SEALING LEAKS IN THE PLUMBING:
GASEOUS CARBON EMISSIONS FROM DRY INLAND WATERS
ON GLOBAL AND LOCAL SCALES

by

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Keller, **P. S.**, Marcé, R., Obrador, B. and Koschorreck, M. (2021). 'Global Carbon Budget of Reservoirs Is Overturned by the Quantification of Drawdown Areas'. *Nature Geoscience*, 14(6), 402–408. DOI: `10.1038/s41561-021-00734-z`.

Keller, **P. S.**, Hentschel, I., Spank, U. and Koschorreck, M. (2021). 'Variability of Greenhouse Gas Emissions from the Drawdown Area of an Oligotrophic Reservoir'. *Aquatic Sciences*. Manuscript submitted for publication.

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Contents

Abstract

Inland waters play an active role in the global carbon cycle. They collect carbon from upstream landmasses and transport it downstream until it finally reaches the ocean. Along this path, manifold processing steps are evident, resulting in (permanent) retention of carbon by sediment burial as well as loss by evasion to the atmosphere. Constraining these carbon fluxes and their anthropogenic perturbation is an urgent need. In this context, attention needs to be set on a widespread feature of inland waters: their partial desiccation. This results in the emergence of formerly inundated sediments to the atmosphere, referred to as dry inland waters. One observed feature of dry inland waters are disproportional high carbon dioxide (CO_2) emissions. However, this observation was so far based on local case studies and knowledge on the global prevalence and fundamental mechanisms of these emissions is lacking. Against this background, this thesis aims to provide a better understanding of the magnitude and mechanisms of carbon emissions from dry inland waters on the global and local scale and to assess the impact of dry inland waters on the global carbon cycle. The specific research questions of this thesis were: (1) How do gaseous carbon emissions from dry inland waters integrate into the global carbon cycle and into global greenhouse gas (GHG) budgets? (2) What effect do seasonal and long term drying have on the carbon cycling of inland waters? The thesis revealed that dry inland waters emit disproportional large amounts of CO_2 on a global scale and that these emissions share common drivers across ecosystems. Quantifying global reservoir drawdown and upscaling carbon fluxes to the global scale suggests that reservoirs emit more carbon than they bury, challenging the current understanding of reservoirs as net carbon sinks. On the local scale, this thesis revealed that both, heterogeneous emission pattern between different habitats and seasonal variability of carbon emissions from the drawdown area, needs to be considered. Further, this thesis showed that re-mobilization of buried carbon upon permanent desiccation of water bodies can explain the observed emission rates, supporting the hypothesis of a positive feedback-loop between climate change and desiccation of inland waters. Overall, the present thesis highlights the importance of adding emissions from dry inland waters as a pathway to the global carbon cycle of inland waters.

Chapter 1

Introduction

1.1 Inland waters and the global carbon cycle

On a global scale, carbon circulates between the reservoirs of the atmosphere, the ocean, and the terrestrial biosphere. Inland waters play a significant role in this global carbon cycle: They collect carbon from upstream landmasses and transport it downstream, first into adjacent systems and eventually into the ocean. Along this path, they process carbon from one species into another and emit gaseous carbon species like carbon dioxide (CO_2) and methane (CH_4) to the atmosphere. But inland waters also remove carbon permanently from this global cycle by storing it in their sediments (Cole et al. 2007; Battin et al. 2009; Regnier et al. 2013; Tranvik et al. 2018). The perception of this complex processing network, and thus of the contribution of inland waters to the global carbon cycle, is the result of intense research for more than one century, and it has been subject to several paradigm shifts (Tranvik et al. 2018).

In the beginning, studies of inland waters, and hence of their carbon cycle, described lakes as confined microcosms, being ‘a little world within itself [...] within which [...] the play of life goes on in full, but on so small a scale as to bring it easily within the mental grasp’ (Forbes 1887). This perception evolved over time. From the realization of a strong effect of imported carbon (Tranvik 1988), via the importance of carbon transformation on regional scales (Cole et al. 1994), to the current view of inland waters as significant players in the global carbon cycle (Raymond et al. 2013; Lauerwald et al. 2015; Mendonça et al. 2017). This evolved perception was accompanied by *plumbing the global carbon cycle*: the replacement of the view of inland waters being *passive pipes*, transporting carbon from land to sea, with a new concept of *active pipes*, where internal processing results in retention of carbon by sediment burial as well as loss by evasion to the atmosphere (Cole et al. 2007; Tranvik et al. 2018) (Figure 1.1).

Although the importance of lateral carbon transport (from land to ocean) and vertical carbon exchange (between water and atmosphere as well as water and sediments) is known for more than two decades now, their anthropogenic disturbance has only recently become apparent (Regnier et al. 2013). Thus, these fluxes are at present neglected in assessments of the budget of anthropogenic CO_2, reported for instance by the Intergovernmental Panel on Climate Change (IPCC) or the Global Carbon Project (IPCC 2019; Friedlingstein et al. 2020), because carbon fluxes conducted by inland waters have so far been considered as a natural loop in the global carbon cycle.

One aspect of this anthropogenic perturbation is the creation of dams and reservoirs. Huge amounts of water are retained on the continents by these artificial water bodies and the extent of impounded area is still on the raise (Zarfl et al. 2015). However, dam construction, flooding and impoundment is not carbon neutral, turning reservoirs into strong emitters of carbon (Barros et al. 2011; Deemer et al. 2016). The exact quantification of this carbon source is therefore important to assess the carbon footprint of reservoir utilization such as irrigation or hydropower production. The latter is of particular interest because hydropower is often considered a carbon neutral renewable source of energy.

1.2 Dry inland waters

While some parts of the Earth‘s surface are constantly covered by water and some parts are never, a considerable extent is covered by water only temporarily. This holds true for various types of inland waters across spatial and temporal scales and it can be both, driven naturally or caused by human activity (Pekel et al. 2016). Examples for such partially drying systems are non-perennial rivers and streams that periodically cease to flow, depending on the seasonal flood regimes (Steward et al. 2012; Messager et al. 2021), small ponds which seasonally shrink (Catalan et al. 2014), human-made reservoirs that alter their waterlevel due to management strategies and expose so-called drawdown areas (Geraldes et al. 2005), natural lakes with seasonal fluctuations e.g. due to snow-melt (Flaim et al. 2019) or long term water loss caused by water diversion (Vardanian 2009).

Water loss and the subsequent desiccation of inland waters emerge formerly inundated sediments to the atmosphere. This is one of the rare mechanisms of land creation and when happening on larger scales, this land can even be used for human needs e.g. for the purpose of agriculture or housing (Chee et al. 2017). Apart from these socio-economical implications, partial or complete desiccation of inland water bodies has various limnological consequences. It shapes, for example, the biogeochemistry of rivers showing flow intermittency (Arce et al. 2019) and affects lake ecology and water quality (Marcé et al. 2010).

One recently identified characteristic of desiccated sediments is, however, high CO_2 emissions. Initial findings showed that emissions from desiccated Mediterranean rivers can significantly exceed the emissions from their water surface and have been found to be in the same range than emissions from Mediterranean soils (von Schiller et al. 2014). High CO_2 emissions were subsequently measured elsewhere in a variety of systems like ponds (Catalan et al. 2014; Obrador et al. 2018), reservoirs (Deshmukh et al. 2018; Almeida et al. 2019; Paranaíba et al. 2020), and streams (Gómez-Gener et al. 2015; Gómez-Gener et al. 2016), confirming these initial findings. However, knowledge about the global prevalence and universal drivers of these CO_2 emissions is lacking. Hence, it remains questionable whether this is a local phenomenon or a relevant process on global scale. Consequently, no robust estimate of global carbon emissions from dry inland waters is currently available due to data scarcity (Marcé et al. 2019).

The assumption that these findings reveal a general property of dry inland waters on a global scale suggests a missing pathway in the current concept of the carbon cycle of inland waters: Gaseous carbon emissions from dry inland waters (Marcé et al. 2019) (Figure 1.1). As a consequence, this pathway needs to be integrated into global carbon inventories. Furthermore, the variable surface area of inland waters has to be considered when upscaling fluxes of carbon, but also of other greenhouse gases (GHGs) like nitrous oxide (N_2O), based on water surface area. Although the relevance of these two points has already been acknowledged, they have not been considered in inland water carbon or GHG budgets and global upscalings so far (Deemer et al. 2016).

1.3 Extent of global surface waters and their desiccation

To produce accurate global estimates of carbon fluxes, a need for improved global inventories of inland waters and the magnitude of their partial desiccation has emerged. However, global mapping of inland waters in general and their partly desiccation in particular is still in the making and an ongoing research process. Classical upscaling approaches multiply area-specific flux rates with total global areas to estimate global emissions. Hence, accurate assessments of flux rates and area estimates are crucial for obtaining reliable results, as the uncertainties associated with both quantities propagate to the final results. So far, only few studies have tried to reduce the uncertainty by correlating global carbon emissions to a proxy

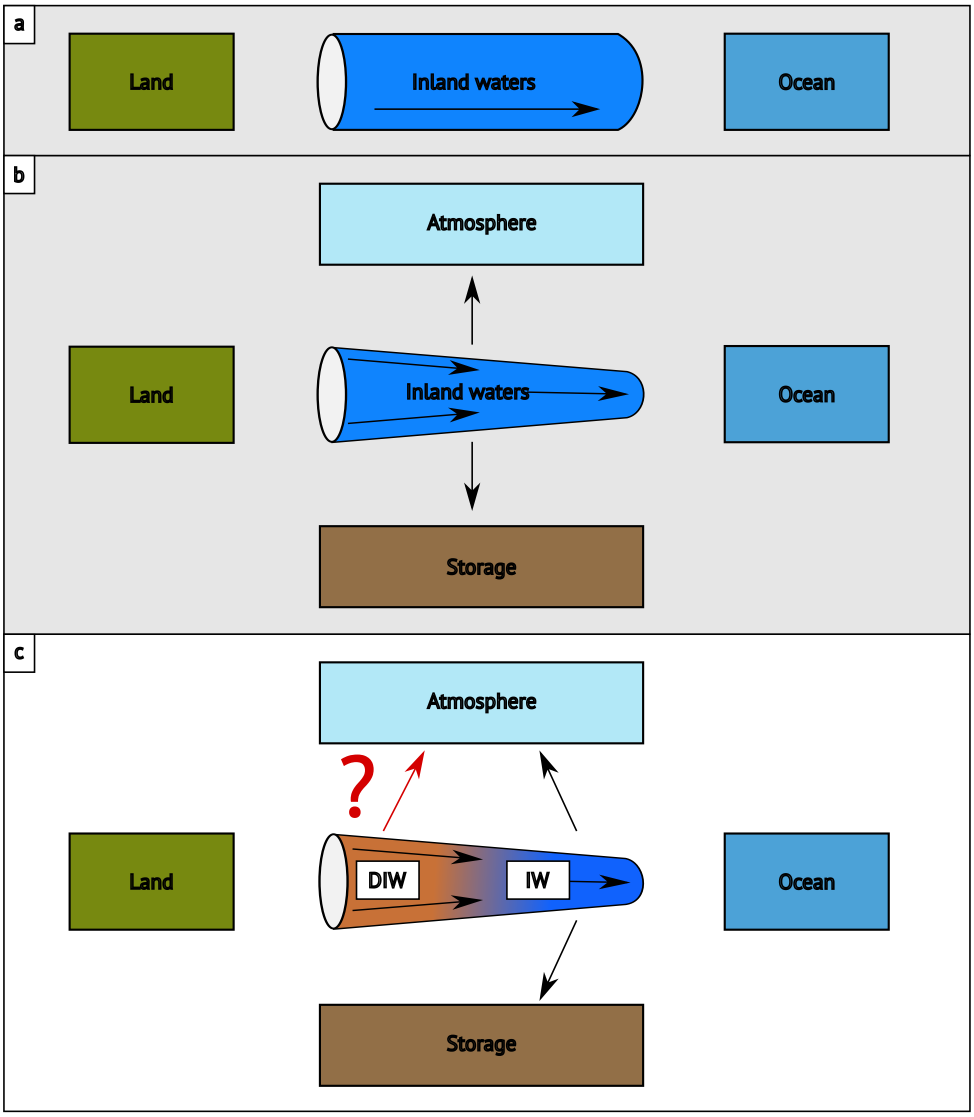

Figure 1.1: Conceptual models contrasting the concepts of *passive pipes* and *active pipes*. a *passive pipe* transporting carbon from land to sea (Cole et al. 2007). **b** *active pipe*, where inland waters retain (by burial in sediments) and emit (to the atmosphere) a substantial fraction of the carbon that enters from watersheds (Cole et al. 2007). **c** *active pipe* model extended by emissions from dry inland waters. This pathway for carbon transport is missing in current models. DIW = dry inland waters, IW = inland waters.

like chlorophyll concentration (DelSontro et al. 2018). However, even with an approach like this, the need for accurate estimates of global surface area of inland waters is inevitable.

However, existing inventories are considered uncertain and incomplete, in particular with respect to small water bodies (Downing et al. 2009; Lehner et al. 2011). Although such inventories are often combined with statistical modelling to account for undetected water bodies (Downing et al. 2006), this approach was also subject to criticism due to a potential overestimation of small water bodies (Seekell et al. 2011). While some databases on the global extent of water bodies are based on manual harvesting of local archives (Lehner et al. 2011), the increasing availability of satellite imagery has allowed a new approach to global mapping of inland waters (Verpoorter et al. 2014). The use of satellite imagery also fostered the analysis of temporal change in the earth's inland water coverage (Pekel et al. 2016).

However, mapping the extent of dry inland waters comprises additional difficulties. The spatial extent of dry inland waters can be modelled e.g. based on bathymetric information and water level data of individual water bodies. But the aggregation of data for enough water bodies to allow for robust global estimations is a daunting challenge. Despite recent progress within the field of remotely sensed mapping of inland waters, the detection and mapping of dry inland waters by means of remote sensing remains challenging. Desiccated sediments are located in a more or less narrow section at the shore of the water bodies which makes them difficult to detect due to the spatial and temporal resolution of satellite images. Seasonal variations in the extent of dry inland waters require constant monitoring of repeated images throughout the year, which is challenging due to changing atmospheric conditions like cloud cover (Pekel et al. 2016; Zhao et al. 2018).

Ultimately, knowledge of both, the global variability of carbon emission rates from dry inland waters as well as an estimate of their global extent, is lacking. In addition, a comprehensive understanding of processes controlling carbon fluxes from dry inland waters on local scales as well as the global magnitude of these carbon emissions is necessary to eventually integrate dry inland waters into the global carbon cycle.

1.4 Research questions, objectives and hypotheses

Carbon dioxide emissions from inland waters constitute a key component of the global carbon cycle, although just starting to be accounted for in global carbon budgets. Constraining these emissions and their anthropogenic perturbation is an urgent need. In this context, attention needs to be set on a global process affecting inland waters: their intermittent and permanent drought. Against this background, the overall goal of this thesis was to provide a better understanding of the impact of desiccation on the contribution of inland waters to global carbon emissions. To achieve this goal, the thesis answered two main research questions.

Research question I: How do gaseous carbon emissions from dry inland waters integrate into the global carbon cycle and into global GHG budgets?

Integrating site-specific carbon emissions from dry inland waters into global budgets requires upscaling of site specific fluxes to the global scale. Usually this is done by multiplying area specific flux rates times the total area of interest. Yet, accurate knowledge on both parts of this equation (i.e. global flux magnitudes and spatial extent of dry inland waters) is missing. Constraining and understanding carbon emissions at the global scale, though, is an urgent need. Consequently, the specific objectives to research question I, and the hypotheses to address these objectives, were:

(1) To confirm the global prevalence of CO_2 emissions from dry inland waters, assess their magnitude and identify drivers and regulating factors

- H1 Elevated CO_2 emissions from dry inland waters compared to corresponding water bodies are a global phenomenon not limited to certain geographic regions
- H2 Elevated CO_2 emissions from dry inland waters compared to corresponding water bodies are not limited to certain types of inland waters

(2) To map the global extent of reservoir drawdown and quantify its contribution to the global carbon balance of reservoirs

- H3 Substantial parts of the global reservoir surface area are not permanently covered by water
- H4 Accounting for drawdown areas affects the carbon budget of reservoirs substantially

Research question II: What effect do seasonal and long term drying have on the carbon cycling of inland waters?

Dry inland waters have been recognized as hotspots of CO_2 emissions. Yet, these emissions were mostly assessed as point measurements of respiration in the sediments during short-term campaigns. It is not well understood how carbon emissions change throughout the year within a single inland water system, and if they can be potentially fuelled solely by degradation of organic matter from permanently desiccated sediments in the long-run. Consequently, the specific objectives to research question II, and the hypotheses to address these objectives, were:

(3) To understand the temporal variability of carbon emissions from the drawdown area of a reservoir and to differentiate between typical habitats

H5 Accounting for both, seasonal variability and habitat characteristics, is required to correctly assess carbon fluxes from the drawdown area and its impact on the reservoirs' carbon budget

H6 Vegetation growing on the drawdown area reduces the impact of the drawdown area to the carbon budget of the reservoir

(4) To assess the re-mobilisation of sequestered carbon from permanently desiccated sediments of a natural lake

H7 CO_2 emissions from the permanently emerged former lake sediments can be plausibly explained be the amount of carbon buried in the sediments while inundated

1.5 Outline of this thesis

This thesis is structured in four parts that each relate to one of the objectives outlined above (Figure 1.2). In Part I, we performed an international sampling campaign to measure CO_2 emissions from a variety of system types world wide and assess their prevalence. Additionally, we identified common control mechanisms of these CO_2 emissions. In Part II, we used a recently developed data product based on satellite observations, to quantify water level drawdown in 6,749 reservoirs worldwide for the period 1985–2015. Furthermore, we integrated the total drawdown extent into the global reservoirs' carbon budget by apportioning published estimates of carbon fluxes to water surface and drawdown area. In Part III, we quantified carbon emissions from the Rappbode reservoir, Germany, and its drawdown area throughout a whole season and differentiated between typical habitats. Furthermore, we modelled the extent of the drawdown area as a function of water level with daily resolution and assessed the contribution of spatial and temporal variability on the total carbon budget. In Part IV, we measured the carbon content and carbon fluxes at Lake Sevan, Armenia, and its permanently desiccated former lake areas. Furthermore, we used remote sensing techniques to quantify the spatial extent of these emerged sediments and characterize different types of land use which have formed on the newly created land, in order to calculate a carbon

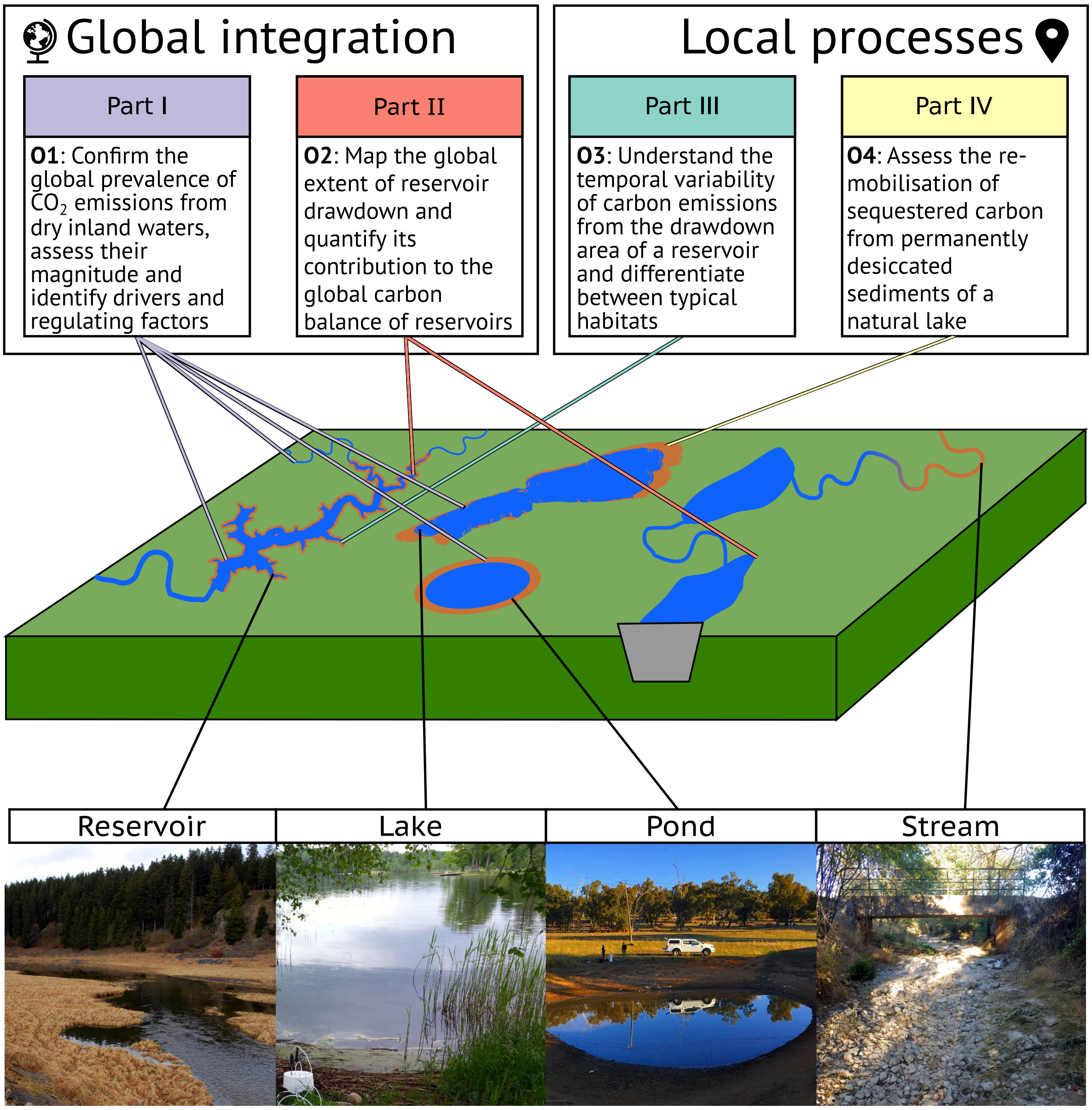

Figure 1.2: Conceptual framework on how the four core research chapters contribute to answer the two research questions of this thesis.

budget for the entire system. Finally, chapter 2 and chapter 3 synthesize the results derived in this dissertation and provide an overview on possible future research directions. Parts I–IV were written as stand-alone manuscripts that were either published in or submitted to international, peer-reviewed journals. The chapters were published or submitted as follows:

Part I Keller, P. S., Catalán, N., von Schiller, D., Grossart, H.-P., Koschorreck, M., Obrador, B., Frassl, M. A., Karakaya, N., Barros, N., Howitt, J. A., Mendoza-Lera, C., Pastor, A., Flaim, G., Aben, R., Riis, T., Arce, M. I., Onandia, G., Paranaíba, J. R., Linkhorst, A., del Campo, R., Amado, A. M., Cauvy-Fraunié, S., Brothers, S., Condon, J., Mendonça, R. F., Reverey, F., Rõõm, E.-I., Datry, T., Roland, F., Laas, A., Obertegger, U., Park, J.-H., Wang, H., Kosten, S., Gómez, R., Feijoó, C., Elosegi, A., Sánchez-Montoya, M. M., Finlayson, C. M., Melita, M., Oliveira Junior, E. S., Muniz, C. C., Gómez-Gener, L., Leigh, C., Zhang, Q. and Marcé, R. (2020). ‘Global CO_2 Emissions from Dry Inland Waters Share Common Drivers across Ecosystems’. *Nature Communications*, 11, 2126. DOI: `10.1038/s41467-020-15929-y` (Appendix A)

Part II Keller, P. S., Marcé, R., Obrador, B. and Koschorreck, M. (2021). ‘Global Carbon Budget of Reservoirs Is Overturned by the Quantification of Drawdown Areas’. *Nature Geoscience*, 14(6), 402–408. DOI: `10.1038/s41561-021-00734-z` (Appendix B)

Part III Keller, P. S., Hentschel, I., Spank, U. and Koschorreck, M. (2021). ‘Variability of Greenhouse Gas Emissions from the Drawdown Area of an Oligotrophic Reservoir’. *Aquatic Sciences*. Manuscript submitted for publication (Appendix C)

Part IV Koschorreck, M., Keller, P. S., Dadi, T. and Wallis, C. I. B. (2021). ‘Mobilisation of Sedimentary Carbon from the Persistent Drawdown Area of Lake Sevan, Armenia’. *Journal of Limnology*. Manuscript submitted for publication (Appendix D)

Chapter 2

Discussion

2.1 Research challenge

Partial desiccation is an inherent property of many inland waters and a considerable part of the global surface area of water bodies is not constantly covered by water (Larned et al. 2010; Pekel et al. 2016; Messager et al. 2021). While a lot of effort is made to refine the global carbon budget of inland waters and its anthropogenic perturbation, partly desiccated areas have been neglected so far from global carbon inventories of inland waters (Regnier et al. 2013; Marcé et al. 2019). Interestingly, this fact has already been acknowledged but the integration of dry inland waters has been either precluded due to missing data or they even have been excluded from the aquatic sphere by definition (Raymond et al. 2013; Deemer et al. 2016). Hence, studying the contribution of dry inland waters is a great opportunity not only to refine the current numbers constituting the global carbon budget but even to add a missing pathway to the current model of the global inland waters carbon cycle. Yet, gaining a better understanding of carbon fluxes from dry inland waters on a global scale is challenging. First, not only flux data but also data on spatial extent of dry inland waters is required for estimating total carbon emissions on local, landscape or even the global scale. Hence, upscaling carbon emissions from measured area-specific flux rates to total budgets is often hampered by missing or insufficient data, a problem that multiplies when working on larger scales. Second, local case studies can be performed to gain insights into individual systems and to derive the required data on the local scale. But the validity of extrapolating these results to larger geographical scales or even to the global scale is limited. On the contrary, when deriving global estimates based on e.g. published information, it remains unclear how well the variability on the local scale is represented by this simplification due to a lack of detail. Third, there is a smooth transition between desiccation of water bodies and flooding of terrestrial surrounding landscape. The definition of the nominal extent of a (desiccated) system and the differentiation of (dry) inland waters from their surrounding terrestrial environment is often blurry. When calculating carbon budgets on the landscape scale, this bears the risk of either double accounting for emissions or neglecting certain areas. An example of a system where the nominal extent of the surface area is relatively easy to define are reservoirs, because their extent is shaped by architectural parameters and the dimension of the dam.

Overall, The number of systems for which both, carbon flux data and information on the spatial extent of desiccation, are available is very limited (Marcé et al. 2019). In this thesis, I assessed the global magnitude of carbon emission from dry inland waters, addressed the contributions of reservoir drawdown on the global carbon budget of reservoirs and analysed the impact of spatio-temporal heterogeneity and long-term desiccation on carbon emissions on the local scale. This was done to better understand the role of dry inland waters as a distinct pathway in the global carbon cycle.

2.2 Cross-cutting insights

By performing a global coordinated distributed sampling campaign (Appendix A) and combining the resulting data with information derived from remote sensing (Appendix B), we created a unique and comprehensive data set on carbon emissions from dry inland waters. This data revealed the global magnitude of CO_2 emissions from various types of dry inland waters. Additionally, by providing information on the spatial extent of global reservoir drawdown, it allowed for a total quantification of carbon emissions from reservoirs in particular. The limited complexity of the global surveys was expanded by performing single-system case studies (Appendix C and Appendix D) to elucidate pressing questions regarding the temporal variability of carbon emissions, differences between typical habitats as well as re-mobilization of sedimentary carbon. The results of the research chapters provided answers to the two research questions of this thesis. Based on these results, five cross-cutting insights emerged that address the overarching goal of this thesis to better understand the global prevalence and mechanisms of carbon emissions from dry inland waters.

First, this thesis corroborates Hypothesis H1 and underpins that emissions from dry inland waters are a blind spot in the global carbon cycle (Marcé et al. 2019). With CO_2 emissions from the desiccated parts of various types of inland waters exceeding those emissions typically reported for inundated water bodies, the emerged sediments contribute disproportionally to the inland waters' carbon budget. Although this has also been reported for streams occasionally (von Schiller et al. 2014; Gómez-Gener et al. 2016), the results in this thesis indicate that streams may be an exception to this finding on a global scale with emissions from running water exceeding those from emerged sediments, and therefore Hypothesis H2 needs to be rejected. This effect may be currently even underestimated because current global estimates of CO_2 emissions to the atmosphere from running water of streams rely primarily on discrete measurements obtained during the day (i.e. ignoring nocturnal emissions), which was found to substantially underestimate the total magnitude of this flux (Gómez-Gener et al. 2021).

Second, while a lack of information on the spatial extent of desiccation hampers upscaling for most inland water types, the results of this thesis shed light on the global extent of reservoir drawdown, corroborating Hypothesis H3. Furthermore the results suggest that reservoirs emit more carbon than they bury, challenging the current understanding that reservoirs are net carbon sinks and corroborating Hypothesis H4. Hence, the results of this thesis shift the bottleneck for global upscaling of reservoirs' carbon emissions to information on flux rates. Conventional upscaling requires global estimates for both, flux rates and surface area. However, by multiplying any process rate with a total surface area in order to upscale a process to the global scale, any uncertainty regarding the global surface area directly affects the resulting global estimates. Some studies try to account for this uncertainty by running different upscaling scenarios that are based on different inventories of e.g. global surface area of reservoirs or inland waters in general (Mendonça et al. 2017; DelSontro et al. 2018). However, this approach was not applicable in this thesis in order to maintain consistency and comparability with the underlying inventory of reservoir surface areas that was used for modelling global reservoir drawdown (Zhao et al. 2018). The results of some area-specific processes (e.g. CO_2 emissions from the water surface) clearly depend on the referenced total surface area and are directly impacted by variability of this area due to (partial) desiccation. Yet, this relationship is more doubtful for other processes and new errors might even be introduced when multiplying area-specific process rates with global estimates of surface area. Total carbon burial in reservoirs for example is dominated by sediment focusing (Blais et al. 1995) and may depend more on carbon input into the system than on fluctuations of the reservoir surface area.

Third, this thesis highlights that budgeting carbon emissions from dry inland waters and quantifying their anthropogenic perturbation requires a solid definition of the system boundaries. When partial desiccation is an inherent feature of some natural ecosystems (e.g. ephemeral streams in the Mediterranean), carbon emissions from their emerged sediments are probably a loop in the natural carbon cycle (Regnier et al. 2013). On the contrary, emissions from dry parts of natural water bodies showing desiccation as the result of human activity or emissions from artificial water bodies (like reservoirs) need to be apportioned to the anthropogenic perturbation of the carbon cycle (Prairie et al. 2018). However, when natural desiccation of water bodies is intensified or prolonged due to climate change, these emissions also become part of the anthropogenic perturbation. Yet, the attribution of extreme weather events (like droughts or cease of water flow) to human made climate change is challenging, and the apportioning of emissions from desiccated areas to natural and human caused budgets even more difficult (Otto 2019; Vautard et al. 2020; Simpson et al. 2021).

Fourth, this thesis reinforces the importance of data with higher temporal and spatial resolution for refining carbon budgets of dry inland waters, corroborating Hypotheses H5. Often measurements with a limited temporal resolution or spatial representation of the systems' conditions are used to upscale e.g. total carbon fluxes (Gómez-Gener et al. 2021). Temporal variability of both, carbon fluxes and drawdown area extent were observed in reservoirs. In the Rappbode reservoir, CO_2 emissions followed seasonal variability of temperature and moisture in the sediments. Emissions of CH_4 were rarely observed by monthly field measurements and its variability was high, even on small local scales. Furthermore, heterogeneous spatial characteristics of the emerged sediments or even the surrounding landscape (Almeida et al. 2019) can shape the magnitude of carbon emissions. Hence, especially the interaction of these variabilities, e.g. a synchronous or anti-cyclical change of flux magnitude and extent of desiccation throughout the year, needs to be considered. All in all, seasonal co-variance of carbon fluxes and the extent of desiccated area might amplify or mitigate total carbon emissions depending on their interaction and concurrence and comprehensive measurements of carbon emissions from the drawdown area are necessary to fully account for their spatial and temporal variability.

Fifth, the results of this thesis underpin that carbon originating from different sources constitute the instantaneous flux rates and characterizing its origin is important for the evaluation of carbon emissions (Regnier et al. 2013; Prairie et al. 2018). For instance, remobilization of sedimentary carbon in permanently desiccated parts of Lake Sevan was found to be sufficient to explain observed carbon flux rates from sites showing no vegetation, corroborating Hypotheses H7. In this case, carbon fluxes add to the carbon emissions caused by anthropogenic perturbation of the inland waters carbon cycle. On the contrary, emissions from the drawdown area of the Rappbode reservoir were not only driven by the degradation of sedimentary carbon but also affected by growing vegetation, corroborating Hypotheses H6. While vegetation may counteract carbon emissions fuelled by sequestered carbon due to photosynthesis, they also increase respiration in the sediments and, hence, carbon release. The fate of plant biomass and the carbon stored in it upon reflooding, either being buried in the sediments or subject to re-mineralization, determines its impact on overall carbon budgets of the system. When re-mineralized, plant biomass may act solely as a temporary buffer for carbon but when buried in the sediments, carbon may be removed from the atmosphere and hence from the global carbon cycle.

2.3 Implications for climate change

While carbon emissions from desiccated sediments to the atmosphere constitute a disproportional contribution of dry inland waters to the global inland waters carbon cycle, the implications on overall global carbon budgets and climate change are complex. For the global carbon balance and, hence, global warming it is of minor important where carbon is released from the global aquatic sphere to the atmosphere. Nevertheless, not only the total amount of released carbon but also the climate forcing of the respective GHGs as well as feedback-loops between global change and magnitude of desiccation of inland waters need to be considered. More specifically, three implications for the feedback between dry inland waters and climate change can be drawn from the results of this thesis.

First, partial desiccation of inland waters may have an impact on global change when desiccation causes more potent GHGs like CH_4 to be emitted to the atmosphere instead of CO_2. While peaks of CH_4 emissions were shown to occur during transition of wet to dry conditions (Paranaíba et al. 2020) and were also occasionally observed at the drawdown area of the Rappbode reservoir as part of this thesis, CH_4 was in total of minor importance for the total carbon balance of the Rappbode reservoir. The results of this thesis indicate that, in terms of climate forcing, the increased CO_2 emissions from the drawdown area of reservoirs might on a global scale even be compensated by reduced CH_4 emissions taking into account the reduced water surface. However, lowering the water table in reservoirs was shown to foster CH_4 release from the water body by lowering the hydrostatic pressure and in turn triggering ebullition of CH_4 (Harrison et al. 2017; Beaulieu et al. 2018). A feedback that is yet to be included into calculations. Additionally, CH_4 emissions from emerged sediments might become relevant for the total carbon budget of a system when environmental conditions and the drying regime lead to a greater prevalence of favourable conditions in terms of CH_4 release throughout the season (Kosten et al. 2018; Paranaíba et al. 2020).

Second, analogously to effects observable in other ecosystems (Schuur et al. 2015), a positive feedback-loop between climate change and partial desiccation of inland waters might be established if carbon buried in the sediments, that was permanently removed from the carbon cycle, gets re-mobilized. Re-mobilization of long-term stored carbon that gets released to the atmosphere shifts the mass balance between the global carbon reservoirs and leads to a net accumulation of carbon in the atmosphere while carbon in the terrestrial storage gets depleted. The results of this thesis indicate that evasion of sedimentary carbon from permanently desiccated sediments is suitable to explain the observed CO_2 emission rates from these emerged sediments. A direct link between climate change and e.g. dropping water levels in lakes, caused by altered precipitation or evaporation pattern (Gronewold et al. 2013; Gronewold et al. 2019), could thus constitute a positive feedback-loop and show similar effects like thawing of permafrost (Schuur et al. 2008; Tesi et al. 2016; Turetsky et al. 2020) or drainage of peatlands (Turetsky et al. 2015; Leifeld et al. 2018).

2.4 Follow-up work and outlook

This thesis has gained new knowledge on gaseous carbon emissions from dry inland waters, and importantly did so at both local and global scales. During the course of this thesis, additional important topics for follow-up research emerged.

In Appendix B we calculated global GHG emissions from reservoirs based on the global extent of reservoir drawdown. By combining scenarios (ranging from 0 % to 100 % reservoir drawdown) with area-specific flux rates for both, the water surface and the drawdown area, we found that increasing magnitudes of desiccation leads to a strong increase of carbon emissions. A logical next step would comprise the transfer of this approach to scenarios of climate change and global warming. However, this remains challenging because our results are based on a linear increase of drawdown area while future climate change scenarios are more complex. They suggest heterogeneous global pattern with e.g. some regions experiencing an increase of precipitation while drought and aridity become more intense in others (Collins et al. 2013; Kirtman et al. 2013). Furthermore different types of reservoir utilization may react in a different way to changing environmental conditions. Reservoir utilization is unevenly distributed around the globe (Lehner et al. 2011) and, hence, interactions with climate change are complex due to the spatial heterogeneity of these projections. Refining our upscaling approach to regional scales would allow for coupling with regional predictions of future desiccation of inland waters.

This thesis calculated the global extent of dry reservoir area (Appendix B). Information on the extent of other types of inland water are necessary to additionally include these systems into upscaling approaches. The progress of global data products on the temporal development of water surface area (Pekel et al. 2016) are a promising basis for extending modelling approaches beyond reservoirs to additional types of inland waters. Additionally, novel data products providing lake water levels and lake water extent are under active development by major research institutions like the European Space Agency (ESA) (Crétaux et al. 2020). These kind of datasets based on the lake water level could be used in a similar way as done in Appendix C to quantify both, emerged sediments but also available water content.

Appendix B used the maximum extent of reservoirs as system boundaries defining the outer geographical limits of the drawdown areas. This was based on the idea that the height of the dam and the architecture of the reservoir determine the nominal water surface area. However, it is more difficult to define the system boundaries for other types of inland waters between the water body itself and the surrounding terrestrial landscape. The transition between desiccated inland waters and flooded terrestrial ecosystems is smooth and challenging to grasp. Future work needs to address this definition in order to avoid double accounting of carbon fluxes between atmosphere and (dry) inland waters as well as between atmosphere and (flooded) terrestrial ecosystems. Additionally, partial desiccation is a natural progress in many ecosystem (Messager et al. 2021). While carbon emissions from their dried parts need to be considered in global carbon budgets, they are not caused by human activity. Hence, future work trying to quantify the anthropogenic perturbation of the global carbon cycle needs to differentiate between natural drying cycles and desiccation that is fostered by human activity (Regnier et al. 2013).

This thesis focuses on the carbon budget, where CO_2 is the dominant species driving the increase of total carbon emissions with advancing desiccation. However, the contribution of dry inland waters to climate change is dominated by emissions of more potent GHGs like CH_4 or N_2O. While we assumed zero CH_4 and N_2O emissions in Appendix B, we didn't observe any N_2O and only little CH_4 emissions from the drawdown area of the Rappbode reservoir in Appendix C. However, sporadic observations of very high CH_4 emissions, both in the field and in lab experiments with incubated sediment cores, prove the potential of these wetland-like ecosystem to also emit significant amounts of more potential GHGs. Hence, more empirical data is required to allow for a more profound assessment of the climate forcing of emissions following desiccation of inland waters.

Chapter 3

Conclusion

The present thesis advances the understanding of how dry inland waters contribute to the global inland waters carbon cycle. It revealed that ignoring temporarily or permanently desiccated areas of water bodies leads to an underestimation of global carbon emissions to the atmosphere. CO_2 emissions from dry inland waters, exceeding typical emissions from water surfaces, were a prevalent feature of different types of water bodies that has been globally observed (Hypothesis H1 corroborated). Hence, desiccated areas of water bodies contributed disproportionally to the carbon cycle of inland waters. However, CO_2 emissions from dry parts of rivers were not found to be higher than what is globally reported for running waters (Hypothesis H2 rejected). This thesis revealed that, on average, a substantial part of the global reservoir surface area was not covered by water (Hypothesis H3 corroborated). Neglecting these drawdown areas leads to an overestimation of processes that are upscaled to global scale based solely on water surface area (e.g. carbon emission and burial), while carbon emissions from the emerged sediments are missing (Hypothesis H4 corroborated). On the local scale, the characteristics of carbon emissions from drawdown areas have been complex. Emissions varied throughout the season following e.g. temperature and moisture variations. Furthermore, emissions differed spatially depending on habitat type. Neglecting these variabilities can lead to a biased estimate of carbon emissions from the drawdown area (Hypothesis H5 corroborated). Growing vegetation had the potential to mitigate the impact of CO_2 emissions from drawdown areas (Hypothesis H6 corroborated). However, a permanent removal of carbon from the atmosphere may only be achieved when the accumulated biomass is getting buried and stored in the sediments upon reflooding. The amount of carbon buried in the sediments has been sufficient to explain the observed CO_2 emission rates from permanently desiccated lake sediments (Hypothesis H7 corroborated). This indicates that re-mobilization of buried carbon following the permanent desiccation of inland waters may contribute to a positive feedback loop between climate change and decreasing water levels of inland waters.

Overall, it can be concluded that dry inland waters, a transitional zone between aquatic and terrestrial ecosystems, are a complex interphase in terms of carbon cycling. They actively participate in what is called the *active pipe*—the complex carbon transport and processing network constituted by inland water bodies. Generally, the present thesis highlights the importance of adding emissions from dry inland waters as a pathway to the this *active pipe* model and thus to the global carbon cycle.

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Author contributions

This thesis is based on four research articles provided in Appendix A–D. I was the lead author of three of the articles (Part I, II and III of the thesis). The contributions of all authors are stated in the following using the authors' initials.

Part I Keller, P. S., Catalán, N., von Schiller, D., Grossart, H.-P., Koschorreck, M., Obrador, B., Frassl, M. A., Karakaya, N., Barros, N., Howitt, J. A., Mendoza-Lera, C., Pastor, A., Flaim, G., Aben, R., Riis, T., Arce, M. I., Onandia, G., Paranaíba, J. R., Linkhorst, A., del Campo, R., Amado, A. M., Cauvy-Fraunié, S., Brothers, S., Condon, J., Mendonça, R. F., Reverey, F., Rõõm, E.-I., Datry, T., Roland, F., Laas, A., Obertegger, U., Park, J.-H., Wang, H., Kosten, S., Gómez, R., Feijoó, C., Elosegi, A., Sánchez-Montoya, M. M., Finlayson, C. M., Melita, M., Oliveira Junior, E. S., Muniz, C. C., Gómez-Gener, L., Leigh, C., Zhang, Q. and Marcé, R. (2020). 'Global CO_2 Emissions from Dry Inland Waters Share Common Drivers across Ecosystems'. *Nature Communications*, 11, 2126. DOI: `10.1038/s41467-020-15929-y` (Appendix A)

Conception and design: MK, RM, BO, NC, HG, DvS
Data acquisition: All authors
Data analysis: PK, RM
Interpretation of results: PK, MK, RM, BO, NC, HG, DvS
Writing the manuscript: PK
Revising the manuscript: All authors

Part II Keller, P. S., Marcé, R., Obrador, B. and Koschorreck, M. (2021). 'Global Carbon Budget of Reservoirs Is Overturned by the Quantification of Drawdown Areas'. *Nature Geoscience*, 14(6), 402–408. DOI: `10.1038/s41561-021-00734-z` (Appendix B)

Conception and design: PK, MK
Data acquisition: PK
Data analysis: PK, RM
Interpretation of results: PK, MK, RM, BO
Writing the manuscript: PK, MK
Revising the manuscript: PK, MK, RM, BO

Part III Keller, P. S., Hentschel, I., Spank, U. and Koschorreck, M. (2021). 'Variability of Greenhouse Gas Emissions from the Drawdown Area of an Oligotrophic Reservoir'. *Aquatic Sciences*. Manuscript submitted for publication (Appendix C)

Conception and design: PK, MK
Data acquisition: PK, IH
Data analysis: PK
Interpretation of results: PK, MK
Writing the manuscript: PK

Revising the manuscript: PK, IH, US, MK

Part IV Koschorreck, M., Keller, P. S., Dadi, T. and Wallis, C. I. B. (2021). 'Mobilisation of Sedimentary Carbon from the Persistent Drawdown Area of Lake Sevan, Armenia'. *Journal of Limnology*. Manuscript submitted for publication (Appendix D)

Conception and design: MK
Data acquisition: MK, PK, TD, CW
Data analysis: MK, PK, CW
Interpretation of results: MK, PK, CW
Writing the manuscript: MK
Revising the manuscript: MK, PK, TD, CW

Declaration

I hereby declare that the thesis entitled *Sealing leaks in the plumbing: Gaseous carbon emissions from dry inland waters on global and local scales* is the result of my own work except where otherwise indicated. It has not been submitted for any other degree at another university or scientific institution.

Sherbrooke, 27th June 2021 ....

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Curriculum Vitae

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Education

since 11.2016	**PhD student**, Faculty of Natural and Environmental Sciences, University of Koblenz-Landau, Landau, Germany
10.2010–11.2016	**MSc Landscape Ecology**, Institute of Landscape Ecology, Westfälische-Wilhelmsuniversität Münster, Münster, Germany. Thesis: 'Resilience of the Mer Bleue peatland against nitrogen and drought—a modelling analysis'
10.2007–10.2010	**BSc Landscape Ecology**, Institute of Landscape Ecology, Westfälische-Wilhelmsuniversität Münster, Münster, Germany. Thesis: 'New directions in mapping the common hamster. Is monitoring by remote sensing an alternative?'

Employment

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I spent a lot of time doing intensive fieldwork at the reservoirs Rappbode and Bautzen. This was essentially made possible by Martin. Without your help, I definitely would have failed this project. Thank you for your altruistic support, for helping me to organize the fieldtrips and for compensating my lack of craftsmanship. The overnight trips to Bautzen were the most fun part of the PhD. Additionally, numerous helping hands supported me doing the fieldwork. Thanks to Corinna, Rico, Anke, Jakob, Rebecca, Fanni, Franzi, Alex and the Staumeister from TSB and LTV. I would also like to thank the guys from TU Dresden, Markus, Udo, Heiko and Uwe for planning, managing and operating the floating platform.

It was very fulfilling to spent more than three years at the Magdeburg chapter of the UFZ. Thanks to Katrin and the entire Mibi group for creating such a nice working environment but also for providing help whenever I asked for something. Furthermore, I would like to thank Karsten and the Seefo department for providing an inspiring scientific environment. Thank you very much Karsten, for keeping an eye on me from a distance and stepping up to convince us to withdraw the first version of the drawdown manuscript. This was truly a game changing move. The UFZ offers pretty unique working conditions for doing a PhD and I always enjoyed travelling to Leipzig. I would like to thank Timo and his friends for welcoming me there and showing me around. It meant a lot to me.

When I started the PhD, I was thrown into managing the *dryflux* project which became a fundamental part of this thesis. It took much longer than everyone was hoping for until progress was made and I would like to thank the core team, Rafa, Matthias, Núria, Dani, H.-P. and Biel, as well as the whole consortium for their patience and their trust. I learned a lot. I would especially like to thank Rafa for hosting me in Girona and for rejecting Matthias suggestion to work on science and instead taking us to Arecibo when we met in San Juan.

Doing a PhD is a peculiar kind of job. It can be very fulfilling but it also has its downsides and it definitely wouldn't be possible without distraction. I want to thank Alex, Maria and Julia for making Magdeburg a home, and all my friends for being there for me. I wrote substantial parts of this thesis at home during the COVID-19 pandemic while moving to another continent. Thanks to the neighbours in Magdeburg, pis je remercie Les Voisins à Sherbrooke, for making the 'homeoffice' a nice place—of course while paying attention to the rules of social distancing.

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Appendix A

Global CO_2 emissions from dry inland waters share common drivers across ecosystems

P. S. Keller, N. Catalán, D. von Schiller, H.-P. Grossart, M. Koschorreck, B. Obrador, M. A. Frassl, N. Karakaya, N. Barros, J. A. Howitt, C. Mendoza-Lera, A. Pastor, G. Flaim, R. Aben, T. Riis, M. I. Arce, G. Onandia, J. R. Paranaíba, A. Linkhorst, R. del Campo, A. M. Amado, S. Cauvy-Fraunié, S. Brothers, J. Condon, R. F. Mendonça, F. Reverey, E.-I. Rõõm, T. Datry, F. Roland, A. Laas, U. Obertegger, J.-H. Park, H. Wang, S. Kosten, R. Goméz, C. Feijoó, A. Elosegi, M. M. Sánchez-Montoya, C. M. Finlayson, M. Melita, E. S. Oliveira Junior, C. C. Muniz, L. Gómez-Gener, C. Leigh, Q. Zhang and R. Marcé

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Appendix B

Global carbon budget of reservoirs is overturned by the quantification of drawdown areas

P. S. Keller, R. Marcé, B. Obrador and M. Koschorreck

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Appendix C

Variability of greenhouse gas emissions from the drawdown area of an oligotrophic reservoir

P. S. Keller, I. Hentschel, U. Spank, and M. Koschorreck

Submitted for publication to *Aquatic Sciences* (2021)

Appendix D

Mobilisation of sedimentary carbon from the persistent drawdown area of Lake Sevan, Armenia

M. Koschorreck, P. S. Keller, T. Dadi and C. I. B. Wallis

Submitted for publication to *Journal of Hydrology* (2021)