Kassel, 31 January 2017

Dear Nandita Basu,

thank you for the positive evaluation of our manuscript. We have now incorporated all points raised by the reviewers. In particular, we aimed at improving the presentation quality of our work. Instead of the analysis, the manuscript now concentrates on our approach as a screening tool to flag particularly vulnerable wetlands. The Chapters 'Discussion' and 'Conclusions' are more focused now describing the meaning of our results as well as limitations and potential applications of our approach. The Introduction was shortened and includes now an extra paragraph on global eFlow assessments of the past. Additionally, we highlight now more the novelty of our approach. The 'Methodology' Chapter is better structured. Here, we included subheadings and a flow chart displaying the single steps of our approach. Under 'Results' we focus on the hotspots now (rather than on single wetlands) and included more comparisons to the literature.

We highly appreciate the scientific discussion that took place and believe that the manuscript has improved significantly on the basis of the valuable and deliberate reviewer comments. Following the point-by-point responses to the three reviewers, this document also contains a marked-up manuscript version with all changes highlighted. In the supplement we added Appendix C where we provide results for each single climate projection and thus show the uncertainty between the five chosen climate models.

We have uploaded the revised manuscript, abstract and supplement as separate files.

Kind regards,
Christof Schneider (on behalf of all authors)

Response to Referee #1

Dear Referee #1,
we are very thankful for the profound and helpful evaluation of the paper and the detailed comments in the PDF version, which certainly improved this paper. We understood that we needed to work especially on the presentation of our results and included your suggestions. Additionally rationales are provided for our methods. Please find below our point-by-point responses describing our revisions in detail (highlighted in blue and italic type).

Hello Ms. Töpfer.

Thank you for the opportunity to provide an internal review of the paper Hydrological threats for riparian wetlands of international importance – a global quantitative and qualitative analysis. The authors have created an innovative and useful screening tool to flag particularly vulnerable wetlands. I am particularly impressed by the integration of quantitative and qualitative methods to achieve their goals. This will be a strong contribution to the literature and useful to organizations seeking to target wetland conservation funds. In addition, the same schematic approach can be applied far beyond wetlands, further enhancing the potential impact of this work. Below, I discuss the major suggestions I have for the manuscript. Finally, I have added comments well over 100 comments directly to the PDF version of the paper and figures, included below within this same document. To read my embedded comments, please hover your cursor over the many red and orange colored icons, shaped like keys, stars, and text bubbles.

1) I feel the authors need to very clearly acknowledge the essence of their study. The way I read the paper, the authors created a diagnostic tool, or procedure, to flag wetlands likely to be most vulnerable in the future. It bridges quantitative and qualitative research, applied in a high profile setting. Most importantly, it helps solve the problem of scale in global assessments. This product satisfies the stated goals (p. 4, line 29 through p. 5, line 7). This is a product worthy of praise and significant to both the science and management communities.

   Unfortunately, the study is not presented in this light. This sets the stage for the real problem with the paper, that the authors do not consistently or explicitly discuss the limitations of the study, resulting in chronic problems with overstating conclusions - addressed in my second major comment.

   To remedy the situation, I recommend:

   1. Reframe the study as the development of a screening tool
   2. In the Discussion/Conclusions section, refrain from restating what the results are, and instead focus on what the results mean. Specifically that they guide future research and/or allocation of resources for wetland protection
   3. In the Discussion/Conclusions section, add a very clear explanation of the study limitations.
   4. Avoid making conclusions about the wetlands themselves - other than to say they are likely to be vulnerable or not. Or that they are vulnerable under future simulated conditions. Perhaps discuss why hotspots exist. There absolutely is no basis to prescribe specific management action other than where to direct conservation resources and future investigation.

Before the review process the focus of the paper was on the wetland analysis. We understood that the approach (i.e. the development of a screening tool) need to be more highlighted and in the focus of this paper. Therefore, we reframed the study as suggested. In accordance with the comments, the paper was revised as followed:

We divided the 'Discussion and clonclusions' chapter into two separate chapters. Under 'Discussion', we explicitly discuss now the limitations of our quantitative-qualitative approach and the consequences of our decisions. Afterwards we describe what the results mean for water management depending on the nature of the threat. Aims and main results of the study are not repeated anymore. Furthermore, we removed all conclusions for single wetlands to avoid overstating our results. We agree that from the global perspective no specific management actions can be provided for single wetlands and this is also not the aim of our screening tool.

Under 'Conclusions and outlook', we conclude and address future research and potential applications of our approach.

2) I feel the authors overstate their conclusions. However, this appears to be a symptom of a structural problem with the paper. With regard to the Methods section, the authors made many decisions on how to go about their study. This is inherent in any study and particularly messy when trying to scale up to a global assessment. Unfortunately, very little is said about the rationale for their decisions. I'm not saying I think the authors made poor decisions; I'm merely saying they should share their rationale. For example, they chose WaterGAP3 as a model. But they never state why they chose that model. I would like to see that they actually thought about other options and felt WaterGAP3 was the best for some actual reason. Also, the authors chose one particular climate change projection to use in their 50-year forecast. I'm happy they discuss this scenario as one of many. But there is no rationale provided for why they chose this one. They could add sentence and I would be happy. I flag several instances of this in my embedded comments.
More importantly, I would like to see the Discussion section evaluate the consequence of these decisions, if relevant. For example, I wonder how sensitive the results are to using that one specific climate projection. Or not considering present allocations of eFlows. This helps delineate the limitations of the study and helps guide where future study should focus.
Once the authors have thought through and delineated the limitations of the study in the Discussion section, they will be far less likely to overstate the conclusions.

Thank you for pointing this out. In the revised version of the manuscript we included the missing explanations:

- *Why we chose WaterGAP3? WaterGAP3 is an integrated global modelling framework to assess impacts of global change on renewable freshwater resources. The model has been developed at the Center for Environmental Systems Research and further improved recently to represent specific flow events (Verzano and Menzel, 2009; Verzano et al., 2012) and during my PhD to conduct studies for identifying river ecosystems at risk (Schneider et al., 2013). WaterGAP3 is a state-of-the-art global water model which performs well compared to other global models (see Beck et al. 2016, Eisner et al. 2017). The model's ability to represent specific flow events has* *been proven for different maximum flow magnitudes (Schneider et al., 2011a; Schneider, 2015; Eisner, 2016). Of particular interest for this study is the high spatial resolution of 5 by 5 arc minutes, the temporal resolution of daily time steps used in the analysis, the global coverage, the operation of >6000 dams with optimisation schemes for different dam types, and water withdrawals and consumption of 5 sectors (domestic, manufacturing, thermal electricity production, irrigation and livestock). Furthermore, we discuss now potential improvements of WaterGAP3 in regard to this analysis in the discussion chapter.*

- *Why we chose the RCP6.0 emission scenario? Current CO_2 emissions are close to the upper end of the scenario range. RCP6.0 is a medium-high emission scenario with a global mean temperature increase of 2.2°C until the end of the century (compared to 1986-2005). Within the future time frame, the differences between the emission scenarios (as represented by the radiative forcing) are smaller than between scenarios based on different GCMs until 2050. Therefore, we considered climate forcing of 5 Global Circulation Models (GCMs) in order to address the uncertainty of projected impacts.*
- *Why current eFlow provisions are not included? Today, no global database exists that describes dam management strategies, operation rules or applied eFlow provisions of large dams. Our study benefits from the qualitative assessment where we collected legal eFlow provisions which we combined with our quantitative model outcomes. However, this data collection does not guarantee that eFlows are actually established in practice, enforced or adequate. As most of this information on legal eFlow provisions was available in qualitative terms we introduce a simple yes-no query to our capacity to act indicator. In particular no quantitative information on eFlow provisions was found for the management of dams.*

Overall, we agree that it is important to provide the rationale for our decisions more clearly. The consequences are also discussed under consideration of the limitations (i.e. consideration of 5 GCMs but only one emission scenario, focus on large dams, no consideration of eFlow provisions in our dam operation scheme) in the Discussion and Conclusions section.

3) I feel the manuscript could better "funnel out" in the Conclusion section. This is a chance for the authors to wave their flag and tell me why their work is important. Scientifically, I'm impressed that they combined qualitative and quantitative methods to navigate issues of scale in a global assessment. They should feel free to state this as an academic contribution. The implications of this study could be far reaching. Guiding resources to protect Ramsar wetlands is a big deal. And sure, this study has its limitations. But the authors created a template that could have more broad applications. This study focused on Ramsar wetlands. But maybe the next one could be a true global wetland assessment. Maybe this template could be tweaked and applied to settings such as coral reefs, forest production, or water supply. I wish the authors would express a vision for how this study advances us in the big picture.

In the revised manuscript we make clearer now that the Ramsar sites have been chosen as an example for our screening tool. In the conclusions and outlook chapter, we point out that many other applications of our quantitative-qualitative approach are possible. (i) A comprehensive assessment of all larger riparian wetlands worldwide. (ii) The quantification of *specific ecosystem services provided by riparian wetlands (e.g. forest production, water purification, fish production, flood control, etc.) and how this is likely to change in the future under climate change and further dam construction. (iii) A comprehensive scenario assessment considering different drivers of global change on renewable freshwater resources by allocating water resources to different water use sectors and evaluating the respective consequences under different management targets. (iv) Support of policy makers at international level in implementing global conservation efforts, targeting wetland conservation funds, planning of water infrastructure location and design, and balancing water allocations to humans and nature. We provide now the big picture which embeds our analysis. Thanks for this valuable remark!*

4) My one objection to their methods is the throwing out of results that suggested more overbank flooding will occur in 2050 than occurs now. This might be justified, but it sounds fishy to me. Of course climate change will cause flooding to increase in some places and decrease in others. Why wouldn't they include that in their assessment? At the very least, I recommend this decision be discussed and a rationale provided. Not providing other studies that have done similarly makes me suspicious this isn't a valid assumption. The Discussion section should provide some assessment of how this decision affected the results.
Floods are one of the most damaging natural disasters to human lives and property. We wanted to be cautious in our paper by not labelling increasing floods as a "positive event" because many people are affected and even lose their belongings. As the focus is on riparian wetlands, we argue in the paper that "only reductions have been documented, because it cannot be distinguished whether an increase in flood volume benefits the wetland or generates flood damages, which, in turn, would be an incentive to build more dams for flood control". Nevertheless, we understood the point raised and quantify now the increase in flood volume by two thresholds distinguishing a low (0-30%) and high (>30%) increase. We felt that more classes would have made the map unclear and difficult to read. However, it enabled us to identify hotspots where flood volumes highly increase in our simulations. The outcomes are provided in the results chapter. Furthermore, we discuss the increasing flood volumes in the discussion chapter by describing the potential consequences for water resource management. We agree that providing these results is an improvement of the paper.

5) I sense the paper was drafted by a non-native English speaker. I am supportive of this and welcome different perspectives in the literature. Unfortunately, I had a difficult time understanding the content. If left unaddressed, I feel this will reduce the impact of the paper. I have some specific recommendations to move forward.
    1. Adding subsections would greatly help keep the text organized.
    The methodology section contains a lot of information and the entire (modelling) approach is quite complex. As suggested, we included subsections in the Chapters 'Methodology' and 'Results' to better structure the paper and improve the understanding/ readability. The subheadings correspond to the flow chart.
    2. Please keep paragraphs short and focused on the topic sentences. For example, the first paragraph of the introduction is almost a page long and drifts away from the topic sentence. That is too much.
    We revised all paragraphs to make them shorter and more focused on the topic sentence.

3. Adding a flow chart to the methods section that schematically illustrates your 3 modeling exercises would be very effective at communicating what you did. I visualize your methods as having 3 'cuts' of modeling: "natural" conditions, "natural + modeled water management," and "climate change 2050 without water management." Even if/when readers become confused by the text, a nice flow chart will communicate your general approach well. See my embedded comments.
   A flow chart at the beginning of the methodology section was another great idea that we adopted. The flow chart corresponds to the new subheadings.
4. I feel adding a table to the Results section is essential and will allow you to delete at least half the text in the current Results section. I visualize one row per wetland in the study and one column each for wetland number, wetland name, vulnerability for the three conditions tested, and perhaps a comment column. The Results section text could be reserved to identify trends and hotspots rather than telling the reader verbally what wetlands were vulnerable. To be clear, any text that simply tells the reader "wetland X was vulnerable" could be deleted and replaced with more substantive information.
   A table with detailed results for each wetland and threat was implemented in the supplementary material. The 'Results' Chapter was shortened and focuses now on hotspots and trends rather than single wetlands.
5. The Discussion section is largely dedicated to re-presenting results. In my own writing, I typically find this to be my #1 problem. Deleting any presentation of results in the Discussion section will free up vast amounts of text to focus instead on what the results mean to your study goals and the limitations of your results.
   The discussion and conclusions section was revised. In the new discussion section the aims of the study are not repeated anymore and limitations of the approach are explicitly discussed. In this context we put emphasize on interpreting our results. (see also major point 1)
6. Similarly, conclusions are also presented in the Results section and this text should also be removed. I flag these instances in my notes on the manuscript PDF, included below within this same document.
   All conclusions were removed in this section.
7. Other issues exist, notably sentence structure. My sense is putting the paper through an editorial review would be the most expedient solution. There is a lot that a good editorial reviewer can add that I simply cannot.
   We checked again grammar, sentence structure and wording and hope we could improve it. Thanks for the given examples!

To conclude my thoughts on the manuscript, I feel it is publishable with major corrections. The corrections, however, are largely limited to the presentation of the paper, not a fundamental problem with the methods, per se. Again, I have added ~130 comments to the manuscript PDF, included below, to further guide revision of the manuscript. Thanks again for the opportunity to review this paper.

We are very thankful for the specific comments in the supplementary, which were summarised in the major points above. We addressed each comment appropriately in the revised manuscript. Please find answers below that are not addressed in the major points above.

- *How did we choose riparian wetlands? The Ramsar Classification System describes different wetland types, but does not categorize riparian wetlands. However, riparian wetlands were selected from the Ramsar list on the basis of information provided by the Ramsar information sheets (RSIS, no date). For each wetland we read the information sheet and a wetland was selected when the information sheet indicated that a wetland depends (at least partly) on flooding by adjacent rivers. For Europe, a higher number of sites could be selected as the European wetland geodatabase (Okruszko et al., 2011) clearly defines wetland type and main source of water for each Ramsar wetland. Here we took into account all wetlands with rivers as a main source of water.*
- *Why we focus on large dams? In order to assess flow alterations due to dam operation, the number of dams implemented in the model has been further increased for this paper. We operate now >6000 dams which is state-of-the-art in comparison to other global models (see supporting information of Haddeland et al., 2013). In order to have a clear cut, we decided to consider all large dams + smaller dams with a storage volume >0.5 km^3. In the discussion chapter we discuss the consequences of this decision.*
- *A basin country unit (BCU) is the portion of a country within a river basin shared by two or more countries. The description of our approach was not clear at this point and so we reformulated our proceeding. Thanks for pointing this out.*
- *Why did we not model climate change together with water management? We agree that future water management plays a crucial role, especially in regard to how we respond to climate change. We decided to focus only on climate change because a high number of new dams is expected in the future and important information on dam type and storage capacity was not available for us. We are still working on collecting this information and further improvements of the screening tool will address the implementation of future dams in the model. Although model outcomes of tier 2 will not reflect future conditions because of not taking into account future water management, this model experiment supports identifying the solely effect of climate change on riparian wetland inundation.*

Response to Referee #2

Dear Referee #2,
we are very thankful for the profound evaluation of the paper and the helpful comments, which further improved this paper. Please find below our point-by-point responses describing our revisions (highlighted in blue and italic type).

Through data synthesis and model interpretations of RAMSAR wetland sites across the world, this paper addresses the issue of past to expected future adverse effects on riparian wetlands from pressures such as climate change and water regulation. In particular the focus is on the available flooding volume - how it has been modified today and how it may change in the future due to these pressures. The magnitude of these changes is taken as a measure of potential ecological impacts.

The authors combine and use multiple methods (e.g. to simulate impact of flow regulation of various dam types etc), many of which have been thoroughly developed in previous work. Although results are associated with considerable uncertainties, the approach is quite reasonable and the outcome is logically synthesised and presented as maps showing e.g. the magnitude of flow alteration impact. Such global state-ofthe-art syntheses is certainly of scientific interest; I would recommend publication of the work if main shortcomings (see below) can be addressed, which is likely to require at least moderate revisions.

In summary, these shortcomings are (1) lack of clarifications regarding novel aspects of the present study, apart from the novel global synthesis perspective, (2) partial lack of information regarding past experiences of the proposed methods, (3) language issues, (4) lack of sufficient results comparison to previous studies, and (5) unfocused conclusions. Overall, this study has high potential and I hope that the detailed comments below can be useful in addressing the current concerns.

1. Presently, the focus of the introduction is on the relevance of the topic, including what is known about vital ecosystem services of floodplain wetlands, effects of dams in a more general sense, and the need for maintaining flow variability etc. This description is on the lengthy side and could probably be condensed. However, more concrete (state-of-the art) regional examples that presumably exist in the scientific literature regarding today's impacts (or expected future impacts) on floodplain wetlands are essentially missing. Such examples should be included in the introduction, such that the readers can understand what is novel about the presented result-maps, in addition to the novel global synthesis perspective. In other words: which previous indications exist in the scientific literature regarding key results, such as the result showing that the degree of overbank flow alteration due to current management is very low in Europe (essentially green in Figure 1) whereas Australia comes out as seriously altered (or other results that are the authors think is important). I would recommend the authors to go through what they consider to be the main results of their study and make sure that the introduction informs sufficiently about the current knowledge. This would provide a necessary basis for enhancing the discussion (see bullet point 4)

We agree that the introduction was too long and information about current knowledge needed to be improved. Accordingly we condensed the text by often providing only key points and referring to the literature. The more detailed descriptions of the flood pulse concept and the paragraph on ecosystem services of wetlands were removed.

We provide 6 regional examples (Hughes, 1988; Maheshwari et al., 1995; Barbier and Thompson, 1998; Kingsford, 2000; Nislow et al., 2002; Middelkoop et al., 2015) in the introduction to show that floodplain wetlands have been downsized and transformed into terrestrial ecosystems due to reduced flooding caused by water resource management. More comparisons to the outcomes of these studies as well as other studies (Georgiyevsky et al., 1995; 1996; 1997; Khublaryan, 2000; Tockner and Stanford, 2002; Uluocha and Okeke, 2004; UNEP, 2008; Schneider et al., 2011b; 2013; Dankers et al., 2013, Zarfl et al., 2014; Grill et al., 2015) are made now in the 'Results' chapter.

Following the description of the current situation and providing the rationale for our indicators, we added an additional paragraph to the introduction. This paragraph mentions valuable studies of the past (Smakhtin and Eriyagama, 2008; Döll et al., 2009; Döll and Zhang, 2010; Schneider et al., 2013; Laize et al. 2014; Pastor et al., 2014; Grill et al, 2015) addressing flow regime alterations on larger-scales and highlights the novelty of our study. In the last years, different authors have assessed ecologically relevant flow regime modifications on larger-scales. In addition and complementary to the published papers, our study considers the following points which have never been applied before in their combination and in its detail to create a screening tool for assessing hydrological threats for riparian wetlands:

1. *Environmental flow provisions that are defined as a percentage of mean discharge can be allocated in many different ways throughout the year. However, complex flow-dependant ecosystem habitats and functions are provided by specific flow characteristics. Consequently, rather than long-term average flow conditions, our approach focuses on a specific, ecologically relevant flow event.*
2. *Most large-scale environmental flow assessments focused on in-channel river flows. Riparian wetlands depend on overbank flows leading to inundation. They are (in combination with subsequent drying) the main driving force for ecological processes in riparian wetlands. Our assessment is the first that applies the flood pulse concept (Junk et al., 1989; Bayley, 1991; Tockner et al., 2000; Junk and Wantzen, 2004) on a global scale.*
3. *In order to address trade-offs between human and ecological water demands, multiple stressors on human water security and ecosystem conservation need to be considered. The applied approach is able to consider different drivers of change such as dam operation, water use and climate change.*
4. *Next to the flow regime modifications, the threat for riparian wetlands also depends on the society's capacity to act to the changes. This kind of threat has not yet been taken into account in large scale studies. In order to fill this gap, we combined quantitative with qualitative results. The implementation of counteractive measures depends especially on the legal and institutional framework in place. Therefore, we collected 6 different criteria (legal environmental flow provisions, presence of RBOs, at least one relevant treaty, and specific treaty provisions such as water allocation mechanism, conflict resolution mechanism, and flow variability management). In addition, new dam construction is likely to further modify flow regimes in the future, but currently no large-scale dataset on major dam initiatives (including planned storage capacities) is publicly available. Therefore, we collected the number of dams that are currently planned, proposed or under construction in the upstream areas to give a first indication, where future dam construction is likely to affect the inundation of specific riparian wetlands.*

5. *Our discharge simulations were done on a daily time-step. This is important as many ecological functions and habitats are facilitated by hydrological events that last only up to some days (e.g. strong precipitation events, bankfull flow, and flood formation).*
6. *Today, river flows are considerably affected by human activities worldwide, and the speed of river ecosystem destruction and biodiversity loss is exceeding the ability of scientists to review applied water management practices and ecological consequences for each river. Therefore this study assesses flow regime modifications on a global scale. The approach is performed on a detailed river network with a spatial resolution of 5x5 arc minutes and can be applied for single reaches of larger rivers with a global coverage.*
7. *The approach will allow new applications related to riparian wetland flooding. Examples include the quantification of specific ecosystem services provided by intact riparian wetlands (e.g. forest production, water purification, fish production, flood control, etc.) and how this is likely to change in the future. The framework could support policy makers at international level (e.g. at forums like UNEP, OECD, European Union, Convention on Wetlands of International Importance, and Convention on Biological Diversity) in balancing water allocations to humans and nature, implementing global conservation efforts, and planning of water infrastructure location and design.*

2. It is stated in the introduction (p. 2, line 26) that a new approach is needed to water resources management, which among other things should allow for sufficiently high flows for sustaining floodplain wetlands. However, in line with comments of bullet point 1 (above), this proposed novelty remains unclear to the reader. For example, haven't we gained some relevant knowledge from regulation schemes applied to the principal Colorado River in the US (Stevens et al., 2001; Stromberg et al., 2007; Cross et al., 2011)? These schemes have included controlled floods as part of the strategy to minimise adverse impacts to downstream ecosystems. Perhaps there other relevant examples.

Thanks for this remark. The aim of this paragraph was not to claim that the "new approach" on water resource management is our idea. Rather we wanted to state that both flood protection for people and controlled floods for riparian wetlands are important and need to be considered in practice within the framework of integrated water resource management. We appreciate the given examples from the literature and also wanted to include them in the paper as good examples for eFlow (controlled flood) provisions in practice. However, in the context of shortening the introduction, we totally removed these sentences.

3. The language of the manuscript is overall good. There are some exceptions though, including the introduction. In particular, the research questions and the related text include awkward formulations (e.g., multiple sentences starting with Thereby. . ./ Therefore. . .), please check.

We agree that the language of this manuscript can be improved. We checked again grammar, formulations and word spelling. Thanks for the given examples, which were corrected. The research questions were revised as well.

4. There is a lack of results comparison to previous studies in the discussion section, which should be addressed before publication. The now included references do mainly not relate to the results (study outcomes) and need therefore to be complemented. For instance, are the results regarding impacts on the 93 Ramsar wetlands in different world regions (p. 17, lines 3-11) consistent with previously

reported results for these regions? Alternatively, do the results partly contradict or point to new and previously unnoticed aspects? (Also, the reader is not well informed about the existence or absence of similar studies, see bullet point 2 above regarding the introduction). The same questions can be asked for other key results, such as impacts of climate change and the related identified hotspots (p. 17, line 12-15), and competition of water (p. 17, lines 31-32). Overall, the discussion section is rather general and would benefit from an extended discussion of results. The aims of the study need not to be reiterated in the beginning of the discussion section.

In order to address this comment, we included more comparisons of our key findings in the results chapter with existing regional (Georgiyevsky et al., 1995; 1996; 1997; Kingsford, 2000; Khublaryan, 2000, Uluocha and Okeke, 2004; UNEP, 2008; Middelkoop et al., 2015) and large-scale (Grill et al. 2015; Schneider et al., 2011b; 2013; Tockner and Stanford, 2002; Dankers et al., 2013, Zarfl et al., 2014) studies. We also formed a bracket by addressing some of the studies already mentioned in the introduction section.

Under 'Discussion', we explicitly discuss now the limitations of our quantitative-qualitative approach and the consequences of our decisions made under the methodology chapter. Afterwards we describe what the results mean for water management depending on the nature of the threat. Aims and main results of the study as well as general descriptions were removed in the discussion section.

5. The main conclusions of the paper are not clearly presented. Maybe a separate conclusion section could help?

Thanks for this remark. In our revised manuscript we put particular attention on the revision of the discussion and conclusions section. We more clearly present now the novelty and limitations of our study. As suggested, we created a separate conclusion section. Here, we included a sub-section on future research and the potential of our approach to be applied to similar research questions related to riparian wetlands. Unfocused conclusions were removed.

References

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Response to Referee #3

Dear Referee #3,
we are very thankful for your profound evaluation of the paper and helpful comments, which further improved this paper. Please find below our point-by-point responses describing our revisions (highlighted in blue and italic type).

The authors aim to address an important issue: Identifying Ramsar riparian wetlands that exhibit current and future variations in ecologically consequential inundation patterns as a result of human-modified flows (e.g., dams). They ask three particular research questions to best identify these wetlands. These questions focus on the impact of current water resource management on riparian wetland flows, the effect of future climate change on inundation of these wetlands, and the implications of low government and societal infrastructure and capacity to make changes to future management.

The goal and research questions the authors attempt to address are broad and could be impactful if addressed and translated well. However, a major revision is required to ensure both the quantitative work behind the research and the communication of this work is effective. Below, I provide major suggestions for the manuscript followed by some general comments.

Major Point 1: The Introduction reads somewhat like a full literature review that continues for quite some time without a direct point. It was well into the sixth paragraph that the goal and research questions were stated. I would suggest tightening up the Introduction, providing only key points throughout, and early on (perhaps at the end of the first paragraph) allude to the main point of the paper (e.g., "We aim to. . ."). Then, the authors can safely state the full objective and research questions at the end of the Introduction.

We agree that the introduction was too long and more like a literature review. Accordingly we condensed the text by often providing only key points and referring to the literature. The detailed descriptions of the flood pulse concept and the paragraph on ecosystem services of wetlands were removed. However, following the description of the current situation and providing the rationale for our indicators, we added an additional paragraph to the introduction. This paragraph mentions valuable studies of the past addressing flow regime alterations on larger-scales and highlights the novelty of our study.

Major Point 2: Something is very misleading and incorrect about discussing a "natural" flow regime in knowingly modified watersheds and aquatic systems. Also, the word "natural" is used throughout the Abstract and Introduction (ala Poff et al. 1997), and it is not until the Methodology that authors define natural flow. The authors describe natural flow for this paper as "simulated taking into account current climate and landcover conditions, but no further anthropogenic impacts." This, by no means, would constitute a "natural" flow regime as described in past literature. I would recommend modifying terminology and the discussion throughout the paper to consider this as your "baseline" flow regime from which the analyses aims to understand current water resource management implications on the riparian wetlands and project changes of these regimes due to climate change

We agree that the use of the terminology 'natural flow regime' is misleading due to the fact current climate and land cover conditions are contained. Therefore, we make use of the terminology *"reference flow" now. The new terminology is applied throughout the manuscript. Under Chapter 2.1.3 we explain the meaning of the reference flow which shall reflect near-natural flow conditions where anthropogenic impacts such as dam operation and water use were not considered. But current climate and land-use are taken into account.*

Major Point 3: The goals of the paper and research questions are poorly worded need more information. What, specifically, are the "riparian wetlands?" In the Abstract, the authors suggest they look at 93 Ramsar sites. Are the "riparian wetlands" the "93 Ramsar riparian wetlands?" For Research Question 1, why are 6025 dams selected? Are these dams specifically located upstream of Ramsar riparian wetlands? What are the "different water use sectors"? Also, delete "Thereby" at the beginning of the second sentence. For Research Question 2: "Inundation" cannot be "impaired" because "inundation" does not necessarily denote a positive quality. The authors could replace "impaired" with "exacerbated or diminished" or "modified." Also, delete "Therefore" at the beginning of the second sentence. Research Question 3 is stated in a grammatically incorrect way, so it took a few re-reads to understand it. Move "could" after the word "sites." Also, what is a "low capacity to act?" This is definitely not clear.

Thanks for these valuable corrections. We made the following changes in the text:

- *Due to comments from Reviewer #1, we put the screening tool more in the focus of this paper (rather than the analysis). In this context, we explain now and make clear from the beginning of this manuscript that the proposed approach is exemplified on 93 riparian wetlands of international importance (Ramsar sites), but can be applied on global scale taking into account all larger riparian wetlands. We also make clearer now that the 6025 dams are allocated to the global WaterGAP3 stream net (Chapter 2.1.1).*
- *In order to assess flow alterations due to dam operation, the number of dams implemented in the model has been further increased. We operate now >6000 dams which is state-of-the-art in comparison to other global models (see Haddeland et al., 2013, supporting information). In order to have a clear cut, we decided to consider all large dams + smaller dams with a storage volume >0.5 km^3.*
- *The different water use sectors are described in Chapter 2.1.1*
- *The proposed corrections for grammatically incorrect sentences and incorrect word use were adopted. Thanks for the examples.*

Major Point 4, WaterGAP3 runs: Streamflow, for what the authors term "daily natural flow regimes" (1981-2010), is simulated with 2004 land cover. Using 2004 land cover is okay; however, going back to the use of the word "natural". . .how can this be considered natural flow when the landscape for each area is likely highly modified and streamflow is a reflection of these anthropogenic activities? Also, there is no mention of calibration and verification of the model, which admittedly would be difficult a global scale. Therefore, is the entire paper a thought experiment using an uncalibrated global model to help explore hypotheses? It would be okay if so, though this framework should be characterized as such throughout the paper. Also, the results (maps, in particular) should emphasize the paper's overarching approach (i.e., the thought experiment – a "screening tool" is mentioned in the Discussion, hypotheses testing, and/or a conceptual model). If calibration and verification did occur at some stage and is not referenced, again, measured streamflow would reflect the managed conditions, not some unattainable "natural" or "near natural" condition. The model scenarios are therefore a bit confusing and need some rethinking, definitely in the presentation of what they are but potentially in which ones should be used. For example, consideration should focus on whether only the managed scenario and future climate/management conditions should be used since the true "natural flow regimes" aren't captured.

Also, the authors talk about the database of dams that are used, but how does that relate back to the Ramsar wetlands? Are these dams all upstream of Ramsar wetlands? As I read on, it became a bit clearer that this is simply a global database, and Ramsar wetland areas within the global domain are analyzed. However, this information (spatial domain and selection of dams) needs to be clearer up front.

The authors likely have all the information mentioned in this Major Point. There is simply a need for better and clearer communication regarding these bits of information. As a result, the Methodology section seems quite disjointed and leaves the reader guessing at how the authors conducted the analyses.

Thank you for these valuable comments. The WaterGAP3 model is calibrated and validated which was described in the manuscript at p.7 line 32 to p.8 line 3. For the verification of the model, we refer to p.8 line 15 and the reference Schneider et al. (2011a) given in the text, which contains details of the model performance with regards to bankfull flow events. However, given this comment we totally understood that the structure of the Methods section and the model description needed to be improved. We addressed this comment by including sub-headings, a flow chart schematically illustrating the single steps of our approach, and an extra paragraph on model calibration and validation in order to increase clarity, transparency and understanding of the paper. Furthermore we added two more references on WaterGAP3's ability to represent maximum flow magnitudes (see validation in Schneider 2015, Eisner 2016). The entire paper is far from being a thought experiment, although any model experiment could be understood as a 'thought experiment'. Hydrological models are useful tools to mirror the reality, i.e. river discharge, in an abstract manner. The higher the agreement of simulated and observed data records the better the model performance. In the calibration process, WaterGAP3 model simulations take into consideration human impacts in terms of managed reservoirs and dams, water abstractions and return flows from 5 different sectors, urban water transfers and land use conditions. The model is calibrated against an observed discharge record by adjusting one free parameter (runoff coefficient) and validated to an independent period of the same discharge record. Based on the calibrated model (i.e. with adjusted runoff coefficient) the 'natural flow' is represented by a model simulation driven solely by the meteorological forcing of the respective time period, i.e. 1981 to 2010. Human interventions in form of managed dams and reservoirs, water abstraction, return flows, urban water transfers are omitted in this model simulation. This approach as well as the terminology 'natural flow' is commonly used in the community of global hydrological modellers. However, recognising the misunderstanding of the information given in the text we improved the manuscript by providing model-specific information and references to the model calibration and validation, and conducted a thorough revision of the entire text. Furthermore, we changed the terminology from 'natural flow' to 'reference flow' (see 'Major Point 2').

The dam database (GRANd) used by the model is initially independent of the Ramsar wetlands. GRANd contains the information on the location, storage capacity and main purpose of the largest dams of the world which are not necessarily located upstream of Ramsar wetlands. We decided to *focus on the Ramsar wetlands to exemplify our screening tool and because of their importance and description found in scientific literature. We now communicate this in a clearer way in the text.*

Major Point 5, Discussion and Conclusions: Be careful here. Because this is thought experiment using a global model (again, unless calibration/verification happened but wasn't mentioned), your conclusions need to be balanced with a statement of the conceptual aims of the paper and associated limitations/assumptions. The quantitative analyses isn't incredibly quantitative, and I wince a bit with the use of numbers like "8% are significantly impaired" and flood volume is likely to be decreased at 41% of the sites. . ." when those are all relative numbers with no basis in reality. Please mention up front in the conclusions or make a separate section of the limitations and assumptions with regard to what the analyses can actually provide.

Thanks for this remark. We revised the discussion section by explicitly discussing the limitations of our approach and the consequences of our assumptions made. This is followed by paragraphs describing what the results mean for water management depending on the nature of the threat. The calibration and validation is described in an extra paragraph now.

Major Point 6: In general, the English is okay as written. However, it's important that someone extremely proficient in English re-review this paper for odd placement of verbs, adjectives, modifiers, etc., and poor word selection. One small example, on Page 5, Line 14 "For Europe, a higher number of sites "were gained" as the European wetland geodatabase. . .". This should be "were selected" or "were chosen". There are many instances like this throughout the paper, and I do not list them all below.

We checked again grammar, wording and spelling. Thanks for the given examples.

Specific Comments

Page 1, Line 9 – Recommend changing all references of "mankind" to "humankind" and "man-made" to "constructed"

Thanks, we modified all terms, respectively.

Page 1, Line 9 – These eco services are provided not only via the regular patterns of inundation but also regular patterns of drying – so actually, it's the *variability* inundation patterns that is important.

Thanks, we included 'regular patterns of inundation and drying' to be more precise.

Page 1, Line 26 – Need to review and add Dixon et al (2016) as well. Dixon, MJR, Loh J, Davidson NC et al. 2016. Tracking global change in ecosystem area: The Wetland Extent Trends index. Biol. Conserv. 193: 27-35.

Thanks, we included this reference.

Page 2, Lines 18-19 – Is this true for all “larger cities?” What spatial scale is this referring to? Are these global or regional estimates? If regional, what regions?

Thanks for this comment. In the context of shortening the introduction, we needed to delete the part on city water transfers.

Page 2, Line 25 – Again, what are “natural sites?”

Thanks, we exchanged ‘natural sites’ with ‘pristine and not heavily altered floodplains’.

Page 2, Line 30 – Not all floodplains are wetlands, which is how this sentence reads. Please correct.

Thanks, the sentence was corrected.

Page 2, Line 32 – What ecological processes are initiated? Some of these processes may be initiated by drying not wetting.

Thanks for this remark. In the context of shortening the introduction, we needed to delete detailed descriptions of the flood pulse concept. However, we made clear in the text from the beginning (abstract) that periodic flooding and drying is responsible for the generation of floodplain ecosystems.

Page 3, Line 2 – What is engendering what? This clause doesn’t make sense.

Thanks. This sentence was rephrased to make clear that “the periodic occurrence of overbank flows engenders one of the most dynamic, diverse and productive systems in the world”.

Page 3, Line 4 – That’s a very broad statement, that all floodplain wetlands contain more species than any other landscape unit. Need more specifics here because it’s likely not what the authors intended to say.

Thanks. In the context of shortening the introduction, we needed to delete this part on ecosystem services.

Page 3, first paragraph – The Roman numerals are not needed when providing full sentences after them. Suggest removing all Roman numerals here.

Thanks, we agree on removing the Roman numerals. However in the context of shortening the introduction, we needed to delete this part.

Page 3, Line 24 - What are “fellow riparians?” Please be more specific.

Thanks, we replaced it by “upstream/downstream water users”

Page 3, Line 25 – What projections? Please be more specific.

Thanks, we rephrased the sentence to be more precise.

Page 4, Lines 12-16 – Break up this sentence into two or more sentences.

Thanks, we broke up the sentence.

Page 5, Lines 19-20 – These sentences can be deleted and are unnecessary.

Thanks, sentences were deleted.

Page 5, Line 23 – "percent change in flood volume": from what period to what period? Please provide time frame.

Thanks for this remark. We included now a flow chart under methodology which clearly illustrates the time periods considered for each model run. The time frames are also provided under each sub-heading.

Page 5, Line 28 – It is not clear at this point what "sufficient capacity to act" means. Suggest modifying this or adding some clarification here to lead the reader to the more specific methods discussion.

Thanks, we rephrased the sentence.

Page 5, Line 3 – The simulation of daily natural flow regimes would still be an expression of a modified landscape, so how are these natural?

See Major point 3. We are using the term 'reference flow' now.

Page 5, Lin 9 – Need clarification of what type of "daily river discharge" is being simulated here – "natural" or "managed"? (After reading on, it becomes obvious it's "natural" but that needs to be mentioned straight away.)

Thanks. We included subheadings and a flow chart in order to better structure the methodology section and be more clear which model run is described.

Page 5, Line 20 – Switched to "near-natural" from "natural" in this sentence. Please be consistent.

Thanks, we are using the term 'reference flow' now throughout the paper.

Page 7, Lines 6-9 – Need to be clear here why the simulation includes these specific 6025 dams. Why were they chosen? Intuition would tell me they are all upstream of Ramsar sites, but further reading seems to suggest that they are simply part of the global database. These questions regarding methods also suggest that clear summary statements of what the quantitative analyses is up front in the Methodology should be added – meaning state your steps: exact simulations, the spatial scale, how dams were selected, how the Ramsar sites were overlain on the global map, etc. Then, details can be added after this summary.

Thanks. Under Chapter 2.1 we describe now up front WaterGAP3 in general and provide a flow chart schematically illustrating the modelling exercises. Under the following subheadings, specific details for each model run are described. All subheadings are in compliance with the items in the flow chart. Additionally, we provide more rationales under methodologies for our decisions (dam selection, scenario selection, model selection, …). The 6025 dams are taken from the GRANd database, which were allocated to the global grid cell raster of WaterGAP. The proposed screening tool can be applied on global scale and is only exemplified on the 93 Ramsar sites. We explain this more clearly now in Chapter 2.1.1.

Page 9, line 14 – What selected sites? The Ramsar wetlands? Again, details are needed here.

See Major Point 3.

Page 9, Lines 14-15 – This sentence is a bit wonky and needs to be reworded.

Thanks, we reworded the sentence.

Page 9, Line 18 – How were the cutoff thresholds for Table 2 selected?

Thanks, we included the missing information.

Page 9, Line 20 – Again, clarify what the “low capacity to act” is.

Thanks. We explain ‘capacity to act’ now in the Chapters introduction and methodology. Under 2.2.2 we describe how we defined the cutoff thresholds.

Page 9, Line 27 – Define blue water

Thanks for this remark. The term “blue water footprint” is used in the cited literature and probably unnecessary jargon. Hence, we rephrased this and describe now that the scarcity threshold is reached when 20% of the streamflow is depleted.

Page 9, Line 30 – Again, how were the Table 3 thresholds derived?

Thanks, we include the missing information.

Page 10, Lines 25-27 - Cut these sentences. Too much introduction here.

Thanks, we agree and removed the mentioned sentences.

Page 11, Line 4 – These wetlands are “moderately impacted” – as far as the map seems to read.

Thanks. We are more specific now about the locations. Here, Southern Europe was exchanged by Iberian Peninsula.

Page 11, Line 17 – N=2, though, correct? So this is only discussing two wetlands, right?

Thanks, we deleted that statement.

Page 12, Line 28 – Is this the ensemble median for the GCMs as input to the WaterGAP3 model or the ensemble average of the output of the WaterGAP3 model?

Thanks for this remark. We rephrased the text accordingly. It’s the ensemble average of the output of the WaterGAP3 model. We included ‘ensemble median derived from five hydrological simulations driven with different GCM-projections’.

Page 13, Liens 16-17 – Now that is a very interesting finding!

Thanks.

Table 1, change “not/slightly” to “none/slightly” – same with the figures: “not/slightly” does not make sense.

Thanks, we changed the text as suggested.

Table 2, delete “the number of” in the caption.

Thanks, we deleted it.

Table 4, define “formal institutional capacity” in the caption to make the table stand alone.

Thanks, we included the missing information to make the table stand alone.

The final edits for the paper are included in the Major Points listed previously.

Hydrological threats for riparian wetlands of international importance – a global quantitative and qualitative analysis

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Abstract. Riparian wetlands have been ~~reportedly~~ disappearing at an accelerating rate. Their ecological integrity as well as their vital ecosystem services for ~~mankind~~humankind depend on regular ~~inundation~~ patterns of inundation and drying provided by natural flow regimes. However, river hydrology has been altered worldwide. Dams cause less variable flow regimes and water abstractions decrease the amount of flow so that ecologically important flood pulses are often reduced. Given growing population pressure and projected climate change, immediate action is required. ~~Adaptive dam management, sophisticated environmental flow provisions, water use efficiency enhancement, and improved flood management plans are necessary for a sustainable path into~~However, the ~~future. Their~~ implementation~~, however,~~ of counteractive measures is often a complex task. This ~~paper aims at identifying~~study develops a screening tool for assessing hydrological threats for riparian wetlands on global scales. The approach is exemplified on 93 Ramsar sites, many of which are located in transboundary basins. First, the ~~WaterGAP3~~hydrological modeling framework WaterGAP3 is used to quantitatively compare current and future modified flow regimes to ~~natural~~reference flow conditions. ~~Results show that~~In our simulations current water resource management seriously impairs riparian wetland inundation at 29% of the analyzed sites. Further 8% experience significantly reduced flood pulses. In the future, Eastern Europe, Western Asia as well as central South America could be hotspots of further flow modifications due to climate change. ~~Second, impacts on riparian wetland flooding are qualitatively assessed. New dam initiatives in the upstream areas were compiled to estimate the potential for future flow modifications. They currently~~Second, a qualitative analysis of the 93 sites determined potential impact on overbank flows resulting from planned or proposed dam construction projects. They take place in one third of the upstream areas and are likely to impair especially wetlands located in South America, ~~Africa,~~ Asia and the Balkan Peninsula. ~~Further qualitative results address the capacity to act for each site by evaluating whether upstream water resource availability and~~ Third, based on the existing legal ~~and~~/ institutional framework ~~could support~~and water resource availability upstream, further qualitative analysis evaluated the capacity to preserve overbank flows given future streamflow changes due to dam construction and climate change. Results indicate hotspots of vulnerability exist especially in Northern Africa and the ~~implementation of conservation measures~~Persian Gulf.

1 Introduction

~~On~~ a global scale, ~~64-71% of all wetlands have been lost since 1900 (Davidson, 2014~~the natural wetland area has further declined by around 31% between 1970 and 2008 (Dixon et al., 2016) and even higher numbers ~~are~~can be expected for floodplain wetlands. ~~For example, in~~In Europe and North America up to 90% of all natural floodplains are functionally extinct and in developing countries they are disappearing at an accelerating rate (Tockner and Stanford, 2002). ~~Moreover~~Today, river systems belong to the most threatened ecosystems on the planet and the global freshwater Living Planet Index, indicating changes of fish, bird, reptile, amphibian and mammal populations, declined by 76% since 1970 (WWF, 2014). One of the main reasons for this situation is the alteration of natural flow regimes ~~(including natural inundation patterns)~~ due to water resource development (Dynesius and Nilsson, 1994; Kingsford, 2000; Tockner and Stanford, 2002).

Dams are built for different purposes~~ such as water supply, hydropower generation, flood control, and navigation.~~. On the one hand, ~~dams~~they offer important benefits and contribute to 12-16% of global food production and 19% of global electricity generation (WCD, 2000; Richter and Thomas, 2007). On the other hand, dams have been identified as the largest anthropogenic impact on the natural environment (Petts, 1984; Dynesius and Nilsson, 1994; Poff et al., 1997). A study of Nilsson et al. (2005) showed that ~~on the global scale~~ dams affect 59% of all large (i.e. ~~virgin mean~~natural annual discharge ≥ 350m^3/s) river systems globally. In the year 2000, the total cumulative storage capacity of large dams accounted for approximately 8300 km^3 (Chao et al., 2008; ICOLD, 2007), ~~so~~meaning that more than 20% of global annual river discharge can be retained in reservoirs (Vörösmarty et al., 1997). In general, dams cause less variable flow regimes by considerably dampening flood peaks and elevating low flows. The downstream effects of individual dams ~~are felt for~~reach up to tens ~~to~~or hundreds of kilometers, reducing the extent and frequency of floodplain wetland inundation (Collier et al., 1996; McCully, 1996; Poff et al., 2007). Further decreases in flow are caused by water abstractions of an exponentially growing world population. In the year ~~2003, 3856~~2014, 3986 km^3 of freshwater were withdrawn globally according to AQUASTAT statistics (FAO, ~~2010~~2016). The main fraction was used by agriculture (~~70~~69%) followed by industrial (19%) and domestic water supply sectors (~~11%). Often, man-made infrastructure is required to transfer water and fulfil water demands of different sectors. In particular large cities, which spatially concentrate freshwater demands of millions of people into small areas, currently divert 184 km³ of water over a cumulative distance of 27000 km (McDonald et al., 2014) causing flow alterations through inter- and intra-basin transfers. River flow regime modifications by dams, abstractions and diversions have come at great costs (WCD, 2000; WWF, 2004; Richter and Thomas, 2007). Reviewing 165 case studies, Poff and Zimmermann (2010) demonstrated that alterations of natural flows lead to ecological consequences. In 92% of the cases, ecological impacts were reported. Similar outcomes (86% of 65 case studies) were found by Lloyd et al. (2004).~~12%).

While floods are known as one of the most damaging natural disasters worldwide affecting human lives and property (Jonkman, 2005; Doocy et al., 2013; Swiss Re 2014), they are ~~also~~ essential at ~~natural sites~~pristine and ~~benefit~~not heavily altered floodplains benefiting river-floodplain ecosystems~~ and their socio-economic functions for society. In this paper we emphasize that a new approach is needed to water resource management. This approach should include not only flood protection for people but also the allowance of sufficient high flows for sustaining floodplain wetlands which also provide vital services to society.~~

~~.~~ A natural river floodplain falls into the wetland category and represents an ecotone at the interface of aquatic and terrestrial realms, which is periodically flooded and dried~~, and falls into the wetland category (Gregory et al., 1991; Bayley, 1995). Here, flows above bankfull are by far the single most important driving force (Welcomme, 1979; Junk et al., 1989; Tockner and Stanford, 2002) initiating ecological processes, shaping habitat structures, and causing an important exchange of water, organisms, organic matter and inorganic nutrients (Matthews and Richter, 2007). All characteristics and interactions caused by flooding are~~ (Gregory et al., 1991; Bayley, 1995). Here, as described by the flood pulse concept (Junk et al., 1989; Bayley, 1991; Tockner et al., 2000; Junk and

Wantzen, 2004~~) and engender~~), the periodic occurrence of overbank flows is by far the single most important driving force (Welcomme, 1979; Tockner and Stanford, 2002) and engenders one of the most dynamic, diverse and productive systems in the world (Naiman et al., 1993; Nilsson and Berggren, 2000~~). Not only do floodplain wetlands contain more species than any other landscape unit (Tockner and Stanford, 2002; Allan et al., 2005), they also possess a disproportionately high number of rare species and community types (Nislow et al., 2002). As hotspots of biodiversity, they provide vital ecosystem services for society and economy: (i) The high productivity of floodplains generates important resources such as wood, reed, hay and fish. Their soils are very fertile due to the regular enrichment of nutrient-rich sediments, and floodplain fishery is an important source of protein and income for millions of people, especially in tropical countries (Bayley, 1991). (ii) Decomposition rates of floodplain wetlands are high as well. They act as biogeochemical reactors that improve water quality during inundation by removing nutrients and toxins. Thus, they help to buffer non-point-source pollution (Dynesius and Nilsson, 1994). (iii) Aesthetic and recreational values support human leisure time activities such as fishing, hunting, hiking and wildlife watching. (iv) The rich genetic and species diversity ensures ecosystem integrity and serves as raw material for adaptation, evolution and medical research, and (v) access to and inundation of natural floodplains buffer extreme hydrological events and hence, help to avoid flood damages.~~; Allan et al., 2005). Costanza et al. (1997) estimated the monetary value of ecosystem services from floodplains and swamps ~~worldwide at US$ 3231 billion per year, and more recently, a global economic assessment of ‘The Economics of Ecosystems & Biodiversity’ (TEEB) determined the value of the world’s wetlands at US$3.4 billion per year (Brander and Schuyt, 2010). Despite the adherent uncertainty of these numbers, they show that next to ecological, social and cultural benefits, also financial gains can be achieved by floodplain conservation methods~~at US$ 3.2 trillion per year worldwide.

Due to population growth, climate change and new dam initiatives, impacts on riparian wetlands are very likely to further increase in the next decades. Currently, major initiatives in hydropower development are taking place as a new source of renewable energy. At least 3700 major dams are either planned or under construction, which is supposed to further reduce the number of remaining free-flowing rivers by~~ further~~ 21% (Zarfl et al., 2014). These dams offer economic opportunities, but have the potential to negatively impact river ecosystem health (Lloyd et al., 2004; WWF, 2004; Poff and Zimmermann, 2010) and cause conflicts among ~~fellow riparians~~upstream and downstream water users. Climate change may severely alter flow regimes over large regional scales as well (Nohara et al., 2006; Laize et al., 2014). ~~Projections~~Hydrological projections indicate that future flow regimes are likely to be different under climate change due to regionally and seasonally changing precipitation patterns and amounts~~. Additionally, the~~ (Schneider et al., 2013). The higher temperatures will influence timing and quantities of snowmelt (Verzano and Menzel, 2009~~),~~) as well as frequency and intensity of extreme weather events such as floods (Milly et al., 2008~~), as well as transpiration by plants and evaporation from surfaces (Frederick and Major, 1997; IPCC, 2007). Depending on the applied scenario,~~). Okruszko et al. (2011) showed that depending on the applied scenario, European wetlands could lose 26 to 46% of their ecosystem services by 2050 due to climatic and socioeconomic impacts on hydrology.~~ Today, a strong consensus exists among scientists that (i) natural flow variability needs to be maintained to some degree to preserve river ecosystems and the goods and services they provide (Poff et al., 1997; Postel and Richter, 2003; Arthington et al., 2006; Richter, 2009), and (ii) ecosystems should be considered as ‘legitimate users’, whose water requirements should be taken into account in allocation schemes in line with other water use sectors (Naiman et al., 2002; Postel and Richter, 2003; Poff and Matthews, 2013). Measures encompass adaptive integrated dam~~

~~management that reconciles interests of different water use sectors, water use-efficiency enhancement, and sophisticated environmental flow (eFlow) provisions, e.g.~~

~~In concept, there are d~~ifferent measures to counteract flow alteration threats to riparian wetlands.~~ according to the Block Building Methodology (BBM; Tharme and King, 1998) or the Basic Flow Methodology (BFM; Palau and Alcazar, 2012). These methodologies respect ecologically relevant flow elements such as flood pulses for riparian wetlands. Additionally, questions are being asked about cost and effectiveness of current flood and floodplain management policies, and the potential of restoring river floodplains and dead stream branches to minimize flood damages (Sparks, 1995).~~ However, implementing such measures is a complex task and faces challenges such as setting strategic goals, identifying operation targets, having conflict resolution mechanisms in place, involving stakeholders, and monitoring the entire development (Pahl-Wostl et al., 2013). International reviews (Moore, 2004; Le Quesne et al., 2010) revealed that the main obstacles for environmental flow (eFlow) implementations around the world include insufficient legal and institutional capacities, as well as conflicts of interests regarding available water resources. This is especially the case in transboundary river basins. The more countries affect the water management upstream of a riparian wetland, the more groups of stakeholders with different interests are present~~, the higher the potential for conflicts, and the more~~. More interdependencies are created at different administrative levels both within and between the countries and the potential for conflicts is higher (GWP, 2014). Hence, international water treaties and institutions are required to agree on common goals, coordinate basin-wide water management and allocate water to different users (Le Quesne et al., 2010). In the past, ineffective governance systems have often led to overexploitation of water resources with detrimental effects for river ecosystems and, in the long-term, for human well-being (Pahl-Wostl et al., 2013).

Despite the political and legal progress in recent years~~,~~ (Naiman et al., 2002; Postel and Richter, 2003; Arthington et al., 2006; Poff and Matthews, 2013), water provisions for river ecosystems are still assigned a low priority in water management (Poff et al., 1997; Revenga et al~~.~~., 2000; Smakhtin et al., 2004), a much ~~less funds have~~smaller amount has been invested into river ecosystem conservation in comparison to human water security (GEF, 2008; Vörösmarty et al., 2010), and ~~in many countries~~ ecological water requirements have not been assessed yet in many countries (Smakhtin and Eriyagama, 2008; Richter, 2009). Thus, most river reaches and wetlands ~~worldwide~~ remain vulnerable to overexploitation worldwide (Poff et al., 2009; Richter et al., ~~2011). Case~~2012). Regional studies show that floodplain wetlands have been downsized and transformed into terrestrial ecosystems due to reduced flooding caused by water resource management (Hughes, 1988; Maheshwari et al., 1995; Barbier and Thompson, 1998; Kingsford, 2000; Nislow et al., 2002; Middelkoop et al., 2015).

~~In this context, the goal of this study is to identify riparian wetlands that are threatened due to modification of inundation regimes. Thereby, the following research questions are addressed:~~

Today, the speed of river ecosystem destruction and biodiversity loss is exceeding the ability of scientists to review applied water management practices and ecological consequences for each river. Thus, there is an urgent need to complement more accurate but time-consuming case studies by global water assessments that cover large-scale developments (Poff and Matthews, 2013). In recent years, different authors have assessed ecologically relevant flow regime alterations on larger-scales (e.g. Smakhtin and Eriyagama, 2008; Döll et al., 2009; Döll and Zhang, 2010; Schneider et al., 2013; Laize et al. 2014; Pastor et al., 2014; Grill et al, 2015). Building on the work from these valuable papers, this study aims at establishing a screening tool to systematically identify riparian wetlands that are threatened due to river flow regime modifications. While most large-scale eFlow assessments focused on in-channel river flows, our assessment is the first that applies the flood pulse concept on a global scale. Complex flow-dependent ecosystem habitats such as floodplain wetlands are provided by specific flow events. Consequently, rather than changes in average flow conditions, our modelling approach focuses on overbank flows leading to inundation of adjacent riparian wetlands considering different drivers of global change such as dam operation, water use and climate change. As many ecological functions and habitats are facilitated by hydrological events that last only up to a few days (e.g. strong precipitation events, flood formation and overbank flows), discharge simulations are carried-out on a daily time-step. The modelling is performed on a detailed river network with a very high spatial resolution for a global model and can be applied for single reaches of larger rivers with a global coverage. Next to flow regime modifications, the threat for riparian wetlands also depends on the society's capacity to act which is required to respond to changes and implement counteractive measures. This kind of threat has not yet been taken into account in large scale studies. In order to fill this gap, we combined quantitative with qualitative indicators which address upstream water resource availability as well as the presence of institutional arrangements facilitating the establishment of eFlows.

In this study, the proposed screening tool is exemplarily applied on 93 selected riparian wetlands of international importance to address the following research questions:

1. ~~What is the~~ impact of current water resource management on riparian wetland flooding? ~~Thereby this study considers operation (rather than reservoir capacity and river fragmentation) of 6025 large dams, distinguishes operation schemes of different dam types, and takes into account water consumption of five different water use sectors including water transfers of larger cities.~~
2. At which sites is inundation likely to be further ~~impaired in the future? Therefore, this study quantifies the impact of~~modified due to climate change ~~on future flood pulses~~ and ~~compiles major~~new dam ~~initiatives upstream of each wetland.~~construction?
3. ~~At which sites~~ could the implementation of conservation measures ~~could~~ be hindered by a low capacity to act? ~~Therefore, upstream water resource availability as well as the presence of institutional arrangements to facilitate the establishment of eFlows are assessed.~~

2 Methodology

~~This study focuses on~~ In order to exemplify the ~~analysis of a~~proposed screening tool, we selected ~~sample of riparian~~ wetlands ~~of international importance which are~~based on two criteria. First, we chose wetlands listed under the Ramsar Convention~~,~~ which is a global framework for intergovernmental cooperation aiming for the conservation and sustainable use of wetlands. This criterion ensured international importance and the designated protection goal for each wetland. Second, the wetlands have to be dependent on lateral overspill of adjacent rivers (i.e. fluviogenic). The Ramsar Classification System describes different wetland types, but does not categorize ~~floodplain~~riparian wetlands ~~as a specific wetland type. Hence, Ramsar~~. However, riparian wetlands were ~~taken into account, which mainly depend on lateral overspill of adjacent rivers (i.e. fluviogenic wetlands) according to~~selected from the Ramsar list on the basis of information provided by the Ramsar information sheets (RSIS, no date~~).~~) indicating a wetland's dependence on flooding. For Europe, a higher number of sites were ~~gained~~chosen as the European wetland geodatabase (Okruszko et al., 2011) clearly defines wetland type and main source of water for each European Ramsar wetland. ~~Altogether,~~In total 93 sites were selected, ranging from 5 to 55374 km^2 in size~~. They are~~ and located in 48 ~~different~~ countries and 47 ~~different~~ river basins~~.~~, respectively. The ~~highest number was found in the~~ Danube basin~~,~~ had the most selected wetlands of all river basins with 19 riparian Ramsar wetlands~~ of international importance~~. A detailed list of all wetlands is provided in Annex A in the ~~Supplement~~Supplementary Material.

~~Today, riparian wetlands are at risk due to dam and water management practices that make river flows less variable and reduce lateral overspill to the adjacent floodplains. Further impairments on the river flow can be expected by climate change. Hence, in a first step, we conducted~~Our wetland assessment combines a quantitative and a qualitative analysis. The quantitative analysis is based on the flood pulse concept, which describes the flood pulse as a major driver determining the extent of the river floodplain and the biota living within it (Junk et al., 1989; Tockner et al., 2000). For each site we determined the percentage change in flood volume ~~due to~~caused by (i) current ~~dam operation and~~ water ~~consumption of five different water use sectors including water transfers of larger cities~~resource management and (ii) future climate change~~ projections for the 2050s. Thereby~~. In each case, we compared the modified river flow regimes to reference conditions which reflect near-natural flow ~~conditions. The natural flow was~~regimes. These were simulated ~~taking into account~~by not accounting for anthropogenic impacts except current climate and land-cover conditions~~, but no further anthropogenic impacts. In a second step, a~~ . The qualitative ~~assessment was conducted addressing threats by~~ analysis addresses vulnerability due to new dam initiatives ~~and~~as well as a missing capacity to act. New dam initiatives have the potential to further reduce wetland inundation in the near future. ~~Sufficient capacity~~Capacity to act is ~~necessary~~often restricted by deficits in legal and institutional arrangements as well as water resource competition (Moore, 2004; Le Quesne et al., 2010), but required to implement complex counteractive measures at threatened sites and equitably allocated water resources to ~~the~~ different water use sectors.

2.1 The quantitative assessment of threats

In order to quantitatively assess anthropogenic alterations of flood pulses, we applied WaterGAP3 (Eisner, 2016). WaterGAP3 is an integrated global modelling framework to assess impacts of global change on renewable freshwater resources. The model has been further improved to represent specific flow events (Verzano and Menzel, 2009; Verzano et al., 2012) and identify river ecosystems at risk (Schneider et al., 2013). ~~In order to quantitatively assess anthropogenic alterations of flood pulses at Ramsar sites, the following procedure was taken: (i) simulation of daily natural flow regimes for the time period 1981-2010, (ii) simulation of daily flow regimes for the same time period modified by current water resource management, (iii) simulation of daily flow regimes for the 2050s according to climate change projections, (iv) estimation of bankfull flow as a crucial threshold that marks the starting point of inundation, (v) analysis of all overbank flows by calculating the mean annual flood volume for the modified and the natural flow regimes, and (vi) determining the deviations in flood volume in the modified flow regimes in comparison to natural flow conditions.~~

For the simulation~~ of daily river discharge, the integrated WaterGAP3 modeling framework was applied (Verzano, 2009), which performs its calculations on a global 5 x 5 arc minute grid cell raster (~9 x 9 km^2 at the Equator). The global~~Of particular interest for this study is the global coverage, the high spatial resolution of 5 by 5 arc minutes (~9 x 9 km at the Equator) to represent hydrological processes, the temporal resolution of daily time steps which is important for modelling flood formation, the operation of currently >6000 dams with optimization schemes for different dam types, and the calculation of water withdrawals and consumption of five different water-related sectors (domestic, manufacturing industries, thermal electricity production, agricultural crop irrigation, and livestock).

Forced by climatic time series, the hydrology model of WaterGAP3 computes the macro-scale behavior of the terrestrial water cycle. In order to run it for the time period 1981-2010, the WATCH-Forcing-Data-ERA-Interim (WFDEI; Weedon et al., 2014) were used as climate input. It consists of a set of daily, 0.5 x 0.5 degree gridded meteorological forcing data, which were simply disaggregated to the 5 arc minute resolution as required by the model. Forced by the climatic time series, WaterGAP3 calculates The daily water balances for each grid cell takingtake into account distributed physiographic characteristics from high spatial resolution maps describing slope, soil type, land cover, aquifer type, permafrost and glaciers, as well as extent and location of lakes and wetlands. The total runoff in each grid cell, derived from the water balances of land and freshwater areas, is routed along a predefined drainage direction map (DDM5; Lehner et al., 2008) to the catchment outlet. Land cover data were derived from the Global Land Cover Characterization map (GLCC; USGS, 2008) and for EU countries from the CORINE Land Cover map (CLC2000; EEA, 2004). This entire setting was used to gain near-natural flow regimes.

For the Simulated river flows are calibrated against observed annual discharge data from the Global Runoff Data Centre (GRDC, 2004) at about 1600 gauging stations globally. The calibration process adjusts only one model parameter, which has an effect on cell surface runoff generation at gauging stations (Eisner, 2016). The model's ability to represent specific flow events has been proven for different maximum flow magnitudes (Schneider et al., 2011a; Schneider, 2015; Eisner, 2016).

In order to assess quantitative changes in floodplain inundation, we conducted different model experiments and proceeded as follows: First, we simulated modified river flow regimes modified byunder current water resource management, additionally, (tier 1) and climate change (tier 2). As assessment of river ecosystem health implies comparison of modified flows to reference conditions (Norris and Thoms, 1999), we simulated reference flow regimes in tier 3 by not accounting for anthropogenic impacts except current climate and land-cover conditions. Bankfull flow constitutes an important parameter in our analysis. It describes the starting point where flow enters the active floodplain and was estimated for each grid cell in tier 4. As floodplain inundation requires overtopping of the banks, each daily flow above bankfull was a critical flow to investigate in tier 5. Here we compared modified to reference flow regimes and determined the change in flood volume. Single steps of the approach are illustrated in Figure 1 and described in more detail in the following subchapters.

2.1.1 Simulation of modified flow regimes under current water resource management

For the simulation of flow regimes under current water resource management (i.e., 1981-2010), we took anthropogenic flow alterations due to water use and dam operation were taken into account. For these model runs, the natural discharge was (tier 1, Figure 1). Regarding water use, river discharge is reduced in each grid cell by consumptive water useconsumption as calculated by the global water use models of WaterGAP3. These models simulate spatially distributed sectoral water uses for the five most important water use sectors: electricity production, manufacturing, domestic use, agricultural crop irrigation and livestock watering (Aus der Beek et al., 2010; Flörke et al., 2013). Assuming an optimal water supply to irrigated crops, net

Net irrigation requirements are simulated for each grid cell based on climatic conditions, dominant crop type and irrigated area around the year 2005 (GMIAv5; Siebert et al., 2013) assuming an optimal water supply to irrigated crops. Livestock water demands are determined by multiplying the number of animals per grid cell by the livestock-specific water use intensity (Alcamo et al., 2003). ~~). Livestock water demands are determined by multiplying the number of animals per grid cell by the livestock-specific water use intensity (Alcamo et al., 2003). The amount of cooling water consumed by~~ For the electricity production sector, the amount of cooling water consumed is calculated by multiplying the water use intensity of each power station with the equivalent annual thermal electricity production. The water use intensity is affected by the cooling system (once-through flow cooling, tower cooling, or ponds) and the type of fuel (coal and petroleum, natural gas and oil, nuclear, or biomass and waste) used at each power station (Flörke et al., 2012). Power station characteristics such as type, size and location are derived from the World Electric Power Plants Data Set (UDI, 2004).

Consumptive water uses of the manufacturing and domestic sectors are computed on a country scale following data from national statistics and reports, which are subsequently allocated to the grid cells of the associated country by means of urban population and population density maps, respectively (Flörke et al., 2013). For the domestic sector, WaterGAP3 also considers ~~the~~ water transfers of 480 larger cities including their 1642 withdrawal points (City Water Map; McDonald et al., 2014).

In order to assess flow alterations due to dam operation, ~~6025 large dams with a total storage capacity~~the number of ~~6200 km^3 were allocated to the WaterGAP3 stream net~~ dams implemented in the model has been further increased based on information ~~of~~provided by the Global Reservoir and Dam (GRanD) database (Lehner et al., 2011). ~~The criteria of implementation were a minimum dam~~ From this dataset, WaterGAP3 considers now all large dams (i.e., dams with a height of ≥15 meters ~~which is in accordance with the ICOLD definition for large dams. Additionally,~~) plus smaller dams exceeding a reservoir storage volume of 0.5 km^3 ~~were considered even with a lower dam height.~~ ^{3}. 6025 dams are currently allocated to the global WaterGAP3 stream net accounting for a total accumulative storage volume of 6200 km^3. This is state-of-the-art in comparison to other global models (Haddeland et al., 2013).

~~The operation of~~ dams is performed in WaterGAP3 as a function of dam type. ~~All dams~~Dams with the main purpose for irrigation are operated according to the algorithm of Hanasaki et al. (2006) with minor modifications by Döll et al. (2009). ~~In the algorithm,~~The annual reservoir release is a function of long-term average annual reservoir inflow, the ~~water balance over the reservoir, and the~~ relative reservoir storage at the beginning of the operational year, and the difference between precipitation and evaporation over the reservoir surface. Subsequently, monthly reservoir releases are calculated depending on the downstream consumptive water use in each month.

All otherOther dam types are operated ~~now in WaterGAP3~~ based on an optimization scheme provided by Van Beek et al. (2011). Depending on the dam type, an objective function is applied that maximizes electricity production by maximizing the hydrostatic pressure head to the turbines (hydropower dams), minimizes flood damages by minimizing overbank flows (flood control dams), and aims for a constant outflow by ~~minimising~~minimizing deviations from the annual mean (water supply and navigation dams). Furthermore, we considered different constraints ~~are considered which~~that reserve sufficient storage capacity to accommodate larger floods for seven days (flood protection) and to keep sufficient water in the reservoir to safeguard a minimum flow for at least thirty days (minimum flow provisions).

Given current reservoir storage and monthly inflow data of the upcoming year, the overall modelling strategy is to find the monthly target storages (and corresponding monthly reservoir releases) that ~~would~~ ensure optimal functioning of the dam. This strategy was realized in WaterGAP3 by evaluating objective functions and constraints through deterministic dynamic optimization (Bellman, 1957) and discretizing reservoir storage by the Savarenskiy's scheme (Savarenskiy, 1940) considering a discretization width of 2%. At the beginning of each month, the accumulated objective function value is computed for the upcoming twelve months taking into account every possible combination of the discrete reservoir storage classes. The combination, which provides the most suitable value for the objective function without harming any constraint, determines the ~~dam operation scheme.~~monthly target storages. As inflow data, forecasted monthly values are used derived from average simulated flows of the last ~~5~~five years (rather than simulated values for the future year). This prospective scheme reflects more realistically the hydrological situation, where water managers have to deal with uncertain forecast as well (van Beek et al., 2011). The monthly target storages together with the actual incoming flow are subsequently used to calculate the daily reservoir releases. ~~At about 1600 gauging stations globally, the simulated river flow is calibrated against observed annual river flow data from the Global Runoff Data Centre (GRDC, 2004). The calibration process adjusts only one model parameter, which has an effect on cell surface runoff generation at gauging stations (Döll et al., 2003).~~

ForIn this modelling study we used the WATCH-Forcing-Data-ERA-Interim (WFDEI; Weedon et al., 2014) for climate input representing current conditions. The time series consists of a set of daily, 30 x 30 arc minutes (~50 x 50 km at the Equator) gridded meteorological forcing data, which were simply disaggregated to the 5 arc minute resolution as required by the model.

2.1.2 Simulation of modified flow regimes under climate change

To simulate future flow regimes modified only by climate change, additional ~~WaterGAP3~~model runs were conducted (tier 2, Figure 1) for the 2050s (represented by the time period 2041-2070). Here, WaterGAP3 was driven with bias-corrected, daily climate data from five different general circulation models (GCMs), namely GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M~~) taken from~~ , provided by ISI-MIP (Hempel et al., 2013). ~~Thereby, we~~We assumed climate drivers to follow the Representative Concentration Pathway leading to a radiative forcing (cumulative measure of human emissions of GHGs from all sources) of 6.0 W/m² (RCP6.0~~), which depicts~~). Current CO_2 emissions are close to the upper end of the scenario range and RCP6.0 is a medium-high emission scenario with ~~stabilization from 2050 onwards~~a global mean temperature increase of 2.2°C until the end of the century compared to 1986-2005 (Riahi et al., 2011). ~~River discharge was modelled for the 2050s (represented by the time period 2041-2070)~~Within the future time frame the differences between the emission scenarios (as represented by the radiative forcing) are smaller than between scenarios based on different GCMs. Thus we considered climate forcing of five different GCMs but ~~also for the baseline period 1981-2010 to gain GCM-driven natural flow regimes as reference condition. In~~ only one emission scenario in order to ~~focus on the exclusive~~address the uncertainty of projected climatic conditions. Although model outcomes of tier 2 will not reflect future conditions because of not taking into account future water management, this model experiment supports identifying the solely effect of climate change~~,~~ on riparian wetland inundation. Therefore, we disabled dam operation and water use ~~were disabled~~ in these model runs.

An important parameter in our analysis is

2.1.3 Simulation of reference flow regimes

The aim of tier 3 was to simulate daily reference flow regimes reflecting near-natural conditions (Figure 1). Hence, anthropogenic impacts such as dam operation and water use were disabled in these model runs. In order to be able to make comparisons with modified conditions, we conducted six different model runs for the reference period 1981-2010. We forced WaterGAP3 with WFDEI climate data to simulate reference flow regimes for the comparison with modified flows of tier 1 and with GCM data for the comparison with flow regimes of tier 2. Land cover data were derived from the Global Land Cover Characterization map (GLCC; USGS, 2008) and for EU countries from the CORINE Land Cover map (CLC2000; EEA, 2004) and kept constant over the entire model simulations.

2.1.4 Estimation of bankfull flow ~~as it describes the point where the flow starts to enter the active floodplain.~~

Bankfull flow was estimated in our approach for each ~~single~~ grid cell by flood frequency analysis (tier 4, Figure 1). We applied the partial duration series (PDS) approach taking into account 30-year time series of daily discharge data modelled by WaterGAP3~~ and applying~~, an increasing threshold censoring procedure, a declustering scheme and the generalized Pareto distribution. In the PDS, bankfull flow is determined by a return period of 0.92 years. The approach including a validation of bankfull flow estimates is described in detail by Schneider et al. (2011a). ~~As floodplain inundation requires overtopping of the banks, each daily flow above bankfull was a critical flow to examine. The~~

2.1.5 Assessment of overbank flow modifications

~~We used t~~the flood volume (i.e. the cumulative amount of daily discharge above bankfull) ~~is~~as a measure for the extent of flooding ~~and~~ in tier 5 (Figure 1) which was determined ~~for the modified and the natural flow regimes as mean~~ as the long-term annual ~~value~~mean over the 30-year time period. The percentage change in ~~mean annual~~ flood volume between the modified and ~~natural~~reference flow regimes describes the anthropogenic impact on floodplain inundation. ~~Results for the climate~~Climate change ~~impact~~impacts on flow regimes are presented as ensemble median, ~~so that~~which reflects the direction of change ~~is reflected by~~of at least ~~3~~three out of the ~~5~~five selected GCMs. ~~Thereby, only reductions have been documented in the results chapter, because it cannot be distinguished whether an increase in flood volume benefits the wetland or generates flood damages, which, in turn, would be an incentive to build more dams for flood control (Poff and Matthews, 2013). The entire approach described above~~The entire approach was carried out for each single grid cell of the global 5 arc minute raster~~.~~ ~~For the analysis of~~ but only grid cells associated to riparian wetlands ~~associated grid cells on the WaterGAP3 raster were investigated~~were further examined.

~~No~~In order to evaluate the ecological consequences of flood volume alterations, thresholds needed to be defined. So far no generalizable relationships between flow alteration and ecological impact are available for large-scale assessments. ~~In order to distinguish levels of modification,~~ Therefore we applied ‘thresholds for potential concern’ ~~were applied~~ (Hoekstra et al., 2011) for the deviation (Δ) in flood volume between the modified and the ~~natural~~reference flow regimes in order to distinguish distinct levels of modification (~~Table 1).~~Table 1). These thresholds are based on the ‘~~20% rule’~~presumptive standard’ suggested by Richter et al. (2012) for daily flow alterations and likely indicating moderate to major changes in ecosystem structure and functions ~~(Richter et al., 2011) and~~as well as initial thoughts from some water resources experts to set a global standard on eFlow requirements~~ (Hoekstra et al., 2011). However,~~. Though it has to be considered in our assessment that already small reductions in flood volume can result in large decreases in the extent of area flooded (Taylor et al., 1996; Kingsford, 2000; Tockner and Stanford, 2002).

In general it can be expected that the greater the deviation from natural ~~condition~~conditions, the greater the expected ecological impact (Poff and Hart, 2002; Magilligan and Nislow, 2005). Quantitative relationships between peak flows and ecosystems are provided, e.g. by Wilding and Poff (2008) for rivers in the U.S. state Colorado. In their study, riparian vegetation responds by a maximum change of 12% in community composition for each 10% reduction in peak flows. Consequently, a reduction of 40% in flood volume, which indicates a serious modification in our analysis, could lead to a 48% change in riparian vegetation. Stream invertebrates, in turn, respond exponentially. A 40% change in peak flow ~~caused~~may cause a maximum response of 54% change in invertebrates.

2.2 The qualitative assessment of threats

The~~ modification of river flow regimes will continue in the coming decades.~~ In order to evaluate further ~~threats for~~impairments on riparian wetland flooding~~,~~ in the coming decades, we conducted a qualitative assessment ~~was conducted~~ considering future dam construction and the capacity to act~~.~~ required responding to ecological threats caused by flow regime alterations.

2.2.1 Future dam construction

Besides climate change, the construction of new dams will further modify flood pulses and thus, put additional pressure on riparian wetlands. Therefore, for each selected site we determined the number of ~~dams was determined from~~ all upstream dam projects which are over 10 megawatts in capacity ~~that~~and were planned, proposed or under construction as of July 2014 (Petersen-Perlman, 2014). A number of sources were used to build ~~the~~this dataset: the United Nations Framework Convention on Climate Change's Clean Development Mechanisms (http://cdm.unfccc.int), International Rivers, and other organizations' websites known to fund dam construction (e.g., World Bank). ~~The defined impact on riparian wetlands is shown in Table 2.~~If no dam initiatives were found in the upstream area, we assigned a low impact. The remaining sites were divided into two almost equally sized groups to define a medium (1-12 dam initiatives) and high (28-276 dam initiatives) impact (Table 2).

In practice, d~~ifferent measures are available to counteract flow alteration threats to riparian wetlands. However, their~~

2.2.2 Capacity to act

The implementation of counteractive measures is ~~not straightforward~~a complex task and depends on the local capacity to act. In order to assess that capacity for each ~~Ramsar~~ site, we calculated two sub-indicators~~ were calculated.~~.

~~The~~ first sub-indicator addresses the availability of water for ecological allocations. ~~A high level of water scarcity in the upstream area indicates a high competition for water resources between different water use sectors and reduces the potential to allocate adequate amounts of water for ecological requirements. In particular,~~Especially flood pulse provisions ~~would~~ require a relatively large amount of water at a specific time of the year. However, in some regions, water ~~withdrawals~~use alone can have a strong impact on the river flow regime. For example, ~~water withdrawals at~~ the outflow of the Colorado and Murray Darling ~~Basin cause that only 36%~~Rivers is reduced by water use to <1% and 36%, respectively, of ~~the~~its natural flow ~~drains into the sea~~ (Jolly, 1996~~).~~ ; Cushing and Allan, 2001). A high level of water scarcity in the upstream area indicates a high water resources competition between different water use sectors and reduces the potential to allocate adequate amounts of water for ecological requirements. Water scarcity was defined ~~in this study according to~~ following the approach of Hoekstra et al. (2012) ~~and occurs when the blue water footprint exceeds blue water availability. This approach assumes~~who suggested that no more than 20% of ~~total~~ monthly river discharge ~~is~~should be depleted by consumptive water use to maintain river ecosystem integrity ~~(Richter et al., 2011).~~. Depending on the average number of ~~month~~months per year with water scarcity (i.e., a consumption-to-availability ratio >0.2) in the upstream area, water availability for ecological purposes was determined (~~Table 3~~Table 3). The cutoff thresholds for low (6-12 months), medium (2-5 months) and high (0-1 month) water availability were arbitrarily chosen.

The second sub-indicator addresses the legal and institutional ~~capacity~~framework in place, and distinguishes between transboundary and non-transboundary upstream areas. For the latter ~~one~~, the sub-indicator depicts whether the country ~~of~~where the ~~site~~riparian wetland is located has legal provisions or official recommendations for the establishment of eFlows (=yes) or not (=no). ~~While having~~Having a legal provision ~~is no guarantee that eFlows are actually established in practice, enforced or adequate, it~~ is an important first step for setting strategic goals, advocating ecological water requirements with stakeholders, securing planning resources, and promoting eFlow implementation (Le Quesne et al., ~~2010). The main sources of information for this~~ 2010). However, it is no guarantee that eFlows are actually established in practice, enforced or adequate. As most of this information on legal eFlow provisions was available in qualitative terms we introduce a simple yes-no query to our capacity to act indicator. In particular no quantitative information on eFlow provisions was found for the management of dams. The main sources of information for this sub-indicator were OECD (2015), Benítez Sanz and Schmidt (2012), Le Quesne et al. (2010), and the FAO Water Lex Legal Database (FAO, no date).

In transboundary upstream areas the ~~complexity of water management increases and conflicts are more likely.~~sub-indicator takes into account five parameters as the complexity of water management increases. Here, we measured formal institutional capacity by (i) the presence of RBOs, (ii) at least one relevant treaty, and specific treaty provisions such as (iii) water allocation mechanism, (iv) conflict resolution mechanism, and (v) flow variability management. Formal arrangements governing transboundary river basins, in the form of international water treaties and river basin organizations (RBOs), can be particularly instrumental in managing disputes among different stakeholders involved in water resources management. The greater institutional capacity is, the higher is the potential for eFlow allocations. Institutional frameworks can determine targets, responsible authorities, reoperation strategies, reallocation of water shares, monitoring efforts and consequences of assessment outcomes (Le Quesne et al., 2010; Pahl-Wostl et al., 2013). ~~Therefore, for all sites with a transboundary~~ For the calculation of this sub-indicator, we divided the upstream ~~area, the formal transboundary institutional capacity was expressed by the presence of RBOs, at least one relevant treaty, and specific treaty provisions such as water allocation mechanism, conflict resolution mechanism, and flow variability management. For each of these components present at~~ areas in basin-country ~~unit (BCU)~~units (BCUs; i.e. the portion of a country within a river basin shared by two or more countries). For each of the five parameters present at BCU level, one point was given, allowing for a score ranging from zero to five. In order to assign a score to each wetland ~~a value~~ reflecting ~~transboundary institutional capacity in its~~ upstream ~~BCUs, the values for~~

~~those upstream BCUs were~~transboundary institutional capacity, we aggregated and weighted the scores of all upstream BCUs based on the contribution of each BCU to the runoff of the total upstream area. ~~An~~We gave an additional point ~~was given~~ in case the country ~~of~~where the ~~site~~wetland is located has legal provisions or official recommendations for the establishment of eFlows. The scores were then grouped into ~~3~~three classes describing a low, mid, and high ~~legal and~~ institutional capacity (~~Table 4~~Table 4). All underlying data were obtained from De Stefano et al. (2012) and complemented with data embedded in international RBOs (Schmeier, no date).

3 Results

3.1 Quantitative analysis

~~*Riparian wetlands depend on natural patterns of inundation. However, flow regimes of most large river systems in the world have been altered due to different anthropogenic impacts with severe consequences for river ecosystems. Comparing current (1981-2010) modified river flow regimes to natural flow conditions, riparian wetlands of international importance with seriously altered inundation volumes can be found on all continents (*~~

3.1.1 Overbank flow alterations caused by current water resource management

~~Fig. 1~~Figure 2~~). Altogether, half (51%) of the 93 selected Ramsar sites are~~ shows the degree of alteration in flood volume at the 93 wetland study sites caused by current (1981-2010) water management practices. When comparing modified to reference flow regimes, every second site (51%) is impaired by at least moderately reduced flood volumes~~. Eight and 29% of the sites, respectively, are even~~ in our simulations. Almost every third site (29%) is seriously and further 8% are significantly ~~and seriously affected. In our analysis,~~affected by the flow regime modifications. Seriously affected sites occur on all continents but particularly in Australia, China, North America, and the Iberian Peninsula as well as at rivers that drain into the Black Sea (e.g. Dnieper and Dniester rivers) or the Persian Gulf (e.g. Tigris and Karun rivers). We found that dams for hydropower generation are the most frequent dam type in almost one third of the selected upstream areas, followed by irrigation dams in one ~~fourth~~quarter of the ~~cases.~~upstream areas. However, ~~regarding only wetlands with seriously modified inundation patterns,~~ irrigation dams are the most frequent dam type in almost half of the cases (48~~%). This illustrates the crucial role of irrigation as a strong competitor to ecological water requirements~~%), when only wetlands with seriously modified inundation patterns are regarded.

~~In general, a high impact by water resource use appears in Europe especially in the south (mainly affected by dams for irrigation) and in the north (mainly affected by dams for hydropower), but also larger rivers that drain into the Black Sea often show serious modifications (e.g. Dnieper, Dniester, and Don rivers). Nevertheless, a high percentage (56%) of the 43 selected European Ramsar sites possess only slightly impacted inundation patterns The seriously impacted sites are Paúl de Boquilobo (#55) and Doñana (#56) in the Iberian Peninsula, Morava Floodplain (#33), Dnieper River Delta (#41), Lower Dniester (#42), and Dniester-Turunchuk Crossrivers Area (#43) close to the Black Sea, and River Luiro Mires (#14) in the far North of Europe. At these sites flood volumes are reduced due to water resource management by more than 40% in comparison to natural flow conditions. Nine of the analyzed sites are located along the Danube River for which slightly (#31), moderately (#44, #48, #50, #51, #52) and significantly (#35, #37, #46) reduced flood volumes were identified. Due to the lower storage capacities of the numerous dams, the Danube River is more affected by fragmentation than flow regulation as shown by Grill et al. (2015). Significantly impaired flood pulses occur as well at the~~

~~Elbauen (#20) in Germany. In Europe, hydropower dams are the most frequent dam type in 56% of the upstream areas. The seriously impacted sites in the Iberian Peninsula are mainly affected by water management for irrigation.~~

~~In North America, seriously modified flooding patterns can be explained by a high number of large dams for various purposes (hydropower, irrigation, flood control, and water supply). However, in northern Canada, Alaska and southern Mexico many river reaches still show only slightly flow modifications. According to our analysis, two of the four selected North American wetlands receive seriously (Peace-Athabasca Delta, #1 and Cache-Lower White Rivers, #4), and one significantly reduced flooding (Lac Saint-Pierre, #2). The Emiquon Complex (#3) is only slightly affected by water resource development.~~

~~In Australia, mainly river reaches of the~~ In Australia, five (#89-93) of six vulnerable sites are located in the Murray-Darling basin ~~are characterized by seriously reduced overbank flow events. For the selected Australian Ramsar areas a strong impact was found in our analysis. Six out of seven sites possess seriously modified flooding regimes: Gwydir Wetlands (#89), Macquarie Marshes (#90), Riverland (#91), Banrock Station Wetland Complex (#92), Barmah Forest (#93), and Ord River floodplain (#88). Except the latter one, all of them are located in the Murray-Darling basin and in~~. In their upstream areas more than 100% of the annual flow can be stored in reservoirs ~~causing~~indicating a high impact on flow regulation, which was also found by Grill et al. (2015). ~~Agricultural~~Intense agricultural irrigation is responsible for the highest water withdrawals and irrigation dams are the most frequent dam type in almost all upstream areas. This is underlined by Kingsford (2000) ~~stated~~who reported that many floodplains ~~at~~in the Murray-Darling basin have turned into terrestrial ecosystems. ~~One of our selected Australian sites is nearly undisturbed, i.e. Kakadu National Park (#87) located in Northern Australia.~~

~~In South America, especially many river reaches in the Amazon basin are still in pristine conditions and many riparian wetlands possess only slightly modified inundation patterns with no or only a few large dams in the upstream area. However, seriously modified inundation patterns are existent in South America as well at three of the nine selected Ramsar sites: La Segua (#5) in Ecuador, as well as Humedales Chaco (#12) and Jaaukanigas (#13) in Argentina.~~

~~In Asia, hotspots of river reaches with seriously modified overbank flows are located in India, eastern China and the Middle East. Today, China possesses the highest number of large dams, followed by the United States and India (Rosenberg et al., 2000). In our analysis, one third of the 15 selected Asian wetlands are seriously impacted by water resource development: the Volga Delta (#74) in Russia, Hawizeh Marsh (#77) and Shadegan Marshes & mudflats of Khor-Al Amaya & Khor Musa (#78) at the Persian Gulf, as well as Shandong Yellow River Delta Wetland (#75) and Dong dongting hu (#79) in China.~~ At the Volga River, the construction of dams for hydropower and navigation during the Soviet Union-era has substantially altered the ~~natural~~ flow regime, which ~~negatively~~seriously influences the dynamics of the Volga Delta (#74~~).~~) in our analysis. This finding is in line with other studies. Khublaryan (2000) reported that ~~due to river regulation,~~ mean high water flow decreased from ~~2/3~~67 to 42% of the annual flow in the Lower Volga~~. The two Ramsar sites at the Persian Gulf (#77, #78) have been heavily affected by water management and abstractions for irrigation. At Yellow and Yangtze River, particularly large dams for water supply and flood protection play a crucial role.~~ River due to river regulation. Middelkoop et al. (2015) found that dam operation caused a decrease in magnitude and duration of spring peak flow in the Lower Volga.

AboutNine of the analyzed sites are located along the Danube River for which we identified slightly (#31), moderately (#44, #48, #50, #51, #52) and significantly (#35, #37, #46) reduced flood volumes. Despite numerous dams, the lower storage capacities cause the Danube River to be more affected by fragmentation than flow regulation as also shown by Grill et al. (2015).

We found the lowest number of vulnerable wetlands in South America and Africa. In South America many riparian wetlands possess only slightly modified inundation patterns. Only a few large dams are located in upstream areas and many river reaches, especially in the Amazon basin, are still in pristine conditions (see also Tockner and Stanford, 2002). Nevertheless, seriously modified inundation patterns exist as well at three (#5, #12 and #13) of nine selected study sites located in Ecuador and Argentina. In Africa, about half of the ~~selected African wetlands~~sites are not or only slightly affected under current conditions. However, one third of the ~~15~~African sites are impaired by seriously or significantly altered overbank flow events. ~~The seriously influenced sites due to current dam operation and water use are Embouchure de la Moulouya (#58)~~These sites are located in Morocco, ~~Marromeu Complex (#69) in~~ Tunisia, Mozambique, ~~as well as Baturiya Wetland (#61) and Lower Kaduna-Middle Niger Floodplain (#64) in Nigeria, followed by Sebkhet Kelbia (#57) in Tunisia with significantly reduced flood volumes. At all moderately to seriously affected sites, crop irrigation accounts for the highest water withdrawals in the upstream areas and irrigation dams constitute the most frequent dam type (except at Tana River Delta where hydropower dams are prevailing). Hence, especially in Africa measures are required that balance environmental and agricultural water requirements without reducing food security.~~and Nigeria. The threat to Nigeria's wetlands is also reported by Uluocha and Okeke (2004) inter alia due to population pressure and dam construction.

3.1.2 Overbank flow alteration due to climate change

~~In the future climate change is likely to further modify river flow regimes with consequences for riparian wetland inundation. In regard to decreasing flood pulses, two hotspots became obvious in our analysis for the 2050s: (i) Eastern Europe/ Western Asia and (ii) central South America (Fig. 2).~~

In Europe, climate change is likely to further decrease flood pulses at more than half of the selected European wetlands as indicated by the ~~ensemble median of the~~model results driven by five GCM-projections. ~~At 23~~According to the ensemble median, the average flood volume is expected to decrease at 41% of the sites in the 2050s due to the exclusive effect of climate change (Figure 3). At 16% of the sites, reductions ~~might~~ are significant or even serious (i.e. >30%). Overall two spatial hotspots could be identified in Eastern Europe/ Western Asia as well as in South America below the Amazon River where flood pulses are likely to be ~~even significantly or seriously. Most of the concerned sites~~reduced under climate change. These WaterGAP3 results are in line with Dankers et al. (2013) who modelled changes in peak flows at the end of this century by nine global hydrology models.

In Europe, most sites of concern are located in Eastern Europe, i.e. in the Ukraine (#24, #26, #43), Hungary (#32, #36), Slovakia (#34), Moldova (#42) and Romania (#45), but also ~~occur~~ in Spain (#56) and Germany (#29). ~~Thereby, lower Dniester~~Climate change will induce an additional threat for three of the sites (#42~~), Dniester-Turunchuk Crossrivers Area (#~~, #43~~) and Doñana (#~~, #56) which already experience ~~already~~ seriously or significantly reduced flood volumes under current water management practices~~ so that climate change induces an additional threat~~. In Asia, wetlands affected by reduced flooding under climate change are located in Russia (#73, #74) and Iraq (#77). ~~At the Volga Delta (#74) and Hawizeh Marsh (#77) flood~~Flood pulses are already seriously reduced under current water management~~. In~~ at two of them (#74, #77). The expected reduction in wetland inundation in Eastern Europe and Western Asia ~~with their~~in the future can be explained by changes in snowmelt. In these two regions characterized by continental climate, global warming is likely to cause a reduction in snow cover ~~leading to~~resulting in lower and earlier snowmelt-induced flood peaks in spring ~~(~~as found by Schneider et al~~.,~~. (2011b~~,~~; 2013). Moreover, analyses of stream flow trends in European Russia indicate that spring flows have been decreasing since the mid-1970s (Georgiyevsky et al., 1995; 1996; 1997).

~~In South America, climate change is likely to decrease riparian wetland inundation at all sites located south of the Amazon River, particularly at the currently slightly affected sites Rio Yata (#8) and Rio Blanco (#9) with reductions of more than 40% according to the ensemble median. At Pantanal Matogrossense (#11) flood pulses might be moderately decreased in the 2050s and remaining wetlands (#7, #10, #12, #13) show slightly reductions between 0 and 20%.~~

~~At the selected North American and Australian sites, the ensemble median of the climate projections indicates no further reduction in flood volume for the 2050s. An exception to this is the Gwydir River in the upper Murray-Darling basin with significantly reduced flood volumes in the future. The climate change impact is relatively small on the African wetlands. At only 4 sites (#58, #63, #68 and #69) flood pulses are slightly reduced in the 2050s. However, Embouchure de la Moulouya (#58) and Marromeu Complex (#69) have already seriously reduced flood pulses under current water resource management.~~

Increasing flood volumes, in contrast, can be found at 51% of the selected riparian wetlands under climate change conditions. The rise in flood volume is expected to be higher than 30% in the 2050s at almost every third (30%) site. Those wetlands tend to be located closer to the coast and especially in Southeast Asia, Southeast Europe, Scotland, West Africa, Tanzania and Kenya. In the analysis of Dankers et al. (2013), increases in flood hazard were projected consistently for Southeast Asia.

3.2 Qualitative analysis

3.2.1 Future dam construction

New dam initiatives have the potential to further impair riparian wetland flooding~~ in the future. Altogether, new~~. New dams are currently planned or under construction in ~~one third of~~ the upstream areas of one third of the selected ~~Ramsar sites~~riparian wetlands (~~Fig. 3~~Figure 4). In agreement with results of Zarfl et al. ~~). The highest percentage was found in South America. Here, two-thirds of the sites are likely to be influenced by new dam initiatives. Especially in the Amazon basin, a very high number of dams is planned or under construction likely to affect flooding patterns of the Mamiraua wetland (#6). Further~~(2014), extensive dam ~~initiatives take place at the Parana and Paraguay River basins. These are likely to impair Humedales Chaco (#12) and Jaaukanigas (#13) with already seriously reduced flooding under current water resource management as well as Pantanal Matogrossense (#11) with slightly reduced flooding under current conditions and a moderate impact by climate change.~~

~~A very high number of new dams is also planned in Asia with the potential to affect 60% of the selected Ramsar areas. Major dam initiatives are likely to impair especially the wetlands Dong dongting hu (#79) and Shandong Yellow River Delta Wetland (#75) in China, Sundarbans Reserved Forest (#80) in the Ganges-Brahmaputra-Meghna basin, as well as Tram Chim National Park (#84), Middle stretches of the Mekong River (#81) and Bau Sau Wetlands (#83) at the Mekong River basin. The two Chinese wetlands possess already~~construction is on the way, particularly in areas upstream of South American (67%) and Asian (60%) wetlands. We found that a large impact is likely in the upstream areas of wetlands located in the basins of Amazon, Parana and Paraguay as well as Yangtze, Yellow, Mekong, and Ganges-Brahmaputra. Riparian wetlands in China (#75, #79) and Argentina (#12, #13) are already characterized by seriously reduced flood volumes under current water management conditions.

~~At~~ Dams are also planned or under construction upstream at about half (47%) of the selected African sites, ~~dams are planned or under construction upstream, though~~although the number of dams is relatively small in most upstream areas. ~~The highest number occurs upstream of Marromeu Complex (#69) and Lower Kaduna-Middle Niger Floodplain (#64) with 12 and 5 dam initiatives, respectively. However, these upstream areas are large in~~ Analyzing future trends for riverine floodplains, also Tockner and Stanford (2002) concluded in their assessment that in South America, Asia and Africa many floodplains will become reduced in size~~, so that the effect on the wetlands might be not so strong. A smaller number of dam initiatives is taking place upstream of the moderately affected Delta Interieur du Niger (#59) and some slightly affected sites (#62, #66, #68 and #70).~~ or even disappear in the future.

While a high number of dams have been constructed in North America and Australia in the last century, no further dams are planned or under construction upstream of the selected Ramsar sites. ~~The same applies to~~This is also the case for most parts of Europe~~. However, at 19% of the European sites quite~~ , but a high number of new dams could be constructed upstream ~~in the near future. All of these sites are~~ of riparian wetlands located in the Balkan Peninsula (i.e. in Croatia, Serbia, Bulgaria and Romania) ~~and the dams are likely to have an impact on~~further threatening riparian wetlands in the lower Danube basin. ~~Currently, the concerned sites are slightly (#47), moderately (#48, #49, #50, #51, #52) or significantly (#46) impaired due to water resource management, but the new dam construction has the potential to further diminish inundation.~~

Different3.2.2 Capacity to act

Implementing counteractive measures ~~are available to minimize anthropogenic flow regime modifications. However these measures are complex and require~~requires that (i) sufficient water is available to satisfy water demands of different water use sectors and (ii) institutional arrangements are in place enabling the establishment of eFlows ~~are in place.~~. Considering these two factors, ~~Fig. 4 depicts for each riparian wetland~~Figure 5 displays the capacity to act in ~~each~~the upstream area for each riparian wetland.

In Europe, e~~Flow~~ Our analysis shows that the highest competition for water exists in the upstream area of the Lake Chad Wetlands (Nigeria) followed by wetlands of the Murray-Darling (Australia), Schatt al-Arab (Persian Gulf), Tana (Kenya), Moulouya (Morocco), and Yellow (China) River basins, where water scarcity occurs upstream in six to ten months of the year on average. Lake Chad lost one-tenth of its size in the last 40 years (Uluocha and Okeke, 2004) and the United Nations Environment Programme stated that human water use is responsible for about half of the decrease (UNEP, 2008) which supports our finding. EFlow applications ~~(including high flow provisions)~~ might be ~~most~~also challenging in the ~~upstream areas of currently seriously impacted sites. Water~~ Iberian Peninsula as water availability for ecological purposes ~~was~~is rated medium ~~for Paúl de Boquilobo (#55) and Doñana (#56) as~~with water scarcity ~~occurs~~occurring on average in ~~5~~five months of the year due to high water requirements for agricultural irrigation. ~~Three to four months of water scarcity were found upstream of Morava Floodplain (#33), Dniepro River Delta (#41), Lower Dniester (#42), and Dniester-~~

~~Turunchuk Crossrivers Area (#43). In most upstream areas of the assessed European wetlands (71% of the cases),~~

Globally, normative eFlow provisions are considered in the national or state Water Act at about 50% of the selected Ramsar sites. The highest percentage of sites without normative eFlow provisions occurs in Asia (87%) and Africa (80%). The lowest values for formal institutional capacity ~~was found to be high, with~~became obvious in the ~~exception~~transboundary upstream areas of wetlands located in the Ukraine~~,~~ (#24, #41), Belarus (#25) and ~~Western~~ Russia~~.~~ (#72). In this study, Eastern Europe ~~was defined in this study~~ and Western Asia were identified as ~~one~~ hotspot regions where climate change is likely to reduce flood pulses in the future. ~~The~~Thus, a high ~~number of major dam initiatives at the lower Danube basin presents a risk for conflicts among riparians. However, the high~~formal institutional capacity ~~in this region might help~~would be of importance here to ~~avoid disputes~~conserve riparian wetlands and ~~balance anthropogenic and ecological~~allocate water ~~requirements. Dniepro~~to different water users.

~~Considering both sub~~-indicators, the lowest values for capacity to act were found for riparian wetlands located in North Africa (#57, #58), Northeast Nigeria (#60, #61), as well as at the Dnipro River Delta (#41) ~~was found to be an area where special efforts may be needed, due to medium water availability for ecological allocations and a low formal institutional capacity.~~ and the Persian Gulf (#77,#78).

~~In North America, the capacity to act appears to be limited for Cache-Lower White Rivers (#4). At this site water availability for ecological allocations is medium (i.e. four months of water scarcity per year) and legal provisions to ensure eFlows still need to be established. In our modeling inundation volumes are seriously reduced under current conditions, but reoperation schemes could be considered especially for flood control dams, which are prevailing in the upstream area. Also non-structural flood control measures could provide opportunities. For example, reconnecting rivers to their floodplains (where possible) reduces flood control storages of reservoirs and thus, increases the potential to allocate water for hydropower generation, water supply or eFlow provisions (Watts et al., 2011).~~

~~EFlow provisions are part of the Australian law and have also been defined e.g. for floodplain wetlands of the Murray-Darling basin (Poff and Matthews, 2013). However, at all seriously affected sites water scarcity is often a major issue. This indicates low water availability for ecological allocations, especially for Banrock Station Wetland Complex (#92), Riverland (#91), Macquarie Marshes (#90), and Gwydir Wetlands (#89) with on average 10, 9, 8, and 7 months of the year with water scarcity, respectively, which reduces the capacity to ensure eFlows. Hence, especially here enhancing water use efficiency in different water use sectors could contribute to riparian wetland conservation.~~

~~The potential for ecological water allocations is high for all South American sites except la Segua (#5), where water scarcity occurs on average in 4 months of the year under current conditions. At Mamiraua (#6), Humedales Chaco (#12) and Jaaukanigas (#13), the formal institutional capacity is medium. Regarding the high number of dams planned in their upstream areas, further institutional arrangements would be of importance for their conservation. The establishment of legal eFlow provisions in the national law could be supportive for the conservation of the Bolivian sites Rio Yata (#8), Rio Blanco (#9) and Rio Matos (#10).~~

~~In Asia, the two Ramsar sites at the Persian Gulf (#77, #78) possess the lowest capacity to act. Here, on the one hand, water scarcity occurs on average in six to seven months of the year indicating a low potential for eFlow~~

allocations. On the other hand, legal eFlow provisions are missing in the related national water laws of both sites. The upstream area of Hawizeh Marsh (#77) intersects with four countries and presents a medium institutional capacity. For Shandong Yellow River Delta (#75), seriously modified flood volumes under current water management and a high number of dams planned or under construction were identified in our analysis. Here the blue water footprint exceeds blue water availability on average in 6 months of the year in the upstream area, which reduces the potential to consider the water requirements of the wetland. In Asia, the highest percentage of sites without normative eFlow provisions occurs (87% of the cases). Establishing legal eFlow provisions in the related national water legislation could improve the capacity to act for many sites, in particular for the Volga Delta (#74), where climate change is likely to further reduce the already seriously altered inundation volumes. In the Mekong River basin, the presence of the Mekong River Commission contributes to water-related institutional capacity, which could help to negotiate transboundary issues and implement eFlow provisions.

In Africa, Lake Chad Wetlands (#60), Sebkhet Kelbia (#57), Tana River Delta (#65) and Embouchure de la Moulouya (#58) are riparian wetlands with a low potential for ecological water allocations due to six to eleven months per year with water scarcity. Here, flood volumes are moderately to significantly reduced under current conditions. The high competition for water resources at these sites demands for water use efficiency enhancement. So far, legal eFlow provisions are only considered for 20% of all African sites. Except at Tana River delta (#65), they are missing at all sites with moderately to seriously reduced flood pulses as well as where new dam initiatives are taking place. Thus, the implementation of legal eFlow provisions could be an important first step to increase the capacity to act at these sites. Detailed results for all wetlands are listed in the Supplement.

Detailed results for all indicators and wetlands are listed in the Supplementary Material.

4 Discussion and conclusions

Freshwater demands of an exponentially growing world population, hydropower development as a new source of renewable energy, and projected climate change pose important challenges to the maintenance of riparian wetlands. Since these provide valuable services and are disappearing at an alarming rate, assessing the alteration of ecologically important flood pulses addresses crucial research questions related to environmental, water and flood management. Therefore, this study aimed at identifying hydrological threats to riparian wetlands of international importance, in particular assessing (i) impacts of current water management on overbank flows, (ii) potential impairments of flooding regimes in the future due to new dam initiatives and climate change, and (iii) the capacity to act required to implement counteractive measures such as eFlow provisions.

Currently, the concept of eFlows is transitioning from an era of ecosystem integrity and conservation at single river reaches to a period of globalization, where regional studies are complemented by global water assessments that cover large-scale developments. MainThe main reasons are increasing socio-economic and climatic changesthreats on global scale (e.g. global warming) and the associated pace of ecosystem destruction, but also because more sophisticated global hydrology models are available now (Poff and Matthews, 2013). InIn this study, we applied the last years,global modeling framework WaterGAP3, which has been further improved and constitutesin recent years to model specific flow events such as floods. WaterGAP3 is a state-of-the-art global water model that performs ~~its calculations on a daily time-step and on 5 x 5 arc minutes spatial resolution. In addition WaterGAP3 operates now more than 6000 dams, uses dynamic optimization schemes for different dam types, and considers the water infrastructure of larger cities. The described approach should be regarded as a screening tool that systematically identifies hotspots of threatened riparian wetlands, where further hydro-ecological research should be focused on taking into account local expertise of site-specific ecological, social and economic conditions.~~well compared to other global and regional models (Beck et al., 2016; Eisner et al., 2017).

O~~ur approach considers~~Despite the ~~operation of a~~ high number of ~~large~~ dams ~~with a total storage volume of 6200km^3. However,~~ (>6000) operated in WaterGAP3, our results for the impacts related to water ~~resource~~resources management ~~impacts~~ should be regarded as an underestimation~~,~~ as only ~~large~~larger dams ~~that are captured by~~ from a global ~~datasets~~ dataset (GRanD, Lehner et al. 2011) are taken into account. The aggregated effect of remaining smaller dams has an impact on floodplain inundation as well (Rosenberg et al., ~~2000). As~~2000), so it can be assumed that the impacts are even higher for some wetlands.

Our analysis is based on dam operation rather than reservoir capacity and river fragmentation. WaterGAP3 operates dams by dynamic optimization schemes taking into account various objective functions and constraints. Since no global ~~datasets exist~~dataset exists that ~~describe~~describes specific operation rules or management strategies ~~for~~of individual dams, the dam operation module ~~in~~as part of WaterGAP3 considers generic operation schemes reflecting the main purpose of each dam. ~~It does not acknowledge eFlow provisions that are already enforced in reality.~~ Thus, the performance of our dam module ~~is~~can be regarded as lower compared to detailed reservoir models using site-specific information. ~~In reality, inundation is also influenced by river construction (e.g. embankment, re-aligning, widening or deepening) and land-use changes (e.g. deforestation, land drainage, or sealing of large urban areas). All these influences interact with~~Accordingly, eFlow provisions that are already enforced in reality are also not acknowledged in the model. Therefore our screening tool could flag vulnerable wetlands that are, at least to some degree, protected by eFlow provisions in practice. For example, eFlow provisions are part of the Australian law and have also been defined for floodplain wetlands of the Murray-Darling basin (Poff and Matthews, 2013). Yet eFlows are defined at only a tiny fraction of rivers worldwide and in most cases restricted to low flows (Poff et al., 2009; Richter et al., 2012), so that most wetlands remain vulnerable to flow regime modifications. Our study benefits from the qualitative assessment where we collected information on legal eFlow provisions from the related national or state Water Act, which we combined with our quantitative model outcomes. Legal eFlow provisions are regarded as a first important step for promoting eFlow implementation. However, legal eFlow provisions do not guarantee eFlow application in practice and hence, could not be considered in the model's operation scheme.

We used flood volume as a proxy indicator for the extent of flooding. Further improvements of the screening tool will address the implementation of floodplain storages in WaterGAP3 based on an elevation model on sub-grid scale. This will enable a better estimation of change in extent of flooding due to flow regime alterations. In order to distinguish different wetland types, it would be useful that future global wetland datasets provide more information on the wetland's main source of water ~~resource uses and climate change, but are out of scope of this study.~~as done in the European wetland geodatabase of Okruszko et al. (2011).

The implementation of appropriate counteractive measures is likely to be most urgent for the identified hotspots of current and future threats. Those measures encompass adaptive integrated dam management that reconciles interests of different water use sectors, improved flood management plans, water use-efficiency enhancement, and sophisticated eFlow provisions, e.g. according to the Block Building Methodology (BBM; Tharme and King, 1998) or the Basic Flow Methodology (BFM; Palau and Alcazar, 2012). ~~For this study, 93 Ramsar wetlands, which depend on lateral overspill of adjacent rivers, were analyzed. About half of them are facing no or only slightly impacts due to human water resource management. However, according to our simulations almost one third of them are seriously and further 8% are significantly impaired by reduced flood pulses. Seriously affected sites occur on all continents and particularly in Australia, China, Southern Europe and North America as well as at rivers that drain into the Black Sea or the Persian Gulf.~~These two methodologies take account of ecologically relevant flow elements such as flood pulses for riparian wetlands. Dam reoperation strategies aiming at ecosystem restoration depend on the dam's main operating purpose (Watts et al., 2011). In our assessment hydropower dams were the most frequent dam type in the upstream areas~~, however~~ of riparian wetlands. However, irrigation dams ~~were prevailing~~dominate in the upstream areas of seriously affected sites. Consequently, notably for irrigation and hydropower dams, innovative and integrative operating rules need to be developed~~, which maintain~~ maintaining global food security and economic benefits, while at the same time releasing eFlows for ecosystem health and biodiversity.

Depending on the location, climate change will increase or decrease floodplain inundation in the future. In our simulations, two hotspots were identified with reduced floodplain wetland inundation under climate change. Especially these sites could benefit from achieving climate targets set in international agreements. Further application of the screening tool presented in this study could take into account a higher number of GCM projections as well as scenarios describing future socio-economic developments. Outcomes could be used for a comprehensive uncertainty analysis in order to make statements for each wetland about the probability and degree of change. Depending on the RCP, projected global mean temperature is likely to increase between 0.3°C and 4.8°C until the end of the 21st century relative to 1986-2005 (IPCC, 2014). For time horizons beyond 2050, it would be also advisable to select climate change projections representing more than one RCP to provide insight into a full range of possible future developments. As the goal of this paper is to demonstrate the screening tool, only results for the ensemble median of five GCMs were presented. The model results on changes in overbank flows as obtained from the five different GCMs are included in Annex C in the Supplementary Material. Regarding sites with simulated increasing flood volumes, it is uncertain from the global perspective whether the increased flood volume benefits the wetland or generates flood damages for people, which, in turn, would be an incentive to build more dams for flood control (Poff and Matthews, 2013). In particular it needs to be assured that high-flow pulses do not expose people to flood risk and damage. ~~In the future, climate change will further modify seasonal flow patterns. In the 2050s, the average flood volume is likely to be decreased at 41% of the sites due to the exclusive effect of climate change. At 16% of the sites, reductions can be significantly or even seriously (i.e. >30%). In our analysis two spatial hotspots could be identified: Especially in Eastern Europe/ Western Asia as well as in South America below the Amazon River, flood pulses are likely to be reduced under climate change. Applying a different set of climate projections, lower snowmelt-induced flood peaks in spring were also found for Eastern Europe by Schneider et al. (2011b; 2013).~~In general, all wetlands could benefit from improved flood management plans taking non-structural measures into account (Sparks, 1995). For example, restoring river floodplains and dead stream branches minimizes flood damages and reduces flood-control storages in reservoirs. This, measure would increase the potential to allocate more water for hydropower generation, water-supply or eFlow provisions (Watts et al., 2011). Further measures encompass dyke relocation, buying land from farmers, defining maximum admissible dam releases for flood provisions, or establishing floodways that direct floodwater around human settlements.

~~Next~~ to flow regime modifications, the threat for riparian wetlands also depends on the society's ~~In agreement with results of Zarfl et al. (2014), extensive dam construction is on the way in one third of the upstream areas with potential ecological impacts in particular for South American (67% of the sites), Asian (60%) and African (47%) wetlands. Additionally, countries of the Balkan Peninsula in Europe show a high activity in new dam initiatives. We found that a large impact by future dam construction is likely in the upstream areas of wetlands that are located in the basins of Amazon, Parana, Paraguay, Yangtze, Yellow, Mekong, Ganges-Brahmaputra, and Danube Rivers. As a next step, the new dam initiatives shall be implemented in the model to improve future assessments of ecological and human water stress.~~

~~Reduced flood pulses can have lasting ecological impacts such as loss of biodiversity, invasion of non-native species (Poff et al., 1997), modification of river food webs (Wootton et al., 1996), salinization of soils (Nilsson and Berggren, 2000), reduced primary and secondary productivity (Tockner and Stanford, 2002), as well as habitat deterioration and loss of floodplain wetlands, river deltas and ocean estuaries (Rosenberg et al., 1997; Rosenberg et al., 2000). For the identified hotspots of current and future threats, the implementation of appropriate eFlows is likely to be most urgent. However, this is a complex task and requires a high~~ capacity to act ~~which depends in particular on two factors: First, the degree of water resource competition in a river basin determines the amount of water that can be allocated for ecological purposes. In our analysis, the highest competition for water is existent in the upstream area of Lake Chad Wetlands (Nigeria) followed by wetlands of the river basins Murray-Darling (Australia), Schatt al-Arab (Persian Gulf), Tana (Kenya), Moulouya (Morocco), and Yellow (China),~~required responding to changes and implementing counteractive measures. Global assessments of threats to riparian wetlands do not account for this. In order to fill this gap, our approach combines qualitative results with quantitative hydrological model results. At sites where ~~water scarcity occurs upstream on average in six to ten months of the year. Therefore, especially at these sites, measures are required which increase water use efficiency (e.g. by water recycling, technological innovations, dripping irrigation, changing crop mix, importing agricultural products, water metering or other incentives to save water) to raise the amount of water which can be allocated for ecological requirements. Second, legal and institutional capacities must be in place that promote stakeholder involvement, conflict resolution, monitoring as well as setting of strategic goals and responsibilities (Le Quesne et al., 2010; Pahl-Wostl~~the capacity to act is limited by a low institutional capacity, ~~et al., 2013). A first important step for eFlow implementation is~~ the acknowledgement of ecological water requirements in the legislation~~. Even if this~~ could be a first important step for eFlow implementation. This does not ~~guarantee~~ensure that eFlows are actually established in practice, enforced or adequate, ~~it~~but shows that ecological water requirements are on the ~~radar~~agenda of legislators and water practitioners, and helps advocating for ~~ecological water requirements. At about half of the sites normative eFlow provisions are considered in the national or state Water Act of the wetland. The highest percentage of sites without normative eFlow provisions occur in Asia (87% of the cases) and Africa (80%).~~

~~acceptance of~~ ecological water requirements. The more countries depend on the available water resources ~~and affect the river flow regime with their management~~within a river basin, the more challenging is the implementation of eFlows. ~~About half of the 93 selected wetlands have~~Therefore, for all transboundary upstream areas ~~and the highest percentages appear in Europe (65%) and Africa (60%). For all transboundary upstream~~

~~areas it is important that river basin organizations~~we aimed at investigating whether RBOs, international water treaties and specific treaty provisions are already put in place ~~that~~to manage disputes and water resource allocation among different ~~stakeholders. The lowest values for formal institutional capacity became obvious in our analysis in the transboundary upstream areas of wetlands that are located in the Ukraine, Belarus and Russia. A medium institutional capacity in combination with new dam construction occurs in the transboundary upstream areas of Mamiraua (#6), Humedales Chaco (#12) and Jaaukanigas (#13). At these sites~~water users. At riparian wetlands in transboundary river basins where institutional capacity is low, the establishment of such formal arrangements ~~would~~could be ~~of special importance~~supportive for ~~riparian~~ wetland conservation. While the institutional capacity indicator considers national laws, international treaties and RBO agreements, it is important to stress that the presence of formal arrangements is no guarantee ~~that they are effectively enforced in practice. Altogether, the lowest capacity to act was found for Sebkhet Kelbia (#57), Embouchure de la Moulouya (#58), and Shadegan Marshes (#78).~~for effective enforcement in practice.

~~Climate change and growing population pressures ask for immediate action to conserve wetlands and river ecosystem integrity. The concept of eFlows can be an important strategy for sustainable development and offers opportunities for society as a whole to benefit from vital ecosystem services of riparian wetlands such as maintenance of genetic diversity, production of food, fiber and fodder, decomposition of pollutants and nutrients, provision of local recreational areas and tourism economies, and control of devastating flood events. In practice, the provision of eFlows for wetland inundation is associated with some challenges. In particular it needs to be assured that high-flow pulses do not expose people to flood risk and damage. This may require, for example, defining a maximum admissible flow for river reaches, buying land from farmers, or establishing floodways that direct floodwater around human settlements. Today, eFlows are defined at only a tiny fraction of rivers worldwide and in most cases those are restricted to low flows (Richter et al., 2011). The potential to implement eFlow provisions and exploit opportunities is by far not exhausted. Even synergies rather than trade-offs between sectors might be possible.~~

The proposed screening tool helps to identify riparian wetlands where the capacity to act is limited by a high water resource competition. Especially at these sites with high water scarcity in the upstream area, measures are likely to be required that increase water use efficiency (e.g. by water recycling, technological innovations, dripping irrigation, changing crop mix, importing agricultural products, water metering or other incentives to save water) in order to raise the amount of water that can be allocated for ecological requirements.

We assessed the threat of future dam construction for specific riparian wetlands globally. Currently no large-scale dataset on major dam initiatives (including planned storage capacities) is publicly available. Therefore, we collected the number of dams that are currently planned, proposed or under construction in the upstream areas to give a first indication, where future dam construction is likely to affect riparian wetland inundation. As a next step, new dam initiatives could be implemented in the WaterGAP3 model to quantitatively judge changes in flood volumes. This would account for operation, location in the upstream area, and storage volume of future dams, and thus improve analysis of future ecological and human water stress. Furthermore, this enhancement of the approach would enable future scenario assessments that quantitatively evaluate the combined effects of dam operation, water use and climate change on river flow regimes. Additionally, different land-use change scenarios could be considered in those WaterGAP3 model runs. Riparian wetland inundation is also influenced by land-use changes (e.g. deforestation, land drainage, or sealing of large urban areas) and river construction (e.g.

embankment, re-aligning, widening or deepening). These influences interact with water resource uses and climate change, but did not fall within the scope of this paper.

5 Conclusions and outlook

Freshwater demands of an exponentially growing world population, hydropower development as a new source of renewable energy, and projected climate change pose important challenges to the maintenance of riparian wetlands worldwide. Since riparian wetlands provide valuable ecosystem services and are disappearing at an alarming rate, assessing the alteration of ecologically important flood pulses addresses crucial research questions related to environmental, water and flood management. Therefore, this study aimed at establishing a global screening tool to systematically identify hotspots and patterns of hydrological change and to flag riparian wetlands vulnerable to inundation regime modifications. The information provided by this tool can be useful to direct further hydro-ecological research that takes into account local information and expertise of site-specific ecological, social and economic conditions.

A multitude of applications is possible with our proposed screening tool. The bankfull flow approach applied at grid cell level enables the assessment of all larger riparian wetlands worldwide and can be used to conduct a comprehensive global riparian wetland assessment. Considering the change in extent of flooding, the quantification of specific ecosystem services from intact riparian wetlands could be performed. Examples comprise production of important resources such as wood, reed, hay and fish, water purification by removing nutrients and toxins, as well as flood control and risk reduction for people, and how this is likely to change in the future under climate change and further dam construction. The integrated global modelling framework WaterGAP3 allows scenario assessment considering different drivers of global change on renewable freshwater resources by allocating water resources to different water use sectors and evaluating the respective consequences under different management targets. Overall, the screening tool based on quantitative and qualitative indicators could support policy makers at international level (e.g. at forums like UNEP, OECD, European Union, Convention on Wetlands of International Importance, and Convention on Biological Diversity) in implementing global conservation efforts, targeting wetland conservation funds, planning of water infrastructure location and design, and balancing water allocations to humans and nature.

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Table 1 : Thresholds for different levels of mean annual flood volume deviation (Δ) between modified and natural flow regimes (as suggested for global assessments by Hoekstra et al., 2011)).

River status	Level of modification	Thresholds for reduction in flood volume
A	notnone/ slightly	Δ ≤ 20%
B	moderately	20% < Δ ≤ 30%
C	significantly	30% < Δ ≤ 40%
D	seriously	Δ > 40%

Table 2 : Defined impact on a riparian wetland ~~subject~~due to ~~the number of~~ new dam initiatives in the upstream area.

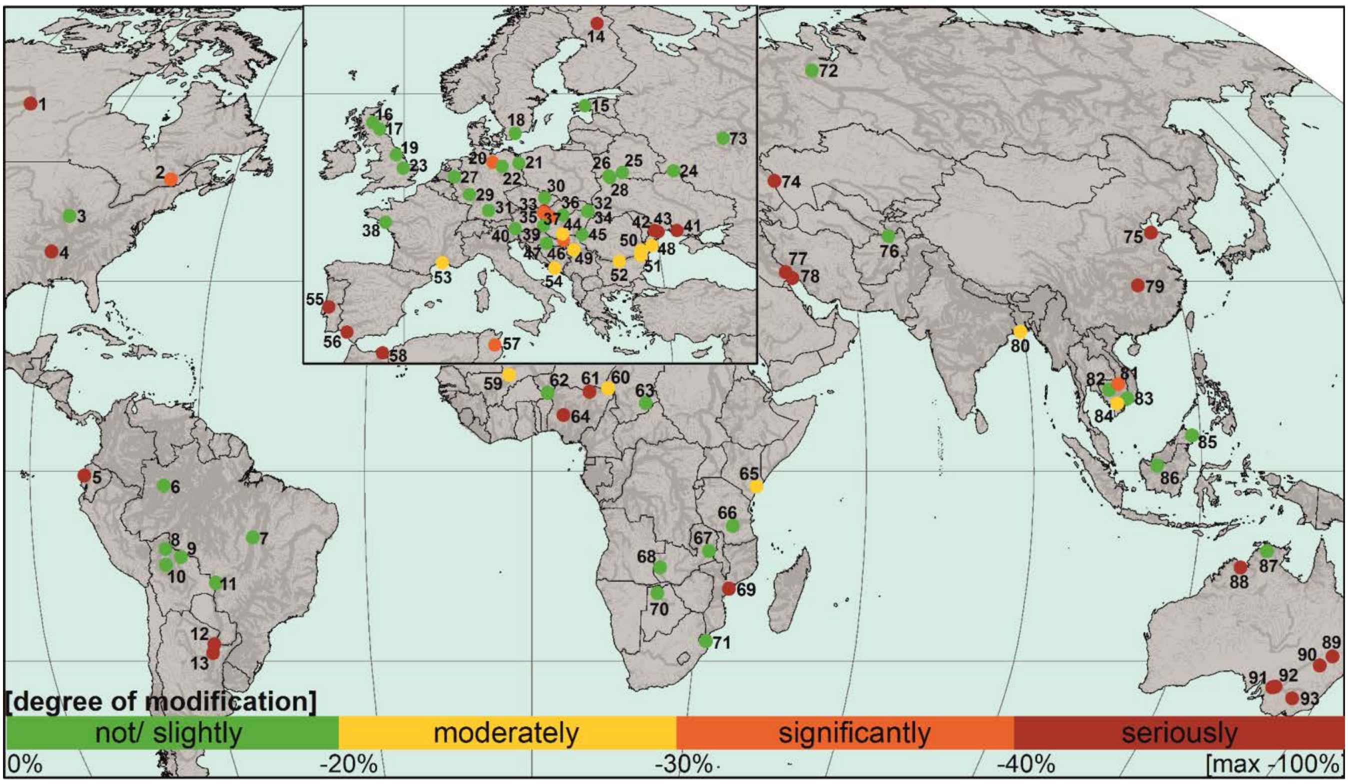
Number of major dam initiatives	Potential impact
0	NONE
1 – 12	MED
28 – 276	HIGH

Table 3 : Water availability for ecological allocations defined by means of the number of ~~month~~months with water scarcity upstream of the Ramsar site.

Number of ~~month~~months with water scarcity	Water availability for ecological ~~allocations~~allocation
6 – 12	LOW
2 – 5	MED
0 – 1	HIGH

Table 4 : ~~Formal institutional~~Institutional capacity in place in transboundary upstream areas of ~~Ramsar sites~~riparian wetlands based on formal arrangements such as international water treaties, river basin organizations, legal eFlow provisions and specific treaty provisions.

Score	Institutional capacity
0 – 2	LOW
3>2 – 4	MED
5>4 – 6	HIGH



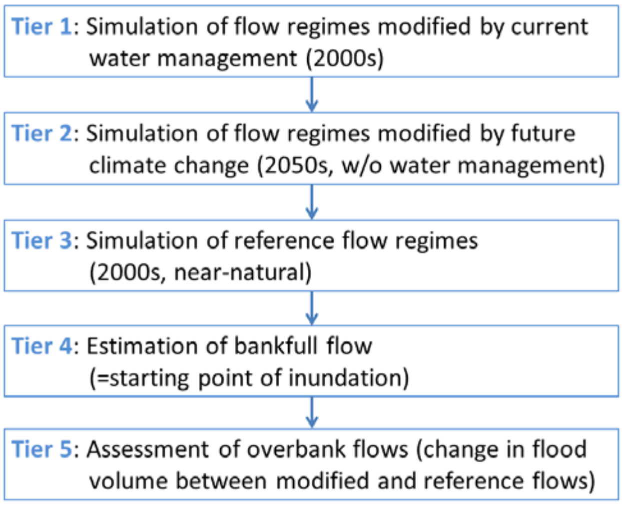
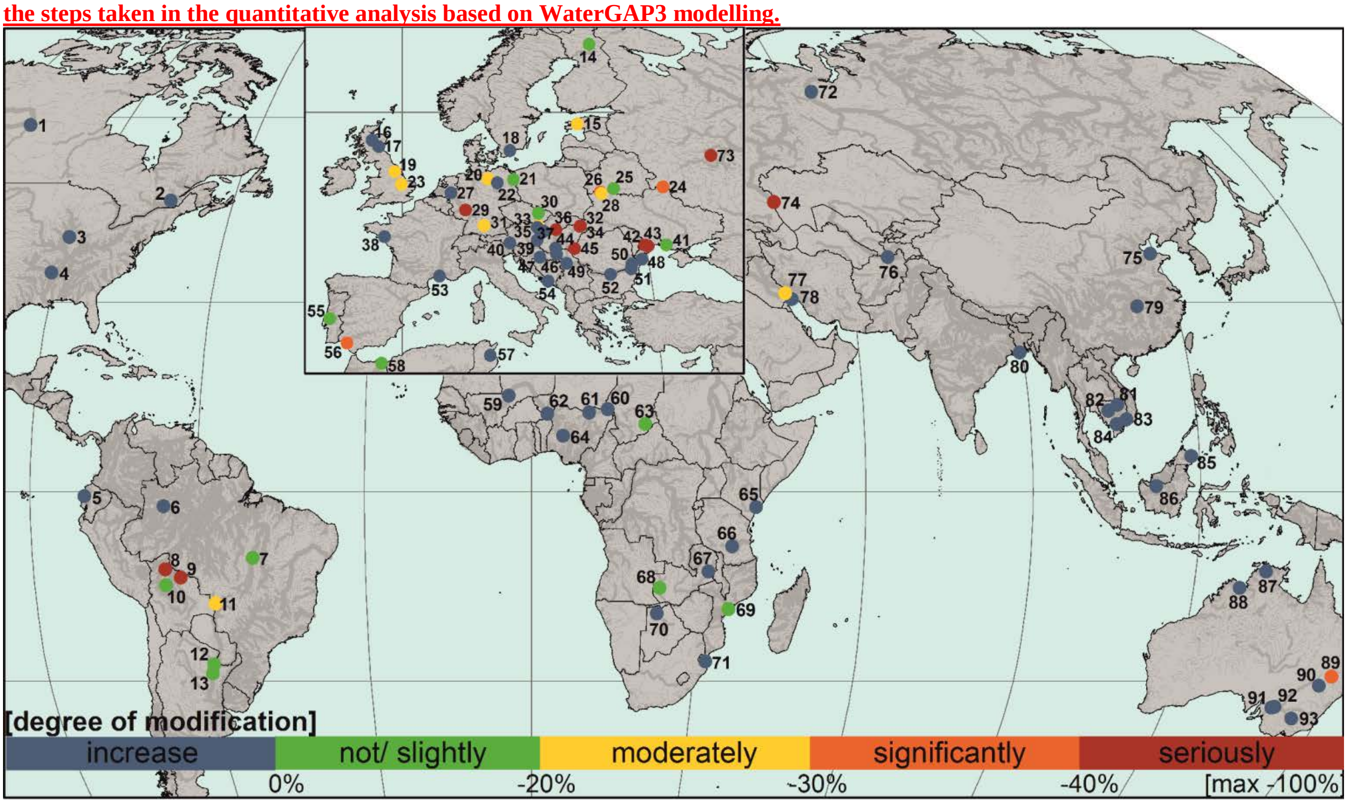


Figure 1: ~~Global map~~Schematic illustration **of** ~~overbank flow alterations for selected riparian wetlands of international importance (#1-93) as a consequence of current water resource management~~

the steps taken in the quantitative analysis based on WaterGAP3 modelling.



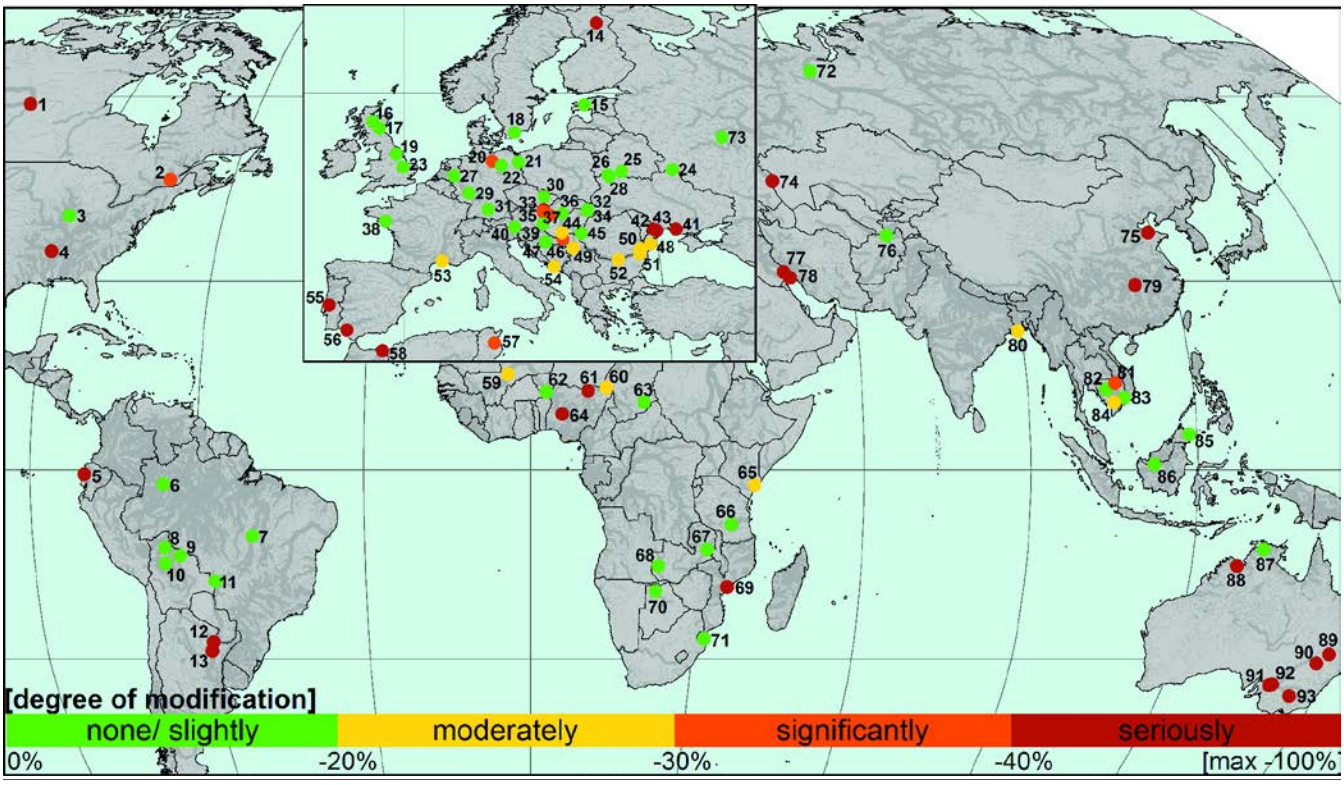


Figure 2: Global map of overbank flow alterations for selected riparian wetlands of international importance (#1-93) as a consequence of current water resource management.

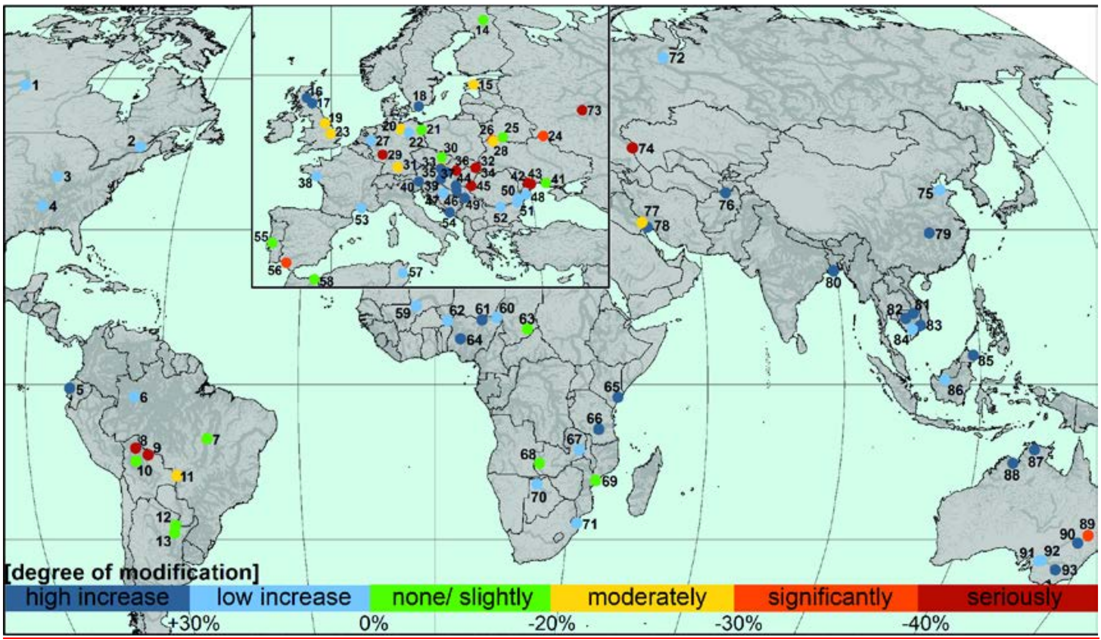


Figure 3: Global map of overbank flow alterations for selected riparian wetlands of international importance (#1-93) as a consequence of the exclusive effect of climate change in the 2050s.

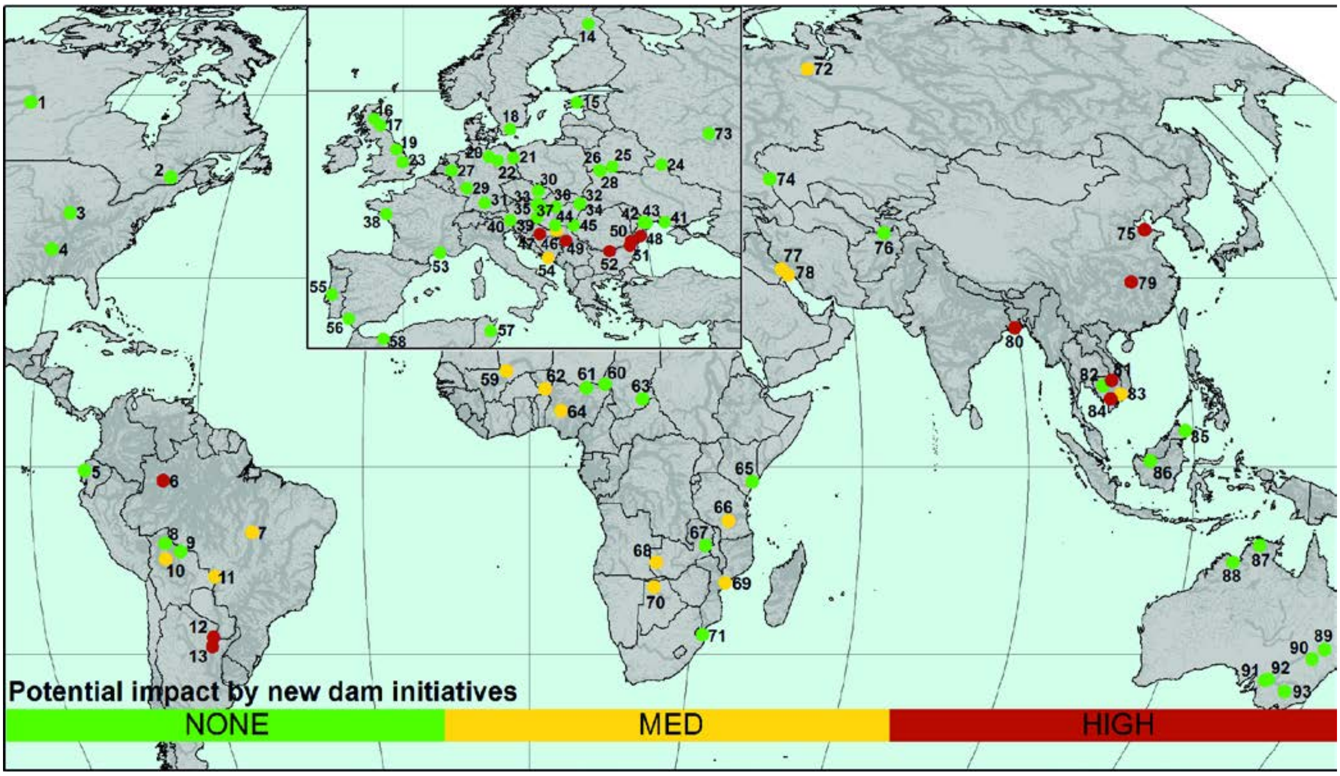


Figure 4: Potential impact ~~by~~of new dam initiatives taking into account ~~the number of~~ dams currently planned or under construction in the upstream area of each riparian wetland.

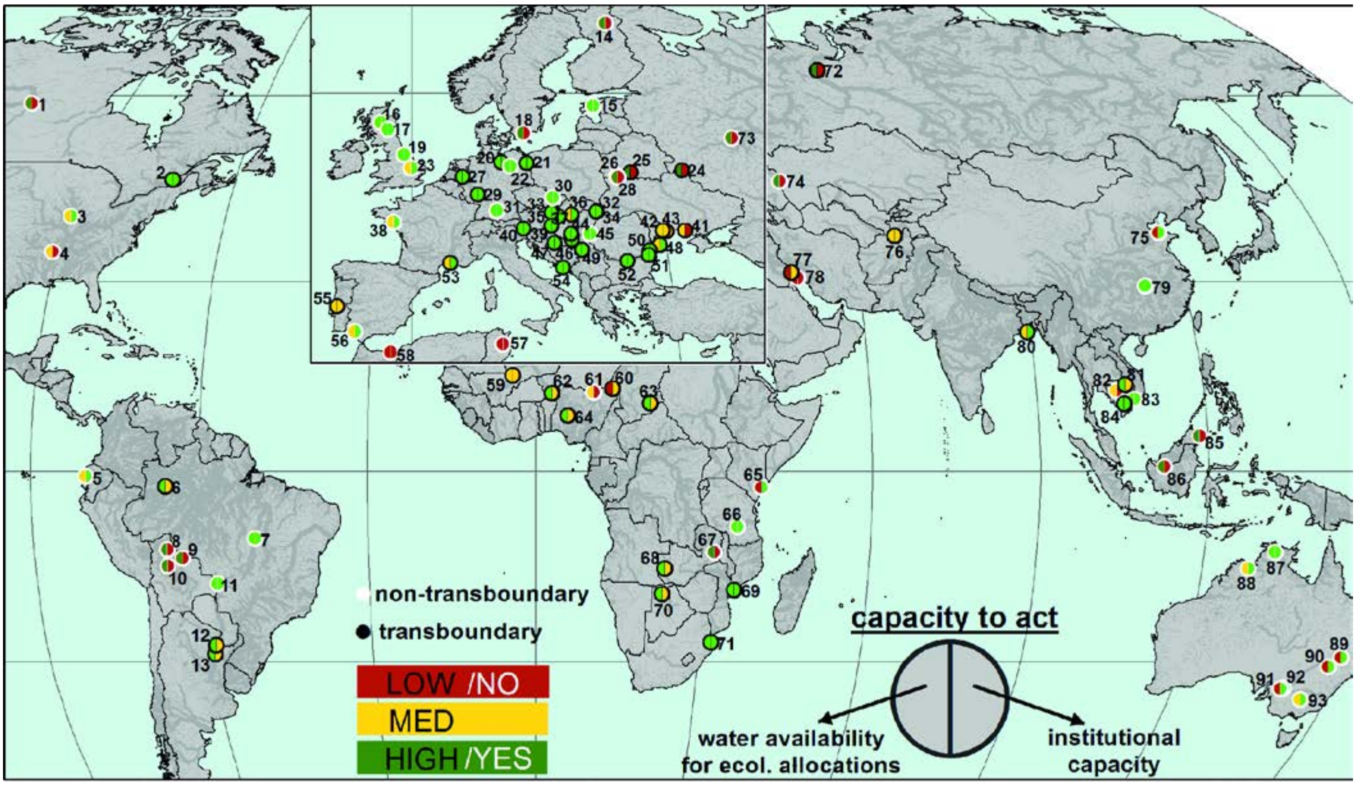


Figure 5: Current capacity to act in regard to anthropogenic flow regime modifications for selected riparian wetlands. The left semicircle represents the water availability for ecological allocations, while the right semicircle characterizes the institutional capacity in the upstream area. For wetlands with a non-transboundary upstream area (white border), the right semicircle represents ~~only~~ presence or absence of legal provisions or official recommendation to establish eFlows.