies have applied hydrological models have been applied to assess the different causes for streamflow changes (Zhang et al., 2012; Bao et al., 2012; Tesfa et al., 2014; Chang et al., 2015; Tesfa et al., 2014), providing simulations of naturalized and reconstructed discharge time series to quantify and separate the different impacts. Alternatively, the paired basin approach has been used to model the impact of human induced land cover changes on streamflow by comparing simulations in catchments of very similar characteristics (Bonell and Bruijnzeel, 2005; Seibert and McDonnell, 2010; Bonell and Bruijnzeel, 2005).

The coupled modelling approach, which incorporates hydrological modelling information into reservoir simulation models, appears to be a promising approach which has been recently used to investigate effects of reservoir operations on hydrological systems. For example, López-Moreno et al. (2014) applied a regional hydrological model (RHESSys Model) combined with a reservoir simulation model to predict the changes of flow due to reservoir operation as well as climate and land use changes in the Aragón River, Spanish Pyrenees. Reservoir operation effects on downstream flow in the Lena, Yenisei and Ob' river basins were evaluated using a reservoir routing model coupled off-line to the Variable Infiltration Capacity (VIC) land surface hydrology model (Adam et al., 2007). Estimated changes of streamflow due to reservoir operation in the Greater Alpine Region were computed using a parsimonious rainfall-runoff model combined with a hydropower simulation model (Wagner et al., 2017). The coupled approach was also used at a global scale to identify the impact of human water consumption on the intensity and frequency of hydrological drought worldwide (Wada et al., 2013).

However, theThe above described studies had the aim to either evaluatefocussed on the evaluation of humaneither human impacts on general streamflow behaviour or on flood risk. The implication of reservoir operation and other human alterations of the hydrological system for drought severity, duration and frequency length have not been addressed in such studies. AlsoAlso, hydrological drought risk is usually looked at on a monthly, seasonal, annual or long termlong-term scale. Hydro-climatic dynamics in the tropics, however, are fast and water management related decisions need to be made based on daily information (eg. to avoid salt water intrusion into the irrigation and drinking water supply systems) (Nauditt et al., 2017).

The overall aim of this study was therefore to quantify and separate the impact of hydropower reservoir operation and climate variability on hydrological drought in the VGTB river basin. Its specific objectives were to (1) simulate discharge for sub-basins throughout the basin as reservoir inflow and to obtain naturalized streamflow time series by applying a distributed Hydrological Response Unit (HRU) (Pfenning et al., 2009) based rainfall-runoff model J2000 ((Fink et al., 2013; Krause, 2002; Fink et al., 2013); (2) model reservoir storage and operation for eight major hydropower reservoirs in order to simulate daily release rates, hydropower production and storage using the HEC-ResSim model (USACE 2007); (3) simulate reservoir impacted reconstructed streamflow for downstream stations at the two main river branches and (4) quantify to which extent hydrological drought duration and severity can be attributed to hydropower reservoir operation or climate variability by applying the variable threshold method approach (Tallaksen et al., 2009; Sung and Chung, 2014) to reconstructed and naturalized stream flow time series.

The combined assessment approach developed in this study enables us to assess the interactions between climate, catchment and reservoir operation on the one hand and water and energy demand on the other. FurthermoreFurthermore, it provides us with a tool to determine drought risk on a daily scale to support water management for irrigation and drinking water supply. The results of this research give provide a detailed insight to the current and potential impacts of reservoir operation on the downstream water availability, which we provided to the water managers, the reservoir operating agencies and other decision makers..

2. Study Area and Data

12.1 Study Area: Vu Gia Thu Bon River Basin (VGTB)

The Vu Gia Thu Bon river basin (VGTB) is located in Central Vietnam (6º 55’ --14 º55' N and 107º15’ --108º 24' E), and covers a total area of approximately 12,577 km^2 (Fig. 1)and shares borders with the Huong River Basin (Hue Province) to the north, the Mekong River Basin (Laos) to the west and with the Tra Khuc River Basin (Quang Ngai Province) in the south. The Mmain provinces in the VGTB are Quang Nam and Da Nang (Fig. 1). It has is characterised by a steep topography and the altitude ranges ranging from 0 m at the coast to 2,598 m of elevation in the South Truong Son Mountains in the west and by the Kon Tum mountain mass in the south (Viet et al., 2017). Almost half of the land area is covered by forest (47 %) followed by cropland (26 %) and grassland (20 %) (Avitabile et al., 2016). Paddy rice cultivation and livestock farming are the two main agricultural activities in the basin. Two crops of paddy rice are planted per year in the lowlands and areas along the major rivers and yield to 5.05 tons ha^{-1} ~~ha~~ in ~~average in~~ 2013 (Quangnam Statistical Office, 2014)~~)~~. The VGTB is home to approximately 2.5 million inhabitants (2013), 80 % of which live in the coastal lowlands, 45 % of which live in the urban areas (General Statistics Office, 2014). The VGTB river system is formed by two major rivers, the Vu Gia and the Thu Bon, which originate in the highlands and flowing into the ocean near the cities of Da Nang and Hoi An.

The climate in the VGTB basin is characterized by a strong ~~rainy~~ wet season with typhoons lasting from September to December~~, which however mainly influenced by the monsoon and typhoons~~and an extended dry season (Souvignet et al., 2013). Next to the two major seasons – which we here term the “dry” and the “wet” seasons – there are four minor seasons observed in this region and referred to in this study as: Summer - June, July, August (JJA); Autumn - September, October, November (SON); Winter – December, January, February (DJF); and Spring - March, April, May (MAM) (Souvignet et al., 2013). ~~Almost 65-80% of the total annual rainfall happens during wet season, in which 70-85 % of the total rainfall occurs in October and November and is responsible for severe floods in the region. Contrast to this, VGTB experiences an extended dry season lasting from January to August and is regularly accompanied by droughts.~~ Rainfall during the wet season accounts for 65 - 80 % of the total annual rainfall, with 40 - 50 % of the annual rainfall occurring in October and November, and this high rainfall regularly causes severe floods (Souvignet et al., 2013). The long dry season lasts from January to August and is frequently accompanied by droughts (e.g., in 1982, 1983, 1988, 1990, 1998, 2005, 2012 and 2013) (Nauditt et al., 2017). February to April considered as the driest month, ~~– a period~~ accounting for only 3 - ~~-~~5 % of the total annual rainfall, resulting in severe water shortages and problems with saline intrusion at the coast (Souvignet et al., 2013).

~~The VGTB river system is formed by two major rivers, the Vu Gia and the Thu Bon, originating in the highlands and flowing into the ocean near the cities of Da Nang and Hoi An.~~ The basin area of Vu Gia until reaching Ai Nghia station is approximately 5~~,~~453 km^2, and the area of Thu Bon until Giao Thuy station is 3532 km^2. Around 3 km beyond the Giao Thuy station, the river enters the tide-affected area and the hydrological regime of the river behaves under the interaction of tidal and upstream inflow. At two hydrological stations - Nong Son (Thu Bon River) and Thanh My (Vu Gia River) discharge has been measured since 1976 (Fig. 1).

Water resources in the Vu Gia Thu Bon River Basin (VGTB), have been intensively developed for a variety of uses, including hydropower generation, large rice irrigation systems in the delta, domestic and industrial water supply. ~~From 2009 until 2014, eight large hydropower reservoirs and plants have been constructed, which have a cumulative storage capacity of more than 2 km^{3}. (Table 1).~~ Inter-basin water transfer from the Vu Gia to the Thu Bon sub-basin to generate electricity from Dak Mi 4 hydropower plant is causing significant changes in the respective flow regimes. Paddy rice is ~~still~~ the dominant crop as it accounts for approximately 70 % of irrigated agricultural area (Pedroso et al., 2016). Water stress during drought periods is a major constraint to agricultural production in the region. Figure 2 shows mean monthly inter-annual discharge for the four gauging stations addressed in this study (two discharge and two water level stations).

2 Data and Methods

2.1 Data

2.1.12.2. Hydro-meteorological data

Hydro-climatic records were purchased at the Regional Centre for Hydro-meteorology (RCHM) within the scope of the German Ministry of Education and Research (BMBF) funded research project "Land Use and Climate Change Interaction in Central Vietnam (LUCCi)" (www.lucci-vietnam.info). A detailed description of the spatial (e.g., soil, vegetation, digital elevation model, land use, geology) and hydro-climatic data used for the hydrological model J2000 was described in Fink et al. (2013), p. 1828 and Souvignet et al. (2013). At two hydrological stations Nong Son (Thu Bon River) and Thanh My (Vu Gia River), discharge has been measured since 1976. Rainfall data at the seventeen stations and climate data at the three stations are completely available from 1980 onwards. Based on the data availability, this study considers the timeframe 1980-2013, which covers a suitable time frame (> 30 years) for most of the available stations. Two water level stations further downstream Ai Nghia (Vu Gia River) and Giao Thuy (Thu Bon River) are also included to capture the downstream impact of hydropower. They are strongly influenced by tide (Giao Thuy) and tend to be flooded during the rainy season (Ai Nghia). Hydro-climatic records for the basin were obtained from the Regional Center for Hydro-meteorology (RCHM). For this study, daily data from sixteen rainfall stations, three climate stations (temperature, evaporation, humidity, radiation, sunshine hours, solar radiation) and two discharge stations were used (see Fig. 1) for the period from 1980 to 2013, to cover an ideal time frame (> 30 years) for most of the available stations. Data were quality checked and pre-processed (Souvignet et al., 2013). The two discharge stations Nong Son and Thanh My are located in the upper basin of Thu Bon and Vu Gia river respectively (Fig. 1). These stations are not influenced by the hydropower stations located upstream of the tributaries in the North (e.g., A Vuong, Bung 4, 5, 6 and Song Con 1, 2). Therefore, we included two more stations (Ai Nghia and Giao Thuy) located further downstream of the basin to capture the effect of these tributaries and hydropower reservoir operation. The latter two stations only measure water level and are strongly influenced by tide (Giao Thuy) and tend to be flooded during the rainy season (Ai Nghia). Ai Nghia station is located downstream of the diversion channel Quang Hue, which diverts water from the Vu Gia to Thu Bon (Fig. 1). Although the Ministry of Natural Resources and Environment (MoNRE) provided routing rules (see Table S1) to estimate how much water is diverted from Vu Gia to Thu Bon through Quang Hue channel, we assume that Ai Nghia station is located upstream of the diversion of the Quang Hue channel to avoid such complexity. J2000 simulations at Ai Nghia and Giao Thuy stations generated the naturalized flow for this study to compare the effects of reservoir operation on stream flow changes.

2.2.1 Data uncertainties

Aside from the uncertainties related to hydro-climatic data described in Fink et al. (2013) and Souvignet et al (2013), there are no discharge time series for the downstream irrigation region. We therefore developed our methodology based on the following assumptions: before Ai Nghia station in the Vu Gia delta region, water is diverted from Vu Gia to Thu Bon via the Quang Hue channel throughout the year. Due to the strong seasonality and tidal influences, it is difficult to predict the actual amount diverted towards the Thu Bon River. There are no data on quantities of water released from the reservoirs (see Table S1), but we rely on the routing rules of water diverted from Vu Gia to Thu Bon through the Quang Hue channel (Ministry of the Environment, MONRE). To avoid complexity, we assumed in the study that Ai Nghia station is located upstream of the diversion of the Quang Hue channel. We found that the proxy station can accurately capture the influences of reservoir impact on the downstream without leading to potential errors, as it accounts for the overall water balance.

2.~~1.2~~3 Hydropower and reservoir data

From 2008 until 2014, ~~E~~eight large hydropower reservoirs and plants ~~were~~ have been constructed, which have a cumulative storage capacity of more than 2 km^3 (Table 1)~~in the Vu Gia and Thu Bon river basins between 2009 and 2014, six on the Vu Gia river basin and two on the Thu Bon~~. The Dak Mi 4 (A& B) ~~Hydropower plant~~dam was built on the Vu Gia sub-catchment, but the water is diverted at its outflow to the Thu Bon river basin, since the turbines are located in the Thu Bon river basins (Fig.1). The reservoir information is summarised in Table 1. The classification of the reservoirs is based on the Vietnamese description of large, medium and small reservoirs (MOIT, 2015). Reservoirs which have an installed capacity of more than 29 megawatts (MW) of energy are considered as large hydropower plants, while the medium and smaller plants are in the range of 10 to 29 MW. The remaining plants produce less than 10 MW (PPC, 2006). For this study we have considered all eight hydropower plants, but to evaluate the model results, we have used the hydropower release data from four of the eight reservoirs: A Vuong (Feb 2009 to Aug 2012), Dak Mi 4 A (Jan 2012 to Dec 2013), Song Con 2 (Sep 2010 to Jun 2012) and Song Tranh 2 (Feb 2011 to Dec 2013), for which the outlet data at the turbine discharge is available. Please note that, A Vuong start its operation in September 2008 and Dak Mi4 reservoir start its operation from September 2011 (Table-1). Three of the remaining four reservoirs have only been operational since 2013 (Song Bung 4, 5 & 6), and the data was not available. The last reservoir, Dak Mi 4 B, is considered as a run-off reservoir and, therefore it was not necessary to account for its outflow in this study. Operational rules and rule curves were collected from the technical documents of each reservoir from the Department of Investment and Trade (DOIT) belonging to the national Ministry of Investment and Trade (MOIT) of the Quang Nam Province, Vietnam (See Table S2).~~This diversion has altered the flow pattern, and has been detected by the two existing hydrological stations of Nong Son and Thanh My. The reservoir information is summarised in Table 1. The classification of the reservoirs is based on the Vietnamese description of large, medium and small reservoirs (MOIT, 2015a). Reservoirs which have an installed capacity of more than 29 megawatts (MW) of energy are considered as large hydropower plants, while the medium and smaller plants are in the range of 10 to 29 MW. The remaining plant is less than 10 MW (PPC, 2006). Only the large scale reservoirs were considered in this study due to their potential implication on storage. Generally, the reservoirs of medium and small scale are streamflow power stations and have minor effects on downstream discharge. Operational rules and rule curves were collected from the technical documents of each reservoir from the Department of Investment and Trade (DOIT) under Ministry of Investment and Trade (MOIT) of the Quang Nam province, Vietnam (See table S2).~~

There are three types of reservoir operational rules: a) flood operation and related spill releases, b) dam security, which corresponds to the highest acceptable water level and c) water storage objective, for upper and lower daily storage goals and hydropower production. However, all these rules strongly depend on two distinct management seasons, namely '*Flood season*' (from 16 Sep to 31 Dec), and '*Dry Season*' (from 1 Jan to 15 Sep). During the flood season, the first considerations are dam safety and spill discharge. If the inflow is greater than the hydropower maximum discharge capacity and water level is above the flood control zone, then the water first is diverted to its full capacity to produce hydropower and the excess water within that day will be released through spill discharge to ensure flood control. During the dry season, the guide curve will determine how the release of water from the reservoir will be managed. However, for each reservoir there is a monthly target for power to be produced, and it is further controlled by the upper and lower limits of the reservoir level. Generally, if the water level is close to the upper limit of the guide curve, then it will maximize the energy production, otherwise if it is close to the lower limit, a limited amount of water will be released from the hydropower considering the environmental flow.

2.23 Methods

3.1 JAMS/J2000 HRU based Rainfall-Runoff model

2.2.1 The combined modelling – drought assessment framework

The J2000 is a physical based distributed and process-oriented model, which is suitable for simulating the hydrological processes of meso- and macro-scale catchments (Kralisch and Krause, 2006; Fink et al., 2007). The model describes the hydrological processes as encapsulated or independent process modules. The model utilises the HRU-approach for the discretisation of the basin, consisting of an overlay of land use, soil, geology and the relief parameters topographic wetness index (Böhner et al. 2002), the mass balance index and solar radiation index (McCune & Dylan 2002, Pfennig et al. 2009). Modules are described in more detail by Nepal et al. (2014) and in the online documentation (http://ilms.uni-jena.de/ilmswiki/index.php/Hydrological_Model_J2000). The J2000 model was calibrated and validated for the gauging station Nong Son for the period of 1996-2005 (Calibration and validation), an undisturbed period before the reservoirs were constructed in 2009.

The calibration was conducted manually and automatically using the multi objective NSGA2 algorithm (Deb et al., 2002). The model efficiency was tested by using different efficiency criteria, which include (1) coefficient of determination (R^2) to show the goodness of fit for the general model dynamics, (2) Nash-Sutcliffe (E2) efficiency to judge the goodness of fit with a focus on peak flow and simulated volumes and (3) the Nash-Sutcliffe efficiency (logE2) with logarithmic values to achieve a stronger focus on the low flow periods (Krause et al., 2005). As an indicator for the overall simulated volumes, we used the percent bias (Pbias) (Table 2). Further information about the utilised objective functions is described in Krause et al. (2005).

To analyse and quantify the impacts of reservoir operation on downstream low flows and to separate them from other impacts, longer time series for both the "pristine" as well as for the impacted period are needed. We termed them "naturalized" and reconstructed" discharge, respectively, in this study. The hydrological model J2000 was utilized to simulate daily discharge for upstream HRU outlets of the Vu Gia Thu Bon river basin system as input streamflow time series to the reservoirs as well as to provide time series for the "naturalized" flow for the four downstream stations addressed in this study (Fig. 1). Impacts of hydropower operation on downstream low flows were assessed by using the reservoir routing model HEC-ResSim coupled off-line to the J2000 for the VGTB river basin. Each reservoir was calibrated by HEC-ResSim individually before it was included in the integrated model. The reservoir model was run on a daily time step considering the hydropower operational rules. The output of this integrated model is referred to here as 'reconstructed streamflow'. A drought analysis was then carried out for the reconstructed (reservoir impacted) and naturalized (pristine) streamflow. Figure 3 gives an overview on the applied methods. The individual methods are described in the following sections.

2.2.2 JAMS/J2000 HRU based Rainfall-Runoff model

The J2000 is characterized as a physical based distributed and process-oriented model, which is suitable for simulating the hydrological process of meso- and macro-scale catchments (Fink et al., 2007); (Kralisch and Krause, 2006). According to (Fink et al., 2013), It is implemented in the Just Another Modelling Framework (JAMS) framework, "which is a software framework for component-based development and application of environmental models. The model describes the hydrological processes as encapsulated or independent process modules. These modules describe for example input data regionalization and correction, calculation of potential and actual evapotranspiration, canopy interception, soil moisture and groundwater processes" (p. 1829). Modules are described in more detail by (Nepal et al., 2014) and in the online documentation (http://ilms.uni-jena.de/ilmswiki/index.php/Hydrological_Model_J2000). The model utilises the HRU approach for the discretisation of the basin, consisting of an overlay of land use, soil, geology and the relief parameters topographic wetness index (Böhner et al., 2002), as well as mass balance index and solar radiation index (McCune and Keon, 2002; Pfenning et al., 2009)

2.2.3.2 HEC-ResSim reservoir operation model

We applied the HEC-ResSim Reservoir system simulation model (USACE, 2007) to simulate reservoir release, hydropower production and storage in the individual reservoirs of the VGTB at a daily time step. HEC-ResSim allows the development of simulations of single or multiple reservoirs in a hydrological network, based on the available hydrological (inflow) data, the physical reservoir characteristics and the operating rules. The model is comprehensively documented in Klipsch and Hurst (2013). J2000 simulated inflow time series (compare locations in Fig. 4a) were introduced and routed, with reservoirs altering the routed flow based on physical constraints and operating rules (Fig. 4b). Based on the technical document provided by the MOIT (more details are provided in the supplementary files for the operational rules of individual reservoirs, see Fig. S1), the reservoirs were first modelled individually, calibrated and evaluated based on the available observed outflow at their outlets. For this study, we have used the hydropower release data from four of the eight reservoirs, A Vuong, Dak Mi 4, Song Con 2 and Song Tranh 2, for which the outlet data for the turbine discharges are available. Three of the remaining four reservoirs have only been operational since 2013 (Song Bung 4, 5 & 6), and the data was not available. The final reservoir, Song Con 1, is considered as a runoff reservoir and therefore it was not necessary to account for its outflow in this study.

At VGTB, the reservoirs were operated based on defined management season, namely '*Flood season*' (from 16 Sep to 31 Dec), and '*Dry Season*' (from 1 Jan to 15 Sep) (MOIT, 2011). During the flood season, the first considerations are dam safety and spill discharge. If the inflow is greater than the maximum hydropower discharge capacity and the water level is above the flood control zone, then water is first diverted to its full capacity to produce hydropower and the excess water within that day will be released through spill discharge to ensure flood control. During the dry season, the guide curve will determine how the release of water from the reservoir will be managed. However, for each reservoir there is a monthly power production target, also controlled by the upper and lower limits of the reservoir level. Generally, if the water level is close to the upper limit of the guide curve, then energy production will be maximised, and if it is close to the lower limit, a limited amount of water will be released for hydropower production, and release rates are made considering the environmental flow.

~~The Reservoir System Simulation (HEC-ResSim) software developed by the U.S. Army Corps of Engineers (USACE, 2007) allows developing simulations of single or multiple reservoirs in a hydrological network based on the available hydrological (inflow) data, the physical reservoir characteristics and the operating rules. The model is comprehensively documented in (Klipsch and Hurst, 2013). J2000 simulated inflow time series (compare locations in Fig. 4a) were introduced and routed, with reservoirs altering the routed flow based on physical constraints and operating rules (Fig. 4b). The program uses a rule-based approach to govern reservoir release, from which hydropower can be generated. Reservoirs are divided in vertical zones having rules associated with each, and the total storage is determined by a storage-elevation-area relationship. In Figure 4a and Figure 4b, the transfer points are shown as well as the node based HEC-ResSim network with the modelled hydropower reservoirs.~~

3.3 The combined modelling – drought assessment framework

To analyse and quantify the impacts of reservoir operation on downstream low flows and to separate them from other impacts, longer time series for both the "pristine" and the impacted periods are needed. We termed them "naturalised" and "reconstructed" discharge, respectively. The hydrological model J2000 was utilised to simulate daily discharge for upstream HRU outlets of the VGTB river basin system as input streamflow time series to the reservoirs and to provide time series for the "naturalised" flow for the four downstream stations addressed in this study (Fig. 1). Impacts of hydropower operation on downstream low flows were assessed by using the reservoir routing model HEC-ResSim coupled off-line to the J2000 for the VGTB river basin (Fig. 4). The output of this integrated model is referred to here as 'reconstructed streamflow'. This provides the estimated streamflow at the two existing gauging stations (Nong Son and Thanh My) and at the two additional locations further downstream of the mouth of the two reaches (Ai Nghia and Giao Thuy), to capture the influences of reservoirs located further downstream (Fig.1). In our analysis the observed discharge data were only used for evaluating the simulated results. In the modelling process, we assumed that all eight reservoirs came into operation in 1980, and then used the reservoir model to produce the synthetic streamflow termed here as reconstructed flow. This gave us the opportunity to evaluate the long-term influences of the reservoirs on streamflow. A drought analysis was then performed for the reconstructed (reservoir impacted) and naturalised (pristine) streamflow simulations. Fig. 3 provides an overview on the applied methods.

2.23.4 Hydrological Drought Assessment

The threshold approach (Zelenhasić and Salvai, 1987) is widely used to determine hydrological drought in temperate regions, where the discharge is usually greater than zero (Tallaksen et al., 2009; van Huijgevoort et al., 2012; van Loon and van Lanen, 2012; Sung and Chung, 2014). It defines drought events based on a threshold value and provides information about its onset, duration and severity (Stahl, 2011; Hisdal et al., 2004).

The daily variable threshold approach (Hisdal et al., 2004) based on flow duration curves (FDCs) has been applied to determine hydrological drought periods. We used the 90th percentile (Q_{90}) of the FDC as the daily variable threshold, which is obtained from the antecedent 365 daily streamflow values. This threshold has been selected to study the drought which has a severe impact on the livelihood of the downstream population, particularly the irrigation sectors within the VGTB river basin, and also has been used in various drought related studies (e.g., (Fleig et al., 2006); Wanders et al., 2015). Q_{90} is defined as follows: for a given day of the hydrological year d (in this study, 1st of September is considered the start of the hydrological year), the daily varying Q_{90} (d) is calculated based on moving average of 30 days centred on day d (i.e., 15 days either side), starting from the first day of the hydrological year (Prudhomme et al., 2011; Van Loon et al., 2015). Due to strong seasonality within the study region, we further introduce the break-days concept to calculate the threshold level for both dry and wet season separately. Here the break-days are the 01/09 and 01/01, which are the starting dates of the wet and dry seasons, respectively. Furthermore, lower than average flow in wet seasons contributed to the development of drought in the following season (Sung and Chung, 2014). A binary approach has been considered to identify whether it is a dry day or normal day based on the daily low flow varying threshold. Finally, the streamflow deficit of the naturalised and the reconstructed streamflow are compared to quantify the impact of reservoirs on streamflow drought.

Threshold approach (Tallaksen et al., 2009), is being extensively used to determine the hydrological drought in temperate regions, where the discharge is usually greater than zero (Tallaksen et al., 2009; van Huijgevoort et al., 2012; van Loon and van Lanen, 2012; Sung and Chung, 2014). This method however also used globally, and also in the tropical region as well (van Lanen et al., 2013). It defines the drought event based on a threshold level and providing information of the onset, duration and its severity (Hisdal et al., 2004). For identifying a drought event, parameters of the flow below threshold (Q_0), drought duration D_i, deficit volume or severity, S_i, and time of occurrence t_e are used for statistical characterization of a drought event (Stahl, 2011). To eliminate minor and mutually dependent droughts from the record of events, pooling procedures have been applied (R1) (Tallaksen et al., 2009). According to Sung and Chung (2014), this pooling procedure is explained as, “If the “inter-event” time t_e between two droughts of duration d_i and d_{i+1} and severity s_i and s_{i+1}, respectively, are less than the predefined critical duration t_c and the pre-allowed inter-event excess volume Z_c, then the mutually dependent drought events are pooled to form a drought event (Zelenhasić and Salvai, 1987; Tallaksen et al., 2009)" (p. 3343)

$$d_{pool} = d_i + d_{i+1} + t_c$$

$$s_{pool} = s_i + s_{i+1} - z_c \quad \text{(R1)}$$

In this study we consider that:

t_c =3 days and z_c =10% of d_i or d_{i+1}

The daily variable threshold approach (Hisdal et al., 2004) based on flow duration curves (FDC) has been applied to determine the droughts. In this study we have used the 90th percentile (Q_{90}) of the FDC as the daily variable threshold, which is obtained from the antecedent 365 daily streamflow values. Q_{90} is defined as follows: for a given day of the hydrological year d (the start of the hydrological year is "01/07" for the VGTB basin), the daily varying Q_{90} (d) is calculated based on moving average (MA) of 30 days centered on day d (i.e., 15 days either side), starting from the first day of the hydrological year (Prudhomme et al., 2011). As the study region has strong seasonality between dry and wet season (i.e., the distinct differences of flow in dry and wet season, see fig.2), we further introduce the break-days concept to address the seasonality, which calculate separately the threshold level for both dry and wet season. In our case, the break-days refer to the 01/07 and 01/01, which is the starting of the wet seasons & dry season, respectively. The advantage of this approach is that it can detect the deviations of the streamflow for both the dry and wet seasons. Furthermore, lower than the average flow in wet seasons could have lead to the development of drought for the following season (Sung and Chung, 2014). A binary based approach (1 or 0) has been considered to identify whether it is a dry day or normal day based on the daily low flow varying threshold. For each streamflow record, the value is compared with threshold, and if the value is less than or equal to the threshold level then it considered as dry day and replaced by a single index equal to 1 and otherwise it considered as 0 (R2) (Prudhomme et al., 2011). Finally, the streamflow deficit of the naturalized and the reconstructed streamflow are compared to quantify the impact of reservoirs on streamflow drought.

$$DI(t) Z \begin{cases} 1 \; if \quad Q(t) \le threshold \\ 0 \; if \quad Q(t) > threshold \end{cases} \quad \text{(R2)}$$

43. Results

3.1. J2000 Hydrological model calibration to simulate reservoir inflow and naturalizsed discharge

The J2000 model was manually calibrated and validated for the discharge station Nong Son for the period of 1996-2005. We also performed an automatic calibration using the multi objective NSGA2 algorithm (Deb et al., 2002), which yielded similar results using the same objective functions as for the manual calibration (Table 2). The second available gauging station (Thanh My) was not separately calibrated, but tested using the same parameter set calibrated for Nong Son (see details in Appendix S4 for the estimation of parameters). This was done to check the ability of the model to simulate discharge for those parts of the basin where no calibration was possible due to the lack of discharge data.

Table 2 shows the efficiencies for each objective function used for the calibration and validation period (1996-2005). It is worth noting that if the model is calibrated using the first half of the time series (1996-2000; E2- Nash-Sutcliffe efficiency of 0.856), the runoff for the second half (2000-2005) is reasonably well simulated (E2 of 0.869), including the low flows during the drought period in 2005 (See details in Appendix S5 for the observed and simulated discharge plot). The average of the three efficiency criteria for Nong Son station resulted in 0.865 and 0.72 for Nong Son and Thanh My, respectively, when validated for the time period from 2000-2005 (Table 2). Following the classification of Nash-Sutcliffe efficiency criteria proposed by Moriasi et al. (2007), most of the calibrated models are rated as “good” (> 65 %) or “very good” (> 75 %). The objective functions logE2 and R^2 show that the low flow periods and the overall dynamics are well represented. For the calculation methods and further information about the utilised objective functions, refer to Krause et al. (2005). Owing to the HRU concept of J2000 as well as JAMS modelling framework, it is possible to generate hydrological state variables for each point in time and space. This facilitates the transfer of flow data at a daily time step at selected points along the river segments to the reservoir model (Fink et al., 2013), for example the points representing the reservoir inflow discharges.

The J2000 model was calibrated for the gauging station Nong Son for the period of 1996-2000. The calibration was conducted manually. We also performed an automatic calibration using the multi objective NSGA2 algorithm (Deb et al., 2002) which gave us similar results according to the objective functions (Table 2). We decided to use the manually calibrated parameters because of the better shape of the hydrograph with the manually calibrated parameter set. The second available gauging station (Thanh My) was not separately calibrated, but tested using the same parameter set acquired from Nong Son. This was done because we wanted to check the ability of the model to simulate the runoff for even those parts of the basin where no calibration was possible due to the lack of discharge data. Table 2 shows the results for the objective functions for the calibration and validation period (2000-2005). Since the Vu Gia datawere not calibrated, both periods are the validation for the parameter transfer. The presented efficiencies are the (1) coefficient of determination (R^2) to show the goodness of fit for the general model dynamics, the (2) Nash-Sutcliffe (E2) efficiency to judge the goodness of fit with a focus on peak flow and simulated volumes and (3) the Nash-Sutcliffe efficiency (logE2) with logarithmic values to achieve a stronger focus on the low flow periods (Krause et al., 2005). As an indicator for the overall simulated volumes, we used the percent bias (Pbias) (Table 2). The objective functions logE2 and R^2 show that the low flow periods and the overall dynamics are well represented. Because of the HRU concept of J2000 as well as JAMS modelling framework, it is possible to generate hydrological state variables for each point in time and space. This facilitates the transfer of flow data at daily basis at selected points along the river segments to the reservoir model (Fink et al., 2013).

43.2. Reservoir Modelling under varying operational rulesSimulation of hydropower reservoir release discharge

We applied the Hec ResSim model to simulate reservoir release discharge for each individual reservoir in the VGTB at a daily time step. Inflow time series from J2000 hydrological models were introduced and routed at inflow locations (Fig. 4). The individual reservoir simulation results are presented in Fig. 5.

The simulation period varied for each of the reservoirs, depending on their year of construction and availability of the discharge data from the turbine. In the case of the A Vuong, we compared the observed release data from February 2009 to August 2012 with the simulated cumulated daily discharge release values (Fig. 5), and there was very good agreement between the time series. There was also strong agreement at Dak Mi 4 with data from January 2012 to end of December 2012. However, for the summer period in 2013, the simulated discharge was consistently lower than the observed discharge (Fig. 5). Simulations for Song Con 2 for the period from September 2010 until beginning of 2011 also showed good results while the dry season cumulative discharge for year 2011 was underestimated but improved during the wet season. The simulation result for Song Tranh 2 was unsatisfactory for the period after January 2012 (Fig. 5).

We applied the HEC-ResSim Reservoir system simulation model to simulate reservoir release, hydropower production and storage in the individual reservoirs of the VGTB at a daily time step. Based on the technical document provided by the MOIT (more detail provided in the supplementary files for the operational rules of individual reservoirs Fig. S1), the eight reservoirs were first modelled individually, calibrated and evaluated based on the observed outflow at their outlets. The water release has been designed to reproduce the observed mean of the daily release. This ensures that the individual reservoir will reproduce well enough to simulate outflow and can then be incorporated into the integrated reservoir model. For this study, we have used the hydropower release data of four of the eight reservoirs - A Vuong, Dak Mi 4, Song Con 2 and Song Tranh 2, for which the outlet data of the turbine discharge is available. Three of the remaining four reservoirs have only been operational since 2013 (Song Bung 4, 5 & 6), and the data was not available. The final reservoir, Song Con 1, is considered as a run-off reservoir and, therefore was not necessary to account for its outflow in this study.

The simulation time varied for each of the reservoirs, depending on their year of construction and availability of the discharge data from the turbine. For A Vuong reservoir, the available data was from February 2009 until August, 2012, and was used to compare the simulated cumulated daily release from the turbine to the observed discharge (Fig. 5). The simulated cumulative discharge showed very good agreement with the observed discharge data from the turbine. The simulated outflow of Dak Mi 4 was in good agreement with the observed flow from January 2012 to end of December 2012. During the summer time in 2013, the simulated cumulative discharge was underestimated compare with the observed discharge (Fig. 5). This phenomenon can be explained by the designed environmental release from the Dak Mi 4 reservoir to the Vu Gia River. As mentioned above (see Fig.1), the Dak Mi 4 hydropower (located at the Vu Gia river upstream) releases water to the Thu Bon river through turbine discharge. Therefore, to maintain the environmental flow to the downstream of Vu Gia river, the reservoir should release a minimum of 25 m^3s^{-1} water from the reservoir to the Vu Gia river (MOIT, 2011). However, because of the high demand for energy during the dry season, some of the water intended for environmental flow for the Vu Gia river was used for the energy production and discharge to the Thu Bon river. The simulation result of Song Tranh 2, was not quite satisfactory after January 2012 (Fig. 5). This is due to the fact that this reservoir experienced leakages from its dam, and any storage of water for the year 2012-2013 was prohibited due to dam safety. Any water coming inside the dam was used immediately through the turbine, increasing discharge from the turbine. As a result, there was no storage functionality in the reservoir during this period. After 2013, the leakages were repaired and the reservoir returned to its normal operating condition.

3.2. Simulation of reconstructed Streamflow

In this study, reconstructed streamflow was simulated which accounts for the effects of reservoirs. The calibrated individual reservoir operating rules and other physical parameter information were incorporated in the integrated modelling system which simulates the reconstructed streamflow for the period 1980-2013 with varying management options such as cascade reservoir operation, flood control and management of water for dry season. This provides the estimated streamflow at the two existing gauging stations (Nong Son and Thanh My) and the two additional locations further downstream of the mouth of the two reaches (Ai Nghia and Giao Thuy) to capture the influences of reservoirs located further downstream (Fig.1). As there are no gauging stations at Ai Nghia and Giao Thuy, we considered the output of the J2000 simulation as a reference value for the natural streamflow, as it produces robust results (described in Section 2.1.1). To evaluate the reservoir simulations, we applied the performance statistics for the period of 2011 to the end of 2013 (Table 3). This timeframe was chosen because the Dak Mi 4 and Song Tranh 2 hydropower plants started their operation after 2011 affecting the discharge stations Nong Son and Thanh My. The streamflow efficiency statistics E2, logE2 and R^2 (Table 3) show that the model has a good overall performance for Nong Son Station and a slightly weaker performance for Thanh My station (E2 = 0.74). This coincides with the results for rainfall-runoff modelling (Fink et al, 2013). The Vu Gia river (at Thanh My station) – which mainly supplies water for the city of Da Nang and large irrigation areas – is strongly impacted by Dak Mi 4 operation and downstream water management is strongly dependent on decisions related to hydropower production and related releases (Figure 5). Further investigation regarding the management strategies for this hydropower plant could improve the simulation performance. However, the high efficiency values (Table 3) of the simulated actual water release confirm the overall model ability to simulate the daily release and reproduce the reconstructed streamflow.

4.3 Reconstructed streamflow simulation

Reconstructed synthetic streamflow was simulated based on the individually simulated reservoir releases (Fig. 5). We simulated the reconstructed streamflow for the period 1980-2013 incorporating varying reservoir operation options such as cascade reservoir operation and flood and dry season control. This was performed for the gauging stations Nong Son (wetter Thu Bon catchment) and Thanh My (drier Vu Gia catchment) and two downstream stations: Giao Thuy (Thu Bon) and Ai Nghia (Thanh My). These latter stations are located in the delta region where water is abstracted for rice irrigation and for the drinking water treatment plant which supplies the city of Da Nang. These simulations were needed to capture the impacts of all reservoirs on water availability in the delta area. As there are only water level but no gauging stations at Giao Thuy and Ai

Nghia for calibration, we used the naturalised streamflow simulated using J2000. To evaluate the efficiency of the calibration, we applied the performance statistics for the period of 2011 to the end of 2013 (Table 3). This timeframe was chosen because the Dak Mi 4 and Song Tranh 2 hydropower plants started operation after 2011 and measured data for calibration were available for this period. The efficiency statistics show reasonable results: e.g., E2 - Nash-Sutcliffe efficiencies of 0.907 and 0.716 for Nong Son and Thanh My stations, respectively (See details in Appendix S6 for the observed and reconstructed streamflow plot for the period from 2011 to 2013). This indicates that the reconstructed streamflow is able to capture the influences of reservoir operation on streamflow. The reconstructed streamflow also shows a very good result considering the overall water balance described by the Pbias (relative volume error in percent). The Pbias values for Nong Son and Thanh My are 0.0052 and -0.077, respectively.

~~3~~4.~~3~~4. Daily, monthly and seasonal effects of hydropower reservoir operation on streamflow in the subcatchments Vu Gia and Thu Bon~~Simulated long term effects of reservoirs on streamflow~~

~~The solid black circles in Figure 1 show the locations of gauging stations used to compare our reconstructed streamflow under reservoir influences, with data inferred from observed streamflow. We assumed in our study that all eight reservoirs came into operation in 1980, then ran the reservoir model to produce the synthetic streamflow termed here as reconstructed flow. This gave us the opportunity to evaluate the influences of the reservoirs on long term streamflow pattern. Raster based visual representation of the naturalized and reconstructed streamflow at a daily basis is presented in Figure 6~~. We compared the daily naturalised and reconstructed streamflow simulations in Fig. 6. For Thanh My station and Ai Nghia stations in the drier Vu Gia catchment, low flows (pink to yellow colours) during the summer time are more prominent in the reconstructed streamflow than in the naturalised streamflow. For Nong Son and Giao Thuy stations, however, less low flows were simulated in the reconstructed time series than in the naturalised one.

~~the effect of the diversion in Dak Mi 4 from Vu Gia to Thu Bon is clearly visible. For downstream Ai Nghia station (also affected by the diversion of Dak Mi 4) extremely low values (pink) are less frequently appearing in the reconstructed simulations compared to the naturalized ones. This can be attributed to the damping effect of the additional reservoirs belonging to this lower part of the sub-basin and their energy production during the naturally very low flow situations. The following analyses of longer time periods show that the overall water availability in Ai Nghia is also reduced due to the diversion. For Nong Son and Giao Thuy a higher water availability is shown due to the additional water diverted to Thu Bon at Dak Mi 4.~~

To quantify the mean monthly reservoir effects for the period from 1980 to 2013 (Fig. 7),~~To quantify the reservoir effects on a monthly scale~~, we plotted the mean monthly values of the reconstructed streamflow against the naturalis~~z~~ed discharges for the four stations~~ (Nong Son, Thanh My, Ai Nighia and Giao Thuy (Fig. 7)~~. ~~At Nong Son station, monthly streamflow had increased by 24-62 $m^3 s^{-1}$ (about 23-85% of the observed discharge) during January to August. Although the mean discharge for September to December had increased by 50 -114 $m^3 s^{-1}$, the proportion in terms of percentage was rather low varying from 1.3% in October to 26.31% in December (Fig. 7a). A sharp contrast was observed F~~for Thanh My station located at the upstream of the Vu Gia River, ~~. M~~monthly streamflow was reduced on average by ~~around~~ approximately 51 $m^3 s^{-1}$ (38 % of the observed flow). The impact of reservoir operation is most ~~obvious~~ pronounced ~~during the months from~~for the dry season(January to August), when ~~in which it experiences a decreasing~~ flows decrease from ~~ranging from~~ 30 to 60 % compared to ~~its original state~~the naturalised mean monthly discharge. During the wet season (September to December), ~~the flow is also reduced~~discharge decreased ~~on average~~ by 30%. At Nong Son station, mean monthly streamflow increased by 24 to 62 $m^3 s^{-1}$ (from 23 to 85 % of the observed discharge) for the period January to August. Although the mean discharge for September to December increased by 50 to 114 $m^3 s^{-1}$, the percentage increase was rather low, varying from 1.3 % in October to 26.3 % in December (Fig. 7a). The Giao Thuy and Ai Nghia stations are located approximately 25 km and 32 km downstream of the Nong Son and ~~Ai Nghia~~Thanh My stations respectively and exhibit a similar pattern of flow changes due to reservoir construction. Analysing the combined seasonal impact of reservoirs on water availability in both catchments, we found that overall discharge during the wet season decreased by 2 to 38 % and increased during the dry season from January to August in which significant increase of flow augmentation was found during March to April (62 - 68 %) (Fig. 7b). Fig. 8 shows the annual and seasonal mean monthly hydrographs for the four stations, comparing the simulated discharge on a seasonal and an annual scale. These results show that there are strong seasonal changes in streamflow for both sub-catchments, with a significant reduction of streamflow for the Vu Gia River especially in the dry season, and an increase of water availability in the Thu Bon River.

~~The combined effect of reservoir operation over the VGTB shows that overall, the flow had increased from January to August (Fig. 7B) and a particularly significant increase of flow augmentation was found during the month of March and April (62-68%), indicating that irrigation during this time can be ensured, when the peak demand for water is required for all activities. The flow during the rainy season decreased by -2 to -38%, which could improve the flood protection in the region. We also addressed the influences of reservoirs on seasonality of discharge. This analysis of seasonality provides insight into the changes that underlie annual effects, and provides an opportunity to assess the adequacy of data reconstruction. The reservoir operation significantly changed the seasonality of discharge from the two major rivers, Vu Gia and Thu Bon. These changes are mainly due to the construction of the Dak Mi 4 reservoir which diverts water from the Vu Gia (Thanh My station) to the Thu Bon (Nong Son station) (Fig. 8). Streamflow for the Nong Son station in both dry and wet seasons has increased significantly, but at the same time, the peak has reduced in November and December, when floods usually occurred. This indicates that normal floods in Thu Bon sub-basin have reduced, and may not have the same impact as they did before the construction of the reservoirs. For the Vu Gia side at Thanh My station, there is an overall decreasing pattern for both seasons, except the flood peak which is high during November and December. This is due to the Dak Mi 4 reservoir's spill operation which allows excess water to pass through the spillway gate.~~

~~Annual time series and mean monthly flows for each of the reconstructed products and the naturalized data are shown in Figures 8b and 8c respectively. Overall, the figures show an increasing flow at Nong Son and Giao Thuy stations, and the opposite pattern of decreasing flow for the Thanh My and Ai Nghia stations. For Nong Son and Thanh My stations, the differences are more obvious.~~

3.44.5. Impacts of Reservoir operation on hydrological drought

For the VGTB, streamflowHydrological drought occurrence, length and severity were was determined through the seasonality (Dry and Wet) along withby using the daily varying threshold level method (Q_{90}) separately applied to the dry and wet seasons (break-days were 01/09 and 01/01). Results show that low flows generally occur in spring (MAM) and extend towards summer (JJA) time (Fig. 9). Hydrological droughts were recorded for the years 1982, 1983, 1988, 1990, 1998, 2005, 2012 and 2013 (Nauditt et al., 2017). Figure 9 shows the drought onset and duration of the naturalisszed and the reconstructed streamflow time series to evaluate the reservoir operation impact on hydrological drought. Thanh My station (Vu Gia catchment), shows more days under drought for the reconstructed period (1061 days) compared to the naturalised period (774 days). Similarly, an increasing number of drought days and frequency was found for the reconstructed period at Ai Nghia (1286 to 1011 days). At Nong Son station located at the upper (Thu Bon river), the analysis shows a general shift of the occurrence of drought from summer to spring (MAM) to summer (JJA) due to reservoir construction and operation (Fig. 9). Specifically, at the beginning of the summer (June and July) this station merely experienced streamflow deficiency which is evident in late summer (August) or the beginning of fall (September). This phenomenon can be explained if we consider two issues: Firstly, there is a higher demand of energy during summer and hydropower has to release water for energy production. Secondly, before autumn, reservoirs need to release water to create capacity to store the monsoon water. Nong Son (upper Thu Bon) and Giao Thuy (lower Thu Bon river) stations exhibit a decreasing number of drought days respectively, from 821 to 680 and from 1025 to 713 days. These reductions are, due to the diversion of the Dak Mi 4 reservoir from Vu Gia to Thu Bon. On the other hand, Thanh My station which is located at the upper Vu Gia, shows more days under drought for the reconstructed period (1061 days) compared to the naturalized period (774 days). Similarly, an increasing number of drought days and frequency was found at Ai Nghia from 1011 to 1286 days. The number of drought days correspond to year at each of the stations are presented in the supplement (Figure S3).

54. Discussion

5.1. Simulating naturalised discharge with J2000 in a data scarce environment

In the VGTB, only two discharge stations and related time series are available for calibration. Therefore, to assess changes in water availability in the delta region where water is needed for irrigation and other purposes (e.g., domestic and industrial uses), we simulated discharges for locations where no validation data were available. The J2000 model was successfully calibrated and validated for the gauging station Nong Son for the period 1996-2005, an undisturbed period before the reservoirs were constructed in 2009. Results for the three applied efficiency criteria ranged from 0.72 to 0.87, which are considered very good simulation performances (Moriasi et al., 2007). The application of the Nong Son validated parameter set to Thanh My station also yielded reasonably good efficiencies (Table 2).

These results allowed us to use J2000 to simulate naturalised discharges for HRU outlets needed as reservoir inflow discharges and for the downstream delta locations Ai Nghia (Vu Gia sub-catchment) and Giao Thuy (Thu Bon sub-catchment). They can be considered as valuable discharge estimations for this study. A simulation uncertainty range is presented in the supplementary materials(SXXX).

5.2 Modelling discharge release from operating hydropower reservoirs

Overall individual reservoir modelling showed good results in simulating released discharges from the turbine (Fig. 5). Available release discharge time series from operating hydropower plants for reservoir model calibration were short, and the simulation period varied for each of the reservoirs depending on their year of construction and availability of discharge data for the turbine.

The simulation results for the Song Tranh 2 reservoir were unsatisfactory for the period after January 2012 (Fig. 5) due to reservoir leakages which led to the prohibition of any storage of water in 2012-2013 to ensure dam safety. Any water entering the reservoir was sent immediately through the turbine, increasing discharge from the turbine. As a result, there was no storage functionality in the reservoir during this period. After 2013, the leakages were repaired and the reservoir returned to its normal operating condition. Data are available since January 2012 for Dak Mi 4, which diverts the water from Vu Gia to Thu Bon. Despite general agreeance over the entire data period, the simulated discharge was lower than the observed discharge for the summer period in 2013 (Fig. 5). Furthermore, simulations for Song Con 2 underestimated dry season cumulative discharge in 2011, but improved again during the wet season. These underestimations of the simulation results can be predominantly attributed to the reservoir release constraints associated with the reservoir operation during the dry season.

54.31 Is the ~~combined~~ integrated modelling framework suitable to assess the hydrological regime under ~~either natural or~~ reservoir operation ~~impacted conditions at different time scales~~?

For reservoir impact assessment, time series for either the pristine or the human impacted period are usually too short to be used for calibration. For the first time, an integrated modelling framework was applied to a data scarce tropical mountainous mesoscale catchment to assess hydrological drought risk by using naturalised and human impacted reconstructed streamflow and two observed discharge time series. Comparing observed, simulated, reconstructed and naturalised discharge time series is a widely used method to assess and quantify anthropogenic impacts on streamflow (Zhang et al., 2012; Deitch et al., 2013; López-Moreno et al., 2014; Chang et al., 2015; Räsänen et al., 2017). Our softly linked model setup shows good results in terms of statistical efficiency performances and provides reliable simulations for both reconstructed and naturalised streamflow. This applies also to the low flow simulations and hydrological drought periods which usually pose the greatest challenges to hydrological modelling (Pilgrim et al., 1988; Nicolle et al., 2014). This method presents several advantages compared to statistics based approaches such as Budyko Curves or double mass curves. The key advantages of this approach are: 1) the possibility to compare long term pristine and modified streamflow without relying on long term hydropower release time series 2) larger flexibility to account for reservoir influences at the local level, thus accurately allowing prediction of long-term influences of reservoir on streamflow, 3) the ability to simulate and analyse scenarios dealing with changes (land use, climate, etc.) in the catchment.

Our integrated modelling approach combined with the hydrological drought analyses provided a unique and suitable set of tools to assess drought risk in a data scarce and reservoir impacted catchment, and can be transferred to any region where reservoirs impact downstream water availability. Existing methods mostly able to compare the streamflow behaviour for the hydropower operations before and after their construction especially those which were built several decades ago. Several studies used the merit of availability long time series data to compare before and after the construction of the hydropower reservoirs (e.g. Ye et al., 2003; Adam et al., 2007; Adam and Lettenmaier, 2008; Arrigoni et al., 2010; Ahn and Merwade, 2014; Tang et al., 2014; Zhang et al. 2015). However, without the required after-construction data such comparative visualisation and characterisation of impacts become immensely challenging. Therefore, the proposed integrated model offers to quantify the impacts of newly built hydropower resources on the downstream water users and resources.

Hydropower development is growing, and as of March 2014, 3100 hydropower reservoirs with a capacity of more than 1 MW have been either planned (83 %) or are under construction (17 %) (Zarfl et al., 2015). Most of this hydropower development is concentrated in developing and emerging economies of Southeast Asia, South America and Africa, where data availability is a major issue. This method offers an opportunity to quantitatively analyse and measure of the impacts of these hydropower operations at the basin scale. The understanding of our methods can be used for streamflow simulation for ensuring environmental flow of water to produce a sustainable level of food and energy production to support the growing population.

Comparing observed, simulated reconstructed and naturalized discharge time series is a widely used method to successfully assess and quantify anthropogenic impacts on streamflow (Zhang et al., 2012; Deitch et al., 2013; López-Moreno et al., 2014; Chang et al., 2015). Here we used the reconstructed streamflow to assess the simulation of longer reservoir impacted discharge time series to assess the long and middle term effects of hydropower operation on the one hand and seasonality and different time scales on the other. The naturalized streamflow is used to quantify the differences under exactly the same climatic conditions. (Adam et al., 2007) for example evaluated the potential contribution of artificial reservoirs to long-term changes in annual and seasonal streamflow. Similarly to our study, they used a combined distributed hydrological model together with a reservoir routing model to generate reconstructed streamflow to be compared to the pristine environment. The soft linked model setup shows very good results in terms of statistical efficiency performances and provides reliable simulations for both reconstructed and naturalized streamflow. This includes the case for the low flow simulations and hydrological drought periods which usually pose the greatest challenges to hydrological modelling (Pilgrim et al., 1988; Nicolle et al., 2014).
As time series for either the pristine or the human impacted period in most cases are too short to fulfil statistical significance, this method is considered the most reliable when assessing the short, middle and long term changes in anthropogenically impacted discharge. Also, as shown in (Nauditt et al., 2017) varying basin characteristics, such as land cover changes and basin

storage only play a minor role in runoff generation processes in the VGTB basin, which is instead dominated by precipitation inputs. Therefore, it can be assumed that all the quantified changes in this study for the different temporal scales can be considered as net values for anthropogenic impacts on low flow discharge.

The main disadvantage of this methodology involving several models is the fact that it is data intensive and time consuming. Also, to make the results more reliable, uncertainties especially related to reservoir operation, precipitation input data or observed discharges used for calibration and validation, need to be further evaluated, described and communicated to the stakeholders.

5.4 Quantification of reservoir impacts on hydrological drought

For the first time we tested the integrated hydrological modelling-drought assessment framework based on hydrological indicators, reservoir operation and rainfall runoff processes.

This study reveals that the intensity and frequency of hydrological drought in the entire VGTB basin is largely dependent on hydropower operation associated with the inter-basin water diversion from the Dak Mi 4. Our modelling results show that drought events simulated for the human-modified catchment system are intensified by 27-37 % in the Vu Gia sub catchment compared to those under pristine catchment conditions (Table 4). This intensification is mainly attributable to the diversion of the Vu Gia river to the Thu Bon due to Dak Mi 4 hydropower generation which controls the reservoir operation in the study region.

Part of the decreased streamflow in the Vu Gia river could be buffered by increasing reservoir release from the Dak Mi 4 reservoir. According to the technical document (MOIT, 2011), the Dak Mi 4 reservoir is required to release a minimum of 25 m^3s^{-1}, a quota which has not been met throughout most of the dry season periods. Because of the high demand for energy during the dry season, some of the water needed for the minimum release towards Vu Gia river was used for energy production and discharge to the Thu Bon River. As a result, at Nong Son and Giao Thuy stations, the drought intensity decreased by 17 and 30 %, respectively.

We found that for the entire Thu Bon catchment, there is an increasing downstream flow during the low flow period when we consider the reservoir effects on both river discharges (Fig. 7b and Table 4). This alleviates the general hydrological drought conditions downstream and the seasonal amplitude of simulated streamflow tends to decrease, which also reduces downstream flood risk.

However, the impacts of reservoir operation are particularly pronounced for the more vulnerable Vu Gia river (Figures 6, 7, 8 and 9). The Vu Gia river supplies water to the city of Da Nang and large rice irrigation systems. While Thanh My station streamflow is reduced by 51.7 m^3s^{-1} which is 37.8 % less compared to the naturalised condition, downstream at Ai Nghia Station, the streamflow reduction is less severe (17. 4 % less water than the naturalised condition) as it receives water from tributaries and rainfall downstream of Thanh My (Table 4). Especially during the dry season, the damping effect of reservoirs belonging to the lower sub-basins increasing (i.e., Song Bung 4, 5, 6; A Vuong and Song Con) due to their energy production during the dry season (Fig. 6 and Fig. 7a).

A further relevant impact of the reservoir operation on hydrological drought is the shift of drought occurrence from summer to spring (Fig. 7 and Fig. 9). As shown in the figures illustrating the naturalised flow simulations, low flows generally occur in spring (MAM) and extend towards summer (JJA) at all stations. Fig. 7 and Fig. 9 show that reconstructed flow simulations, and indicate more hydrological drought periods during summer. The applied threshold level approach (Q_{90}) was able to capture the drought events (Fig. 9) in VGTB, consistent with the observed drought events for VGTB (1982, 1983, 1988, 1990, 1998, 2005, 2012 and 2013) (Nauditt et al., 2017).

Generally, reservoir operation leads to reduced runoff volumes in the rainy season and increased runoff in the dry season, and typically serves to mitigate droughts rather than contribute to their aggravation (Wada et al., 2013; Wanders and Wada, 2015; He et al., 2017; Di Baldassarre et al., 2017). We found that the overall reservoir operation at VGTB leads to an increase flow during the dry season of approximately 32.54 m^3s^{-1}, which is 27.23 % more than the naturalised situation, and a decreases flow during the wet season of approximately 106.53 m^3s^{-1}, which is 3.61 % less than to the naturalised situation (Fig. 4). A similar pattern of streamflow changes due to hydropower operation was found in the Mekong river basin, where the dry season discharge increased by 60-90 % and the wet season discharge decreased by 17-22 % (Hoanh et al. 2010; Lauri et al. 2012; Räsänen et al. 2012).

However, due to the increased energy demand in summer, the last months of the dry season (August and September) exhibit lower streamflow values under reservoir operation than under the natural flow condition. Also, there is a lower drought risk at the beginning of the dry season, because of the additional storage in the system. At the end of the dry season, the storage is lower which might lead to a higher likelihood of droughts. These findings on the overall impact of the reservoir operation can be transferred to other locations featuring similar climatic and topographic conditions, whereas the separate findings for the Vu Gia and Thu Bon rivers are very much influenced by the diversion at Dak Mi 4, and are therefore specific to this catchment.

5.5. Consequences of the hydrological changes

Droughts are usually assessed at a large scale and based on indices which are related to parameters such as precipitation, soil moisture or vegetation. However, human alterations of the hydrological system and abstractions from the rivers are not incorporated in such drought analyses (Van Loon et al., 2015). A variety of anthropogenic alterations of the natural environment and river network can cause changes in downstream water availability, and these anthropogenic alterations include land cover changes, major water abstractions and infrastructure for irrigation and drinking water supply. Nauditt et al. (2017) used varying spatial basin characteristics, such as land cover changes, to simulate low flows in the VGTB basin, and found that these only play a minor role in runoff generation processes, which are instead dominated by precipitation inputs. Therefore, it can be assumed that all the quantified changes in this study for the different temporal scales can be considered as net values for reservoir operation impacts on low flow discharge.

We found that reservoirs can have multiple effects on the downstream users particularly if they are not operated properly. In the VGTB, hydropower reservoir operation strongly alters the natural hydrological functions of the river basin. In particular one hydropower reservoir (Dak Mi 4) generates electricity by transferring water from the drier sub-catchment Vu Gia to the wetter Thu Bon sub-catchment, due to its superior slope to produce energy (Nauditt et al., 2017). During the dry season, the combined effect of the reservoir operations at Ai Nghia and Giao Thuy (Table 4 and Fig. 7b) indicated that overall flow increases during the dry season and reduce the wet season flows. These changes resulted in dampening VGTB's annual flood pulse. This decreased flow pattern during the flood season is expected to reduce the sediment and nutrient transport, and can affect the aquatic habitat (Pitlcik and Wilcok, 2001). The fluctuation of water supply due to the reservoir operation degraded the riverbed immediately after the turbine discharge. This degradation is typically accompanied by a coarsening of the river bed with associated loss of useable habitat for fish and benthic invertebrates (Pitlcik and Wilcok, 2001). The loss of these important habitats, combined with changes in water quality due to sediment imbalance and introduction of non-native fishes, has potentially caused long-lasting impacts on the native fish community at VGTB.

One of the major concerns is that the seasonal shift of drought occurrences, from spring (MAM) to summer (JJA), was observed at most of the stations in the VGTB. This may have impacted the VGTB's ecological productivity, which is the basis for livelihood, income and food security for millions of people. This shift could have impacted the cropping pattern of the downstream, which relies heavily on the water during the summer season. However, the results indicated that the dry season discharge may vary considerably due to rainfall and hydropower operations. For example, in 2013, due to the low rainfall in 2012 (Sep - Dec), there was a severe shortage of water for hydropower operation during the dry season, which exacerbated the drought in the downstream for Vu Gia catchment.

4.2 Which potential uncertainties need to be addressed in this combined modelling approach?

Although the results of this study are plausible and provided reasonable quantitative information for water resources management and reservoir operation, uncertainties in the simulations have not been quantified or estimated due to the complexity of the study. To use the final model setup and resulting simulations for water management, the main sources for uncertainties need to be identified while their relative portion contributing to the final simulations should be quantified and communicated to stakeholders.

Different sources of uncertainties in environmental modelling are described e.g. in (Walker et al., 2003; Refsgaard et al., 2007; Refsgaard et al., 2006; Refsgaard et al., 2007; Beven and Binley, 1992). For this study, uncertainties related to the following three categories are discussed: 1) data input as precipitation data, discharge and 2) operational rules of reservoirs and 3) parameter and model setup related uncertainties.

Regarding 1), to date there is no way of reliably estimating **areal basin precipitation** especially for a high temporal and spatial resolution. More rainfall measurements in the basin headwaters would help however, this is impractical given the remoteness and inaccessibility. Therefore resulting uncertainties for hydrological modelling related to areal precipitation is a first order limitation. (Refsgaard et al., 2006) found that the uncertainties related to rainfall estimations were by far larger than those related to parameter uncertainty. However, this depends on basin size, response time, the model type and the assumptions made in representing the different sources of uncertainty. In the data sparse VGTB river basin, uncertainties related to precipitation model inputs are very high. All climate stations are all located below 120 m of elevation and no information is available for the higher elevations of up to 2250 m.

To overcome such underrepresentation of high elevation P and missing spatial coverage of P, J2000 relies on a comprehensive regionalization methodology to distribute precipitation which is described in (Krause, 2002) that combines a linear regression approach applied to station data with an elevation gradient to account for the vertical variability. The residues from the individual stations to the calculated regression line are interpolated with the Inverse Distance Weights (IDW) method to account for the lateral variability. R^2 of the regression line is used to determine if the relation between the rain and the altitude is strong enough to be used for the modelling. A threshold value of R^2 of 0.75 is typically used for this decision. If the threshold is not met by the data, only the IDW interpolation without the altitude regression is utilized to determine the values for the individual HRUs. This combined method considers the altitude effect if it can be identified using the measured values to potentially compensate for some of the missing precipitation at higher elevations. However, total distributed daily inputs are still uncertain and difficult to quantify.

Discharge is monitored at Nong Son and Thanh My station by measuring water level using a boat at each point of the river every day. Discharge is then calculated based on a monthly updated rating curve. This method is not very accurate especially during high flows and hence also a source of uncertainties.

Further input data contributing to output related uncertainties are the operational rules for the reservoir operation which are strongly dependent on the energy production demand on National level. Although they should follow the rules used for calibration of the HEC-ResSim model which consider flood protection storage and a minimum release for downstream water users, real operation is much more variable on an hourly and even on a daily scale. Therefore uncertainties related to the input data **"operational rules" 2)** are more difficult to analyse as they depend on human decision making which is not always "ruled". (Mateus and Tullos, 2016) estimated changes in streamflow and reservoir reliability under climate variability in two basins with different hydro-geological settings in North-western United States. They assessed climate related sensitivity and uncertainties in HEC-ResSim modelling performance by comparing model results with inputs from VIC hydrological modelling simulations forced with eight climate model projections. A range of output percentiles 2.5, 50, and 97.5 was assessed. They found that changes in streamflow are much more sensitive to reservoir operational rules compared to climate variability which in their case would lead to higher streamflow in spring and lower streamflow in summer. This coincides with our observations in central Vietnam. For our study, the uncertainty range will be assessed by comparing our reconstructed streamflow with simulation results incorporating the historical real reservoir operation, with parameters such as volume and discharge differences quantified as uncertainty ranges.

3) Model parameter and structural uncertainty is related to the simplifying assumptions of the conceptualisation in modelling processes compared to reality and the associated parameter values and ranges. The combined modelling framework used in this study involves a large number of such uncertainty sources belonging to each model structure and the correspondent parameters. Uncertainties related to HEC-ResSim modelling algorithms deal with channel routing and reservoir storage without taking into consideration spatially distributed environmental processes. It can be assumed that uncertainties are more related to input data and the extreme tropical hydro-morphological dynamics (Mateus and Tullos, 2016).

For the J2000 model, however, the knowledge on uncertainties related to model structure and especially parameter sensitivity would help to define an uncertainty range for the use of the model framework for predictions and decision support. The J2000 model was calibrated against the Nong Son discharge station daily time series (1996-2000) in the VGTB. The good calibration results in terms of statistical efficiencies and hydrograph representation have encouraged us to use the model for this assessment without carrying out a comprehensive uncertainty analysis addressing uncertainties related to parameter behaviour, climate inputs, spatial data inputs and the discharge time series used for calibration and validation. The parameter range behaviour might be further analysed to identify the most sensitive features and their representation in the real environment. J2000 parameter sensitivity for selected parameters was for instance assessed by (Nepal et al., 2014) for a snow-melt dominated environment. A toolbox with different statistical methods to analyse parameter sensitivity and uncertainties in J2000 was described in (Fischer et al., 2012). However, the assessment of parameter sensitivity and identifiability for 34 parameters for such a distributed model would require a large computation effort. Such potential uncertainties should be communicated to the stakeholders before using the model framework for decision support.

Uncertainties in water management are often still not sufficiently addressed which can lead to that wrong decisions being made and planning not carried out in a sustainable way.

56. Conclusion

We assessed human impacts on hydrological droughts in the VGTB river basin and found that the intensity and frequency of hydrological droughts in the entire Vu Gia Thu Bon basin are largely dependent on hydropower operation associated with the Dak Mi 4 related inter-basin water diversion. Our modelling results show that drought events simulated for the human-modified catchment system were intensified by 27 - 37 % in the Vu Gia sub-catchment compared to the ones under pristine catchment conditions. However, when combining the overall impact of reservoir operation for the entire VGTB, we found an increase in dry season flows (ca. 27 %) and reduced flood season flows (ca. 3.5 %) compared to the naturalised condition, and a similar pattern of changes due to reservoir operation was also found in another basin in the Mekong Region.

Furthermore, a seasonal shift of drought occurrence, from spring (MAM) to summer (JJA) was observed severely affecting rice cultivation as the cropping season particularly relies on the water during the spring and summer. We also identified hydropower reservoir operation impact patterns which show how energy production and demand can influence seasonality in streamflow in a tropical environment.

The multi-model framework combined with the application of a daily varying drought threshold turned out to be a suitable method to analyse human impacted hydrological drought. To our knowledge, such a distributed hydrological model as J2000 had never been applied to such a data scarce tropical environment. Linking the physically based model with a reservoir operation model is an effective approach to assess such a complex river system with a large number of recently built operating hydropower reservoirs and a basin transfer. In combination with the hydrological drought analysis it represents an innovative integrated framework for drought risk characterization which can be applied to any data scarce catchment worldwide where hydropower is developed, also suitable for snowmelt driven environments.

We conclude that the calibrated model setup combined with the streamflow drought analysis provides a valuable tool to support cross-sectoral water management and planning in a tropical monsoon dominated region of strong seasonality.

The tropical mountainous VGTB Basin in Central Vietnam is frequently affected by hydrological drought and related salt water intrusion. To a large extent this is attributable to increasing water abstractions for irrigation and domestic water supply as well as to hydropower development. Based on a coupled modelling approach, the impacts of recent hydropower development on downstream streamflow and drought risk were assessed for this mesoscale basin. To quantify such impacts for different time scales, a naturalized and a reconstructed simulated time series was needed to be compared with the observed time series. The J2000 model was used to simulate reservoir inflow discharge and the naturalized flow for the target points. The HEC-ResSim reservoir operation model simulated following on the discharge from all major existing and planned hydropower stations in the basin as well as the reconstructed streamflow for the main river branches Vu Gia and Thu Bon. Naturalized and reservoir impacted drought risk was assessed by applying a threshold based drought severity analysis.

Efficiency statistics for both models show good model performance. A strong impact of reservoir operation on downstream discharge at the daily, monthly, seasonal and annual scale was detected for four discharge stations relevant for water allocation points of the river basin. In accordance with the reports from local stakeholders, we found a stronger hydrological drought risk for the reconstructed streamflow at Thanh My and Ai Nghia station, located in the upstream of Da Nang city and large rice irrigation systems facing water shortage in the dry season. Uncertainties related to climatic and reservoir input data, models and parameters were not yet quantified but we observed a strong source of uncertainties related to the reservoir operational rules which were not harmonized with the designed dimensions of the reservoirs which leads to model errors. Incorporating the adapted dimension in turn allowed quantifying the volume differences. Further major uncertainties could be identified for the precipitation input data especially for the Vu Gia sub-basin were the measurement station density is extremely low.

We conclude that the calibrated model setup provides a valuable tool to support cross-sectorial water management and planning in the region suitable to be transferred to similar regions. The threshold level method proved to be an efficient method to estimate the drought in the tropical monsoon dominated area, which however have strong seasonal characteristics. After a thorough uncertainty analysis and the development of scenarios under changing climatic and water demand conditions, a drought management plan for the region will be developed.

References

Adam, J. C., Haddeland, I., Su, F., and Lettenmaier, D. P.: Simulation of reservoir influences on annual and seasonal streamflow changes for the Lena, Yenisei, and Ob' rivers, Journal of Geophysical Research: Atmospheres, 112, n/a-n/a, doi:10.1029/2007JD008525, 2007.

Adam, J. C. and Lettenmaier, D. P.: Application of New Precipitation and Reconstructed Streamflow Products to Streamflow Trend Attribution in Northern Eurasia, J. Climate, 21, 1807–1828, doi:10.1175/2007JCLI1535.1, 2008.

AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T., and Lund, J.: Water and climate: Recognize anthropogenic drought, Nature, 524, 409–411, doi:10.1038/524409a, 2015.

Ahn, K.-H. and Merwade, V.: Quantifying the relative impact of climate and human activities on streamflow, Journal of Hydrology, 515, 257–266, doi:10.1016/j.jhydrol.2014.04.062, 2014.

Arrigoni, A. S., Greenwood, M. C., and Moore, J. N.: Relative impact of anthropogenic modifications versus climate change on the natural flow regimes of rivers in the Northern Rocky Mountains, United States, Water Resour. Res., 46, n/a-n/a, doi:10.1029/2010WR009162, 2010.

Avitabile, V., Schultz, M., Herold, N., Bruin, S. de, Pratihast, A. K., Manh, C. P., Quang, H. V., and Herold, M.: Carbon emissions from land cover change in Central Vietnam, Carbon Management, 7, 333–346, doi:10.1080/17583004.2016.1254009, 2016.

Bao, Z., Zhang, J., Wang, G., Fu, G., He, R., Yan, X., Jin, J., Liu, Y., and Zhang, A.: Attribution for decreasing streamflow of the Haihe River basin, northern China: Climate variability or human activities?, Journal of Hydrology, 460-461, 117–129, doi:10.1016/j.jhydrol.2012.06.054, 2012.

~~Beven, K. and Binley, A.: The future of distributed models: Model calibration and uncertainty prediction, Hydrol. Process., 6, 279–298, 1992.~~Biskop S.: Advancing the understanding of hydro-climatic controls on water balance and lake-level variability in the Tibetan Plateau - Hydrological modeling in data-scarce lake basins integrating multisource data. PhD Thesis, Friedrich Schiller University of Jena, 2016.

Böhner, J., Köther, R., Conrad, O., Gross, J., Ringeler, A., and Selige, T.: Soil regionalisation by means of terrain analysis and process parameterisation, European Soil Bureau, Research Report No. 7, 10 pp., 2002.

Bonell, M. and Bruijnzeel, L.: Forests Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management, Cambridge University Press., Cambridge, 2005.

Budyko, M. I.: Climate and life, International geophysics series, 18, Academic Press, New York, 1 online resource (xvii, 508, 1974.

Chang, J., Zhang, H., Wang, Y., and Zhu, Y.: Assessing the impact of climate variability and human activity to streamflow variation, Hydrol. Earth Syst. Sci. Discuss., 12, 5251–5291, doi:10.5194/hessd-12-5251-2015, 2015.

Deb, K., Korhonen, P., and Wallenius, J.: A fast and elitist multi-objective genetic algorithm: NSGA-II, IEEE Transactions on Evolutionary Computations, 6, 182–197, 2002.

Deitch, M. J., Merenlender, A. M., and Feirer, S.: Cumulative Effects of Small Reservoirs on Streamflow in Northern Coastal California Catchments, Water Resour Manage, doi:10.1007/s11269-013-0455-4, 2013.

Di Baldassarre, G., Martinez, F., Kalantari, Z., and Viglione, A.: Drought and flood in the Anthropocene: feedback mechanisms in reservoir operation, Earth Syst. Dynam., 8, 225–233, https://doi.org/10.5194/esd-8-225-2017, 2017.

Fink, M., Krause, P., Kralisch, S., Bende-Michl, U., and Flügel, W.-A.: Development and application of the modelling system J2000-S for the EU-water framework directive, Adv. Geosci., 11, 123–130, doi:10.5194/adgeo-11-123-2007, 2007.

Fink, M., Fischer, N., Frührer, N., Firoz, A., Viet, T. Q., Laux, P., and Flügel, W. A.: Distributive hydrological modeling of a monsoon dominated river system in central Vietnam, in: MODSIM2013, 20th International Congress on Modelling and Simulatio, Piantadosi, J., and Anderssen, R. S. (Eds.), MODSIM 2013, Australia, December 2013, Australia, 1826–12832, 2013.

Fischer, C., Kralisch, S., Krause, P., and Flügel, W.-A.: An Integrated, Fast and Easily Useable Software Toolbox Allowing Comparative and Complementary Application of Various Parameter Sensitivity Analysis Methods, in: 2012 International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Seppelt, R., Voinov, A. A., Lange, S., and Bankamp, D. (Eds.), Sixth Biennial Meeting, Leipzig, Germany, IAHS, 2012.

Fleig, A. K., Tallaksen, L. M., Hisdal, H., and Demuth, S.: A global evaluation of streamflow drought characteristics, Hydrol. Earth Syst. Sci., 10, 535–552, doi:10.5194/hess-10-535-2006, 2006.

General Statistics Office: Statistical Yearbook of Vietnam, Statistical Publishing House, Hanoi, Viet Nam, 2014.

He, X., Wada, Y., Wanders, N., and Sheffield, J.: Intensification of hydrological drought in California by human water management, Geophys. Res. Lett., 44, 1777–1785, https://doi.org/10.1002/2016GL071665, 2017

Hisdal, H., Tallaksen, M. L., Clausen, B., Peters, E., and Gustard, A.: Ch.5 Hydrological Drought Characteristics, in: Hydrological Droughts: Process and Estimation Methods for Streamflow and Groundwater, Developments in Water Science, Elsevier, Amsterdam, 139–198, 2004.

Hoanh, C. T., Jirayoot, K., Lacombe, G., and Srinetr, V.: Impacts of climate change and development on Mekong flow regime, First assessment – 2009. MRC Technical Paper No. 29. Mekong River Commission, Vientiane, Lao PDR, 2010.

Hu, Z., Wang, L., Wang, Z., Hong, Y., and Zheng, H.: Quantitative assessment of climate and human impacts on surface water resources in a typical semi-arid watershed in the middle reaches of the Yellow River from 1985 to 2006, Int. J. Climatol., 35, 97–113, doi:10.1002/joc.3965, 2015.

ICEM: Strategic Environmental Assessment of the Quang Nam Province Hydropower Plan for the Vu Gia-Thu Bon River Basin, Prepared for the ADB, MONRE, MOITT & EVN, Hanoi, Viet Nam., 205 pp., 2008.

Klipsch, J. D. and Hurst, M. B.: HEC-ResSim Reservoir System Simulation Version 3.1: User's Manual, US Army Corps of Engineers, Institute for Water Resources, Davis, CA, 2013.

Kralisch, P. and Krause, P.: JAMS - A Framework for Natural Resource Model Development and Application., in: Proceedings of the iEMSs Third Biannual Meeting, Voinov, A., Jakeman, A., and Rizzoli, A. E. (Eds.), iEMSs Third Biannual Meeting, Burlington, USA, IAHS, 1–4, 2006.

Krause, P.: Quantifying the impact of land use changes on the water balance of large catchments using the J2000 model, Physics and Chemistry of the Earth, Parts A/B/C, 27, 663–673, doi:10.1016/S1474-7065(02)00051-7, 2002.

Krause, P., Boyle, D. P., and Bäse, F.: Comparison of different efficiency criteria for hydrological model assessment, Adv. Geosci., 5, 89–97, doi:10.5194/adgeo-5-89-2005, 2005.

Lauri, H., Moel, H. de, Ward, P. J., Räsänen, T. A., Keskinen, M., and Kummu, M.: Future changes in Mekong River hydrology: Impact of climate change and reservoir operation on discharge, Hydrol. Earth Syst. Sci., 16, 4603–4619, doi:10.5194/hess-16-4603-2012, 2012.

López-Moreno, J. I., Zabalza, J., Vicente-Serrano, S. M., Revuelto, J., Gilaberte, M., Azorin-Molina, C., Morán-Tejeda, E., García-Ruiz, J. M., and Tague, C.: Impact of climate and land use change on water availability and reservoir management: scenarios in the Upper Aragón River, Spanish Pyrenees, The Science of the total environment, 493, 1222–1231, doi:10.1016/j.scitotenv.2013.09.031, 2014.

Mateus, C. and Tullos, D.: Reliability, sensitivity, and uncertainty of reservoir performance under climate variability in basins with different hydrogeologic settings in Northwestern United States, International Journal of River Basin Management, 15, 21–37, doi:10.1080/15715124.2016.1247361, 2016.

McClelland, J. W.: Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change, J. Geophys. Res., 109, doi:10.1029/2004JD004583, 2004.

McCune, B. and Keon, D.: Equations for potential annual direct incident radiation and heat load, Journal of Vegetation Science, 13, 603–606, doi:10.1111/j.1654-1103.2002.tb02087.x, 2002.

Min, S.-K., Zhang, X., Zwiers, F. W., and Hegerl, G. C.: Human contribution to more-intense precipitation extremes, Nature, 470, 378–381, doi:10.1038/nature09763, 2011.

MOIT: Decision Number 6801/QD-BCT, Decision on Dak Mi 4 Reservoir Operation,, Ministry of Investment and Trade, Socialist Republic of Vietnam, Hanoi, Viet Nam, 2011.

MOIT: Decision for Hydropower Plant Operation: Technical Document, Ministry of Investment and Trade, Socialist Republic of Vietnam, 2015a.

Moriasi, D. N., Arnold, J. G., van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L.: Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations, Transactions of the ASABE, 50, 885–900, doi:10.13031/2013.23153, 2007.

MOIT: Decision for Hydropower Plant Operation: Technical Document, Ministry of Investment and Trade, Socialist Republic of Vietnam, 2015b.

Nauditt, A., Firoz, A., Viet, T. Q., Fink, M., Stolpe, H., and Ribbe, L.: Hydrological drought risk assessment in an anthropogenically impacted tropical catchment, in: Land Use and Climate Change Interactions in Central Vietnam: LUCCi, Nauditt, A., and Ribbe, L. (Eds.), Water Resources Management and Development, Springer Book Series, 2017.

Nepal, S., Krause, P., Flügel, W.-A., Fink, M., and Fischer, C.: Understanding the hydrological system dynamics of a glaciated alpine catchment in the Himalayan region using the J2000 hydrological model, Hydrol. Process., 28, 1329–1344, doi:10.1002/hyp.9627, 2014.

Nicolle, P., Pushpalatha, R., Perrin, C., François, D., Thiéry, D., Mathevet, T., Le Lay, M., Besson, F., Soubeyroux, J.-M., Viel, C., Regimbeau, F., Andréassian, V., Maugis, P., Augeard, B., and Morice, E.: Benchmarking hydrological models for low-flow simulation and forecasting on French catchments, Hydrol. Earth Syst. Sci., 18, 2829–2857, doi:10.5194/hess-18-2829-2014, 2014.

~~Patterson, L. A., Lutz, B., and Doyle, M. W.: Climate and direct human contributions to changes in mean annual streamflow in the South Atlantic, USA, Water Resources Research, 49, 7278–7291, doi:10.1002/2013WR014618, 2013.~~

Pedroso, R., Tran, D. H., Thi, M. H. N., van Le, A., Ribbe, L., Dang, K. T., and Le, K. P.: Cropping systems in the Vu Gia Thu Bon river basin, Central Vietnam: On farmers' stubborn persistence in predominantly cultivating rice, NJAS - Wageningen Journal of Life Sciences, doi:10.1016/j.njas.2016.11.001, 2016.

Penedo-Julien, S., Nauditt, A.; Künne, A., Souvignet, M., Fischer, C., Krause, P. 2017. Hydrological modelling to assess runoff generation from semi-arid Andean headwater catchments to inform water management in central Chile, in: Andean Hydrology, eds. Diego Rivera, Elsevier, 2017, accepted for publication and under revision.

Pfenning, B., Kipka, H., Fink, M., Krause, P., and Flügel, W. A.: Development of an extended spatially distributed routing scheme and its impact on process oriented hydrological modelling results, in: Joint IAHS & IAH International Convention, Hyderabad, 37–43, 2009.

Pilgrim, D. H., Chapman, T. G., and Doran, D. G.: Problems of rainfall-runoff modelling in arid and semiarid regions, Hydrological Sciences Journal, 33, 379–400, doi:10.1080/02626668809491261, 1988.

PPC: Master Plan for Electricity Development in Quang Nam Province, Period of 2006-2010 Towards 2015, Provincial Peoples Committee, Quangnam, 2006.

Prudhomme, C., Parry, S., Hannaford, J., Clark, D. B., Hagemann, S., and Voss, F.: How Well Do Large-Scale Models Reproduce Regional Hydrological Extremes in Europe?, J. Hydrometeor, 12, 1181–1204, doi:10.1175/2011JHM1387.1, 2011.

Quangnam Statistical Office: Statistical Yearbook of Quang Nam 2010-2014, Statistical Publishing House, Hanoi, Viet Nam, 2014.

Räsänen, T. A., Koponen, J., Lauri, H., and Kummu, M.: Downstream Hydrological Impacts of Hydropower Development in the Upper Mekong Basin, Water Resour Manage, 26, 3495–3513, doi:10.1007/s11269-012-0087-0, 2012.

Räsänen, T. A., Someth, P., Lauri, H., Koponen, J., Sarkkula, J., and Kummu, M.: Observed river discharge changes due to hydropower operations in the Upper Mekong Basin, Journal of Hydrology, 545, 28–41, doi:10.1016/j.jhydrol.2016.12.023, 2017.

Refsgaard, J. C., van der Sluijs, J. P., Brown, J., and van der Keur, P.: A framework for dealing with uncertainty due to model structure error, Advances in Water Resources, 29, 1586–1597, doi:10.1016/j.advwatres.2005.11.013, 2006.

Refsgaard, J. C., van der Sluijs, J. P., Højberg, A. L., and Vanrolleghem, P. A.: Uncertainty in the environmental modelling process – A framework and guidance, Environmental Modelling & Software, 22, 1543–1556, doi:10.1016/j.envsoft.2007.02.004, 2007.RCHM: Time series of meteo-hydrologic data in 1977–2010 in the Vu Gia Thu Bon River Basin, Regional Centre for Hydro-meteorology, 2013.

Ribbe, L., Viet, T. C., Firoz, A., Nguyen, A. T., Nguyen, U., and Nauditt, A.: Integrated River Basin Management in the Vu Gia Thu Bon Basin, in: Land Use and Climate Change Interactions in Central Vietnam: LUCCi, Nauditt, A., and Ribbe, L. (Eds.), Water Resources Management and Development, Springer Book Series, 2017.

Rossi, A., Massei, N., Laignel, B., Sebag, D., and Copard, Y.: The response of the Mississippi River to climate fluctuations and reservoir construction as indicated by wavelet analysis of streamflow and suspended-sediment load, 1950–1975, Journal of Hydrology, 377, 237–244, doi:10.1016/j.jhydrol.2009.08.032, 2009.

Santer, B. D., Mears, C., Doutriaux, C., Caldwell, P., Gleckler, P. J., Wigley, T. M. L., Solomon, S., Gillett, N. P., Ivanova, D., Karl, T. R., Lanzante, J. R., Meehl, G. A., Stott, P. A., Taylor, K. E., Thorne, P. W., Wehner, M. F., and Wentz, F. J.: Separating signal and noise in atmospheric temperature changes: The importance of timescale, J. Geophys. Res., 116, n/a-n/a, doi:10.1029/2011JD016263, 2011.

Seibert, J. and McDonnell, J. J.: Land-cover impacts on streamflow: A change-detection modelling approach that incorporates parameter uncertainty, Hydrological Sciences Journal, 55, 316–332, doi:10.1080/02626661003683264, 2010.

Sharon A. Johnson, Jery R. Stedinger, and Konstantin Staschus: Heuristic operating policies for reservoir system simulation, Water Resources Research, 27, 673–685, doi:10.1029/91WR00320, 1991.

Song, W.-z., Jiang, Y.-z., Lei, X.-h., Wang, H., and Shu, D.-c.: Annual runoff and flood regime trend analysis and the relation with reservoirs in the Sanchahe River Basin, China, Quaternary International, 380-381, 197–206, doi:10.1016/j.quaint.2015.01.049, 2015.

Souvignet, M., Laux, P., Freer, J., Cloke, H., Thinh, D. Q., Thuc, T., Cullmann, J., Nauditt, A., Flügel, W.-A., Kunstmann, H., and Ribbe, L.: Recent climatic trends and linkages to river discharge in Central Vietnam, Hydrol. Process., 28, 1587–1601, doi:10.1002/hyp.9693, 2013.

Stahl, K.: Hydrological Drought: A Study across Europe, PhD, Albert-Ludwigs-Universität Freiburg, Geowissenschaftlichen Fakultät, Freiburg, 144 pp., 2011.

Sung, J. H. and Chung, E.-S.: Development of streamflow drought severity-duration-frequency curves using the threshold level method, Hydrol. Earth Syst. Sci., 18, 3341–3351, doi:10.5194/hess-18-3341-2014, 2014.

Tallaksen, M. L., Madsen, H., and Clausen, B.: On the definition and modelling of streamflow drought duration and deficit volume, Hydrological Sciences Journal, 42, 15–33, doi:10.1080/02626669709492003, 2009.

Tang, J., Yin, X.-A., Yang, P., and Yang, Z.: Assessment of Contributions of Climatic Variation and Human Activities to Streamflow Changes in the Lancang River, China, Water Resour Manage, 28, 2953–2966, doi:10.1007/s11269-014-0648-5, 2014.

Tesfa, T. K., Li, H.-Y., Leung, L. R., Huang, M., Ke, Y., Sun, Y., and Liu, Y.: A subbasin-based framework to represent land surface processes in an Earth system model, Geosci. Model Dev., 7, 947–963, doi:10.5194/gmd-7-947-2014, 2014.

Trenberth, K. E.: Attribution of climate variations and trends to human influences and natural variability, WIREs Clim Change, 2, 925–930, doi:10.1002/wcc.142, 2011.

USACE: HEC Res Sim, U. S. Army Corps of Engineers, Hydrologic Engineering Center, 2007.

van Huijgevoort, M. H. J., Hazenberg, P., van Lanen, H. A. J., and Uijlenhoet, R.: A generic method for hydrological drought identification across different climate regions, Hydrol. Earth Syst. Sci., 16, 2437–2451, doi:10.5194/hess-16-2437-2012, 2012.

van Lanen, H. A., Laaha, G., Kingston, D. G., Gauster, T., Ionita, M., Vidal, J.-P., Vlnas, R., TALLAKSEN, L. M., Stahl, K., Hannaford, J., Delus, C., Fendekova, M., Mediero, L., Prudhomme, C., Rets, E., Romanowicz, R. J., Gailliez, S., Wong, W. K., Adler, M.-J., Blauhut, V., Caillouet, L., Chelcea, S., Frolova, N., Gudmundsson, L., Hanel, M., Haslinger, K., Kireeva, M., Osuch, M., Sauquet, E., Stagge, J. H., and van Loon, A. F.: Hydrology needed to manage droughts: The 2015 European case, Hydrol. Process., 30, 3097–3104, doi:10.1002/hyp.10838, 2016.

van Lanen, H. A. J., Wanders, N., Tallaksen, L. M., and van Loon, A. F.: Hydrological drought across the world: Impact of climate and physical catchment structure, Hydrol. Earth Syst. Sci., 17, 1715–1732, doi:10.5194/hess-17-1715-2013, 2013.

van Loon, A. F. and van Lanen, H. A. J.: A process-based typology of hydrological drought, Hydrol. Earth Syst. Sci., 16, 1915–1946, doi:10.5194/hess-16-1915-2012, 2012.

van Loon, A. F. and Laaha, G.: Hydrological drought severity explained by climate and catchment characteristics, Journal of Hydrology, 526, 3–14, doi:10.1016/j.jhydrol.2014.10.059, 2015.

van Loon, A. F., Gleeson, T., Clark, J., van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., TALLAKSEN, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., and van Lanen, H. A. J.: Drought in the Anthropocene, Nature Geosci, 9, 89–91, doi:10.1038/ngeo2646, 2016.

Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B.: Global Water Resources: Vulnerability from Climate Change and Population Growth, Science, 289, 284–288, doi:10.1126/science.289.5477.284, 2000.

Viet, T. Q., Nauditt, A., Ribbe, L A., and Firoz, A.:Biophysical and Socio-economic Features of the LUCCi-Project Region: The Vu Gia Thu Bon River Basin , in: Land Use and Climate Change Interactions in Central Vietnam: LUCCi, Nauditt, A., and Ribbe, L. (Eds.), Water Resources Management and Development, Springer Book Series, 2017.

Wada, Y., van Beek, L. P. H., Wanders, N., and Bierkens, M. F. P.: Human water consumption intensifies hydrological drought worldwide, Environ. Res. Lett., 8, 34036, doi:10.1088/1748-9326/8/3/034036, 2013.

Wanders, N., Wada, Y., and Van Lanen, H. A. J.: Global hydrological droughts in the 21st century under a changing hydrological regime, Earth Syst. Dynam., 6, 1–15, https://doi.org/10.5194/esd-6-1-2015, 2015.

Wagner, T., Themeßl, M., Schüppel, A., Gobiet, A., Stigler, H., and Birk, S.: Impacts of climate change on stream flow and hydro power generation in the Alpine region, Environ Earth Sci, 76, 33, doi:10.1007/s12665-016-6318-6, 2017.

Walker, W. E., Harremoës, P., Rotmans, J., van der Sluijs, J. P., van Asselt, M., Janssen, P., and Krayer von Krauss, M. P.: Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support, Integrated Assessment, 4, 5–17, doi:10.1076/iaij.4.1.5.16466, 2003.

Wang, D. and Hejazi, M.: Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States, Water Resources Research, 47, doi:10.1029/2010WR010283, 2011.

Wang, H., Chen, L., and Yu, X.: Distinguishing human and climate influences on streamflow changes in Luan River basin in China, CATENA, doi:10.1016/j.catena.2015.02.013, 2015.

Wang, S., Yan, M., Yan, Y., Shi, C., and He, L.: Contributions of climate change and human activities to the changes in runoff increment in different sections of the Yellow River, Quaternary International, 282, 66–77, doi:10.1016/j.quaint.2012.07.011, 2012.

Ye, B., Yang, D., and Kane, D. L.: Changes in Lena River streamflow hydrology: Human impacts versus natural variations, Water Resour. Res., 39, n/a-n/a, doi:10.1029/2003WR001991, 2003.

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., and Tockner, K.: A global boom in hydropower dam construction, Aquat Sci, 77, 161–170, doi:10.1007/s00027-014-0377-0, 2015.

Zelenhasić, E. and Salvai, A.: A method of streamflow drought analysis, Water Resour. Res., 23, 156–168, doi:10.1029/WR023i001p00156, 1987.

Zhang, A., Zhang, C., Fu, G., Wang, B., Bao, Z., and Zheng, H.: Assessments of Impacts of Climate Change and Human Activities on Runoff with SWAT for the Huifa River Basin, Northeast China, Water Resour Manage, 26, 2199–2217, doi:10.1007/s11269-012-0010-8, 2012.

Zhang, R., Zhang, S.-h., Xu, W., Wang, B.-d., and Wang, H.: Flow regime of the three outlets on the south bank of Jingjiang River, China: An impact assessment of the Three Gorges Reservoir for 2003–2010, Stoch Environ Res Risk Assess, 29, 2047–2060, doi:10.1007/s00477-015-1121-6, 2015.

Zhang, X., Zwiers, F. W., Hegerl, G. C., Lambert, F. H., Gillett, N. P., Solomon, S., Stott, P. A., and Nozawa, T.: Detection of human influence on twentieth-century precipitation trends, Nature, 448, 461–465, doi:10.1038/nature06025, 2007.

Zhou, Y., Zhang, Q., Li, K., and Chen, X.: Hydrological effects of water reservoirs on hydrological processes in the East River (China) basin: Complexity evaluations based on the multi-scale entropy analysis, Hydrol. Process., 26, 3253–3262, doi:10.1002/hyp.8406, 2012.

Item	Unit	A Vuong	Song Tranh 2	Dak Mi 4 A	Dak Mi 4 B	Song Bung 4	Song Bung 5	Song Bung 6	Song Con 2
First year of operation	Year	2008	2011	2011	2011	2015	2014	2014	2009
River System		VuGia	ThuBon	Vu Gia	Vu Gia	VuGia	VuGia	VuGia	VuGia
Catchment Area	km²	682	1100	1125	29	1448	2369	2386	250.1
Mean Annual Flow	$m^3 s^{-1}$	39.8	106	67.80	1.1	73.7	118	119	13.2
Full Supply Level (FSL)	m.a.s.l	380	175	258	106	222.5	60	31.8	275
Minimum Operation level (MOL)	m.a.s.l	340	138	240	105	195	58.5	~~31~~30.~~8~~0	274
Reservoir Area at FSL	km²	9.1	21.5	10.4	0.45	15.65	1.68	0.398	0.13
Reservoir Area at MOL	km²	4.3	9.3	7	0.4	7.8	1.68	0.398	0.12
Reservoir Total Storage	$10^6 m^3$	343.6	733.4	310	2.6	510.8	20.27	3.29	1.2
Reservoir Active Storage	$10^6 m^3$	266.5	521.1	158	0.6	233.99	17.82	3.29	0.7
Spillway Design Flood	$m^3 s^{-1}$	5730	11069	7864	642	15427	16780	17011	3217
Maximum Tail Water Level	m.a.s.l	86.6	87.5	108	71.5	121.3	32.33	15.5	29.7
Normal Tail Water level	m.a.s.l	58	71	106	67.5	101.6	30.7	12	18
Design Head	m	300	88.3	135	37.5	112.4	27	13.4	246
Total Turbine Design Discharge	$m^3 s^{-1}$	78.4	209.7	121	122	172.7	239.24	243.2	22.8
Installed Capacity	MW	210	162	141	39	156	57	29	46
Annual Average Energy Potential	GWh	825	620.7	582	161	618	220	151	168

Table 1: Reservoirs in the VGTB River basin (MOIT, 2015b; ICEM, 2008; MOIT, 2015a)

Station	Thu Bon (Nong Son)		Vu Gia (Thanh My)
Time	Calibration	Validation	Validation
Frame	01.11.1996 – 31.10.2000	01.11.2000 – 31.10.2005	01.11.1996 – 31.10.2005
E2	0.856	0.869	0.610
logE2	0.863	0.856	0.776
R^2	0.869	0.870	0.774
Pbias	-10.6	-5.37	8.59

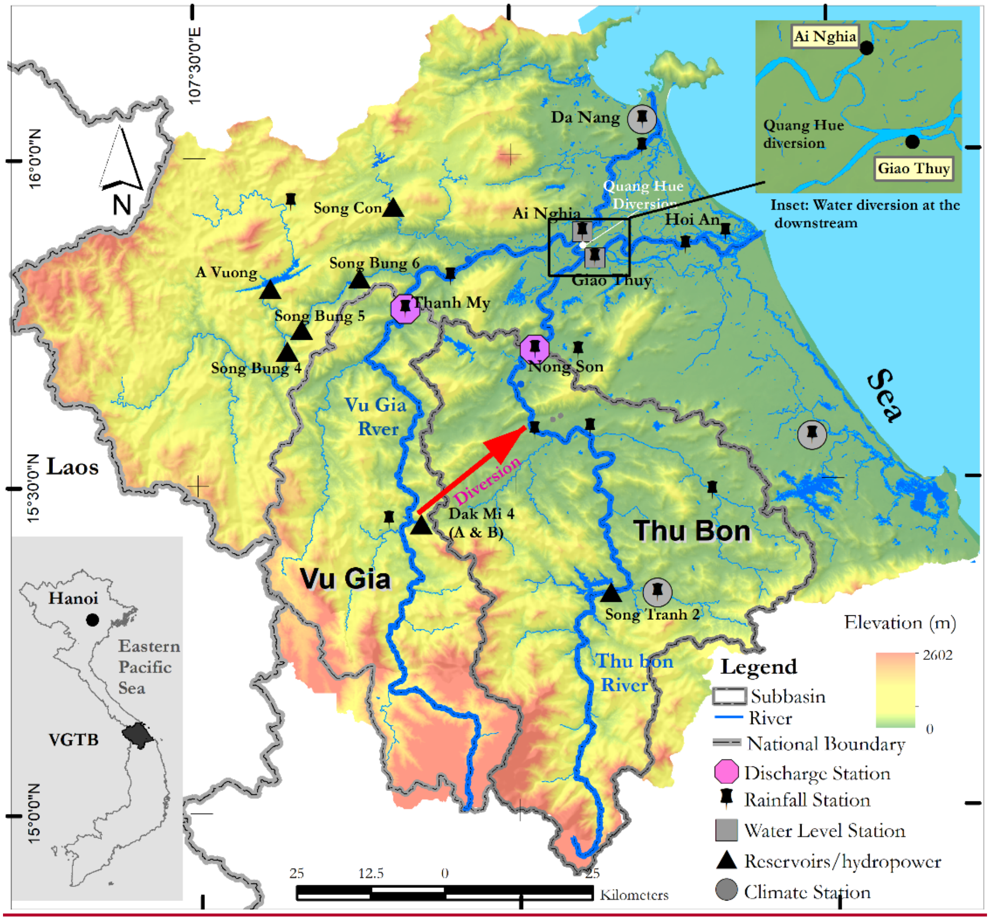
Table 2: Performance of efficiency statistics for the J2000 hydrological model: E2, Nash-Sutcliffe efficiency; logE2 Nash-Sutcliffe efficiency with logarithmic values; R^2, coefficient of determination and Pbias relative volume error in percent.

Stations	Nong Son	Thanh My
	01.01.2011-31.12.2013	01.01.2011-31.12.2013
E2	0.907	0.716
logE2	0.79	0.74
R^2	0.954	0.809
Pbias	0.0052	-0.077

Table 3: Performance statistics: Nash Sutcliff Efficiency, (E2), logE2, R^2, & Pbias of the reservoir model for the two gauging stations

		Nong Son	Giao Thuy	Thanh My	Ai Nghia	Combined
a) Drought duration (%)		-17.17	-30.43	37.08	27.20	-1.81
b) Changes of flow (%)						
	Ann	19.46	10.09	-37.82	-17.41	-13.82
	Dry	43.3	27.23	-44.67	-7.91	32.54
	Wet	10.84	3.61	-35.03	-21.10	-106.53
c) Changes of flow (in m^3s^{-1})						
	Ann	51.52	38.32	-51.66	-52.14	-7.32
	Dry	45.65	42.51	-26.43	-9.97	19.31
	Wet	63.25	29.93	-102.12	-136.47	-17.48

Table. 4. Impact of human alterations on drought intensity and changes of flow in the VGTB for the period 1980-2013 on an annual and seasonal scale. a) Drought duration is calculated based on percentage changes of the number of drought days from naturalised condition to reconstructed condition (Fig 9). b) Changes of flow (%), are calculated based on the percentage changes of the mean flow between the naturalised and reconstructed streamflow for the corresponding time frame. c) The changes of flow are calculated based on mean differences of reconstructed streamflow from the naturalised mean flow. The positive value indicates increasing flow or drought intensity in relation to the naturalised condition.


Ai Nghia
Quang Hue diversion
Giao Thuy
Inset: Water diversion at the downstream
Da Nang
Quang Hue Diversion
Hoi An
Song Con
A Vuong
Song Bung 6
Song Bung 5
Song Bung 4
Thanh My
Nong Son
Vu Gia Rver
Laos
Diversion
Dak Mi 4 (A & B)
Thu Bon
Vu Gia
Song Tranh 2
Thu bon River
Sea
Hanoi
Eastern Pacific Sea
VGTB
Elevation (m)
2602
0
Legend
Subbasin
River
National Boundary
Discharge Station
Rainfall Station
Water Level Station
Reservoirs/hydropower
Climate Station
25 12.5 0 25
Kilometers
107°30'0"E
16°0'0"N
15°30'0"N
15°0'0"N
N

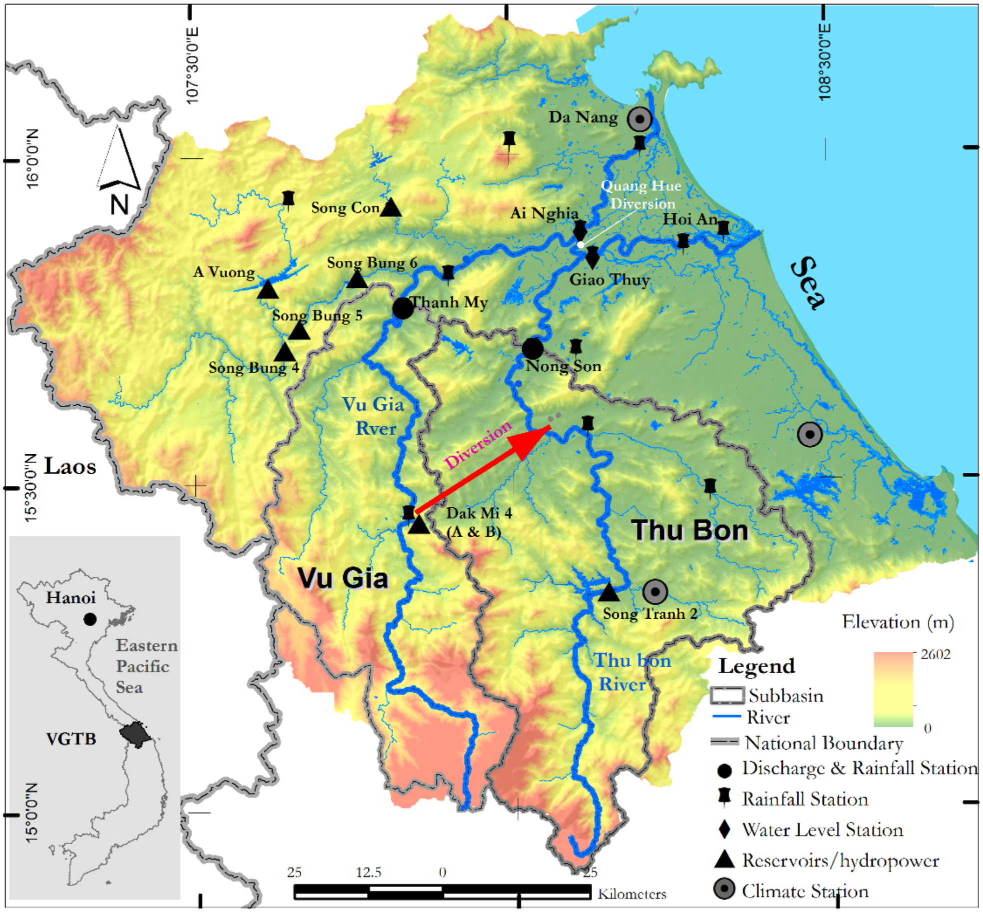


Figure 1: Topographical map of the VGTB river basin showing hydrology, hydro-meteorological monitoring network and eight major hydropower reservoirs as well the diversion (in red color) from VuGia to Thu Bon at Dak Mi 4 hydropower plant

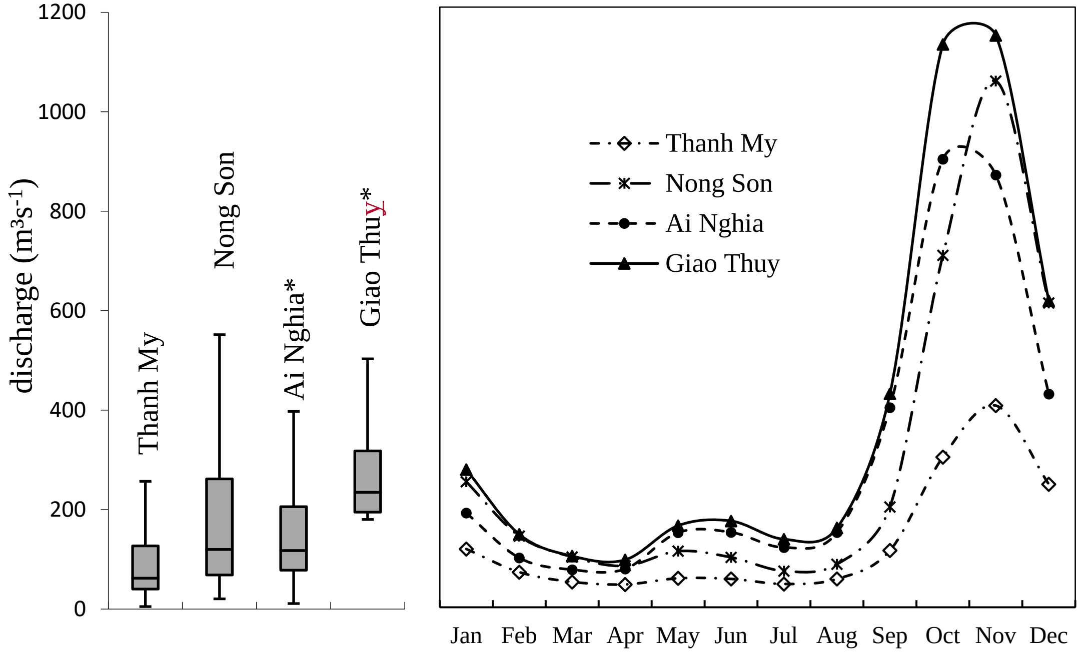


Figure 2: Mean monthly discharge at the four stations under study for the period 1979-2013 (right side). Naturalized flow data for Ai Nghia and Giao Thuy stations were simulated with J2000. Box plots (left side) indicate the 25th , 50th (median) and 75th percentiles %ile, 50%ile (median) and 75%ile of the daily streamflow time series. Outliers have been removed from the plots. The whiskers are defined as the first quartile minus 1.5*IQR and the third quartile plus 1.5*IQR.

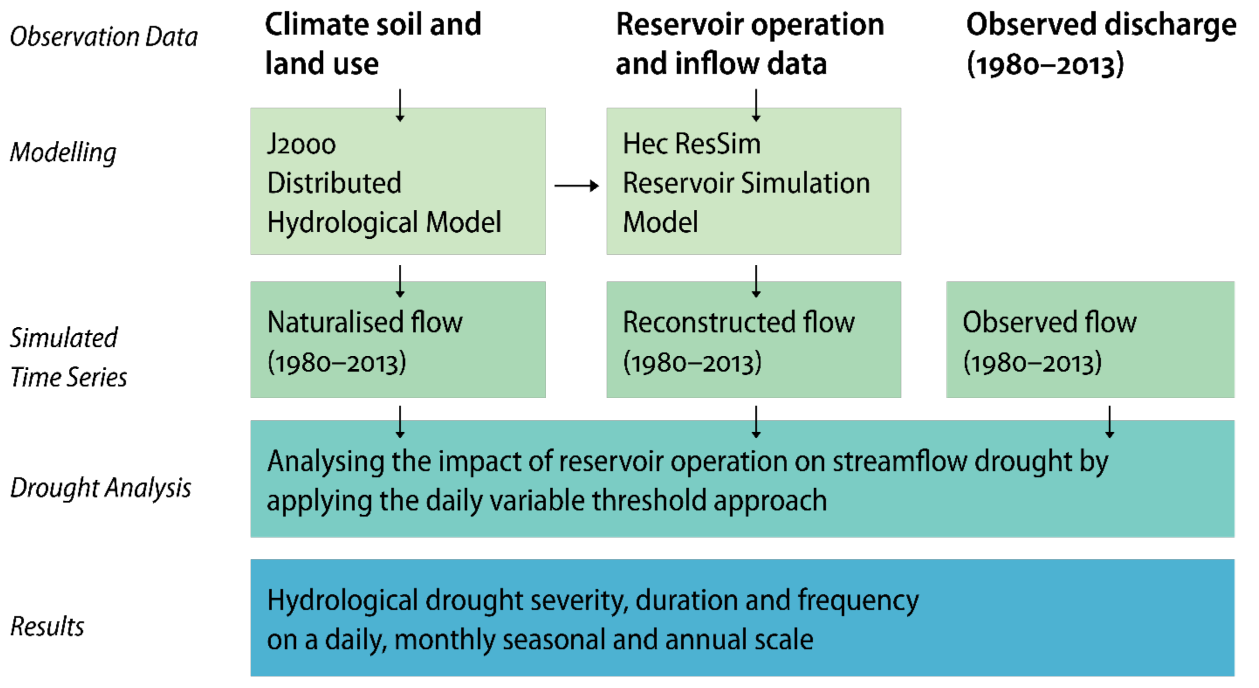


Figure 3: Drought assessment framework- 1) Distributed Hydrological Model (J2000) (Krause, 2002) provides the simulated inflow data at various nodes and naturali~~z~~sed streamflow 2) HEC-ResSim simulates reconstructed streamflow for the entire observation period and 3) Streamflow Deficiency analysis through threshold level methods provides information about the drought duration and extent~~ on different temporal pattern~~. ~~And t~~The reservoir impact on the downstream ~~stream~~flow ~~has ~~have been assessed based on the reconstructed and ~~naturalized ~~naturalised streamflow differences.

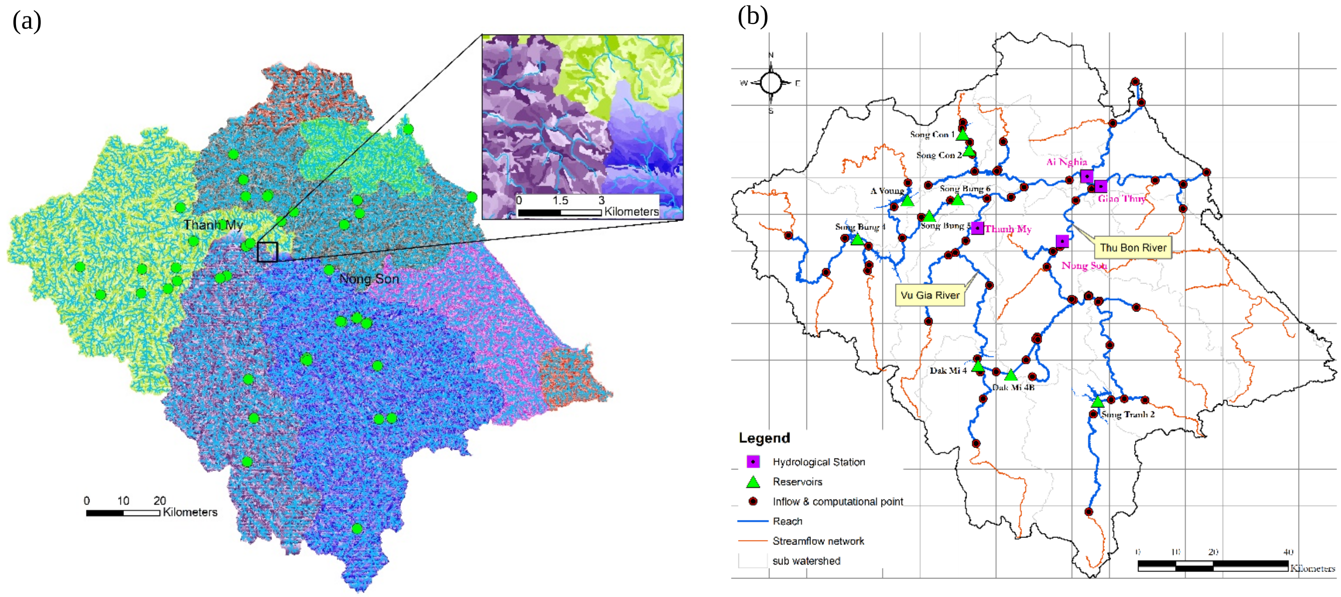


Figure 4: Coupling of J2000 model with the HEC-ResSim model. (a) HRU of the J2000 model along the major sub-basin, virtual discharge stations (green points) for which J2000 simulated time series for the reservoir inflow and relevant abstraction points in the downstream area. (b) The HEC-ResSim model node network, J2000 inflow discharge points (brown dots) and the location of the reservoirs that haves been incorporate within the reservoir model.

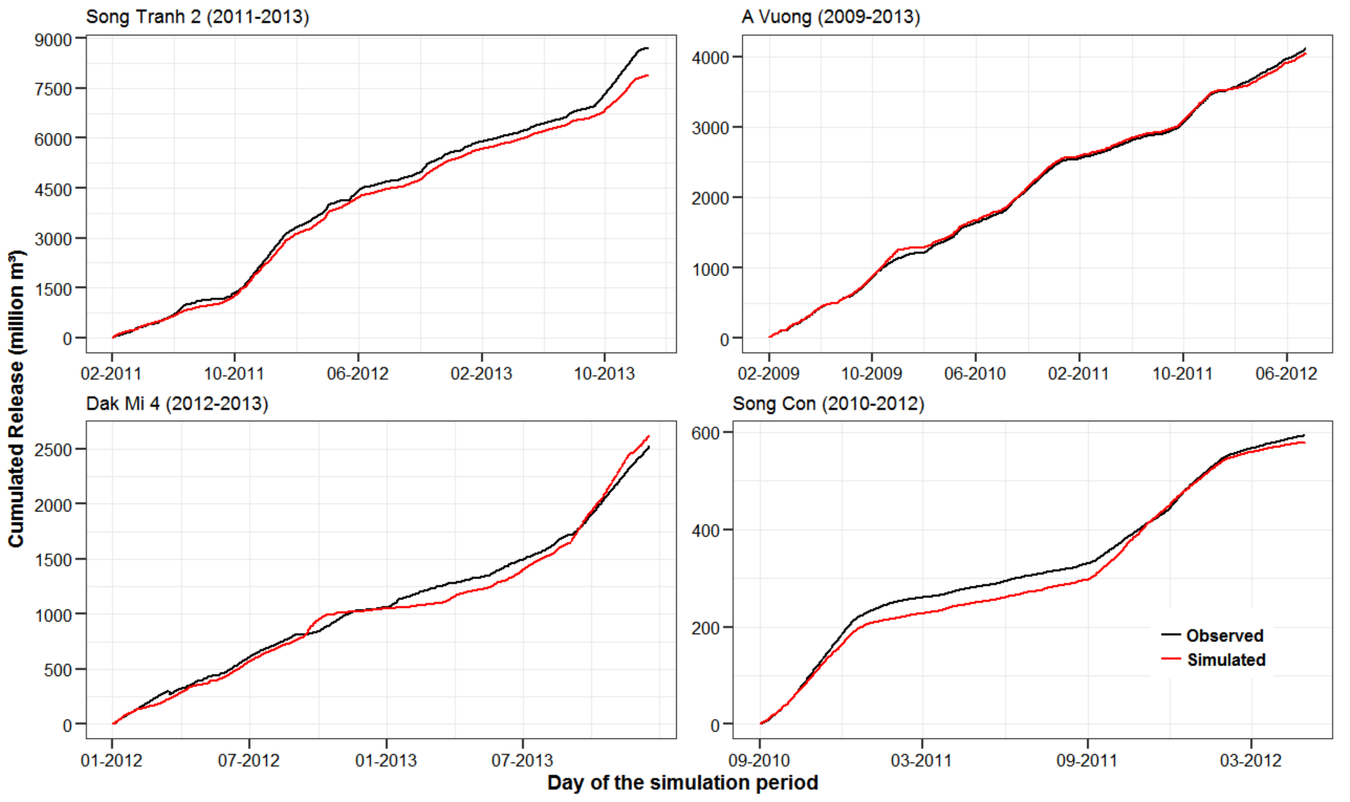


Figure 5: Simulated and observed cumulated daily release of the individual reservoirs

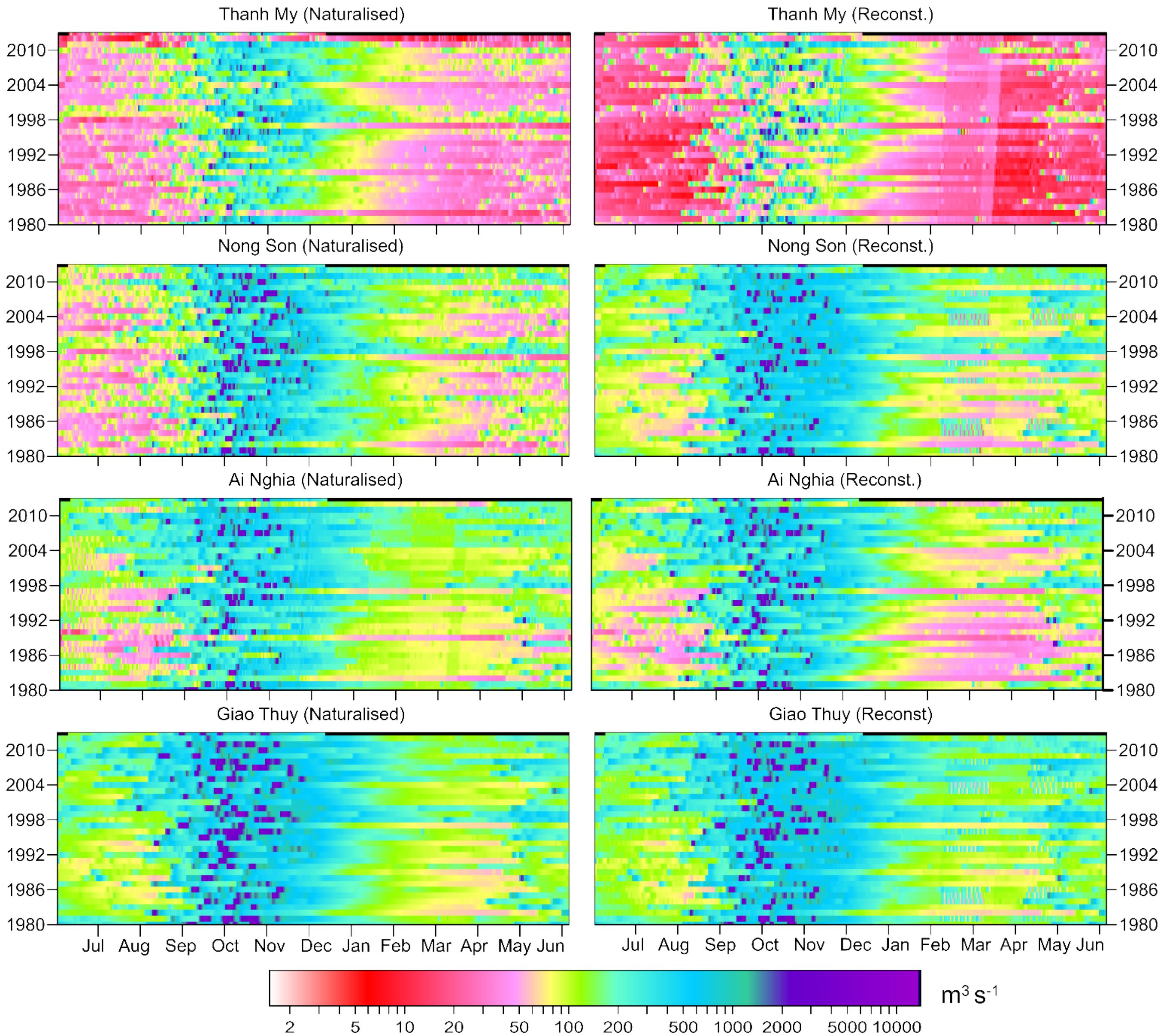


Figure 6: ~~illustrates d~~Daily values of discharge ~~in~~ (m^3 s^{-1}) at the four discharge stations. Each pixel in the plot ~~is~~ represents one day and its colour ~~represents~~ denotes discharge ~~in m^3 s^{-1}~~. The ~~bottom~~ x axis represents the hydrological year, starting ~~from~~ in July and ending ~~at~~ in June. The figures on the -left ~~side plot showing~~show the ~~naturalized~~ naturalised condition based on the J2000 model simulation. The ~~right-side~~ figures on the right ~~are~~ show the reconstructed streamflow product based on the reservoir simulation model.

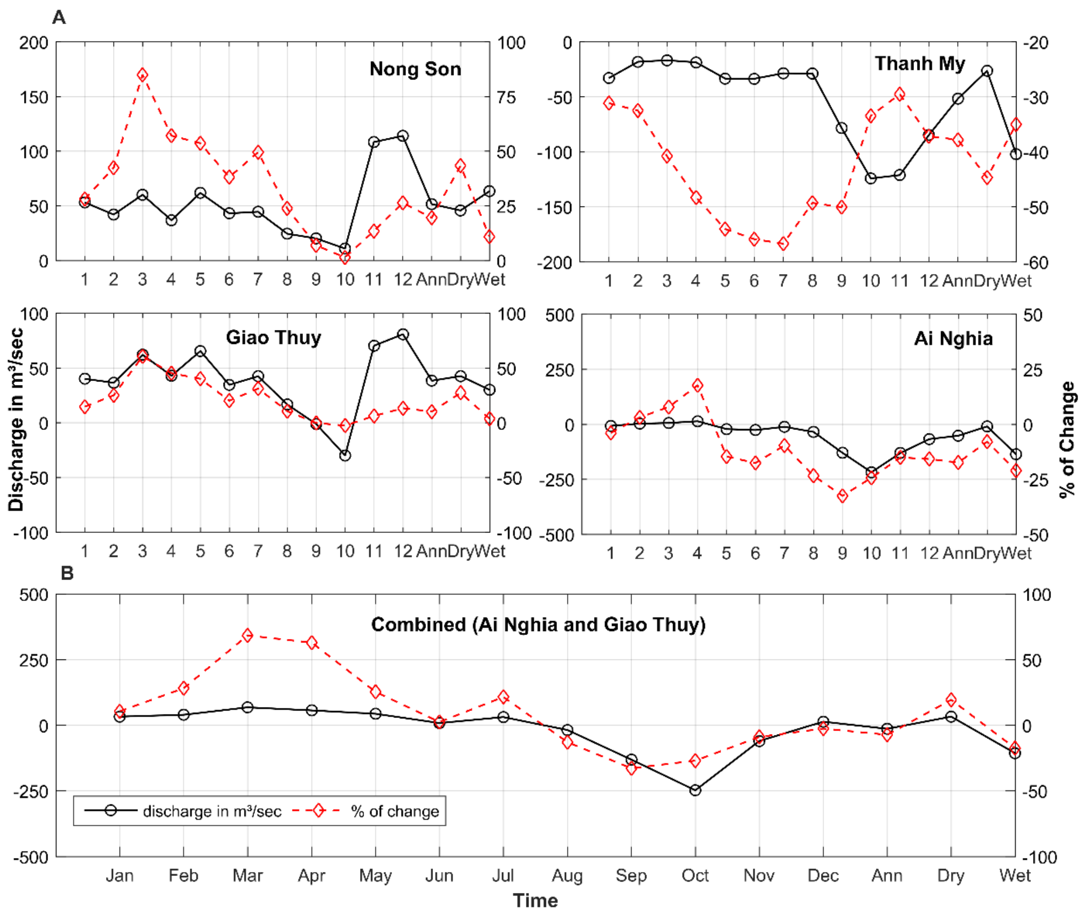


Figure 7: Reservoir impact on streamflow changes. (a) Mean differences of reconstructed streamflow pattern (Discharge in $m^3 s^{-1}$) and the percentage (%) of changes of streamflow from the ~~naturalized~~ naturalised mean flow for the period of 1980-2013. ~~The~~ A negative value indicates a decreasing flow compared with the ~~naturalized~~ naturalised one ~~and vice versa~~. The number indicates the month starting ~~from~~ with January referred to as 1. (b) Combined effect of reservoirs impact for Ai Nghia and Giao Thuy, represents the overall impact on the streamflow on the VGTB basin due to reservoir construction.

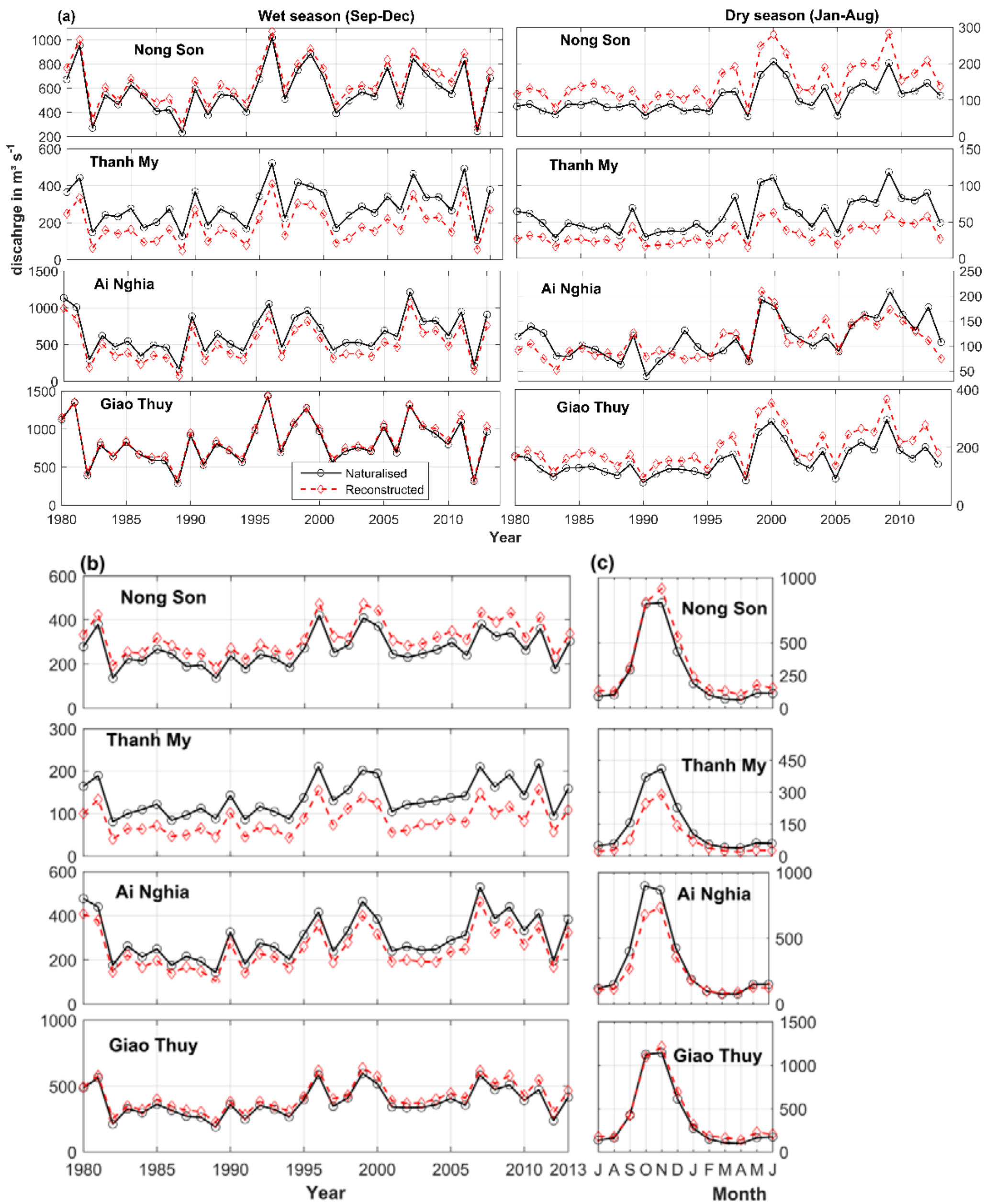


Fig 8 Comparison of mean streamflow pattern (naturalizsed and reconstructed streamflow); (a) comparison of mean seasonal flows for the dDry (Jan to JulAug) and Wet wet (Sep to Dec) seasons; (b). comparison of mean annual streamflow and; (c) comparison of mean monthly streamflow, month start from July. Units are in(m^3 s-^{1})..

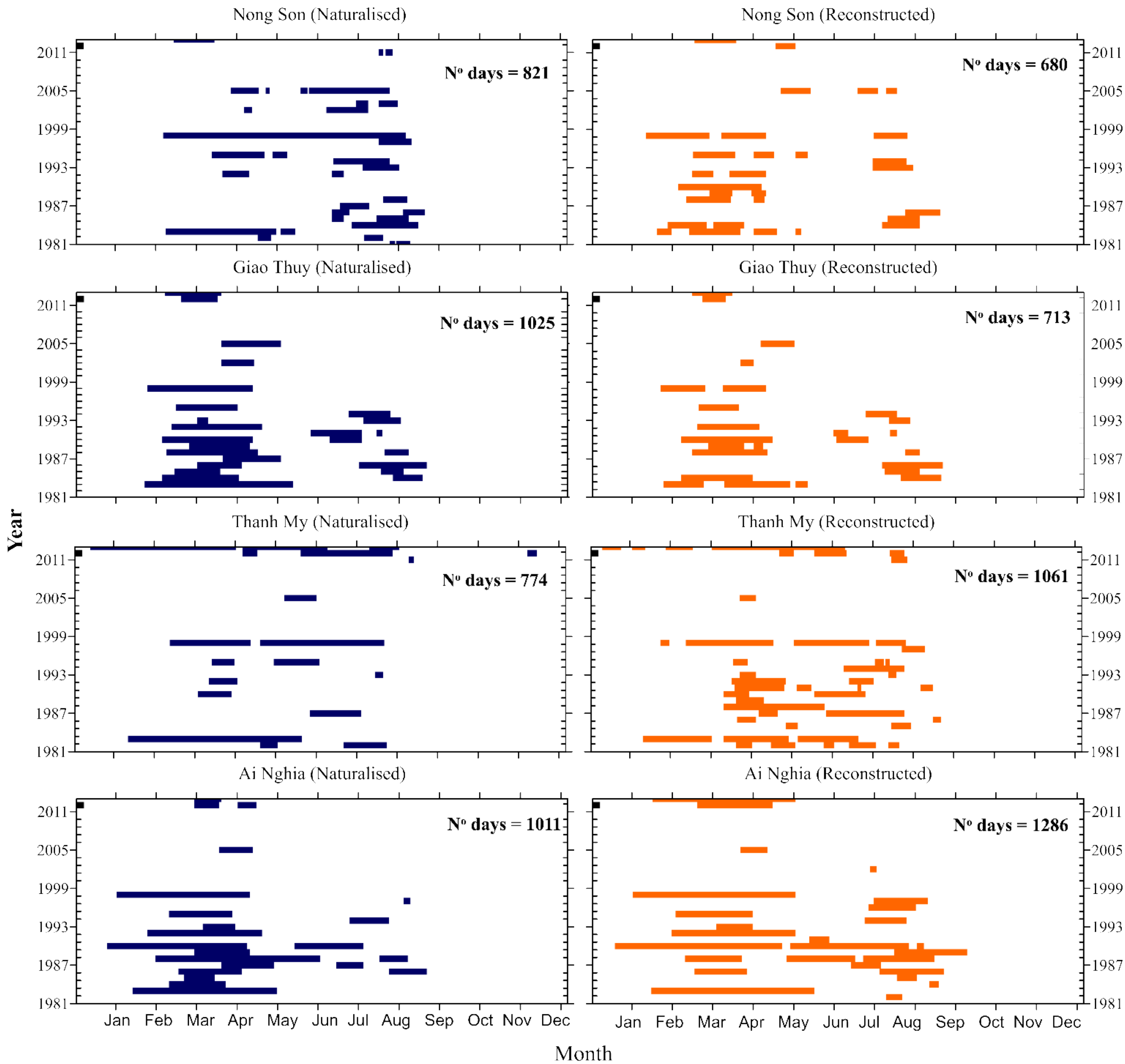


Figure 9: Number of days below the Q_{90} variable drought threshold for the VGTB at the four discharge stations (1981-2013). One day of streamflow drought is a day in which the 30-day running mean discharge is below the 10th percentile of 30-day mean discharge. The blue colour bars (left-side) show the drought onset and duration for the naturalizsed stream flow ~~while~~ whereas the orange colour bars (right-side) represent the reconstructed reservoir impacted discharge. Nºo indicates the total number of drought days.