Responses to reviewer comments for:

Reviews and syntheses: Dams, water quality and tropical reservoir stratification

R. Scott Winton[1,2], Elisa Calamita[1,2], Bernhard Wehrli[1,2]

[1]Department of Environmental Systems Science, ETH Zürich, Zürich, 8092, Switzerland
[2]Department of Surface Waters Eawag, Kastanienbaum, 6047, Switzerland

Correspondence to: R. Scott Winton (Robert.winton@usys.ethz.ch)

Includes in-line responses and changes based on reviewer comments and manuscript with changes tracked.

Reviewer 1 comments

In this interesting and useful work, Winton and co-authors aimed at synthesizing the impact of tropical damming on water quality with two main focuses: 1) Stratification effect on discharged water hypoxia and thermal regimes, and 2) the sediment trapping. The authors additionally reported the most recent large reservoir constructions and analyzed if stratification pattern can be predicted. The study ends with potential management and calls for further measurements and tool development specific to tropical reservoirs. This is a good review overall. All information stated by the authors seems correct to me, although I am not specifically an expert on water quality impact on freshwater ecosystems. I have a few suggestions to improve, in my opinion, the readability and the impact of the review.

General comments

1) Although they all make sense, most of the examples seem rather theoretical and look like hypotheses more than facts. I feel like the presented damming impacts would benefit from adding more actual data proving that downstream rivers are impacted or could be potentially impacted. For example, could the authors add reservoir temperature profiles, or give some idea of how much colder bottom waters could be. And how hypoxic it can be by giving some example of O2 concentration measured in rivers near a reservoir discharge. Same for P and Si concentrations. Such data should be reported in the literature. If such data are not available, it would be good to mention it.

AR: We have added data and sources to illustrate these problems in a more quantitative way in the specific sections and subsections. This also gives a better comparison between known physiological thresholds and field observations associated with dams.

2) It looks to me that most of the potential impacts for tropical systems are also true for temperate/boreal reservoirs. What makes tropical reservoirs/dams particular? The authors mentioned that tropical reservoir can also stratify, similar to temperate ones, and that less is known about tropical systems. Are there any other main differences? Particularities of tropical systems should be explicitly emphasized in each section.

AR: We added some additional sentences to the introduction to explain some of the important differences that were left out, such as differences in oxygen saturation, differences in decomposition rates.

3) Section 3 is overly long for the ultimate message that tropical reservoirs do stratify. The authors have the stratification information for more than half of the reviewed reservoirs, so I am questioning how relevant (although quite interesting itself) is this thorough analysis of tropical reservoir stratification (i.e. Figs. 3 and 4). This statement (that tropical reservoir do stratify) can be delivered more efficiently and earlier in the manuscript, e.g. implemented in section 2.1. If section 3 is reduced (or implement in section 2.1), this would leave more room of a more in-depth review of tropical damming effect on water quality, and maybe no limited by the 50 most cited papers.

AR: As we previously wrote in our public responses, we feel that it is important to preserve this section even though it does require quite a few words to work through the technical analyses. We added some text to the start and end of this section to better tie it to the rest of the paper and also to the fourth paragraph of the introduction to more explicitly make the case to reader for the section's relevance.

4) It is not always clear if the focus of this work is on water quality of the reservoir itself or the downstream river water quality. For example, the eutrophication impact discussion is mostly on reservoir water itself, and not on the downstream river. This distinction must be clear throughout the manuscript.

   AR: We have made changes that we feel resolves this ambiguity throughout the paper. The primary focus is on fivers, but as we learned while researching this topic, there are quite a lot of within-reservoir processes that must be explained in order to understand how the dams are impacting the downstream river reaches. These are quite explicitly displayed in Fig. 2. On the issue of eutrophication of downstream rivers from nutrient remobilization, we found no direct evidence to documenting this type of impact and made clear that, in contrast to the other impacts, it is hypothetical. And in reality dams often impose oligotrophication, so a boost in productivity would probably represent a temporary correction to an already altered downstream trophic state.

Specific comments

L12: This looks like 3 processes, not 2

AR: removed mention of oxygen depletion, which is a secondary effect and not one of the two ultimate physical processes.

Introduction: Many small paragraphs (often 2 or 3 sentences) make the introduction seems disconnected. Joining themes to form larger paragraphs may improve readability. Also, it should be clearer why low latitude research is needed from the beginning. The authors gave an example of fish behavior but this is not the focus of the review, right?

AR: We have added a couple additional sentences and a source about the differences between high and low latitude systems (ie oxygen saturation, decomposition rate) and also moved the sentence about fish to this paragraph. We also added some connector/transition sentences to help the introductory paragraph flow together better.

P1 L30: remove “relationship”

AR: fixed

Figure 1: I am not convinced by the usefulness of the construction period data. Also, I don’t understand what is the “projects started (5–year running sum)” meaning. However, the map with new reservoirs and volume is more useful.

AR: We added a sentence that explains why the construction timing is relevant. The main point is that construction of these really large dams is continuing after a hiatus. If this large dam construction was a thing of the past, then this analysis would be less relevant because the logic it wouldn’t necessarily to newer smaller projects. The reality is that newer projects aren’t necessarily going to be any smaller than many of these existing mega-dams. I think some readers will also be interested to see that the recent mega-dams are in Asia/Africa whereas there have been no projects of this size in South America yet this century.

We have change “projects started (5–year running sum)” to “Projects started in previous five years” to be more clear.

P4 L6: “important” instead of “import”?

AR: fixed

Section 2 title: Specify water quality of what: downstream river or reservoir?

AR: Changed this title to “Impacts of dams on river water quality”

Section 2.1: Would it be possible to implement here a shortened version of the stratification analysis?

AR: this is a short version of general comment 3. We refer to our response there.

P5 L6-8: This sentence can go in its specific section. Same for sentence at lines 10-11.

AR: Deleted these sentences which are redundant information from their respective sections

P5 L8-9: Is there any information on this? What is the most common depth of water releasing? I think this is a very important feature for this review. Adding information regarding this question would greatly improve the quality of this review.

AR: We agree with the sentiment, but unfortunately each dam has its own design and the turbine depth is not something reported in dam databases, so it is difficult to claim a certain depth as being "common" without doing an additional in-depth gray literature review. We report the depth of the Kariba dam turbines as an example and explain the dilemma of not having ready access to turbine and thermocline depths. Rather examining the tailwater chemistry gives a good idea as to whether hypolimnetic discharges are occurring and is more useful information for assessing downstream impacts anyway.

Section 2.1.1: It would be interesting to report some data about water temperature difference between epilimnion and hypolimnion.

AR: We give an example from Lake Kariba.

P6, L27: How frequent is dam water intakes deeper than oxycline? This information would be useful.

AR: Unfortunately this isn't really known, as we have clarified in section 2.1.

P6, L28-29: Is there any reported data on O2 concentrations of released water from reservoirs?

AR: cited some data from a big hypoxia study (Higgins and Brock 1999).

P7, L11-12: Is there any reported evidence of persistent hypoxia in rivers downstream?

AR: yes, from the same study we added above and the Australian example.

Section 2.1.3: This section rather focuses on the water quality of the reservoir itself. Is there any studies reporting P loading to downstream ecosystems, and/or example of downstream ecosystems eutrophication due to damming as suggested by Fig. 2?

AR: Actually this impact is largely hypothetical. At least we are not aware of any direct observations of sudden spikes in nutrient availability and productivity downstream of a bottom releasing dam. We have rewritten the end of this paragraph to clarify.

Section 2.1.4: Is there any reported data on such reduced compound concentrations in tropical reservoirs?

AR: Added some data on downstream H_2S concentrations.

Section 2.2: Maybe the authors could briefly explain some mechanisms involved in sediment trapping occurs.

AR: added an extra sentence here to explain the physical processes involved.

P8, L28: I don't understand the meaning of "hungry" water here.

AR: rewrote this sentence removing the confusing use of the word 'hungry'

P9, L6-7: I don't understand this sentence. Please re-phrase.

AR: Yes this was bad. Fixed this.

P9, L10-11: This sentence is not clear. Is this statement more general or specific to the last example? Also, this seems more like a hypothesis than a fact.

AR: A general statement, supported by data and the previous examples. Added the supporting evidence and citation.

Section 2.2.2: This impact seems important, although very few examples are given, and they are mostly related to fisheries. Is there any more information on such impact reported?

AR: Added the example of the Aswan dam / nile. Also a fish story, but baseline pre-dam data is very rare when there is not a fishery involved.

P9, L30-31: Since the review is on tropical systems, would it be worth to develop on these examples?

AR: Good idea. We developed the Mississippi example further. On further review the Nile example is a better fit for the oligotrophication section than the elemental ratio section, so we've moved it.

Section 2.3: I wonder if this section would be better suited at the beginning of the management section.

AR: We don't think so as there isn't any management involved in this section. We are still describing the nature of the problems here and think this section should stay in the section on water quality impacts.

P10, L6-8 (related to comment P7, L11-12): This is a good example of hypoxia in the downstream river of a dam and should be moved to the hypoxia impacts section.

AR: Added info about the magnitude of the hypoxia to the respective section, but this issue of propogation is a separate one, so we keep this information here as well.

Section 3: This section is too long for the main message that tropical reservoirs usually stratify. I suggest to first report that stratification occurs, and maybe report examples of temperature differences between epilimnion and hypolimnion. Then, maybe briefly show that for the unknown reservoirs, stratification is likely based on e.g. morphometric predictors.

AR: We think it's important to show the details of this analysis because text books and other authoritative sources indicate that tropical reservoirs behave differently.

Section 4.1: I don't know what eflow is and what it does. Maybe the authors could briefly describe it main principle/objectives?

AR: Added a couple sentences to briefly describe it.

P15, L17-19: Is this the only example of tropical systems reaeration strategy?

AR: Many reaeration strategies are baked into dam design. This a tropical example we are aware of in which this type of post-hoc management action has been proposed. We have reworded the paragraph to make clear that in newer dams, oxygen management is typically part of the deign process.

Section 4: This section could be very extensive and that probably many aspects of managing can be covered: technical challenges, financial aspects, examples of successful management exercises, etc. However, this might be not the focus of this review. Here the authors seemed to have limited the number of examples/aspects, which result in an unfocused section. Could the authors try to refocus this section on fewer aspects and be more thorough regarding the most interesting/useful ones?

AR: We are not quite sure how to address this comment. We are confused because the proposed solution here: "refocus this section on fewer aspects..." seems quite similar to the source problem: us having "…limited the number of examples/aspects…" The reviewer is correct that this section could be a lot longer and that management is not meant to be the focus of the review. Our goal for this section was to give an overview of some of the methods that may be used to mitigate the water quality problems we identified. Going into depth on a couple approaches doesn't seem like it would do much to strengthen the paper in our opinion.

Section 5. This is overall a good section and very important.

P17, L1: Is "hydro" an accepted noun to designate a hydroelectric reservoir?

AR: Changed to "hydroelectric systems"

P17, L30-31 and P18, L1-2: Maybe mention that these are hypotheses and it further needs to be tested in the future.

AR: Good point. We point out that it is not yet clear how commonly these problems arise as we are mostly dealing with anecdotal case studies and are biased toward examples that show the problem being most pronounced. A further study could assess how commonly these issues are encountered and what factors are responsible.

P18, L3: add "to" in "It is difficult to assess".

AR: Fixed

<u>Reviewer 2 comments</u>

General Comment The review is very timely as the number of both large and small dams increase, and more planned, in lower latitudes. Knowledge on impacts are currently skewed to that of higher latitudes. The focus on specific mechanisms relating to effects of dams on water quality is a particular strength of the paper. This provides both insight to general effects of e.g stratification as well as how this might differ in tropical compared with temperate climates. A good use of the more limited information on tropical systems, and resisting the temptation of drifting into too many temperature examples will likely help the reader keep attention on the topic and make the paper a highly relevant resource.

AR: We have removed some of these less relevant temperate examples, as the reviewer suggested further below.

Following the general review, the paper makes a further important step in comparing some traditional held beliefs on the effect of tropical reservoirs on water quality with more recent ideas supported by physical models. This is a key contribution as it separates conjecture from evidence based conclusions for dams holding back the largest volumes of water in the tropics. Collectively, the general review and the application of models to existing large dams enables the paper to review existing knowledge and its application, and present ideas for future work.

Specific comments. Page 6, line 6. I don't see the need for the sentences "The Colorado River. . .Glen canyon Dam (Holden and Stalnaker)" as the focus in on tropical systems and not convinced that this example adds anything to the general message of the paper. If this change is adopted, then close up the next paragraph, starting with "Several case studies exists".

AR: We agree. Removed this paragraph.

Page 8, line 28. Term "hungry river" seems a little too idiosyncratic and suggest a clearer phrase and brief description provided as to what this means.

AR: removed this term and restructured this sentence.

Page 9, line 20. Seems that the crucial point here is the balance between sediment/nutrient supply and loss against a background of possible intensification of land and loss of forest cover. This leads to a net effect of nutrient gain or loss.

AR: We added a sentence to the end of this paragraph pointing out that dams contribute to broader problems of trophic state changes in rivers.

Page 10, line. See above comment as surely even if there is sediment input from tributaries downstream, unless this is very high from erosion in the sub-catchments, the issue of net sediment depletion remains.

AR: very true. We have restructure this sentence to point out that downstream tributaries are unlikely to adequately compensate for losses behind dams.

Page 15, line 19. The consideration of mitigation measures also raises the important issue of local individual and institutional capacity development to aid decision making. It would be useful to address this general point in the Discussion.

AR: Yes, we agree that this is important, but think the issue of decision-making, optimization and capacity development are all their own rather deep topics that fall beyond the scope of this review (and our own expertise), so we are a bit shy to bring them up other than as a brief mention of capacity building in the conclusion section.

Page 16, line 27. The term “would help” seems very mild as a recommendation. Surely given the scale of the issues and future importance, more extensive and, where required, intensive monitoring is a basic need. While there are current financial and (related) capacity limitations given the very high finances involved in dam construction and the critical importance in general for attempting to optimise water management, developing financial and (then) capacity mechanisms for better monitoring would seem an obvious consideration. This is mentioned in the Conclusions, but not in a very strong way

AR: Changed “would help” to “are needed.” We also added a sentence to the conclusion suggesting that building capacity for low latitude countries to monitor river water quality is important.

Page 17, line 4. While the smaller schemes were not the focus of the review, an obvious recommendation is the need to better understand their impact.

AR: Yes, we have added a short sentence suggesting exactly this.

Page 18, line. This is repetition of first point made in the Conclusions.

AR: We found the repeated point about propagation and deleted.

Page 18, line 11. This would seem a good place to mention the need for Environmental Impact Assessments for all new dams, combined with follow up monitoring to inform Strategic Environmental Assessment.

AR: Good idea. We added a sentence here.

Technical corrections. Includes mainly suggestions for improvement to be considered by the authors.

Page 1, line 11. The term “context”’ is not very precise and can normally simply be omitted by a small adjustment if the sentence. Here simply add an “s” after “latitude” and delete “contexts”.

AR: fixed

Page 1, line 18. Replace “efficiently trapping sediments” with “efficient trapping of sediments”’.

AR: fixed

Page 1, line 19. Replace "which alters"" with "' altering"", replace "causes losses" with "loss".

AR: the suggested edit actually doesn't quite work. We reworked the sentence in a slightly different way.

Page 1, line 23. Delete "the worlds" and "systems", and add "s" after "river". Following sentence replace "The. . .. .impacts" with "These changes, and associated environmental impacts, ". The following phrase "could be better understood" could be stronger but e.g. replacing with "need".

AR: fixed

Page 1, line 24. Suggest that the final paragraph of Abstract has a small addition of e.g. "to both mitigate existing, and future potential, impacts.

AR: added a sentence along these lines

Page 1, line 29. Replace "drastically altered" with "altered drastically".

AR: fixed

Page 1, line 29. Replace "quality" with "sufficient quality of".

AR: fixed

Page 1, line 30. Add a comma after "UNEP 2016) and then delete following "and"" and "relationship".

AR: fixed

Page 1, line 32. Delete comma after "quality" and change "dam impacts" to "impacts pf dams".

AR: fixed

Page 2, line 3. Add full stop before and then change "and therefore not delivering on" to "Such impacts act against"

AR: fixed

Page 2, line 7. Delete "contexts".

AR: fixed

Page 2, line 9. Replace "Certainly" with "While" and delete "but".

AR: fixed

Page 2, line 14. Delete "ground has been broken on".

AR: fixed

Page 2, line 15. After "reservoirs" insert "have occurred".

AR: put "have appeared"

Page 3, line 2. I suggest changing "context" to "biomes".

AR: fixed

Page 4, line 6. Replace "import" with "important".

AR: fixed

Page 4, line 22. Add comma after the brackets and delete “efforts”.

AR: fixed

Page 5, line 12. Delete comma and “exerting”.

AR: deleted this sentence based on another reviewer’s suggestion

Page 5, line 13. After “pronounced”, insert “than temperate climates,

AR: fixed

Page 5, line 14. Delete “patterns which comprise”, the inverted commas and add an “s” after “regime”.

AR: fixed

Page 5, line 17. Sentence would seem to merit a reference or two, maybe from some review paper or book.

AR: There actually isn’t one review that pulls all of these together, but a variety of case studies cited in the following 2 paragraphs that support this statement. It doesn’t seem like it would be helpful place several of these references here out of context.

Page 6, line 2. Replace “threshold requirements” with “thresholds required”.

AR: fixed

Page 6, line 5. The sentence “When. . ..will shift” requires revision. I suggest “Altered thermal regimes can shift species distribution”.

AR: fixed

Page 6, line 21-22. Replace “monitored” with “monitoring”, and later in line delete the “and” after “river” and “were effective at” and replace “promoting” with “promoted”.

AR: fixed

Page 6, line 22-23. Delete “to emigrate. . ...downstream ecosystems”. The reference of “(King et al., 1998)” can be retained.

AR: fixed

Page 6, line 28 and 29. Delete “levels”.

AR: fixed

Page 7, line 4. Add comma after L-1, and delete “(the rule varies” and “context” and insert bracket before “Higgins”.

AR: fixed

Page 7, line 6. Here and in general replace “to” with “”with”.

AR: fixed

Page 7, line 14. Add full stop after “macronutrient”, delete “and” and continue with capital “T”. Delete “the”.

AR: fixed

Page 7, line 15. Replace “productivity” with “eutrophication”. Page 7, line 16. Delete “a process called eutrophication”.

AR: fixed

Page 7, line 24. Replace “cause eutrophication and algal blooms” with “stimulate algal and other submerged plant growth”.

AR: fixed

Page 7, line 28. Replace “at” with “in”.

AR: fixed

Page 8, line 5. Replace “to” with “”with”.

AR: fixed

Page 8, line 19. Insert comma after “stresses” and “sustained”, replace “and” with “which” and “lead to the expiration of” with “be lethal to”.

AR: fixed

Page 8, line 24. After “chemical” suggest replace colon wit semi-colon (editor to view).

AR: fixed

Page 9, line 4. Suggest restructuring line as “disruption of the flood-pulse, affecting the ecological functioning of floodplains (Junk et al., 1989).

AR: fixed

Page 9, line 11. Add “many” after “of” and replace “appears to be” with “is”.

AR: fixed

Page 9, line 14. Add “also” after “can”.

AR: fixed

Page 9, line 25. Rephrase first part of the sentence as “The attention to the importance of phosphorus and nitrogen can obscure the importance of other nutrients and their ratios. Silicon efficiently. . ..

AR: fixed

Page 10, line 2. I suggest “’variable” is used rather than “parameter” for the intended meaning here.

AR: fixed

Page 10, line 5. Delete “be” and replace “dependent” with “depend”.

AR: fixed

Page 10, line 6. Replace “be fed. . ..predictions” with “provide input to predictive models”.

AR: fixed

Page 10, line 8. Delete “In contexts”.

AR: fixed

Page 10, line 17. Delete “as a necessary pre-condition”.

AR: fixed

Page 10, line 18. Delete “these”.

AR: fixed

Page 11, line 13. Delete full stop after “. . .per year)” and replace “but upon” with “on”.

AR: fixed

Page 11, line 28. Delete “be”.

AR: fixed

Page 11, 33. Suggest to replace “lines dividing the different” with “boundaries of difference”.

AR: fixed

Page 14, line 4, Delete firs use of “depth” and “replace “max” with “maximum”.

AR: fixed

Page 14, line 9 &10. Replace “stopping here . . .recall that” with “reflecting that”.

AR: fixed

Page 14, line 27. Replace “parameters” with “variables”.

AR: fixed

Page 14, line 9. Delete “do” and “in contexts”, replace “they” with “these” nd delete following “these”.

AR: fixed

Page 16, line 14. See earlier comments on the use of “hungry water”.

AR: replaced “hungry water” with “sediment-starved water”

Page 16, line 29. Replace “Compared to” with “Compared with”.

AR: fixed

Page 17, line 6. Delete “have been”.

AR: fixed

Page 17, line 10. Replace “compared to” with “compared with”.

AR: fixed

Page 17, line 22. Delete "and repurposed”.

AR: fixed

Page 18, line 3. Insert “to” after “difficult”.

AR: fixed

Page 18, line 6. Move comma after “value” to after “which”.

AR: fixed

Page 18, line 9. Delete “does the”.

AR: fixed

Page 18, line 10. Replace “some contexts” with “places”.

AR: fixed

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R. Scott Winton[1,2], Elisa Calamita[1,2], Bernhard Wehrli[1,2]

[1]Department of Environmental Systems Science, ETH Zürich, Zürich, 8092, Switzerland
[2]Department of Surface Waters Eawag, Kastanienbaum, 6047, Switzerland

Correspondence to: R. Scott Winton (Robert.winton@usys.ethz.ch)

Abstract. The impact of large dams is a popular topic in environmental science, but the importance of altered water quality as a driver of ecological impacts is often missing from such discussions. This is partly because information on the relationship between dams and water quality is relatively sparse and fragmentary, especially for low latitude developing countries where dam building is now concentrated. In this paper, we review and synthesize information on the effects of damming on water quality with a special focus on low latitudes. We find that most water quality changes are driven by two ultimate physical processes: the trapping of sediments and nutrients, and thermal stratification in reservoirs. Since stratification emerges as an important driver and there is ambiguity in the literature regarding the stratification behavior of low latitude water bodies, we synthesize data and literature on the 54 largest low latitude reservoirs to assess their mixing behavior using three classification schemes. Direct observations from literature as well as classifications based on climate and/or morphometry suggest that most, if not all, low latitude reservoirs will stratify on at least a seasonal basis. This finding suggests that

low latitude dams have the potential to discharge cooler, anoxic deep water, which can degrade downstream ecosystems by altering thermal regimes or causing hypoxic stress. Many of these reservoirs are also capable of efficient trapping of sediments and bed load, transforming or destroying downstream ecosystems, such as floodplains and deltas. Water quality impacts imposed by stratification and sediment trapping can be mitigated through a variety of approaches, but implementation often meets physical or financial constraints. The impending construction of thousands of planned low latitude dams will alter water quality throughout tropical and subtropical rivers. Theses changes and associated environmental impacts need to be better understood by better baseline data and more sophisticated predictors of reservoir stratification behavior. Improved environmental impact assessments and dam designs have the potential to mitigate both existing and future potential impacts.

1. Introduction

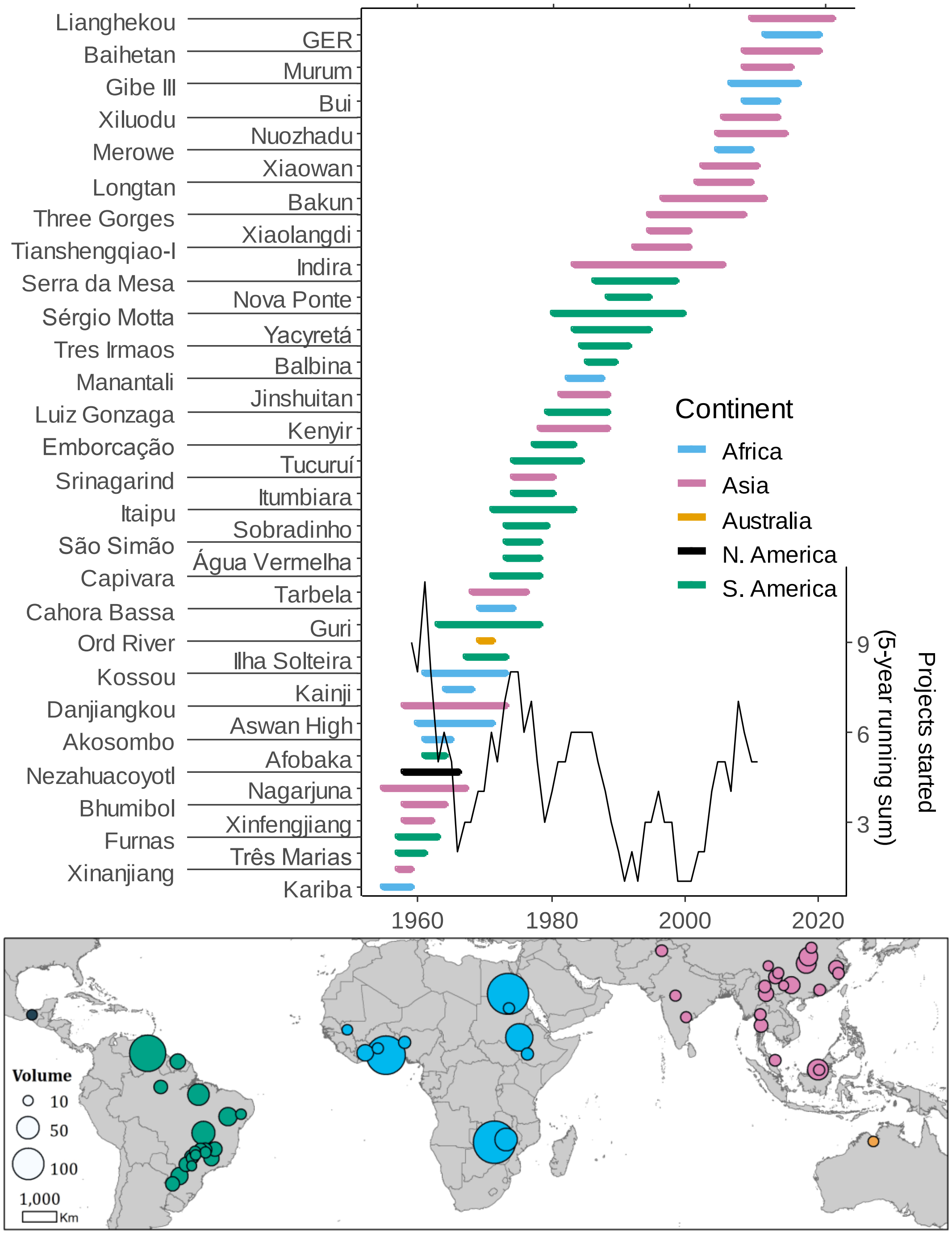
As a global dam construction boom transforms the world's low latitude river systems (Zarfl et al., 2014) there is a serious concern about how competing demands for water, energy and food resources will unfold. The challenge created by dams is not merely that they can limit the availability of water to downstream peoples and ecosystems, but also that the physical and chemical quality of any released water is often altered drastically (Friedl and Wüest, 2002; Kunz et al., 2011). Access to sufficient quality of water is a United Nations Environment Programme sustainable development goal (UNEP 2016), and yet the potential negative effects of dams on water quality are rarely emphasized in overviews of impacts of dams (Gibson et al., 2017).

Dams are often criticized by ecologists and biogeochemists for fragmenting habitats (Anderson et al., 2018; Winemiller et al., 2016), disrupting floodplain hydrologic cycles (Kingsford and Thomas, 2004; Mumba and Thompson, 2005; Power et al., 1996), and for emitting large amounts of methane (Delsontro et al., 2011). Such impacts act against the promise of carbon neutral hydropower (Deemer et al., 2016). In contrast, scientists have committed less investigative effort to documenting the potential impacts of dams on water quality. In cases where investigators have synthesized knowledge of water quality impacts (Friedl and Wüest, 2002; Nilsson and Renofalt, 2008; Petts, 1986), the conclusions are inevitably biased towards mid/high latitudes where the bulk of case studies and mitigation efforts have occurred.

While there is much to be learned from more thoroughly-studied high latitudes rivers, given the fundamental role played by climate in river and lake functioning, it is important to consider how the low latitude reservoirs may behave differently. For example, the process of reservoir stratification, which plays a crucial role in driving downstream water quality impacts, is governed to a large degree by local climate. Additionally, tropical aquatic systems are more prone to suffer from oxygen depletion because warmer water contains less oxygen at saturation and because organic matter decomposition, an oxygen sink, proceeds more rapidly (Lewis, 2000). Latitiude also plays an important role in considering ecological or physiological responses to altered water quality. Studies focused on coldwater fish species may have little applicability to warmer rivers in the subtropics and tropics.

Low latitude river systems are also currently experiencing and will continue to experience a high rate of new impacts from very-large dam projects. A review of the construction history of very large reservoirs of at least 10 km^3 below ± 35 ˚ latitude reveals that few projects were launched between 1987 and 2000, but in the recent decade (2001-2011) low latitude mega-reservoirs have appeared at a rate of one new project per year (Fig. 1). Given that ongoing and proposed major dam projects are concentrated at low latitudes (Zarfl et al., 2014), a specific review of water quality impacts of dams and the extent to which they are understood and manageable in tropical biomes, is needed.

Fig. 1. *Construction history of the world's 54 largest reservoirs located below ± 35˚ latitude. Project year of completion data are from the International Commission on Large Dams (http://www.icold-cigb.net/). Project start data are approximate (± 1 year) and based on either gray literature source, or for some more recent dams, visual inspection of Google Earth satellite imagery. Grand Ethiopian Renaissance*



abbreviated as GER. Volume in map legend is in km^3.

Large dams exert impacts across many dimension, but in this review, we largely ignore the important, but well-covered impacts of altered hydrologic regimes . Instead we focus on water quality, while acknowledging that flow and water quality issues are often inextricable. We also disregard the important issue of habitat fragmentation and the many acute impacts on ecosystems and local human populations arising from dam construction activities (i.e. displacement and habitat loss due to inundation). These important topics have been recently reviewed elsewhere (e.g. Winemiller et al., 2016; Anderson et al., 2018).

In order to understand the severity and ubiquity of water quality impacts associated with dams, it is necessary to understand the process of lake stratification, which occurs because density gradients within lake water formed by solar heating of the water surface prevent efficient mixing. By isolating deep reservoir water from surface oxygen, stratification facilitates the development of low oxygen conditions and a suite of chemical changes that can be passed downstream, To address the outstanding question of whether low latitude reservoirs are likely to stratify and experience associated chemical water quality changes, we devote a section of this study to predicting reservoir stratification, which includes an analysis of the largest low latitude reservoirs based upon their morphometric and hydrologic characteristics. This analysis of physical processes within reservoirs is critical to understanding the potential for downstream water quality impacts.

Finally, we review off-the-shelf efforts to manage or mitigate undesired chemical and ecological effects of dams related to water quality. The management of dam operations to minimize downstream ecological impacts follows the concept of environmental flows (eflows). The primary goal of eflows is to mimic natural hydrologic cycles for downstream ecosystems, which are otherwise impaired by conventional dam-altered hydrology of diminished flood peaks and higher minimum flows. Although restoring hydrology is vitally important to ecological functioning, it does not necessarily solve water quality impacts, which often require different types of management actions. Rather than duplicate the recent eflow reconceptualizations (e.g. Tharme, 2003; Richter, 2009; Olden & Naiman, 2010; O'Keeffe, 2018), we focus our review on dam management efforts that specifically target water quality, which includes both eflow and non-eflow actions.

2. Impacts of dams on river water quality

The act of damming and impounding a river imposes a fundamental physical change upon the river continuum. The river velocity slows as it approaches the dam wall and the created reservoir becomes a lacustrine system. The physical change of damming leads to chemical changes within the reservoir, which alters the physical and chemical water quality, which in turn leads to ecological impacts on downstream rivers and associated wetlands. The best-documented physical, chemical and ecological effects of damming on water quality are summarized in Fig. 2 and described in detail in this section. In each subsection we begin with a general overview and then specifically consider the available evidence for low latitude systems.

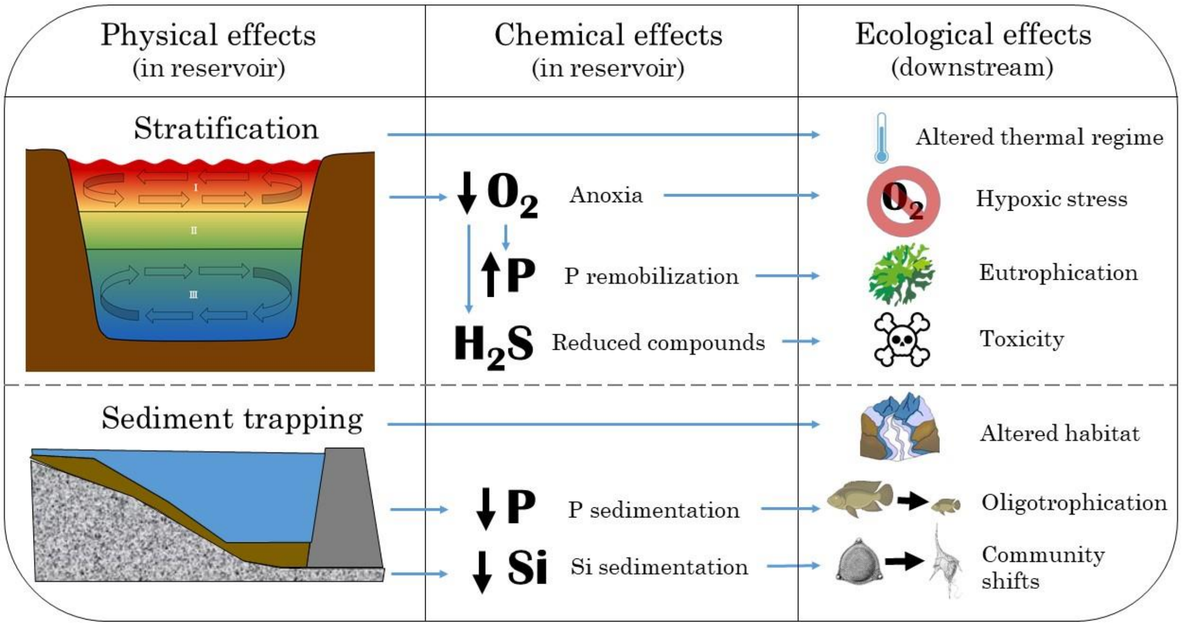


Fig. 2. Conceptual summary of the physical and chemical water quality effects of dams and how they impact river ecology.

2.1 Stratification-related effects

Stratification, that is, the separation of reservoir waters into stable layers of differing densities, has important consequences for river water downstream of dams. A key to understanding the impacts of dams on river water quality is a precise understanding of the depth of the reservoir thermocline/oxycline relative to spillway or turbine intakes. At many high head storage hydropower dams the turbine intakes are at least 10 s of meters deep, to preserve generation capacity even under extreme drought conditions. For example, Kariba Dam's intakes pull water from 20 to 25 m below the typical level of the reservoir surface, which roughly coincides with the typical depth of the thermocline. In more turbid tropical reservoirs, thermocline depth can be much shallower, for example at Murum Reservoir in Indonesia where it is just 4 to 6 m. Unfortunately, the turbine intake depths are not typically reported in dam databases. Furthermore, for many reservoirs, especially those in the tropics, the mixing behavior and therefore the typical depth of the thermocline are not well understood. Collecting the reservoir depth profiles necessary to generate this key information may be more difficult than simply analyzing water chemistry below dams. Dam tailwaters with low oxygen, or reduced compounds such as hydrogen sulfide or dissolved methane are likely to stem from discharged deep water of a stratified reservoir.

2.1.1 Changing thermal regimes

Even at low latitudes where seasonal differences are less than temperate climates, aquatic ecosystems experience water temperatures that fluctuate according to daily and annual thermal regimes (Olden and Naiman, 2010). Hypolimnetic releases of unseasonably cold water represent alterations to a natural regime. Although the difference between surface and deep waters in tropical lakes is typically much less than those at higher latitudes (Lewis, 1996), the differences are often much greater than the relatively subtle temperature shifts of 3-5 °C that have been shown to serious impacts (King et al., 1998; Preece and Jones, 2002). For example, at 17 degrees south of the equator, Lake Kariba seasonally reaches a 6 to

7 °C difference between surface and deep waters (Magadza, 2010). The ecological impacts of altered thermal regimes have been extensively documented across a range of river systems.

Many aquatic insects are highly sensitive to alterations in thermal regime (Eady et al., 2013; Ward and Stanford, 1982), with specific temperature thresholds required for completion of various life cycle phases (Vannote and Sweeney, 1980). Since macroinvertebrates form an important prey-base for fish and other larger organisms there will be cascading effects when insect life cycles are disrupted. Fish have their own set of thermal requirements, with species often filling specific thermal niches (Coutant, 1987). Altered thermal regimes can shift species distributions and community composition. Development schedules for both fish and insects respond to accumulated daily temperatures above or below a threshold, as well as absolute temperatures (Olden and Naiman, 2010). Fish and insects have both chronic and acute responses to extreme temperatures. A systemic meta-analysis of flow regulation on invertebrates and fish populations by Haxton and Findlay (2008) found that hypolimnetic releases tend to reduce abundance of aquatic species regardless of setting.

There exist several case studies from relatively low latitudes, suggesting that tropical and sub-tropical rivers are susceptible to dam-imposed thermal impacts. The Murray cod has been severely impacted by coldwater pollution from the Dartmouth Dam in Victoria, Australia (Todd et al., 2005) and a variety of native fish species were similarly impacted by the Keepit Dam in New South Wales, Australia (Preece and Jones, 2002). In subtropical China, coldwater dam releases have caused fish spawning to be delayed by several weeks (Zhong and Power, 2015). In tropical Brazil, Sato et al., 2005 tracked disruptions to fish reproductive success 34 km downstream of the Tres Marias Dam. In tropical South Africa, researchers monitoring downstream temperature-sensitive fish in regulated and unregulated rivers found that warm water flows promoted fish spawning, whereas flows of 3 to 5 °C cooler hypolimnetic water forced fish to emigrate (King et al., 1998).

2.1.2 Hypoxia

Stratification tends to lead to the deoxygenation of deep reservoir water, because of heterotrophic consumption and a lack of resupply from oxic surface layers. When dam intakes are deeper than the oxycline, hypoxic water can be passed downstream where it is suspected to cause significant ecological harm. Oxygen below 3.5 to 5 mg L^{-1} typically trigger escape behavior in higher organisms, whereas only well-adapted organisms survive below 2 mg L^{-1} (Spoor, 1990). A study of 19 dams in the southeastern United States found that 15 routinely released water with less than 5 mg dissolved oxygen L^{-1} and 7 released water with less than 2 mg dissolved L^{-1} (Higgins and Brock, 1999).Hypoxic releases from these dams often lasted for months and the hypoxic water was detectable in some cases for dozens of km downstream. Below an the Hume Dam in Australia researchers found that oxygen concentrations reached an annual minimum of less than 50% saturation (well under 5 mg L^{-1}), while other un-impacted reference streams always had 100% oxygen saturation (Walker et al., 1978). Researchers recently observed similar hypoxic conditions below the Bakun Dam in Malaysia with less than 5 mg L^{-1} recorded for more than 150 km downstream (Wera et al., 2019). Although observations and experiments have demonstrated the powerful stress hypoxia exerts on many fish species (Coble, 1982; Spoor, 1990), there exist few well-documented field studies of dam-induced hypoxia disrupting downstream ecosystems. This is partly because it can be difficult to distinguish the relative importance of dissolved oxygen and other correlated chemical and physical parameters (Hill, 1968). Hypolimnetic dam releases containing low oxygen will necessarily also be colder than surface waters and they may contain toxic levels of ammonia and hydrogen sulfide, so it was not clear which factor was the main driver for the loss of benthic macroinvertebrate diversity documented below a dam of the Guadelupe River in Texas (Young et al., 1976).

Regardless, regulators in the southern US found the threat of hypoxia to be sufficiently serious to mandate that dam tail-waters maintain a minimum dissolved oxygen content of 4 to 6 mg L^{-1}, depending on temperature (Higgins & Brock, 1999). These dams in the Tennessee Valley are on the northern fringe of the subtropics (~35-36°N), but are relatively warm compared with other reservoirs of the United States. Since oxygen is less soluble in warmer water and gas-transfer is driven by the difference between equilibrium and actual concentrations, it follows that low-oxygen stretches downstream of low-latitude dams will suffer from slower oxygen recovery.

In addition to the direct impact imposed by hypoxic reservoir water when it is discharged downstream, anoxic bottom waters will also trigger a suite of anaerobic redox processes within reservoir sediments that exert additional alterations to water quality. Therefore anoxia can also exert indirect chemical changes and associated ecological impacts. Here we discuss two particularly prevalent processes, phosphorus re-mobilization and the generation of soluble reduced compounds.

2.1.3 Phosphorus re-mobilization and eutrophication

Phosphorus (P) is an important macronutrient. Its scarcity or limited bioavailability to primary producers often limits productivity of aquatic systems. Conversely, the addition of dissolved P to aquatic ecosystems often stimulates eutrophication, leading to blooms of algae, phytoplankton or floating macrophytes on water surfaces (Carpenter et al., 1998; Smith, 2003). Typically, eutrophication will occur when P is imported into a system from some external source, but in the case of lakes and reservoirs internal P loading from sediments can also be important. Most P in the aquatic environment is bound to sediment particles where it is relatively unavailable for uptake by biota, but anoxic bottom-waters of lakes greatly accelerate internal P loading (Nurnberg, 1984). Iron oxide particles are strong absorbers of dissolved P, but under anoxic conditions the iron serves as an electron acceptor and is reduced to a soluble ferrous form. During iron reduction, iron-bound P also becomes soluble and is released into solution where it can build up in hypolimnetic waters. Water rich in P is then either discharged through turbines or mixed with surface waters during periods of destratification. Therefore, sudden increases in bioavailable P can stimulate algal and other aquatic plant growth n the reservoir epilimnion. Theoretically, discharging of P-rich deep water could cause similar blooms in downstream river reaches, but we are not aware of any direct observations of this phenomenon. Typically, nutrient releases are thought of as beneficial to downstream ecosystems because they would counteract the oligotrophication imposed by the dam through sediment trapping (Kunz et al., 2011).

Although dams seem to typically lead to overall reductions in downstream nutrient delivery (see the section on sediment trapping), the phenomenon of within-reservoir eutrophication because of internal P loading has been extensively documented in lakes and reservoirs worldwide. In the absence of major anthropogenic nutrient inputs, the eutrophication is typically ephemeral and is abated after several years following reservoir creation. A well-known tropical example is Lake Kariba, the world’s largest reservoir by volume. For many years after flooding a 10 to 15% percent of the lake surface was covered by Kariba Weed (*Salvinia molesta*), a floating macrophyte. Limnologists attributed these blooms to decomposing organic matter and also gradual P release from inundated soils exposed to an anoxic hypolimnion (Marshall and Junor, 1981).

Indeed, some characteristics of tropical lakes seem to make them especially susceptible to P regeneration from the hypolimnion. The great depth to which mixing occurs (often 50 or more meters) during destratification, a product of the mild thermal density gradient between surface and deep water, provides more opportunity to transport deep P back to the surface (Kilham and Kilham, 1990). This has lead limnologists to conclude that deep tropical water bodies are more prone to eutrophication compared with their temperate counterparts (Lewis, 2000). There is of course variability within tropical lakes. Those with larger catchment areas tend to receive more sediments and nutrients from their inflowing rivers and are also more prone to eutrophication (Straskraba et al., 1993). These findings together suggest that thermally stratified low latitude reservoirs run a high risk of experiencing problems of eutrophication because of internal P re-mobilization.

2.1.4 Reduced compounds

Another ecological stressor imposed by hypoxic reservoir water is a high concentrations of reduced compounds, such as hydrogen sulfide (H_2S) and reduced iron, which limit the capacity of the downstream river to cope with pollutants. Sufficient dissolved oxygen is not only necessary for the support of most forms of aquatic life, but it is also essential to maintaining oxidative self-purification processes within rivers (Friedl and Wüest, 2002; Petts, 1986). Reduced compounds limit the oxidative capacity of river water by acting as a sink for free dissolved oxygen. The occurrence of H_2S has been documented in some cases in the tail waters of dams, but the co-occurrence of this stressor with low temperatures and hypoxia make it difficult to attribute the extent to which it causes direct ecological harm (Young et al., 1976). Researchers investigating fish mortality below Greens Ferry Dam in Arkansas, USA, found H_2S concentrations of 0.1 mg L^{-1} (Grizzle, 1981), well above the recognized lethal concentrations for fish of 0.013 to 0.045 mg H_2S L^{-1} based on toxicological studies (Smith et al., 1976). Lethal concentrations for fish of ammonia are 0.75 to 3.4 mg un-ionized NH_3 L^{-1} (Thurston et al., 1983), though we are unaware of specific cases where these thresholds have been surpassed because of dams. At the very least the presence of reduced compounds at elevated concentrations indicates that an aquatic system is experiencing severe stresses, which if sustained, will be lethal to most macroscopic biota.

2.2 Sediment trapping

Dams are highly efficient at retaining sediments (Donald et al., 2015; Garnier et al., 2005; Kunz et al., 2011). As rivers approach reservoirs, the flow velocity slows and loses the potential to slide and bounce along sand and gravel, while lost turbulence allows finer sediments to fall out of suspension. Blockage of sediments and coarse material drives two related impact pathways. The first is physical, stemming from the loss of rivers sediments and bedload that are critical to maintaining the structure of downstream ecosystems (Kondolf, 1997). The second is chemical; the loss of sediment-bound nutrients causes oligotrophication of downstream ecosystems including floodplains and deltas (Van Cappellen and Maavara, 2016).

2.2.1 Altered habitat

The most proximate impact of sediment starvation is the enhancement of erosion downstream of dams from outflows causing channel incision that can degrade within-channel habitats for macroinvertebrates and fish (Kondolf, 1997). Impacts also reach adjacent and distant ecosystems such as floodplains and deltas, which almost universally depend upon rivers to deliver sediments and nutrients to maintain habitat quality and productivity. In addition to sediment/nutrient trapping, dams also dampen seasonal hydrologic peaks, reducing overbank flooding of downstream river reaches. The combination of these two dam-effects leads to a major reduction in the delivery of nutrients to floodplains, which represents a fundamental disruption of the flood-pulse, affecting the ecological functioning of floodplains (Junk et al., 1989).

River deltas also rely on sediment delivered by floods and damming has lead to widespread loss of delta habitats (Giosan et al., 2014). Sediment delivery to the Mekong Delta has already been halved and could drop to 4% of baseline if all planned dams for the catchment are constructed (Kondolf et al., 2014a). Elsewhere in the tropics, dam construction has been associated with the loss of mangrove habitat, such as at the Volta estuary in Ghana (Rubin et al., 1999). The morphology of the lower Zambezi’s floodplains and delta were dramatically transformed by reduced sediment loads associated with the Cahora Bassa mega-dam in Mozambique (Davies et al., 2001). With diminished sediment delivery and enhanced erosion from rising sea levels, the future of many coastal deltas is precarious, as most of the world’s medium and large deltas are not accumulating sediment fast enough to stay above water over the coming century (Giosan et al., 2014).

2.2.2 Oligotrophication

Although the densely populated and industrialized watersheds of the world typically suffer from eutrophication, dam-induced oligotrophication, through sediment and nutrient trapping, can also severely alter the ecological functioning of rivers and their floodplains, deltas and coastal waters. Globally, 12 to 17% of global river phosphorus load is trapped behind dams (Maavara et al., 2015), but in specific locations, trapping efficiency can be greater than 90%, such as at Kariba Dam on the Zambezi River (Kunz et al., 2011) and the Aswan Dam on the Nile (Giosan et al., 2014). Such extreme losses of sediments and nutrients can cause serious acute impacts to downstream ecosystems, though examples are relatively scarce because pre-dam baseline data is not often available.

Most of the best-documented examples of impacts stemming from oligotrophication are from temperate catchments with important and carefully-monitored fisheries. For example damming led to the collapse of a valuable salmon fishery in Kootenay Lake, British Columbia, Canada through oligotrophication (Ashley et al., 1997). The fishery was eventually restored through artificial nutrient additions. Oligotrophication may impose similar ecological impacts in tropical contexts, such as in southern Brazil where an increase in water clarity following the closure of the Eng Sergio Motta (Porto Primavera) dam is associated with a shift in fish communities (Granzotti et al., 2018). Impacts have been perhaps most dramatic in the eastern Mediterranean following the closure of the Aswan Dam. The Lake Nasser reservoir, following its closure in 1969, began capturing the totality of the Nile’s famously sediment-rich flood waters, including some 130 million tons of sediment that had previously reached the sea. In the subsequent years there was a 95% drop in phytoplankton biomass and an 80% drop in fish landings (Halim, 1991). With dams driving rivers toward oligotrophy and land-use changes, such as deforestation and agricultural intensification, causing eutrophication, most rivers globally face some significant change to trophic state.

2.2.3 Elemental ratios

The attention to phosphorus and nitrogen can obscure the importance of other nutrients and their ratios.Tthe element, Silicon (Si), which is also efficiently sequestered within reservoirs, is an essential nutrient for certain types of phytoplankton. The simultaneous eutrophication and damming of many watersheds has lead to decreases in Si to nitrogen ratios, which tends to favor non-siliceous species over diatoms (Turner et al., 1998). In the Danube River efficient trapping of Si in reservoirs over several decades lead to a shift in Black Sea phytoplankton communities (Humborg et al., 1997), coinciding with a crash in an important and productive fishery (Tolmazin, 1985). A similar phenomenon has been documented at at lower latitude in the Mississippi Delta. Decreases in Si loading lead to a drop in the abundance of copepods and diatoms relative to the total meso-zooplankton population in the Gulf of Mexico (Turner et al., 1998). These community shifts may have important implications for coastal and estuarine fish communities and the emergence of potential harmful algal blooms.

2.3 Reversibility and propagation of impacts

One way to think of the scope of dam impacts on water quality is in terms of how reversible perturbations to each variable may be. Sediment trapped by a dam may be irreversibly lost from a river and even unregulated downstream tributaries are unlikely to compensate . Temperature and oxygen impacts of dams, in contrast, will be undone gradually through exchange with the atmosphere as the river flows. The speed of recovery will depend upon river depth to surface areas, turbulence and other factors that may provide input to predictive models (Langbein and Durum, 1967). Field data from subtropical Australia and tropical Malaysia suggests that, in practice, hypoxia can extend dozens or hundreds of kilometers downstream of dam walls (Walker et al., 1978; Wera et al., 2019). Where reaeration measures are incorporated into dam operation, hypoxia can be mitigated immediately, or within a few kilometers, as was the case in Tennessee, USA (Higgins and Brock, 1999). A study in Colorado, USA found that thermal effects could be detected for hundreds of kilometers downstream (Holden and Stalnaker, 1975). Regardless of the type of impact, it is clear that downstream tributaries play an important role in returning rivers to more “natural” conditions by providing a source of sediment and flow of more appropriate water quality. Water quality impacts of dams are therefore likely to increase and become less reversible when chains of dams are built along the same river channel or on multiple tributaries of a catchment network.

3. How prevalent is stratification of low latitude reservoirs?

Because the chemical changes of hypoxia and altered thermal regimes both stem from the physical process of reservoir stratification, understanding a reservoir’s mixing behavior is an important first step toward predicting the likelihood of water quality impacts. Unfortunately, there exists ambiguity and misinformation in the literature about the mixing behavior of low latitude reservoirs. To resolve the potential confusion, we review literature on the stratification behavior of tropical water bodies and then conduct an analysis of stratification behavior of the 54 most voluminous low-latitude reservoirs.

3.1 Stratification in the tropics

For at least one authority on tropical limnology, the fundamental stratification behavior of tropical lakes and reservoirs is clear. Lewis (2000) states that "Tropical lakes are fundamentally warm monomictic…," with only the shallowest failing to stratify at least seasonally, and that periods of destratification are typically predictable events coinciding with cool, rainy and/or windy seasons. Yet, there exists confusion in the literature. For example, the World Commission on Large Dams' technical report states that stratification in low latitude reservoirs is "uncommon" (McCartney et al., 2000). The authors provide no source supporting this statement, but the conclusion likely stems from the 70-year-old landmark lake classification system (Hutchinson and Loffler, 1956), which based on very limited field data from equatorial regions, gives the impression that tropical lakes are predominately either oligomictic (mixing irregularly) or polymictic (mixing many times per year). The idea that low latitude water bodies are fundamentally unpredictable or aseasonal, as well as Hutchinson and Loffler's (1956) approach of classifying lakes without morphometric information critical to understanding lake stability (Henry & Tundisi 1988), has been criticized repeatedly over subsequent decades as additional tropical lake studies have been published (Lewis, 1983, 2000, 1973, 1996). And yet, the original misleading classification diagram continues to be faithfully reproduced in contemporary limnology text books (Bengtsson et al., 2012; Wetzel, 2001). Since much of the water quality challenges associated with damming develop from the thermal and/or chemical stratification of reservoirs, we take a critical look at the issue of whether low latitude reservoirs are likely to stratify predictably for long periods of time.

3.2 The largest low latitude reservoirs

To assess the prevalence of prolonged reservoir stratification periods that could impact water quality, we reviewed and synthesized information on the 54 most voluminous low latitude reservoirs. Through literature searches we found descriptions of mixing behavior for 32 of the 54. Authors described nearly all as "monomictic" (having a single well-mixed season, punctuated by a season of stratification). One of these reservoirs was described as meromictic (having a deep layer that does not typically intermix with surface waters) (Zhang et al., 2015). The review indicates that 30 reservoirs are stratified regularly for months-long seasons and thus could be expected to experience the associated chemical and ecological water quality issues, such as thermal alterations and hypoxia. The two exceptions are Brazilian reservoirs, Tres Irmaos and Ilha Solteira, described by Padisak (2000) to be "mostly polymitic" (mixing many times per year). On further investigation, this classification does not appear to be based on direct observations, but is a rather general statement of regional reservoir mixing behavior (see Supplement).

We compared our binary stratification classification based on available literature to the results of applying reservoir data to three existing stratification classification schemes. First, we consider the classic Hutchinson and Loffler (1956) classification diagram based on altitude and latitude. Second, we plot the data onto a revised classification diagram for tropical lakes proposed by Lewis (2000) based on reservoir morphometry. Finally we apply the concept of Densimetric Froude Number which can be used to predict reservoir stratification behavior (Parker et al., 1975) based on morphometry and discharge.

The Hutchinson and Loffler (1956) classification is meant to be applied to "deep" lakes and therefore is not useful for discriminating between stratifying and non-stratifying reservoirs based on depth. It does suggest that all sufficiently deep reservoirs (except those above 3500 m altitude) should be well-stratified. Most of the reservoirs in our data set fall into an "oligomictic" zone, indicating irregular mixing (Fig. 3) when available literature suggests that most would be better described as monomictic, with a predictable season of deeper mixing. This finding reaffirms one of the long-running criticisms of this classification scheme: its overemphasis on oligomixis (Lewis, 1983).

We found that the Lewis (2000) classification system for tropical lakes correctly identified most of the reservoirs in our data set as monomictic, however six relatively shallow reservoirs known to exhibit seasonal stratification were mis-classified into polymictic categories (Fig. 4A). Five of these six lie within a zone labelled “discontinuous polymictic,” which refers to lakes which do not mix on a daily basis, but mix deeply more often than once per year. The literature suggests that these lakes would be better described as “monomictic.” We should note that Lewis’s (2000) goals in generating this diagram were to improve upon the Hutchinson and Loffler (1956) diagram for low latitude regions and to develop a classification system that could be applied to shallow lakes. Lewis (2000) does not mathematically define the boundaries of difference and describes them as “approximate” based on his expert knowledge, so it is not terribly surprising that there appear to be some misclassifications.

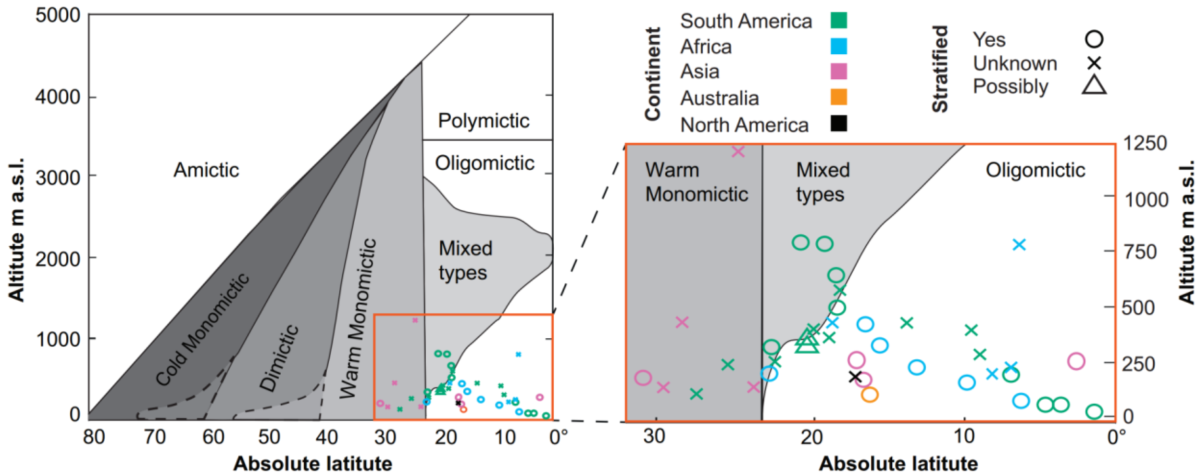


Fig. 3. The 54 most voluminous low-latitude reservoirs overlaid onto a lake classification diagram (redrawn from Hutchinson and Loffner 1956)

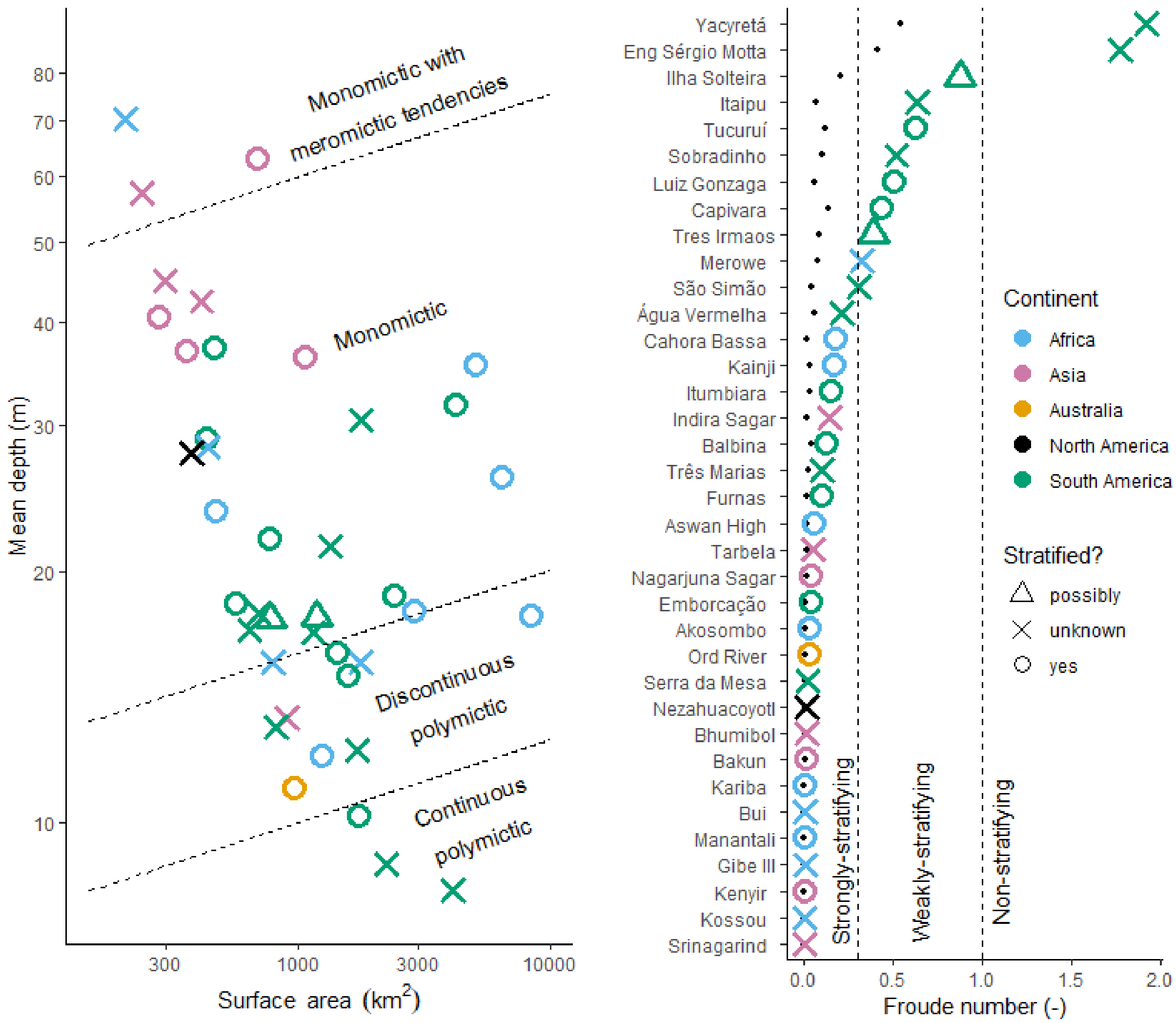


Fig. 4. Reservoir morphometry and stratification behavior. A) Relationship between area and depth for 40 of the 54 world's most voluminous reservoirs located below ±35° latitude. Data are from the International Commission on Large Dams (http://www.icold-cigb.net/) (14 reservoirs are excluded because of missing surface area data). Stratification behavior classification is synthesized from literature: "yes" indicates that the reservoir has an extended, predictable season of stratification and/or mixes deeply at most one time per year; "possibly" refers to two Brazilian reservoirs which authorities suggest are likely to be polymictic, but for which no direct observations exist (see Tundisi 1990; Padisak 2000); for "unknown" reservoirs, no published information on stratification behavior appears in literature searches. Dashed lines and classification labels are approximations proposed by Lewis (2000). B) Reservoirs sorted by densimetric Froude number, which is a function of reservoir depth, length, volume and discharge (Parker et al, 1975). The vertical dashed lines at F = 1 and F = 0.3 indicates the expected boundaries between strongly-, weakly- and non-stratifying reservoirs (Orlob, 1983). Small dots represent Froude numbers if maximum depth (height of dam wall) is used instead of mean depth as suggested by (Ledec and Quintero, 2003). Discharge data is from the Global Runoff Data Centre (https://www.bafg.de/GRDC); five dams were excluded because of missing discharge data.

In a final stratification assessment, we compared the known mixing behavior from literature to calculations of Densimetric Froude Number (F) (see supplemental material) for the 35 reservoirs for which discharge and surface area data are available (Fig. 4B). We calculated F using two different values for depth: first, using mean depth by dividing reservoir volume by area; and second using dam wall height as a proxy for maximum depth. While some authors have suggested that either value for depth can be used (Ledec and Quintero, 2003), our analysis suggests that this choice can have a strong impact on F calculations and interpretation. The ratio between mean and maximum depth within our data set ranges from 0.1 to 0.4 with a mean of 0.23. This means that all F values could be re-calculated to be roughly one-quarter of their value based on mean depth. This is inconsequential for reservoirs with the small F, but for those with large F it can lead to a shift across the classification thresholds of 0.3 and 1. For example, two reservoirs in our data set exceeded the threshold of F = 1 to indicate non-stratifying behavior when using mean depth, but they drop down into the weakly stratifying category when maximum depth is used instead. Nine other reservoirs shift from weakly to strongly stratifying. So which value for F better reflects reality? It is worth reflecting that reservoirs are typically quite long and limnologists often break them down into sub-basins, separating shallower arms closer to river inflows from deeper zones close to the dam wall. Use of maximum depth for F calculations probably better reflects stratification behavior at the dam wall, whereas average depth may better indicate behavior in shallower sub-basins that are less likely to stratify strongly. Since the deepest part of a reservoir is at the dam wall and because stratification in this zone is the most relevant to downstream water quality, it is probably most appropriate to use maximum depth in F calculations.The two reservoirs described as polymictic by Tundisi (1990) and Padisak et al (2000), fall into the intermediate category of weakly-stratifying (when using mean depth), but three others within this zone are reported to exhibit strong stratification (Deus et al., 2013; Naliato et al., 2009; Selge and Gunkel, 2013). Better candidates for non-stratifying members of this reservoir data set are Yacreta and Eng. Sergio Motta, but unfortunately we could find no description of their mixing behavior in the literature. A field study with depth profiles of these reservoirs could dispel this ambiguity and determine whether all of the largest low latitude reservoirs stratify on a seasonal basis.

Overall, this exercise of calculating F for the reservoirs seems to indicate that most, if not all, are likely to stratify. This is an important realization because it opens the possibility for downstream water quality problems associated with deep water releases. Furthermore, the bulk of evidence suggests that these reservoirs mix during a predictable season and not irregularly throughout the year or across years. This means that under normal conditions these reservoirs should be able to stratify continuously for periods of at least a few months.

4. Managing water quality impacts of dams

4.1 Environmental flows

The most developed and implemented approach (or collection of approaches; reviewed by Tharme, 2003) for the mitigation of dam impacts is the environmental flow (eflow), which seeks to adjust dam releases to mimic natural hydrologic patterns. An eflow approach to reservoir management could, for example, implement a simulated flood downstream by releasing some reservoir storage waters during the appropriate season. Although the eflow approach has traditionally focused on the mitigation of ecological problems stemming from disrupted hydrologic regimes, there is a growing realization that water quality (variables such as water temperature, pollutants, nutrients, organic matter, sediments, dissolved oxygen) must be incorporated into the framework (Olden and Naiman, 2010; Rolls et al., 2013). There is already some evidence that eflows successfully improve water quality in practice. In the Tennessee valley, the incorporation of eflows into dam management improved downstream DO and macroinvertebrate richness (Bednařík et al., 2017). Eflows have also been celebrated for preventing cyanobacteria blooms that had once plagued an estuary in Portugal (Chícharo et al., 2006). These examples illustrate the potential for eflows to solve some water quality impacts created by dams.

Unfortunately, eflows alone will be insufficient in many contexts. For one, flow regulation cannot address the issue of sediment and nutrient trapping without some sort of coupling to a sediment flushing strategy. Second, the issues of oxygen and thermal pollution often persist under eflow scenarios when there is reservoir stratification. Even if the natural hydrologic regime is effectively simulated by eflow actions, there is no reason why this should solve water quality problems as long as the water intake is positioned below the depth of the reservoir thermocline and residence time is not significantly changed. The solution to hypoxic, cold water is not simply more of it, but rather intakes must be modified to draw a more desirable water source, or destratification must be achieved. To address the problems of aeration and coldwater pollution, dam managers turn to outflow modification strategies or destratification.

4.2 Aeration

Hypoxia of reservoir tailwaters is a common problem imposed by dams. As a result, various management methods for controlling dissolved oxygen content in outflows exist, ranging in cost-effectiveness depending on the characteristics of the dam in question (reviewed by Beutel & Horne, 1999). Options include: turbine venting, turbine air injection, surface water pumps, oxygen injection and aerating weirs. As the issue of dam-induced hypoxia has been recognized for many decades, most modern dams incorporate some sort of oxygenation design elements. Where dissolved oxygen is strictly regulated in the Tennessee Valley, United States, hydropower operators continuously monitor DO in large dam outflows. DO levels are managed by hydropower plant personnel specializing in water quality, aeration and reservoir operations (Higgins and Brock, 1999). However dams do not always function as designed, especially older constructions in regions with less regulation and oversight and in such cases retrofits or adjusted management strategies may be effective. For example, Kunz et al. (2013) suggest that hypoxic releases from Zambia's Itezhi Tezhi Dam (built in the 1970s) could be mitigated by releasing a mixture of hypolimnetic and epilimentic waters. This proposed action could help protect the valuable fisheries of the downstream Kafue Flats floodplain.

4.3 Thermal buffering

The problem of coldwater pollution, much like hypoxia, is driven by reservoir stratification and thus can be addressed by similar management strategies (Olden and Naiman, 2010). Most commonly multilevel intakes are designed, so that outflows be derived from an appropriate mixture of epi- and hypolimnetic waters to meet a desirable downstream temperature threshold (Price & Meyer, 1992). A remaining challenge is a lack of understanding what the thermal requirements are for a given river system. Rivers-Moore, Dallas & Morris (2013) propose a method for generating temperature thresholds for South African rivers based on time series data from dozens of monitoring stations. Unfortunately, basic monitoring data for many regions of the tropics is sparse and quite fragmentary, which further complicates the establishment of ecological thermal requirements.

4.4 Sediment manipulation

Sediment trapping by dams is not only a water quality problem, as we have discussed, but also a challenge for dam management because it causes a loss of reservoir capacity over time. Thus, in order to maintain generation capacity, many managers of hydropower dams implement sediment strategies, which include the flushing of sediments through spillways or sediment bypass systems. A recent review of sediment management practices at hydropower reservoirs provides a summary of techniques in use and evaluates their advantages and limitations, including operations and cost considerations as well as ecological impacts (Hauer et al., 2018). Sediment management can be implemented at the catchment scale, within the reservoir itself or at the dam wall. Sediment bypass systems are regarded as the most comprehensive solution, but may be expensive or infeasible because of reservoir dimensions, or cause more ecological harm than they alleviate (Graf et al., 2016; Sutherland et al., 2002).

Typically, sediment flushing is practiced in an episodic manner, creating a regime of sediment famine punctuated by intense gluts that are not so much a feast, but rather bury downstream ecosystems alive (Kondolf et al., 2014b). Environmentally-optimized sediment flushes show potential for minimizing risks where these are feasible, but are rare in practice. A limitation is that not all dams are designed to allow for sediment flushes, or reservoir characteristics imposed by local geomorphology render them impractical. Furthermore, no amount of flushing is able to transport coarser bedload material (i.e. gravel or larger) downstream. To compensate for lost bedload and sediments some managers have made the expensive effort of depositing loose gravel piles onto river margins so that they can gradually be incorporated into the downstream sediment pool as sediment-starved waterinevitably cuts into banks (Kondolf et al., 2014b).

An alternative to sediment management at the site of the dam is the restoration of sediment-starved floodplain or delta wetlands, but this process is likely to be prohibitively expensive in most if not all cases. Restoration of drowning Mississippi River Deltas in Louisiana, United States are estimated to cost USD 0.5 to 1.5 billion per year for 50 years (Giosan et al., 2014).

5. Further research needs

5.1 More data from low latitudes

It is telling that, in this review focused on low latitudes, we had to frequently cite case studies from the temperate zone. For example, we were able to locate one study describing ecological impacts stemming from dam-driven oligotrophication at low latitudes (Granzotti et al., 2018). The simple fact is that most of the tropics and subtropics lie far from the most active research centers and there has been a corresponding gap in limnological investigations. Europe and the United States have 1.5 to 4 measurement stations for water quality per 10,000 km^2 of river basin on average. Monitoring density is 100 times smaller in Africa (UNEP, 2016). Our review found that of the 54 most voluminous low latitude reservoirs, 22 (41%) have yet to be the subject of basic limnological study to classify their mixing behavior. Further efforts to monitor river water quality and study aquatic ecology in regulated low latitude catchments are needed to elucidate the blind spots that this review has identified.

5.2 Studies of small reservoirs

Compared with larger dams, the ecological impact of small hydropower dam systems have been poorly documented. Although small dams are likely to have smaller local impacts than large dams, the scaling of impacts is not necessarily proportional. That is, social and environmental impacts related to power generation may be greater for small dams than large reservoirs (Fencl et al., 2015). Generalizations about small hydroelectric systems are difficult because they come in so many different forms and designs. For example, non-diversion run-of-river systems will trap far less sediment than large dams, and those that do not create a deep reservoir, are not subject to stratification-related effects. Thus, it is tempting to conclude that small-scale hydro will have minimal water quality impacts, but without a systematic assessment it is impossible to make a fair comparison with large scale hydropower (Premalatha et al., 2014). Our analysis is biased towards large systems for the practical reason that larger systems are much more likely to be described in databases and studied by limnologists. Future studies on the environmental impacts of small hydropower systems would be valuable.

5.3 Better predictions of reservoir stratification behavior

Our predictions of reservoir stratification behavior based upon morphometric and hydrologic data, while helpful for understanding broad patterns of behavior, are not terribly useful for understanding water quality impacts of a specific planned dam. It would be much more useful to be able to reliably predict the depth of the thermocline, which could be compared with the depth of water intakes to assess the likelihood of discharging hypolimnetic water downstream. Existing modelling approaches to predicting mixing behavior fall into two categories: mathematically complex deterministic or process-based models and simpler statistical or semi-empirical models. Deterministic models holistically simulate many aspects of lake functioning, including the capability to predict changes in water quality driven by biogeochemical processes. Researchers have used such tools to quantify impacts of reservoirs on downstream ecosystems (Kunz et al., 2013; Weber et al., 2017), but they require a large amount of in situ observational data, which is often lacking for low-latitude reservoirs. This data-dependence also makes them unsuitable for simulating hypothetical reservoirs that are in a planning stage and thus they cannot inform dam environmental impact statements. A promising semi-empirical approach was recently published, proposing a 'generalized scaling' for predicting mixing depth based on lake length, water transparency and Monin-Obukhov length, which is a function of radiation and wind (Kirillin and Shatwell, 2016). This model was tuned for and validated against a data set consisting of mostly temperate zone lakes, so it is unclear how well it can be applied to low latitude systems. If this or another semi-empirical model can be refined to make predictions about the stratification behavior of hypothetical reservoirs being planned, it could provide valuable information about potential risks of water quality impacts on ecosystems of future dams.

6. Conclusions

We have found that damming threatens the water quality of river systems throughout the world's lower latitudes, a fact that is not always recognized in broader critiques of large dam projects. Water quality impacts may propagate for hundreds of kilometers downstream of dams and therefore may be a cryptic source of environmental degradation, destroying ecosystem services provided to riparian communities. Unfortunately, a lack of pre-dam data on low latitude river chemistry and ecology makes it a challenge to objectively quantify such impacts. Building the capacity of developing countries at low latitudes to monitor water quality of their river systems should be a priority.

Seasonal stratification of low latitude reservoirs is ubiquitous and is expected to occur in essentially any large tropical reservoir. This highlights the risk for low latitude reservoirs to discharge cooler and anoxic hypolimnetic waters to downstream rivers depending on the depth of the thermocline relative to turbine intakes. Of course, in the absence of a randomized sampling study it is difficult to assess whether the anecdotes we have identified are outliers, or part of a more general widespread pattern. Further research could investigate how common these problems are and assess the geographic or design factors that contribute toward their occurrence.

It is difficult to assess which of the water quality impacts are most damaging for two reasons. First, dams impose many impacts simultaneously and it is often difficult to disentangle which imposed water quality change is driving an ecological response, or whether multiple stressors are acting synergistically. Second, to compare the relative importance of impacts requires a calculation of value which, as we have learned from the field of ecological economics (Costanza et al., 1997), will inevitably be controversial. It does appear that water quality effects, which can render river reaches uninhabitable because of anoxia and contribute to losses of floodplain and delta wetlands through sediment trapping, exert a greater environmental impact than dam disruption to connectivity, which only directly impacts migratory species.

The mitigation of water quality impacts imposed by dams has been successful in places, but its implementation is dependent on environmental regulation and associated funding mechanisms, both of which are often limited in low latitude settings. Environmental impact assessments and follow-up monitoring should be required for all large dams. The feasibility of management actions depends upon the dam design and local geomorphology. Thus, solutions are typically custom-tailored to the context of a specific dam. We expect that, as the dam boom progresses, simultaneous competing water uses will exacerbate the degradation of water quality in low latitude river systems. Further limnological studies of data-poor regions combined with the development and validations of water quality models will greatly increase our capacity to identify and mitigate this looming water resource challenge.

Data availability

All data used to produce Figures 1, 3 and 4 are available in the ETH Zurich Research Collection (doi: 10.3929/ethz-b-000310656). The data on reservoir size and morphometry are available in the World Register of Dams database maintained by the International Commission on Large Dams, which can be accessed (for a fee) at: https://www.icold-cigb.org/. The data on discharge is available in the Global Runoff Data Centre, 56068 Koblenz, Germany accessible at: https://www.bafg.de/GRDC/.

Supplement link

Author contributions

RSW, BW and EC developed the paper concept. RSW and EC extracted the data for analysis. BW provided mentoring and oversight. RSW produced the figures. RSW wrote the original draft. RSW, BW and EC provided critical review and revisions.

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