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Final report

Climate-relevant greenhouse gas emissions of inland waters in Germany and estimation of their mitigation potential by restoration measures

A review

by:
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biota – Institut für ökologische Forschung und Planung GmbH, Bützow

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Abstract: Climate-relevant greenhouse gas emissions of inland waters in Germany and estimation of their mitigation potential by restoration measures

The quantification of greenhouse gas (GHG) emissions is essential to predict future developments of climate change. However, the quantification of GHG emissions in the sector of inland waters remains challenging due to a scarce database and highly uncertain estimations of emission factors provided by the IPCC. This review deals with the role of inland waters in Germany, including natural and heavily modified waters such as lakes, streams, rivers, estuaries and artificial waters such as canals, reservoirs, ponds and ditches, as sources of GHG emissions under natural, but primarily under anthropogenically altered conditions. The three most relevant GHGs were considered, which are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The aims of this review were (1) to conduct a systematic meta-analysis of national and international studies on the carbon (C) cycle and GHG emissions of natural, heavily modified and artificial inland waters (according to the Water Framework Directive, WFD) and (2) to estimate the mitigation potential of GHG emissions through restoration measures. The main focus was on impounded waters in temperate zones.

As a result of the meta-analysis, 252 studies were identified, categorised and analysed. Two main chapters of this review deal with the description of relevant anthropogenic pressures and their impacts on GHG emissions, as well as with potential mitigation measures to reduce GHG emissions from inland waters. Anthropogenic pressures were selected according to the reporting system of the German Working Group on Water Issues of the Federal States and the Federal Government for the Implementation of the WFD and Marine Strategy Framework Directive (MSFD) (LAWA 2022) and include substance loads (organic and inorganic), hydromorphological pressures (dams, barriers, reservoirs, and other hydrological and morphological alterations) and other pressures.

The review of the current literature revealed that anthropogenically impaired inland waters were identified to be hotspots of GHG emissions compared to natural conditions. The most relevant pressures are the input of organic and inorganic substances and hydromorphological changes.

Types of measures to restore inland waters were described according to the list of types of measures for the WFD and MSFD reporting in Germany. Shortly, measures on the reduction of organic and inorganic pollution, improvement of river continuity and restoration, reconnection of rivers to floodplains and natural water retention were included to describe their benefits on the reduction of GHG emissions. Ultimately, current knowledge gaps and research needs were identified and summarised. Results show that the potential of restoration measures to prevent further anthropogenic GHG emissions seems to be very high, so that global and extensive measures could greatly reduce the GHG production and emission of inland waters.

This review mainly highlights the urgent need for a more profound and representative database of GHG emissions from German inland waters. In addition, efforts are needed to record emissions not only from artificial water bodies, but also from natural and heavily modified water bodies, as these have been scientifically proven to make a significant contribution to the production and release of GHGs. A major advantage is the high overlap between water and nature conservation measures. Existing synergies should be taken into account both to improve the general ecological status and to reduce anthropogenically increased GHG emissions from German inland waters.

Kurzbeschreibung: Klimarelevante Treibhausgasemissionen aus deutschen Binnengewässern und Abschätzung des Minderungspotenzials durch Renaturierungsmaßnahmen

Die Quantifizierung von Treibhausgasemissionen (THG-Emissionen) ist für die Vorhersage künftiger Entwicklungen des Klimawandels unerlässlich. Die Quantifizierung der THG-Emissionen im Bereich der Binnengewässer ist jedoch aufgrund der spärlichen Datenbasis und der sehr unsicheren Schätzungen der Emissionsfaktoren des IPCC nach wie vor schwierig. Dieser Bericht befasst sich mit der Rolle der Binnengewässer in Deutschland, unter Berücksichtigung von natürlichen und erheblich veränderten Gewässern wie Seen, Bächen, Flüssen, Ästuaren und künstlichen Gewässern wie Kanälen, Reservoiren, Teichen und Gräben, als Quelle von THG-Emissionen unter natürlichen, aber vor allem unter anthropogen veränderten Bedingungen. Dabei wurden die drei wichtigsten THG Kohlendioxid (CO_2), Methan (CH_4) und Lachgas/Distickstoffmonoxid (N_2O) betrachtet. Ziel dieses Berichts war es, (1) eine systematische Literaturrecherche nationaler und internationaler Studien über den Kohlenstoffkreislauf und die THG-Emissionen natürlicher, erheblich veränderter und künstlicher Binnengewässer (gemäß der Wasserrahmenrichtlinie, WRRL) durchzuführen und (2) das Minderungspotenzial von THG-Emissionen durch Renaturierungsmaßnahmen abzuschätzen. Das Hauptaugenmerk lag dabei auf aufgestauten Gewässern in gemäßigten Zonen.

Als Ergebnis der Literaturrecherche wurden 252 Studien identifiziert, kategorisiert und analysiert. Zwei Hauptkapitel dieses Berichts befassen sich mit der Beschreibung relevanter anthropogener Belastungen und ihrer Auswirkungen auf THG-Emissionen, sowie mit potenziellen Maßnahmen zur Reduzierung von THG-Emissionen aus Binnengewässern. Die anthropogenen Belastungen wurden nach dem Berichtssystem der Bund-Länder-Arbeitsgemeinschaft Wasser zur Umsetzung der WRRL und der Meeresstrategie-Rahmenrichtlinie (MSRL) (LAWA 2022) ausgewählt und umfassen Stoffeinträge (organisch und anorganisch), hydromorphologische Belastungen (Dämme, Barrieren, Stauseen, andere hydrologische und morphologische Veränderungen) und sonstige Belastungen.

Die Auswertung der aktuellen Literatur ergab, dass anthropogen beeinträchtigte Binnengewässer im Vergleich zu natürlichen Gewässern als Hotspots für THG-Emissionen identifiziert wurden. Die wichtigsten Belastungen bzw. Ursachen dabei sind der Eintrag von organischen und anorganischen Stoffen und hydromorphologische Veränderungen.

Die Maßnahmenkategorien zur Renaturierung von Binnengewässern wurden entsprechend der wichtigsten Maßnahmentypen für die nationale Berichterstattung zur WRRL und MSRL beschrieben. Hierbei wurden Maßnahmen zur Verringerung der organischen und anorganischen Verschmutzung, zur Verbesserung der Durchgängigkeit und Renaturierung von Flüssen, zur Wiederanbindung von Flüssen an Überschwemmungsgebiete (Auen), zur Verbesserung des hydrologischen Regimes in den Gewässern und zum natürlichen Wasserrückhalt in den Bericht aufgenommen, um deren Nutzen für die Verringerung der THG-Emissionen zu beschreiben. Schließlich wurden die aktuellen Wissenslücken und der Forschungsbedarf ermittelt und zusammengefasst. Das Potenzial von Renaturierungsmaßnahmen zur Vermeidung weiterer anthropogen verursachter THG-Emissionen wird auf Basis der Literaturrecherche als sehr hoch eingeschätzt, so dass globale und umfassende Maßnahmen die THG-Produktion und -Emissionen von Binnengewässern stark reduzieren könnten.

Dieser Bericht verdeutlicht vor allem den dringenden Bedarf an einer umfassenderen und repräsentativen Datenbasis zu den THG-Emissionen deutscher Binnengewässer, insbesondere der aufgestauten Gewässer. Darüber hinaus ist es notwendig, nicht nur Emissionen aus künstlichen, sondern auch aus natürlichen und erheblich veränderten Gewässern zu erfassen, da diese wissenschaftlich erwiesenermaßen einen hohen Beitrag zur Produktion und Freisetzung von THG leisten. Ein großer Vorteil ist die hohe Überschneidung zwischen Wasser- und

Naturschutzmaßnahmen. Bestehende Synergien sollten sowohl zur Verbesserung des allgemeinen ökologischen Zustands als auch zur Reduzierung der anthropogen erhöhten THG-Emissionen deutscher Binnengewässer berücksichtigt werden.

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List of abbreviations

Abbreviation	Explanation
AWB	Artificial water body (according to WFD)
C	Carbon
C_{org}	(Easily degradable) Organic carbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalents
DOM	Dissolved organic matter
GHG	Greenhouse gas
GIS	Geographical information system
GWP/GWP_{100}	Global warming potential of a substance/gas; the GWP value is based/standardised on the CO_2 equivalent, GWP_{100}: on a 100-year time scale
HMWB	Heavily modified water body (according to WFD)
IPCC	Intergovernmental Panel on Climate Change
KSG	German Federal Climate Protection Act (Bundes-Klimaschutzgesetz)
KTM	Key Types of Measure for WFD and MSFD reporting of the German Working Group on water issues of the Federal States and the Federal Government represented by the Environment Ministers Conference (LAWA 2022)
kWh	Kilowatt hours (measuring unit for energy)
MSFD	EU Marine Strategy Framework Directive
MWh	Megawatt hours (measuring unit for energy)
N	Nitrogen
NWB	Natural water body (according to WFD)
N_2O	Nitrous oxide (laughing gas)
OGewV	German Ordinance of Surface Waters
OM	Organic matter
P	Phosphorus
ppb	Parts per billion
ppm	Parts per million
POM	Particulate organic matter
T	Tonnes
Tg	Teragram (1 Tg = 10^{12} g)
TOC	Total organic carbon

Abbreviation	Explanation
US	United States (US) respectively United States of America (USA)
WFD	European Water Framework Directive

Summary

The significance of German inland waters in the context of the release of greenhouse gases (GHGs) as a driver of global warming has not yet been sufficiently recognised. However, international and national studies suggest that the overall release of GHGs from inland waters is relatively high and thus significant.

According to the European Water Framework Directive (WFD), the term “inland waters” includes natural and heavily modified waters such as lakes, streams, rivers, estuaries and artificial waters such as canals, reservoirs, ponds and ditches. Inland waters are natural sources especially of carbon dioxide (CO_2). For rivers, Harmon (2020) stated that 25– 44 % of terrestrial riverine C is respired and emitted to the atmosphere. However, anthropogenic alterations can not only increase the production of CO_2, but also of other GHGs.

The three most important GHGs are CO_2, methane (CH_4, 27 times more potent than CO_2 in terms of global warming potential in 100 years, IPCC 2021) and nitrous oxide/dinitrogen monoxide (N_2O, 273 times more potent than CO_2 in terms of global warming potential in 100 years, IPCC 2021). With regard to these GHGs, this review addresses the following key issues:

1. Research, analysis and evaluation of national and international literature on the carbon (C) cycle and GHG emissions of natural, heavily modified and artificial inland waters.
2. Estimation of the reduction potential of GHG emissions through restoration measures on inland waters (and their floodplains).

Important questions in this context are:

- Which significant anthropogenic changes (e.g. eutrophication, loss of floodplains due to the development of watercourses) lead to which changes in the C cycle and in GHG emissions?
- What are the differences in the GHG balance of dammed rivers compared to non-dammed rivers?
- How can GHG emissions be quantified? How plausible are the emission factors/default values for CH_4 according to the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) for cold-temperate climate zones (including Germany)?
- Which measures have the greatest impact for natural climate protection?

All of this is particularly important because for the first time, the current National Inventory Report (NIR) 2023 on the German GHG inventory (UBA 2023a) also reports on emissions from water bodies, but only from flowing and standing artificial water bodies. In addition, only CH_4 emissions were calculated by using the standard method of the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) to estimate the national inventory of anthropogenic emissions.

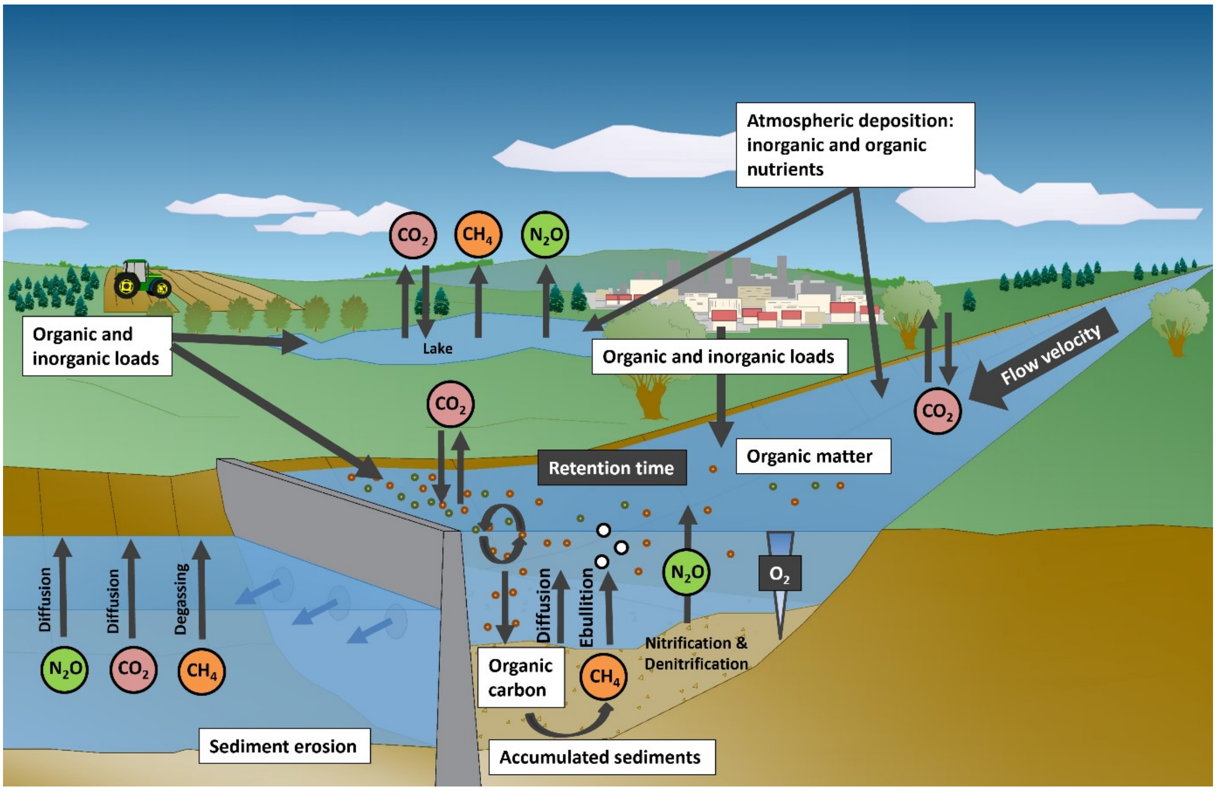
This study first describes the basic principles of natural and anthropogenically enhanced GHG production and emission in inland waters (Chapter 3). Subsequently, the results of the systematic meta-analysis are presented as a central component of this study (Chapter 4).

In order to primarily include state-of-the-art studies that are likely to use up-to-date methods for determining and evaluating GHG emissions, the search focused mainly on studies from 2015 to 2023 (cut-off date: 14 December 2023). The meta-analysis identified 252 relevant studies. The majority of these were carried out in Europe. All studies were labelled according to the following main categories: Continent, landscape, GHG species, pressure type, flow type (standing or flowing), water body type/type of terrestrial area, type of study, study with reference to measures (e.g. restoration), not GHG-related and dealing with specific elements (carbon,

nitrogen, phosphorus). With the help of the meta-analysis, numerous studies with a high information content or with specific results on scientifically substantiated relationships were identified and included for the chapters described below.

A broad chapter is devoted to the effects of anthropogenic pressures on the C cycle and GHG emissions in/from inland waters (Chapter 5; Figure 1, identical with Figure 11).

Figure 1: Scheme of CO_2, CH_4 and N_2O cycling in heavily modified or artificial water bodies using the example of rivers with barriers (identical with Figure 11)



Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

The types of pressures analysed in this review correspond to the reporting system of the German Working Group on Water Issues of the Federal States and the Federal Government for the Implementation of the WFD and Marine Strategy Framework Directive (MSFD) (LAWA 2022). The following types of pressures relevant to GHG emissions are analysed here (with subcategories):

- Substance loads from point and diffuse sources
  - Input of organic substances into the aquatic environment
  - Input of inorganic substances into the aquatic environment and subsequent internal production of organic matter
- Hydromorphological pressures
  - Dams, barriers and locks
  - Reservoirs (due to their great importance as a separate category)
  - Hydrological alterations

  - Morphological alterations

- Other pressures

After dealing with the pressure types, basic options for the quantification of GHG emissions are described (Chapter 6). This chapter deals with the approaches (1) representative in situ measurements, (2) statistical modelling, (3) stochastic modelling, (4) deterministic modelling and (5) the mixed form of stochastic-deterministic modelling. Measurements with the highest possible representativeness (spatial, temporal, load-dependent, water body type, properties of the hydrological catchment area, etc.) are always of fundamental importance.

Subsequently, the focus is on possible measures to reduce GHG emissions from inland waters (Chapter 7). The majority of restoration measures that lead to an improvement in the ecological status of inland waters also have a high potential for reducing GHG emissions, meaning that extensive synergies can be exploited.

The measures discussed in this review were derived directly from the system of key types of measures for the WFD reporting of the German Working Group on Water Issues (LAWA) and the Federal Government (LAWA 2022) but were summarised into groups. For each of the following groups, descriptions of the measures and their physical and biogeochemical impacts were provided, as well as descriptions of the benefits in terms of reducing GHG emissions:

- Reduction of organic pollution and inorganic nutrient pollution of waters
- Improvement of longitudinal river continuity (but only measures aimed at completely or at least significantly reducing the hydrodynamic barrier effect)
- River restoration
- Reconnecting rivers to floodplains (C storage in floodplains, especially in peatlands)
- Improvements in flow regime and/or re-establishment of a functional water balance/hydrological regime
- Natural water retention measures (in the floodplain and catchment area)

Key findings of this review

- The significance of GHG release (CO_2, CH_4, N_2O) from inland waters is currently not sufficiently quantifiable but should be considered comparatively high. This is due to their natural function as a preflood of runoff from land areas, so that large quantities of organic and inorganic substances are concentrated and biologically processed. On a global scale, Lauerwald et al. (2023b) estimate the contribution of inland waters to CH_4 emissions at around 20 %. The proportions of CO_2 and N_2O are not yet known.
- The meta-analysis revealed that the greatly increased GHG release compared to natural conditions is of anthropogenic origin. A stronger anthropogenic pressure therefore stimulates a higher GHG production and release.
- The main cause of increased GHG release is the pollution of waters by organic and inorganic matter inputs (especially P and N). The latter stimulates primary production (algae and macrophytes) and results in a secondary organic pollution. Especially N inputs promote an increased N_2O release. The persistent organic pollution of German inland waters is evident, as demonstrated by the results of the national reporting on the implementation of the WFD (Völker et al. 2022).

- Results of the meta-analysis show that increasing nutrient loads over the next century could lead to an increase of CH_4 emissions from lakes and reservoirs by 30 – 90 % (Beaulieu et al. 2019). With regard to CO_2, CH_4 and N_2O, a global increase of eutrophication could result in an increase of the GHG effect by 5 – 40 % (DelSontro et al. 2018). Concerning the global temperature increase, it is estimated that each temperature increase by 1°C could result in 6 – 20 % more CH_4 originating from ebullition in freshwaters (Aben et al. 2017).

- In natural and heavily modified waters and their floodplains, anthropogenic alterations to water bodies and their floodplains (morphological, hydrological) increase organic pollution, reduce self-cleaning processes, intensify eutrophication and promote an increased accumulation of organic matter in the sediment with a simultaneous lack of oxygen. These conditions favour the release of GHGs. In artificial waters, unnatural hydromorphological/hydraulic conditions promote the release of GHGs, especially CH_4 and N_2O.

- Dams and barriers enable the accumulation of organic material in their backwater and thus, appear to be particularly negative or disadvantageous in terms of GHG emissions.

- A comparison of GHG emissions from natural boreal lakes and reservoirs revealed 10x higher emissions in the reservoirs (Tranvik et al. 2009). GHG emissions from reservoirs are estimated to account for 1 % of global anthropogenic emissions (Li et a. 2022), where the highest contribution originates from CH_4 emissions (Deemer et al. 2016). N_2O emissions from reservoirs, as CO_2-equivalents, were found to potentially account for around 30 % of the CH_4 emissions given as CO_2-equivalents (Descloux et al. 2017).

- Consideration of drawdown areas raises global CO_2 emissions of reservoirs by 53 % (Keller et al. 2021). This results in an increase of CO_2 emissions of inland waters by 6 – 10 % (Marcé et al. 2019; Keller et al. 2020).

- Hydropower replaces non-renewable energy and therefore generally leads to a reduction in GHG emissions from electricity production. However, a case study based on in situ data (Lorke & Burgis 2018) shows that the GHG emissions resulting from the reservoir upstream of the barrage cancels out this climate protection benefit to a large extent (21 % of the emission savings in terms of CO_2-equivalents from the relevant hydropower plant are already lost due to increased CH_4 emissions). The negative impact of barrages on water ecology is also evident from a WFD perspective.

- The analysis of the pressure types for anthropogenically increased GHG emissions shows that there is a considerable overlap with the pressure types in the field of water protection. However, this also opens up the possibility of considering water protection and climate protection measures synergistically. Water protection measures are therefore usually also effective climate protection measures.

- Currently, the real extent of GHG release from German inland waters is significantly underestimated by the national GHG inventory (UBA 2023a) due to the current consideration of only CH_4 emissions from artificial waters.

- The emission factors used in UBA (2023a) for the sole CH_4 release from water bodies on mineral soils and > 20 years old only represent global average values and are subject to large uncertainties (IPCC 2019). Thus, the current estimation of German CH_4 release balances for standing and flowing artificial waters should be considered uncertain.

- The IPCC's (2019) technical recommendation to exclude GHG emissions from natural waters (including also heavily modified water bodies) in the national GHG inventories for international reporting should be critically scrutinised. Currently, only artificial water bodies are considered which account for only 14 % of the area of all German inland waters (UBA 2023a). However, more than 90 % of all natural German water bodies do not achieve the "good ecological status" required by the WFD (Völker et al. 2022), indicating significant anthropogenic pollution and a high potential for currently unconsidered GHG emissions.

- Overall, the release of GHGs from German inland waters is unknown to a large extent. This emphasises the urgency of improving the state of knowledge, as well as the database in order to identify measures of the various legal instruments for water protection and nature conservation and their synergies with climate protection goals. For instance, the Federal Government's current "Action Programme for Nature-based Climate Protection" (BMUV 2023b) focuses on the interface between nature conservation and climate protection, as natural and near-natural ecosystems are not only fundamental to biodiversity, but also play a key role in climate protection.
- To estimate the effectiveness of the types of measures in terms of reducing the release of GHGs from inland waters, a three-class assessment was carried out, differentiated for CO_2, CH_4 and N_2O (Table 1, identical with Table 5).

Table 1: Effectiveness of types of measures to reduce GHG release from inland waters (identical with Table 5)

Three-class evaluation based on the meta-analysis (low, moderate, high)

Measure types	Effectiveness in reducing the release of CO_2	Effectiveness in reducing the release of CH_4	Effectiveness in reducing the release of N_2O
Reduction of organic pollution and inorganic nutrient pollution of water bodies	high	high	high
Improving longitudinal continuity *(only measures aimed at completely or at least significantly reducing the hydrodynamic barrier effect)*	low	high	high
River restoration	moderate - high	moderate - high	moderate
Reconnecting rivers to floodplains (C storage in floodplains, especially in peatlands)	moderate - high	moderate - high	moderate
Improvements in flow regime and/or re-establishment of a functional water balance/hydrological regime	low	moderate - high	low - moderate
Natural water retention measures	moderate - high	moderate - high	moderate - high

Open research questions

This review identified two main research topics:

1. An improvement of the database of GHG emissions from inland waters as an essential part of the analysis, balancing and evaluation of anthropogenic GHG pollution as a driver of global climate change.
2. Consideration and linking of GHG emissions from inland waters with the objectives and measures of water and floodplain protection (water management and nature conservation).

The following differentiated research tasks arise from the national perspective:

- It is necessary to obtain sufficient in situ data on GHG release of inland waters in Germany according to the standards of (1) spatial and temporal representativeness, such as covering complete annual cycles over several years, (2) reflection of the diversity of water body types and the main parameters influencing GHG release (morphometry, hydrology, etc.) and (3) coverage of the different trophic situations.
- There is a great need for action in Germany to develop (1) a suitable, representative and standardised measurement strategy for the release of GHGs (CH_4, N_2O and CO_2) from all types of inland waters and (2) appropriate transfer functions for balancing (in the form of emission factors, see also Lauerwald et al. 2023a, b) based on profound statistical approaches.
- Four transfer pathways of GHGs from water bodies to the atmosphere should be adequately considered: (1) release through upwelling gas bubbles, (2) diffusive gas exchange at the water surface, (3) degassing downstream and (4) emission via emersed macrophytes. Degassing, for instance, was found to be previously highly underestimated and it seems likely that this pathway might account for the highest CH_4 release from reservoirs (Harrison et al. 2021).
- In the short/medium term, it is necessary to obtain reliable (statistical) transfer functions as a basis for well-founded estimates (emission factors for appropriate water body types with regard to key parameters/characteristics and organic and inorganic loads). In the medium/long term, the derivation of deterministic and/or mixed stochastic-deterministic models can help to improve the transfer approaches.
- The current German GHG inventory (UBA 2023a) is lacking data on: a) CO_2 release from all categories of inland waters, b) N_2O release from all categories of inland waters, c) CH_4 release from standing and flowing waters of natural origin (including natural and heavily modified water bodies according to the WFD), d) CH_4 release from standing and flowing artificial waters constructed less than 20 years ago. Thus, there is a considerable need for supplementation.
- The approach used in UBA (2023a) to determine average emission factors depending on the trophic status of water bodies is appropriate (reduction/other scaling of the default values according to IPCC 2019), as is the data basis used for this approach (based on Hoehn et al. 2009). However, it is very likely not representative of the diversity of water types and their individual trophic situation, especially of small waters. Methodological enhancements should be made here, including the necessary data acquisition.
- Natural climate protection ("Natural Climate Protection Action Programme", BMUV 2023a) along inland waters and their floodplains is essentially based on water protection measures. Nature-based water protection solutions (Albert et al. 2022a, b) are predominantly also climate adaptation measures, since e.g. wetland buffer zones are estimated to retain 43 % of total nitrogen and 21 % of total phosphorus loads (Walton et al 2020), resulting in smaller nutrient pools and less GHG production. The corresponding synergies should be demonstrated and evaluated, also in terms of multiple target fulfilment and cost-effective implementation (see e.g. Mehl et al. 2023a). This should also apply to measures within the German federal programme “Blaues Band Deutschland” (BMVI/BMU 2020).
- The great importance of GHG release from water bodies and floodplains should also be considered when assessing ecosystem services in terms of the natural retention of GHGs (Scholz et al. 2012; Mehl et al. 2013, 2020; Podschun et al. 2018a; Mehl 2021; Von Keitz et al. 2022).

Existing methods should continuously be improved as further knowledge of the scientific basis increases (Podschun et al. 2018b; Gerner et al. 2023).

- Implemented measures in accordance with the type of measures under the WFD/LAWA (2022) should be monitored for their effectiveness on the reduction of GHG release. It is also advisable to investigate the interactions of GHG release/binding in water bodies and floodplains (especially peatlands).

Zusammenfassung

Die Bedeutung der deutschen Binnengewässer im Kontext der Freisetzung von Treibhausgasen (THG) als Treiber der globalen Erderwärmung ist bislang nicht bzw. nur ungenügend bekannt. Internationale und nationale Studien lassen darauf schließen, dass die THG-Freisetzung aus Binnengewässern insgesamt relativ hoch und damit bedeutsam ist.

Unter den Begriff der Binnengewässer fallen gemäß Europäischer Wasserrahmenrichtlinie (WRRL) natürliche und (anthropogen) erheblich veränderte Gewässer wie Seen, Bäche, Flüsse, Flussmündungen/Ästuare sowie künstliche Gewässer wie z. B. Kanäle, Stauseen, Teiche und Gräben. Binnengewässer sind natürliche Quellen insbesondere von Kohlendioxid (CO_2). Für Flüsse stellte Harmon (2020) fest, dass 25 bis 44 % des terrestrisch eingetragenen Kohlenstoffs biologisch abgebaut und als CO_2 in die Atmosphäre abgegeben werden. Anthropogene Veränderungen können jedoch nicht nur die Produktion von CO_2, sondern auch von anderen THG erhöhen.

Für die drei wichtigsten THG Kohlendioxid (CO_2), Methan (CH_4, 27-mal stärker als CO_2 im Hinblick auf das globale Erwärmungspotenzial in 100 Jahren, IPCC 2021) und Lachgas/Distickstoffmonoxid (N_2O, 273-mal stärker als CO_2 im Hinblick auf das globale Erwärmungspotenzial in 100 Jahren, IPCC 2021) befasst sich die vorliegende Studie daher mit folgenden zentralen Aufgabenstellungen:

1. Recherche, Analyse und Bewertung der nationalen und internationalen Fachliteratur zum C-Kreislauf und zu den THG-Emissionen natürlicher, erheblich veränderter und künstlicher Binnengewässer.
2. Abschätzung des Minderungspotenzials von THG-Emissionen durch Renaturierungsmaßnahmen an Binnengewässern (und deren Auen).

Wichtige Fragen sind in diesem Zusammenhang:

- Welche signifikanten anthropogenen Veränderungen (z. B. Eutrophierung, Verlust von Überschwemmungsgebieten durch den Ausbau von Fließgewässern) führen zu welchen Veränderungen im C-Kreislauf und bei den THG-Emissionen?
- Welche Unterschiede gibt es in der THG-Bilanz von aufgestauten Flüssen im Vergleich zu freifließenden Flüssen?
- Wie können die THG-Emissionen quantifiziert werden? Wie plausibel sind die Emissionsfaktoren/Standardwerte für CH_4 gemäß dem 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) für kalt-gemäßigte Klimazonen (wozu auch Deutschland zählt)?
- Welche Maßnahmen haben die größte Wirkung für den natürlichen Klimaschutz?

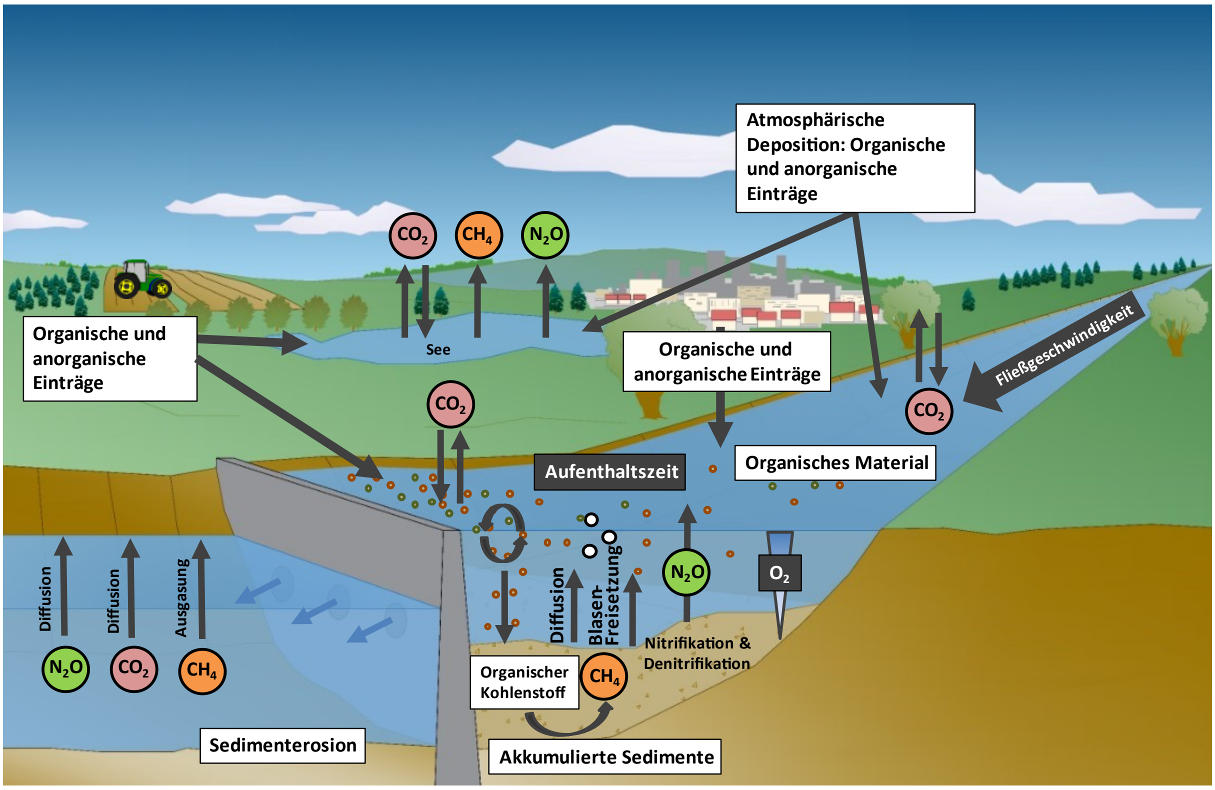
Besondere Bedeutung kommt alldem zu, weil der aktuelle Nationale Inventarbericht (NIR) 2023 zum deutschen THG-Inventar (UBA 2023a) erstmals auch über Emissionen aus Gewässern berichtet, allerdings nur aus fließenden und stehenden künstlichen Gewässern. Zudem wurden nur CH_4-Emissionen in Anlehnung an die Standardmethode zur Abschätzung des nationalen Inventars anthropogener Emissionen des 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) berechnet.

In der vorliegenden Studie werden zunächst die Grundprinzipien der natürlichen und anthropogen verstärkten THG-Entstehung und -Emission in Binnengewässern beschrieben (Kapitel 3). Anschließend werden die Ergebnisse der systematischen Literaturrecherche und -analyse als zentraler Bestandteil dieser Studie dargestellt (Kapitel 4).

Um möglichst aktuelle Methoden und Ergebnisse, die zur Ermittlung und Bewertung von THG-Emissionen verwendet werden, zu analysieren, wurde der Zeitraum für die ausgewählte Literatur auf 2015 bis 2023 (Stichtag: 14.12.2023) begrenzt. Die durchgeführte Literaturrecherche ergab 252 relevante Studien. Davon stammt der Großteil aus Europa. Alle Studien wurden nach den folgenden Kategorien sortiert: Kontinent, Landschaft, Art des Treibhausgases, Belastungstyp, stehendes oder fließendes Gewässer, Gewässerart/-typ bzw. Typ des terrestrischen Areals, Art der Studie, Studie mit Maßnahmenbezug (z. B. Renaturierung), nicht direkt THG-relevant und sich mit anderen, relevanten Elementen befassend (Kohlenstoff, Stickstoff, Phosphor). Mit Hilfe dieser Literaturanalyse konnten zahlreiche Studien mit hohem Informationsgehalt bzw. mit spezifischen Ergebnissen zu wissenschaftlich begründeten Zusammenhängen identifiziert und für die folgenden Kapitel verwendet werden.

Ein umfangreiches Kapitel widmet sich den Auswirkungen der anthropogenen Belastungen der Binnengewässer auf den C-Kreislauf und die THG-Emissionen (Kapitel 5; Abbildung 1, identisch mit Figure 11).

Abbildung 1: Schema zu Prozessen, die CO_2, CH_4 und N_2O in erheblich veränderten oder künstlichen Gewässern beeinflussen, hier am Beispiel von durch Barrieren beeinflussten Flüssen (identisch mit Figure 11)



Quelle: Eigene Darstellung, biota – Institut für ökologische Forschung und Planung GmbH.

Die hier analysierten Arten von Belastungen entsprechen dem Berichtssystem der Bund-Länder-Arbeitsgemeinschaft Wasser für die Umsetzung von WRRL und Meeresstrategie-Rahmenrichtlinie (MSRL) (LAWA 2022). Die für die THG-Emissionen relevanten Belastungsarten sind hiernach (mit Unterkategorien):

- Stoffeinträge aus Punkt- und diffusen Quellen
    - Eintrag von organischen Stoffen in die Gewässer

  - Eintrag von anorganischen Stoffen in die Gewässer und deren gewässerinterne Umsetzung in organische Stoffe

- Hydromorphologische Belastungen
  - Dämme, Wehre und Schleusen
  - Stauseen (wegen ihrer großen Bedeutung als eigene Kategorie)
  - Hydrologische Veränderungen
  - Morphologische Veränderungen
- Sonstige Belastungen

Hieran schließt sich ein Kapitel an, das die grundsätzlichen Möglichkeiten zur Abschätzung/Bilanzierung von THG-Emissionen behandelt (Kapitel 6). Eingegangen wird auf die Ansätze (1) repräsentative In situ-Messungen, (2) statistische Modellierung, (3) stochastische Modellierung, (4) deterministische Modellierung sowie (5) die Mischform stochastisch-deterministischer Modellierung. Von grundlegender Bedeutung sind stets Messungen mit möglichst hoher Repräsentativität (räumlich, zeitlich, belastungsabhängig, Gewässertyp, Eigenschaften des hydrologischen Einzugsgebiets etc.).

Im Anschluss stehen mögliche Maßnahmen zur Verringerung der THG-Emissionen von Binnengewässern im Fokus (Kapitel 7). Die Mehrzahl von Renaturierungsmaßnahmen, die zu einer Verbesserung des ökologischen Zustands von Binnengewässern führen, haben auch ein hohes Potenzial zur Reduzierung von THG-Emissionen. Hier können umfangreiche Synergien genutzt werden.

Die in der Studie behandelten Maßnahmentypen wurden unmittelbar aus der Systematik der Maßnahmentypen für die WRRL-Berichterstattung der Bund-Länder-Arbeitsgemeinschaft Wasser (LAWA 2022) abgeleitet, aber größtenteils zu Gruppen zusammengefasst. Für jede der folgenden Maßnahmengruppen erfolgten Beschreibungen der Maßnahmen und ihrer physikalischen und biogeochemischen Auswirkungen sowie Darstellungen zu den Vorteilen in Bezug auf die Reduzierung von THG-Emissionen:

- Verringerung der organischen Verschmutzung und der anorganischen Nährstoffbelastung der Gewässer
- Verbesserung der Längsdurchgängigkeit (aber nur Maßnahmen, die darauf abzielen, die hydrodynamische Barrierewirkung vollständig oder zumindest deutlich zu verringern)
- Renaturierung von Flüssen
- Wiederanbindung von Flüssen an Auen (C-Speicherung in Auen, insbesondere in Mooren)
- Verbesserung des Abflussregimes und/oder Wiederherstellung eines funktionsfähigen Wasserhaushalts/hydrologischen Regimes
- Natürliche Wasserrückhaltemaßnahmen (in der Flussaue und im Einzugsgebiet)

Zentrale Ergebnisse dieser Studie

- Die Bedeutung der THG-Freisetzung (CO_2, CH_4, N_2O) aus Binnengewässern ist derzeit nicht ausreichend quantifizierbar, sollte aber als vergleichsweise hoch eingeschätzt werden. Dies liegt in ihrer natürlichen Funktion als Vorflut der Abflüsse von Landflächen begründet, sodass große Mengen organischer und anorganischer Stoffe gebündelt und biologisch prozessiert werden. Im globalen Maßstab schätzen Lauerwald et al. (2023b) den Beitrag von Binnengewässern an den CH_4-Emissionen auf rund 20 %. Die Anteile von CO_2 und N_2O sind bisher nicht bekannt.

- Die Literaturanalyse zeigt, dass die stark erhöhte THG-Freisetzung im Vergleich zu natürlichen Referenzbedingungen anthropogenen Ursprungs ist. Je stärker die anthropogene Belastung und Veränderung der Gewässer ist, desto stärker wird die THG-Produktion und -Freisetzung stimuliert.

- Die Ursache erhöhter THG-Freisetzung ist die Verschmutzung der Gewässer durch Einträge organischer und anorganischer Stoffe (vor allem Phosphor - P und Stickstoff - N). Letztere erhöhen die Primärproduktion (Algen und Wasserpflanzen in den Binnengewässern) und führen zu einer sekundären organischen Belastung. Vor allem N-Einträge fördern zudem eine erhöhte N_2O-Freisetzung. Die anhaltende organische Verschmutzung der deutschen Binnengewässer ist offensichtlich, was die Ergebnisse der nationalen Berichterstattung zur Umsetzung der WRRL (Völker et al. 2022) belegen.

- Ergebnisse der Literaturanalyse zeigen, dass die zunehmende Nährstoffbelastung im nächsten Jahrhundert zu einem Anstieg der CH_4-Emissionen aus Seen und Stauseen um 30 - 90 % führen kann (Beaulieu et al. 2019). In Bezug auf CO_2, CH_4 und N_2O ist ein globaler Anstieg der Eutrophierung mit einem Anstieg des Treibhauseffekts um 5 - 40 % nicht unwahrscheinlich (DelSontro et al. 2018). Bezüglich des globalen Temperaturanstiegs wird geschätzt, dass jeder Temperaturanstieg um 1° C zu 6 - 20 % mehr CH_4 infolge der Eutrophierung von Binnengewässern führen könnte (Aben et al. 2017).

- In natürlichen und erheblich veränderten Gewässern und ihren Auen erhöhen anthropogene Veränderungen (morphologisch, hydrologisch) die organische Verschmutzung, verringern die Selbstreinigungsprozesse, verstärken die Eutrophierung und begünstigen eine verstärkte Anreicherung von organischem Material im Sediment bei gleichzeitigem Sauerstoffmangel. Dies forciert eine Freisetzung von THG. In künstlichen Gewässern wirken sich die nicht naturgemäßen hydromorphologischen bzw. hydraulischen Eigenschaften negativ auf die Freisetzung von THG, insbesondere CH_4 und N_2O, aus.

- Dämme und Barrieren verursachen in großem Umfang die Akkumulation von organischem Material in den Rückstaubereichen und sind in Bezug auf die THG-Emissionen daher als besonders negativ oder nachteilig einzustufen.

- Ein Vergleich der THG-Emissionen von natürlichen Seen und Stauseen zeigte 10-fach höhere Emissionen aus Stauseen (Tranvik et al. 2009). THG-Emissionen aus Stauseen machen schätzungsweise 1 % der globalen anthropogenen Emissionen aus (Li et al. 2022), wobei der größte Beitrag von CH_4-Emissionen ausgeht (Deemer et al. 2016). N_2O-Emissionen aus Stauseen können aber, bezogen auf CO_2-Äquivalente, auch etwa 30 % der Klimawirksamkeit der CH_4-Emissionen erreichen (Descloux et al. 2017).

- Die durch Wasserabsenkung beeinträchtigten Randbereiche erhöhen die globalen CO_2-Emissionen von Stauseen um bis zu 53 % (Keller et al. 2021). Diese Erhöhung resultiert in einem

Anstieg der globalen CO_2-Emissionen von Binnengewässern um 6 - 10 % (Marcé et al. 2019; Keller et al. 2020).

- Wasserkraft ersetzt nicht-regenerative Energie und führt daher grundsätzlich zur Verringerung von THG-Emissionen in der Stromproduktion. Ein Fallbeispiel auf der Basis von Messwerten (Lorke & Burgis 2018) zeigt jedoch, dass durch die THG-Emissionen infolge des Stauraumes oberhalb der Staustufe dieser Klimaschutzvorteil in hohem Maße zunichte gemacht wird (21 % der Emissionseinsparung nach CO_2-Äquivalenten durch die relevante Wasserkraftanlage werden hiernach bereits nur durch erhöhte CH_4-Emissionen verloren). Der negative gewässerökologische Einfluss von Staustufen ist zudem aus WRRL-Sicht evident.

- Die Analyse der Belastungsarten für anthropogen erhöhte THG-Emissionen zeigt, dass diese mit den Belastungsursachen im Bereich des Gewässerschutzes praktisch identisch sind. Damit eröffnet sich aber auch die Möglichkeit, Gewässer- und Klimaschutz bezüglich der Maßnahmen synergistisch zu betrachten. Gewässerschutzmaßnahmen sind daher auch regelmäßig wirksame Klimaschutzmaßnahmen.

- Das tatsächliche Ausmaß der THG-Freisetzung aus deutschen Binnengewässern wird durch das nationale Treibhausgasinventar (UBA 2023a) aktuell deutlich unterschätzt, da nur CH_4-Emissionen und diese lediglich aus künstlichen Gewässern berücksichtigt wurden.

- Die bei UBA (2023a) verwendeten Emissionsfaktoren für die alleinige CH_4-Freisetzung aus Gewässern auf mineralischen Böden und einem Alter von > 20 Jahren stellen zudem nur globale Mittelwerte dar und sind mit großen Unsicherheiten behaftet (IPCC 2019). Daher ist die aktuelle Abschätzung der deutschen CH_4-Freisetzungsbilanzen für stehende und fließende künstliche Gewässer zusätzlich als unsicher zu betrachten.

- Auch die technische Empfehlung des IPCC (2019), THG-Emissionen aus natürlichen Gewässern (einschließlich auch erheblich veränderter Gewässer) in den nationalen THG-Inventaren für die internationale Berichterstattung nicht zu berücksichtigen, sollte kritisch hinterfragt werden. Derzeit werden nur künstliche Gewässer berücksichtigt, die nur 14 % aller deutschen Binnengewässer (bezogen auf die Gewässerfläche) umfassen (UBA 2023a). Mehr als 90 % aller natürlichen deutschen Gewässer erreichen jedoch nicht den von der WRRL geforderten "guten ökologischen Zustand" (Völker et al. 2022), was auf erhebliche anthropogene Veränderungen und ein hohes Potenzial für derzeit nicht berücksichtigte THG-Emissionen hinweist.

- Insgesamt ist die Freisetzung von THG aus deutschen Binnengewässern weitgehend unbekannt. Dies unterstreicht die Dringlichkeit, den Kenntnisstand und die Datenbasis zu verbessern, um Maßnahmen der unterschiedlichen rechtlichen Instrumente zu Gewässer- und Naturschutz und deren Synergien zu den Klimaschutzzielen zu identifizieren. So setzt das aktuelle "Aktionsprogramm Natürlicher Klimaschutz" der Bundesregierung (BMUV 2023b) an der Schnittstelle zwischen Natur- und Klimaschutz an, da natürliche und naturnahe Ökosysteme nicht nur für die biologische Vielfalt von grundlegender Bedeutung sind, sondern auch eine Schlüsselrolle für den Klimaschutz spielen.

- Zur Abschätzung der Wirksamkeit der Maßnahmengruppen im Hinblick auf die Verringerung der Freisetzung von THG aus Binnengewässern erfolgte eine 3-stufige Bewertung, differenziert für CO_2, CH_4 und N_2O (Tabelle 1, identisch mit Table 5).

Tabelle 1: Effektivität der Maßnahmentypen zur Reduzierung von THG-Emissionen aus Binnengewässern (identisch mit Table 5)

3-stufige Abschätzung basierend auf der Meta-Analyse (gering, moderat, hoch)

Maßnahmentyp	Effektivität zur Reduktion von CO_2-Emissionen	Effektivität zur Reduktion von CH_4-Emissionen	Effektivität zur Reduktion von N_2O-Emissionen
Verringerung der organischen Verschmutzung und der anorganischen Nährstoffbelastung der Gewässer	hoch	hoch	hoch
Verbesserung der Längsdurchgängigkeit (aber nur Maßnahmen, die darauf abzielen, die hydrodynamische Barrierewirkung vollständig oder zumindest deutlich zu verringern)	gering	hoch	hoch
Renaturierung von Flüssen	moderat - hoch	moderat - hoch	moderat
Wiederanbindung von Flüssen an Auen (C-Speicherung in Auen, insbesondere in Mooren)	moderat - hoch	moderat - hoch	moderat
Verbesserung des Abflussregimes und/oder Wiederherstellung eines funktionsfähigen Wasserhaushalts/hydrologischen Regimes	gering	moderat - hoch	gering - moderat
Natürliche Wasserrückhaltemaßnahmen	moderat - hoch	moderat - hoch	moderat - hoch

Offene Forschungsfragen

Aus der vorliegenden Studie resultieren zwei zentrale Forschungsthemen:

1. Verbesserung der Datenlage zu THG-Emissionen aus Binnengewässern als wesentlicher Bestandteil der Analyse, Bilanzierung und Bewertung der anthropogenen THG-Belastung als Treiber des Klimawandels.
2. Berücksichtigung und Verknüpfung der THG-Emissionen von Binnengewässern mit den Zielen und Maßnahmen des Gewässer- und Auenschutzes (Wasserwirtschaft und Naturschutz).

Folgende differenzierte Forschungsaufgaben erwachsen daraus aus der nationalen Perspektive:

- Es ist notwendig, ausreichende In-situ-Daten zur THG-Freisetzung von Binnengewässern in Deutschland mit folgenden Maßstäben zu erhalten: (1) räumliche und zeitliche Repräsentativität, wie z. B. die Abdeckung vollständiger Jahreszyklen über mehrere Jahre, (2) Berücksichtigung der Vielfalt der Gewässertypen und der wichtigsten Parameter, welche die THG-Freisetzung beeinflussen (Morphometrie, Hydrologie usw.) und (3) Abdeckung der verschiedenen trophischen Situationen.

- In Deutschland besteht großer Handlungsbedarf für die Entwicklung (1) einer geeigneten, repräsentativen und standardisierten Messstrategie für die Freisetzung von THG (CH_4, N_2O und CO_2) aus den Binnengewässern und (2) geeigneter Transferfunktionen (Schätzfunktionen) für die Bilanzierung (in Form von Emissionsfaktoren, vgl. auch Lauerwald et al. 2023a, b) auf der Grundlage fundierter statistischer Ansätze.

- Bei der Übertragung von THG aus Gewässern in die Atmosphäre müssen vier Übertragungswege angemessen berücksichtigt werden: (1) Freisetzung durch aufsteigende Gasblasen, (2) diffusiver Gasaustausch an der Wasseroberfläche, (3) Entgasung stromabwärts und (4) Emission über emerse Makrophyten. Die Entgasung beispielsweise wurde in der Vergangenheit stark unterschätzt und es erscheint wahrscheinlich, dass dieser Weg für die höchste CH_4-Freisetzung aus Stauseen verantwortlich sein könnte (Harrison et al. 2021).

- Kurz- bis mittelfristig sind zuverlässige (statistische) Transferfunktionen (Schätzfunktionen) als Grundlage für fundierte Abschätzungen erforderlich (Emissionsfaktoren für die entsprechenden Gewässertypen in Bezug auf die wichtigsten Parameter/Merkmale und die organischen und anorganischen Frachten). Mittel-/langfristig kann die Ableitung von deterministischen und/oder gemischt stochastisch-deterministischen Modellen zur Verbesserung der Transferansätze beitragen.

- Im deutschen Treibhausgasinventar (UBA 2023a) fehlen derzeit Daten zu: a) CO_2-Freisetzung aus allen Kategorien von Binnengewässern, b) N_2O-Freisetzung aus allen Kategorien von Binnengewässern, c) CH_4-Freisetzung aus stehenden und fließenden Gewässern natürlichen Ursprungs (einschließlich natürlicher und erheblich veränderter Wasserkörper gemäß WRRL), d) CH_4-Freisetzung aus stehenden und fließenden künstlichen Gewässern, die vor weniger als 20 Jahren angelegt wurden. Hier besteht demnach erheblicher Ergänzungsbedarf.

- Der in UBA (2023a) verwendete Ansatz zur Ermittlung durchschnittlicher Emissionsfaktoren in Abhängigkeit vom trophischen Zustand der Gewässer ist demgegenüber angemessen (Reduktion/andere Skalierung der Standardwerte nach IPCC 2019), ebenso die dafür verwendete Datengrundlage (basierend auf Hoehn et al. 2009). Insgesamt ist sie jedoch sehr wahrscheinlich nicht repräsentativ für die Vielfalt der Gewässertypen und deren individuelle trophische Situation, insbesondere bei kleinen Gewässern. Hier sollten methodische Erweiterungen vorgenommen worden, die auch die notwendige Datengewinnung umfassen.

- Natürlicher Klimaschutz ("Aktionsprogramm Natürlicher Klimaschutz", BMUV 2023a) an Binnengewässern und ihren Auen basiert im Wesentlichen auf Maßnahmen des Gewässerschutzes. Naturnahe Gewässerschutzlösungen (Albert et al. 2022a, b) sind überwiegend auch Klimaschutz- bzw. Klimaanpassungsmaßnahmen. So können z. B. Pufferzonen in Feuchtgebieten schätzungsweise 43 % der gesamten Stickstoff- und 21 % der gesamten Phosphorbelastung zurückhalten (Walton et al. 2020), was zu kleineren Nährstoffpools und einer geringeren THG-Produktion führen würde. Die entsprechenden Synergien sollten nachgewiesen und bewertet werden, auch im Hinblick auf die Erfüllung mehrerer Ziele und die kosteneffiziente Umsetzung (siehe z. B. Mehl et al. 2023a). Dies sollte auch für Maßnahmen im Rahmen des Bundesprogramms "Blaues Band Deutschland" (BMVI/BMU 2020) gelten.

- Die große Bedeutung der THG-Freisetzung aus Gewässern und Auen sollte auch bei der Bewertung von Ökosystemleistungen berücksichtigt (Scholz et al. 2012; Mehl et al. 2013, 2020; Podschun et al. 2018a; Mehl 2021; Von Keitz et al. 2022) und bestehende Methoden mit zunehmendem Wissen über die wissenschaftlichen Grundlagen sollten kontinuierlich weiterentwickelt werden (Podschun et al. 2018b; Gerner et al. 2023).

- Umgesetzte Maßnahmen in Übereinstimmung mit den Maßnahmentypen der WRRL/LAWA (2022) sollten auf ihre Wirksamkeit zur Verringerung der THG-Freisetzung hin untersucht werden. Dazu ist es auch ratsam, die Wechselwirkungen von THG-Freisetzung/Bindung in Gewässern und Auen (insbesondere in Mooren) zu untersuchen.

1 Introduction and aims of this review

1.1 Climate change and the role of greenhouse gases (GHGs)

Global and regional climate development is currently strongly characterised by the consequences of the global increase in greenhouse gases (GHGs), commonly referred to as "global climate change". The Intergovernmental Panel on Climate Change (IPCC), as an institution of the United Nations, regularly provides scientific reports on the current status of climatic issues.

The current Synthesis Report of the IPCC's Sixth Assessment Report (AR6; IPCC 2023) summarises the state of knowledge on climate change, its widespread impacts and risks, and on mitigation and adaptation to climate change based on peer-reviewed scientific, technical and socio-economic literature since the publication of the IPCC's Fifth Assessment Report (AR5) in 2014. This Synthesis report (IPCC 2023) shows that the global surface temperature between 2011–2020 was around 1.1°C (1.09 [0.95 to 1.20] °C) above the average of the period between 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C).

The observed warming is clearly induced due to anthropogenic activities and driven by the increasing release and atmospheric accumulation of GHGs since 1750, primarily carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Other gases that contribute to warming are tropospheric ozone (O_3) and halogenated gases in particular. Human-induced climate change is the result of more than a century of net GHG emissions from the use of fossil fuels (coal, oil, natural gas), land use and land-use change, some of which contribute significantly to GHG emissions (e.g. peatland drainage), unsustainable lifestyles, energy-intensive consumption patterns and industrial production processes (see also European Environment Agency 2020, 2023). IPCC (2023) states that atmospheric concentrations of the abovementioned GHGs increased to the following concentrations in 2019: CO_2 reached 410 million parts per million (ppm), CH_4 reached 1,866 parts per billion (ppb) and N_2O reached 332 ppb. Compared to pre-industrial levels, CO_2 increased by 43 %, CH_4 by 150 % and N_2O by 20 % (UBA 2023a). At the international reference station, Mount Mauna Loa (Hawaii), the following values were recently achieved, illustrating the steady increase in GHG concentrations: CO_2 reached 428 million parts per million (ppm) (in April 2024), CH_4 reached 1,932 parts per billion (ppb) and N_2O reached 337 ppb (both in December 2023) (Global Monitoring Laboratory 2024).

In Germany, CO_2 originates mainly from the combustion of fossil fuels and accounted for 89.3 % of total GHG emissions. CH_4 is produced mainly by livestock breeding and landfills, accounting for 6 % of GHG emissions. Lastly, N_2O emerges from agriculture, industry and the combustion of fossil fuels and contributes 3.3 % to the total GHG emissions of Germany (UBA 2023a).

Due to different physical characteristics, GHGs contribute differently to the GHG effect of the Earth, and thus, each gas has its own so-called "Global Warming Potential" (GWP) (IPCC 2021). The standardised reference value is the climate impact of CO_2 (GWP of CO_2 = 1), meaning that the GWPs of other gases are measured relative to CO_2. The GWP value (as CO_2 equivalent [CO_2eq]) therefore indicates the standardised global warming potential of a substance. With the GWP, the time horizon (e.g. 20, 100 or 500 years) is decisive for comparable statements. It is often based on 100 years, given as GWP_{100}. According to this, CH_4 has a GWP_{100} of 27, fossil CH_4 has a GWP_{100} of 30 and N_2O has a GWP_{100} of 273 (IPCC 2021), which emphasises the high significance of these GHGs in terms of climate change. For an overview of general characteristics of the most important GHGs, see Table 2.

Table 2: Overview of general characteristics of the GHGs CO_2, CH_4 and N_2O

Category	CO_2	CH_4	N_2O
Atmospheric lifetime (years)[1]	-	9.1 ± 0.9	116 ± 9
Current atmospheric concentration[2]	410 ppm	1866 ppb	332 ppb
Global warming potential (as CO_2eq, on a 100-year time scale)[1]	1	27 (30 by fossil)	273

[1] IPCC (2021), [2] UBA (2023a)

According to IPCC (2021), an increase in meteorological and thus hydrological extremes was observed in the past and can be assumed for the future as a result of climate change:

- It is virtually certain that heat extremes (including heat waves) have become more frequent and more intense in most regions on land since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe.
- The frequency and intensity of heavy precipitation events have increased over most land areas since the 1950s. In this respect, the observation data is sufficient for a trend analysis and trend estimation (high confidence). Climate change has contributed to an increase in droughts in landscapes and agriculture in some regions, which is due to increased evapotranspiration from land systems (medium confidence).
- With each additional increase in global warming, an increase in meteorological extremes becomes more likely. For example, each additional 0.5 °C of global warming leads to clearly recognisable increases in the intensity and frequency of heat extremes, including heat waves (very likely), and heavy precipitation (high confidence), as well as agricultural and environmental droughts in some regions (high confidence).
- Recognisable changes in the intensity and frequency of meteorological droughts are seen in some regions for each additional 0.5 °C of global warming (medium confidence), with more regions showing increases than decreases.
- Some extreme events that have never been recorded in observational data will occur more frequently with additional global warming, even with global warming of only 1.5 °C. According to the projections, the percentage changes in frequency are higher for rare events (high confidence).

Observed and expected impacts and associated loss of and damage to ecosystems due to climate change include changes in the structure of all types of ecosystems, shifts in species' ranges and changes in seasonality (phenology). In human society, climate change affects water availability and food production, health and well-being, as well as cities, settlements and infrastructure, e.g. by inland flooding and associated damage, and damage to infrastructure and key economic sectors (IPCC 2023).

All of this is also evident in Germany. The mean annual air temperature in Germany rose by 1.7 °C between 1881 and 2022 with statistical certainty (areal average, linear regression). This value is 0.6 °C higher than the global mean temperature rise during the same period. This is confirmed by the updated 2023 monitoring report on the "German Strategy for Adaptation to Climate Change" (UBA 2023b). It also shows that Germany has repeatedly been confronted with exceptional heatwaves, droughts, flash floods and floods in the recent past. The frequency and extent of extreme weather events has increased. These consequences of global warming are reflected even more clearly in the data used for the 2023 monitoring report compared to 2019. Air, water and soil temperatures have continued to rise recently, which has increased the impact on the environment, humans, infrastructure and economy.

1.2 Inland waters as sources of GHGs

In this review, inland waters constitute of natural water bodies such as lakes, rivers, streams, estuaries, as well as artificial water bodies such as canals, reservoirs, ponds and ditches. Thus, both lotic (running) and lentic (standing) types of inland water bodies are included.

Despite being unaffected by anthropogenic pressures, natural water bodies are naturally emitting especially CO_2, but also CH_4 and N_2O. However, these natural background emissions are not yet assessed or considered, neither in national inventories of Germany, nor in the IPCC assessment reports.

In particular, artificial and heavily modified water bodies, as defined by the WFD, represent a significant source of GHG emissions that has not yet been fully assessed in Germany. Generally, inland waters are severely affected by climate change, which means that climate adaptation measures are required.

Especially due to pollution by anthropogenic organic and inorganic matter, highly enhanced biological processes of the carbon (C) and nitrogen (N) cycling of water catchment areas, surface and ground waters play a major role. Inland waters play a very important role in the global carbon cycle (Tranvik et al. 2018, Vachon et al. 2020).

According to Rosentreter et al (2021), half of global methane emissions come from highly variable sources in aquatic ecosystems (including coastal and marine waters). Numerous international studies (e.g. Deemer et al. 2016; Prairie et al. 2018; DelSontro et al. 2018), show that artificial and dammed lakes (reservoirs) are sources of very high GHG emissions, especially CH_4. Current estimates assume that the world's reservoirs release around 800 Tg (0.8 billion t) of CO_2 equivalents (CO_2eq) into the atmosphere every year (Deemer et al. 2016). The global release of GHGs in 2020 amounted to 46.12 billion t of CO_2eq (Statista 2023). According to this, reservoirs alone would account for approximately 2 % of the global GHG release.

In recent studies, an international team of scientists has re-evaluated GHG emissions from rivers, streams, lakes and reservoirs and re-estimated them on a global scale (but conservatively, i.e. no water bodies or wetlands under 10 ha, no ephemeral waters). In these studies by Lauerwald et al. (2023a, b), the following global orders of magnitude were estimated for the annual GHG release from inland waters: 5.5 petagrams (5.5 billion t) of CO_2, 82-135 teragrams (82-135 million t) of CH_4, a third of which comes from North American and Russian lakes, and 248-590 gigagrams (248,000-590,000 t) of N_2O, a quarter of which comes from North American inland waters.

Saunois et al. (2020) determined the global annual CH_4 release at 576 Tg as the mean value for the decade 2008 to 2017. Lauerwald et al. (2023b) suggest that inland waters could account for around 20 % of total global CH_4 emissions. At the same time, the authors consider the contributions of inland waters to the global CO_2 and N_2O budget to be relatively small. The latter statement should initially be viewed critically against the background of fewer (and also non-representative) measurements (even for CH_4), see below. According to Schödel (2024), N_2O in particular should not be underestimated. The uncertainties in the data area are too high and prioritising CO_2 and CH_4 in terms of climate policy does not do justice to the situation. Particularly dammed rivers are potentially major sources of GHGs (Maeck et al. 2013), as Lorke & Burgis (2018), for example, have demonstrated by measurements in dammed sections of the rivers Danube and

Main. Large organic or peatland-dominated floodplains in Germany have also already been analysed with regard to their natural ecosystem service "GHG sequestration or release" as a function of the floodplain or peatland condition, and their restoration potential has been identified (Scholz et al. 2012; Mehl et al. 2013). Besides inland waters, also coastal peatland-dominated floodplains have received attention with regard to their GHG dynamics and the potential risk of nutrient release after rewetting (Breznikar 2023; Pönisch & Breznikar et al. 2023).

In the German National Inventory Report (NIR; UBA 2023a), emissions from (water) reservoirs, dredging and open-cast mining lakes, ponds and artificial freshwater basins of all kinds were subsumed as “artificial lakes”. In the case of flowing artificial bodies of water, mainly canals and drainage ditches for water management and harbour basins on inland waterways were included to estimate their emissions. The CH_4 emissions of both water categories (flowing and standing artificial waters) were calculated using the default method of the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019).

There is currently a lack of basic data and knowledge for determining or at least establishing a well-founded estimate of GHG emissions from German inland waters. The following, already known gaps and uncertainties should be mentioned here in particular:

1. So far, only a small number of artificial water bodies (or types of water bodies) has been assessed on the basis of the IPCC approaches within the framework of the NIR (UBA 2023a), which means that the real GHG emissions of German inland waters are probably massively underestimated. This is because the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) is orientated towards artificial water bodies (according to the WFD's understanding of the term) and therefore excludes natural and heavily modified water bodies.
2. It is also questionable whether the IPCC approaches are sufficiently valid and representative for Central European and German waters in cool temperate climates. In Germany in particular, there is a lack of standardised and sufficiently representative measurement data depending on water body type, size, hydrological and biogeochemical conditions and anthropogenic pressures. Factors such as land use and land cover have a major influence on pollution (Panique-Casso et al. 2024; Schödel 2024).

1.3 Potential mitigation measures

As the main drivers of anthropogenically-increased GHG emissions from inland waters fall within the scope of water protection, there are interdependencies and numerous potential synergies of mitigation measures. Article 4 (1) of the WFD stipulates that, in principle, "good status" must be achieved for all surface water bodies, i.e. good ecological quality and good chemical status. For all water bodies that do not achieve good status, there is a fundamental obligation to take appropriate measures to ensure that this objective will be achieved.

According to the WFD, the following main pollution categories have a very high importance for German surface water bodies, which also have a strong influence in connection with GHG emissions (data according to Völker et al. 2022):

- 98 % of water bodies are polluted by substance inputs from diffuse sources,
- 86 % of water bodies are affected by flow regulation and morphological changes and
- 32 % of water bodies are polluted by substance inputs from point sources.

Together with the implementation of the WFD, the proposal for a Regulation of the European Parliament and of the Council on nature restoration (“Nature Restoration Law”, European

Commission 2022a) is also of great importance. Annex VII of the regulation provides a range of possible restoration measures for water bodies and floodplains, including:

- Restore wetlands, by rewetting drained peatlands, removing peatland drainage structures or de-poldering and terminating peat excavation.
- Improve hydrological conditions by increasing quantity, quality and dynamics of surface waters and groundwater levels for natural and semi-natural ecosystems.
- Re-establish the meandering of rivers and reconnect artificially cut meanders or oxbow lakes.
- Remove longitudinal and lateral barriers (such as dikes and dams), give more space to river dynamics and restore free-flowing river stretches.
- Re-naturalise river beds, lakes and lowland watercourses by e.g. removing artificial bed fixation, optimising substrate composition, improving or developing habitat cover.
- Restore natural sedimentation processes.
- Stop, reduce or remediate pollution from nutrients, pharmaceuticals, hazardous chemicals, urban and industrial wastewater, and other waste including litter and plastics as well as light in all ecosystems.

1.4 Relevant political frameworks

In Germany, both the WFD and the Nature Restoration Law are supported by the National Water Strategy (BMUV 2023a), which aims to ensure the sustainable use of water resources by 2050 and beyond. A key part of this strategy is to preserve the natural water balance and to support the ecological development of water bodies towards good status. In parallel, efforts have also been made for many years to improve the condition of floodplains (Brunotte et al. 2009; Ehlert et al. 2018; Koenzen et al. 2021) as well as of federal waterways by developing the federal programme "Blaues Band Deutschland" (BMVI/BMU 2020), which also aims to restore ecologically functional river landscapes and a corresponding biotope network of national importance.

In addition, the federal government's current "Natural Climate Protection Action Programme" (BMUV 2023b) addresses the interface between nature conservation and climate protection. Natural and near-natural ecosystems are not only fundamental for biodiversity, but also play a key role in climate protection. In particular, the promotion of the restoration of peatlands, water bodies, floodplains and forests should therefore not only create habitats for plants and animals, but also make a substantial contribution to GHG sequestration in the sense of "ecosystem- or nature-based solutions" (Wüstemann et al. 2015, 2017).

This view corresponds to the European and national legal basis for climate protection: the European Climate Law and the Federal Climate Protection Act (KSG). According to preliminary paragraph 23 of the European Climate Law, the restoration of ecosystems can help to conserve, manage and enhance natural sinks, promote biodiversity and at the same time combat climate change. Scientific expertise and the best available up-to-date knowledge are essential, as is evidence-based and transparent information on climate change, to form the basis for the Union's climate action and its efforts to achieve climate neutrality by 2050 (preliminary paragraph 24 of the European Climate Law). An improvement in the state of knowledge on GHG emissions from inland waters and their relevant driving factors is therefore necessary from an environmental law and technical perspective.

In this review, floodplains, which are strongly intertwined with inland waters in terms of hydrology and ecosystem function, are only considered due to their partially very high significance on the production of GHGs (especially peatlands accompanying water bodies). Thus, hydromorphological or hydrological effects due to watercourse development and other changes and also as a result of renaturation measures are shown. Consequently, no explicit consideration is given to methods for quantifying GHG emissions from peatlands or organic floodplains. Reference is made here to the specialist literature, e.g. Couwenberg et al. (2011); Mehl et al. (2012); Emmer & Couwenberg (2017); Tiemeyer et al. (2020); UBA (2023a). Nevertheless, it is important to emphasise that the close geo- and bioecological connection between waters (rivers, lakes) and their floodplains or hydrologically interlinked peatlands should always be sufficiently guaranteed, both in research and through practical measures.

1.5 Aims and questions of this review

The aims of this review consist in particular of the following two aspects:

1. Analysing national and international peer-reviewed literature on the C cycle and GHG emissions from natural, heavily modified and artificial inland surface waters.
2. Estimation of the mitigation potential of GHG emissions as a result of restoration measures in inland waters (and their floodplains).

The resulting questions to be addressed by this review are primarily:

- Which significant anthropogenic pressures (e.g. eutrophication, loss of floodplains due to watercourse development) lead to which changes in the C cycle and in GHG emissions?
- What are the differences in the GHG balance of dammed rivers compared to non-dammed rivers?
- How can GHG emissions be quantified? How plausible are the emission factors/default values for CH_4 according to the 2019 Refinement to the 2006 IPCC Guidelines (IPCC 2019) for cold temperate climates?
- Which measures have the greatest impact for natural climate protection concerning surface water GHG emissions?

2 Methodological approach

2.1 Meta-analysis

Firstly, a list of relevant key words for all addressed questions was elaborated (Table 3). Secondly, a variety of online resources was selected to be used for the key word research, including search engines, webpages of journals, institutes, and agencies of mostly European countries. Several national and international databases were included to cover a wide range of existing knowledge (Table 4). During this process, not only the key words by themselves, but also appropriate combinations were used. Thirdly, the results of the research were checked for their relevance to this review. If a potential relevance was confirmed, the study was downloaded to be included into the database. Fourthly, all downloaded files were then categorised by using the professional reference management program "Citavi 6", version 6.17. Within Citavi, several categories and subcategories were created to assign the references to, in order to ensure a systematic review. The assigned categories and results of the meta-analysis are presented in Chapter 4.

The meta-analysis mainly focused on references from 2015 to December 2023 (cut-off date: 14.12.2023). A few more relevant studies were found or gained access to after this date, which were not included into the meta-analysis but were still considered for general descriptions.

If publications with a more general knowledge were found that suited to the research questions, these references were included as well.

Table 3: Overview of key words used for the meta-analysis (in alphabetical order)

Term	Abbreviation, if applicable
artificial/natural	
budgeting	
carbon dioxide	CO_2
dam (artificial), reservoir, barrage	
damming	
degassing	
eutrophication	
flux	
greenhouse gas emission	GHG emission
hydromorphological measure	
impounded waters	
inland waters	
lake	
lake type	
methane	CH_4
nitrous oxide	N_2O
organic load/pollution	
pond	
renaturation/restoration	
river type	
river/fluvial	
saprobity	
stream/creek	
temperate climate/zone/region	
trophic level/state	
water body	
weir	

Table 4: Overview of national and international resources used for the meta-analysis

Category	Resource			
	Journals	**Search engines**	**Institutes**	**Agencies**
National (for Germany)	Hydrologie & Wasserbewirtschaftung Wasserwirtschaft Korrespondenz Wasserwirtschaft (KW)	-	University Koblenz-Landau Leibniz-Institute for Freshwater Ecology and Inland Fisheries Helmholtz Centre Hereon Geesthacht Helmholtz Centre for Environmental Research Magdeburg	Federal environmental agencies
International	(no specific journals were searched in)	Google Scholar ScienceDirect ResearchGate		European Environment Agency (EEA) National Environment Agencies of European countries

2.2 Answering the research questions

Answers to the central research questions are based in particular on the results of the meta-analysis. The impacts of anthropogenic pressures on the C cycle and GHG emissions are therefore systematically dealt with in Chapter 5, whereby the technical reference to WFD implementation is established.

Chapter 6 focuses on the basic possibilities of quantification options of GHG emissions and their application status in the light of international studies. Chapter 7 deals with potential mitigation measures to reduce GHG emissions of inland waters. The potential can only be estimated qualitatively, as there is a lack of data and a proper methodology has yet to be developed. Chapter 8 concludes with the resulting open research questions.

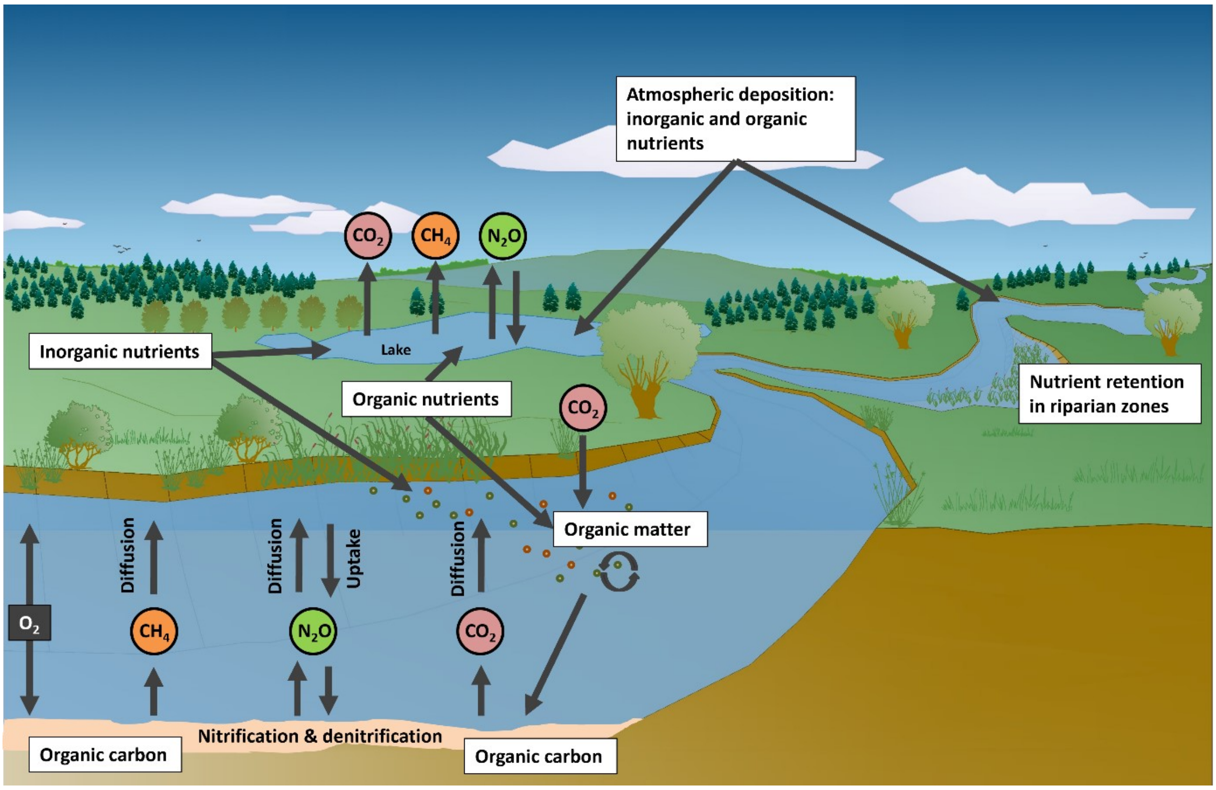
3 Basic principles of the natural GHG production and emission in inland waters

3.1 Carbon dioxide (CO_2)

Carbon dioxide (CO_2) occurs in water predominantly in dissolved form and as carbonic acid in equilibrium with hydrogen carbonates and carbonates. The physical process of absorption of atmospheric CO_2 by bodies of water and also its release (e.g. due to a temporary increase in water temperature and thus lower solubility) are globally occurring, natural processes and are therefore in principle of secondary importance in relation to the global, climate-damaging release of GHGs. Lakes, streams and rivers are primarily natural sources of CO_2 (Figure 2). However, the release of CO_2 as an end product of biological, oxidative degradation processes in water bodies is of crucial importance.

Both the input of easily degradable organic matter into the water body (high significance of wastewater pollution) and the primary production within the water body are decisive for the biogenic formation of CO_2 in waters. The organic load in many trophically dominated waters is therefore strongly dependent on the input of inorganic dissolved nutrients, especially phosphorus (P) and N compounds. Saprobicity is a measure of the organic matter content in the water that can be easily degraded under oxygen consumption (Caspers & Karbe 1967).

Figure 2: Scheme of CO_2, CH_4 and N_2O cycling in natural inland waters



Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

In natural, unpolluted waters, organic substances are a natural part of the food web. In anthropogenically influenced waters, biological self-purification is of great importance, leading to a reduction of saprobicity. Self-purification refers to the overall process in a watercourse that leads to a reduction in organic pollution. The following sub-processes can be distinguished (Uhlmann 1988):

1. dilution and/or equalisation
2. chemical and physicochemical mechanisms (flocculation, precipitation, neutralisation, absorption, etc.)
3. biochemical degradation or incorporation of relevant substances into biomass

The term "biological self-purification" is used for the process under 3., where bacteria and also growing algae have by far the largest share on the turnover of organic matter. This process takes place both on the surface of biologically active substrates ("biofilm"), as well as in the hyporheic zone, i.e. the space below the surface sediments of the river beds, which can sometimes continue beyond the bank and into which the river water infiltrates (Schwoerbel 1964, 1967; Romberg 1976; Schönborn 1992). The most important factors influencing biological self-purification according to Uhlmann (1988) and Schönborn (1992) are:

a) concentration of active biomass in the water

b) geometry of the river bed (especially with regard to the surface area of biologically active substrates)

c) flow velocity and turbulence (decisive for equalisation/dispersion of different in-situ concentrations and gas exchange at the water-air interface)

d) concentration of organic (but also inorganic) nutrients

e) temperature (water and air)

f) light intensity

g) oxygen supply

It is precisely the presence or absence of oxygen in soils and waters that determines the biogeochemical processes in which gases are formed. Biological self-purification in water bodies is an important process that controls greenhouse gas emissions.

The formation of CO_2 (which takes place in the presence of sufficient oxygen) is probably more serious in terms of its overall climate impact than the formation of CH_4 or N_2O, both of which are mainly formed under anaerobic conditions in the sediment. However, the two gases CH_4 or N_2O are specifically much more harmful to the climate (see below), which should be taken into account accordingly when setting priorities or implementing measures.

3.2 Methane (CH_4)

In contrast to CO_2, CH_4 is produced at the opposite end of the C cycle. CH_4 producing microbes are called “methanogens” which are dependent on organic C as substrate. Methanogenesis, as the degradation of organic C which results in the production of CH_4, is performed mostly by archaea, but also by cyanobacteria (Bizic et al. 2020), usually under the absence of oxygen. Sediments, in which the oxygen concentration drops within the first few mm to cm, become anoxic with increasing depth and thus, display hotspots for the production of CH_4. However, the formation of CH_4 was also found to take place in the oxic water column, when methanogens are attached to photoautotrophs who can provide anoxic microniches and appropriate substrates (Grossart et al. 2011).

As for CO_2, the air and water temperature were found to be highly important for methanogenesis to take place (e.g. Sanches et al. 2019; Rocher-Ros et al. 2023), resulting in highest global CH_4

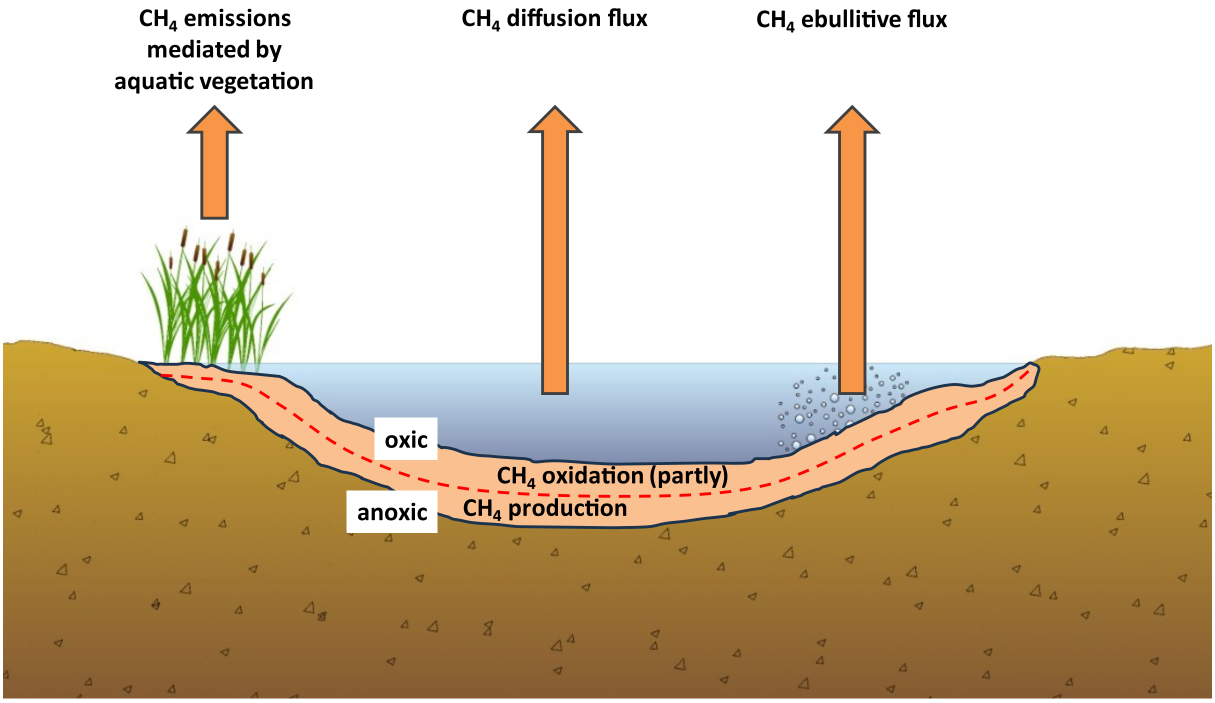
concentrations and emissions near the equator. Other studies, however, did not find a significant correlation between CH_4 and latitude (Deemer et al. 2016; D'Ambrosio & Harrison 2021).

In inland waters, the input of external (allochthonous) organic matter from proportionally large catchment areas, as compared to their surface area, fuels the aquatic production of both CO_2 and CH_4. Besides this input, also stocks of internal (autochthonous) organic matter play a major role e.g. in wetlands and lakes. Estimations of global CH_4 emissions from freshwater systems identified wetlands (contributing up to 55 % to total global CH_4 emissions; Rosentreter et al. 2021) and lakes (Sanches et al. 2019) as the most relevant ecosystems of natural CH_4 production.

Besides the input of organic matter, the influence of (external) nutrients is also of great importance. Nutrients directly affect the production of organic matter by primary production, thus increasing the chlorophyll-a concentration as a proxy of productivity. After the decay of a phytoplankton bloom, its biomass sinks down and is used as substrate for natural remineralisation processes such as methanogenesis. This linkage between chlorophyll-a and CH_4 was confirmed by several studies (e.g. DelSontro et al. 2018; Beaulieu et al. 2019).

The emission of CH_4 is naturally conducted via three main pathways: diffusion, ebullition and plant-mediated transport (Figure 3). A fourth pathway is degassing, which is mainly attributed to dams and reservoirs. Thus, it can be defined as "anthropogenic" (Figure 11) and will be described in Chapter 5.3.2.

Figure 3: Scheme of natural CH_4 emission pathways. Adapted from Sanches et al. (2019)



Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

Diffusion is mostly wind- and turbulence-driven and often identified to be responsible for highest CH_4 emissions (e.g. Robison et al. 2022) for streams. Additionally, diffusive fluxes of CH_4 are often diminished due to the microbial oxidation of CH_4. In streams, for instance, CH_4 oxidation at the sediment surface or within the water column can prevent approximately up to 50 % of CH_4 emissions (Robison et al. 2022).

Ebullition describes the release of accumulated CH_4 bubbles from sediments into the water column. Depending on the sediment type, sediment porosity, sediment deposition rate (Marcon et al. 2023) and the disturbance frequency e.g. due to bioturbation (Booth et al. 2021), ebullition can contribute large amounts to the total CH_4 emissions or even represent the dominant emission pathway, as was shown for wetlands (due to high C stocks) and reservoirs (due to high sediment accumulation; e.g. Maeck et al. 2013; Deemer et al. 2016; Miller et al. 2017).

The last main natural CH_4 emission pathway is plant-mediated transport. It is usually conducted by vascular plants such as macrophytes that are able to transport CH_4 from the rhizosphere through their roots and stems into the air, called the “chimney effect” (e.g. Bhullar et al. 2013).

3.3 Nitrous oxide (N_2O)

N_2O is predominantly produced by microbial processes such as nitrification, denitrification and nitrifier-denitrification (e.g. Stein & Yung 2003; Kool et al. 2011; Quick et al. 2019). The dominant variables influencing these processes are the ambient oxygen and dissolved N (nitrate, nitrite and ammonium) concentrations. Under oxic conditions, nitrification was found to be the dominant process to produce N_2O. By contrast, under hypoxic or anoxic conditions, denitrification is mainly responsible for the formation of N_2O. Boundary layers e.g. in sediments and soils, where oxic and anoxic conditions prevail, are favourable for both processes, as well as for nitrifier-denitrification and thus, display hotspots of N_2O production. In detail, the close spatial coupling of the processes is responsible for this finding, because one depends on the other as will be described below.

Nitrification is a two-step process by which ammonium (NH_4^+) is firstly oxidised to nitrite (NO_2-) by ammonia-oxidising archaea, followed by the oxidation of NO_2- to nitrate (NO_3-) by NO_2- oxidising bacteria. Besides being dependent on oxygen, nitrification is also influenced e.g. by the pH in the soil/sediment. N_2O is produced as a side-product, so that it can be regularly released during the process. Nitrification is not only occurring in the soil/sediment, but can also be found in the water column, predominantly in areas with high turbidity. This turbidity is caused by high amounts of suspended particles that are favoured surfaces for nitrifiers to attach to (e.g. Brion et al. 2000).

Denitrification is the microbial reduction of NO_3^- to dinitrogen gas (N_2), occurring under hypoxic or anoxic conditions. Due to the dependency on its substrate (NO_3^-), denitrification is usually conducted in environments with high NO_3^- concentrations, either originating from external sources or from the close vicinity to nitrification, e.g. at the abovementioned boundary layers. In contrast to nitrification, N_2O is produced as an intermediate and thus, is often further reduced to N_2 by an enzyme called N_2O reductase. To be released, N_2O needs to be the end product of the (incomplete) denitrification process which is favoured e.g. by inhibition of the N_2O reductase. This inhibition can be influenced by several factors such as the quality of organic C and the NO_3^- concentration (Senbayram et al. 2012), ultimately leading to an increased N_2O/N_2 ratio and thus, a higher release of N_2O. Overall, denitrification is seen as an important process to be enhanced by restoration measures because it provides an effective, natural way to remove reactive N from polluted ecosystems.

Lastly, the so-called nitrifier-denitrification is another process that contributes to the production of N_2O. It is conducted by nitrifiers who firstly oxidise NH_4^+ to NO_2^-, followed by the reduction of NO_2^- to N_2O. Under low oxygen conditions, nitrifier-denitrification can be a significant source of N_2O, being able to contribute up to 66 % to the total N_2O production (Zhu et al. 2013).

In natural inland waters, N_2O emissions are usually negligible or even negative due to low concentrations of dissolved inorganic N species such as NO_3^-, NO_2^- and NH_4^+. One source of N for natural waters is atmospheric deposition which can lead to higher N_2O emissions (McCrackin & Elser 2011). Despite naturally receiving N, one recent study found that natural inland waters often remove N_2O from the atmosphere, indicated by a widespread occurrence of undersaturated conditions in streams, rivers and lakes across different biomes (Aho et al. 2023) which hints towards the uptake of N_2O. This uptake is based on the consumption of N_2O by denitrifying microorganisms under hypoxic conditions within the sediment or the water column.

4 Results of the meta-analysis

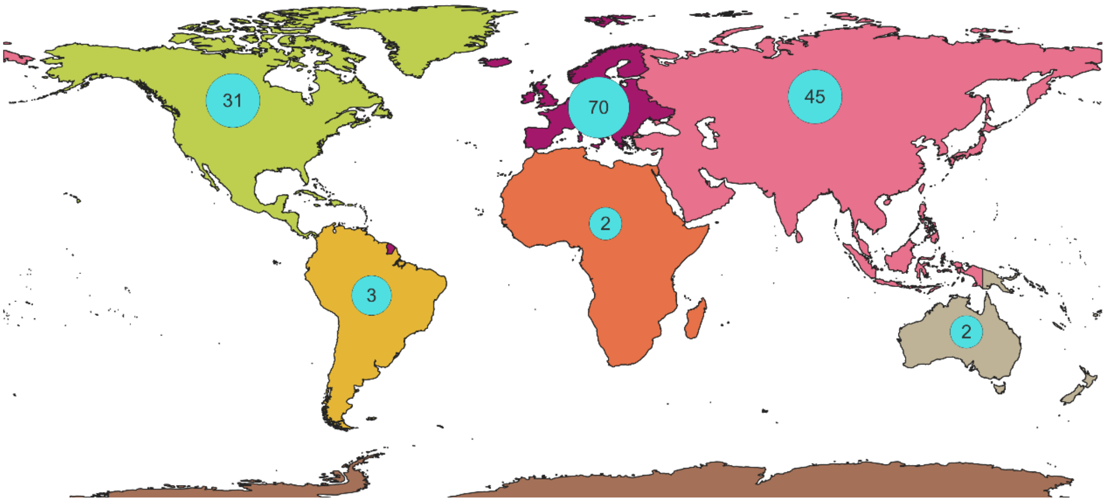
The focus of this review is on temperate zones and dammed-up areas which is why references being suitable for these categories are the most abundant ones within the meta-analysis.

Generally, references consist mostly of peer-reviewed articles from various national and international journals. Overall, 252 relevant references were found and included into the database for this review. To conduct a systematic review, 10 main categories were set up:

1. Continent
2. Landscape
3. Greenhouse gas species
4. Pressure type
5. Flowing type
6. Water body type/terrestrial area type
7. Type of study
8. Measures included
9. Not GHG-related
10. Element

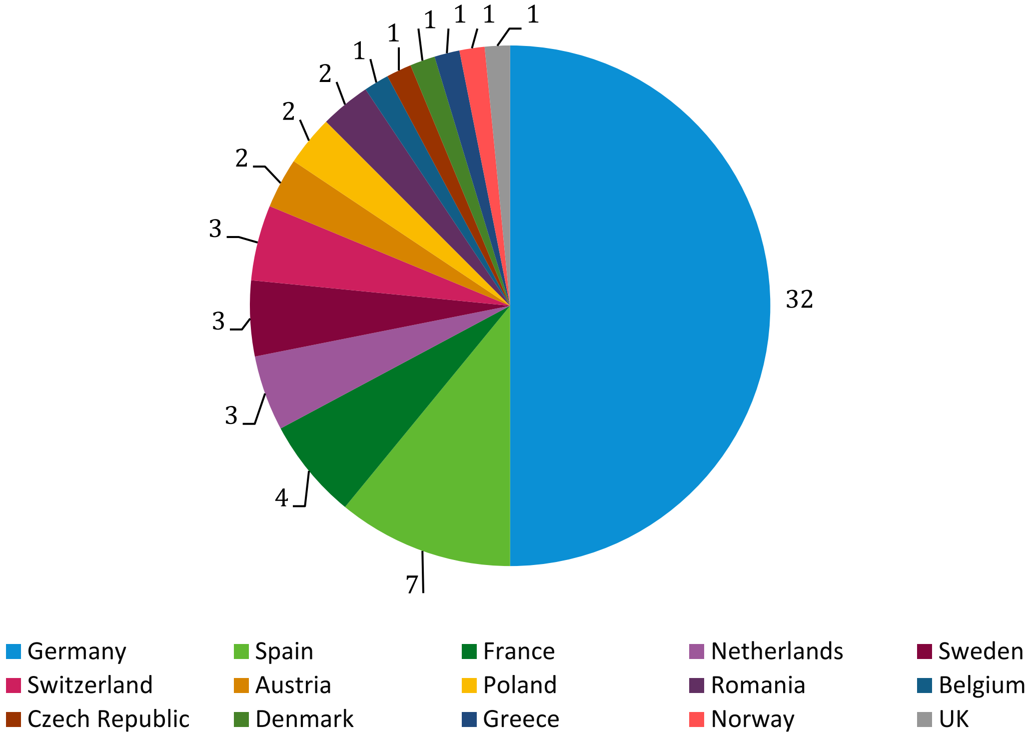
Within category 1 “Continent”, not every reference could be assigned to a specific country. Most studies were found for Europe (number of studies: 70, almost half of them from Germany), Asia (45) and North America (31) (Figure 4). For 8 of the 10 main categories, several subcategories were created. In category 1 „Continent“, the subcategory 1.4 „Africa“ does not consist of any subcategory. Due to its predominant affiliation, Russia was assigned to Asia although the prevailing opinion is that Europe extends as far as the Ural Mountains. A few studies are not country-specific, so that deviations between the numbers in the text and illustrations can be explained by this. As a result, the totals for continents are often greater than the sum of the country-specific studies for each continent. For Europe, it is therefore easy to differentiate between the countries for which the studies were carried out (Figure 5). The corresponding illustrations for Asia are shown in Figure 6. The figures for the other continents are briefly discussed below.

Figure 4: Numbers of included studies for each continent (blue circles). GIS-Data source: Natural Earth Data (2023)



Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

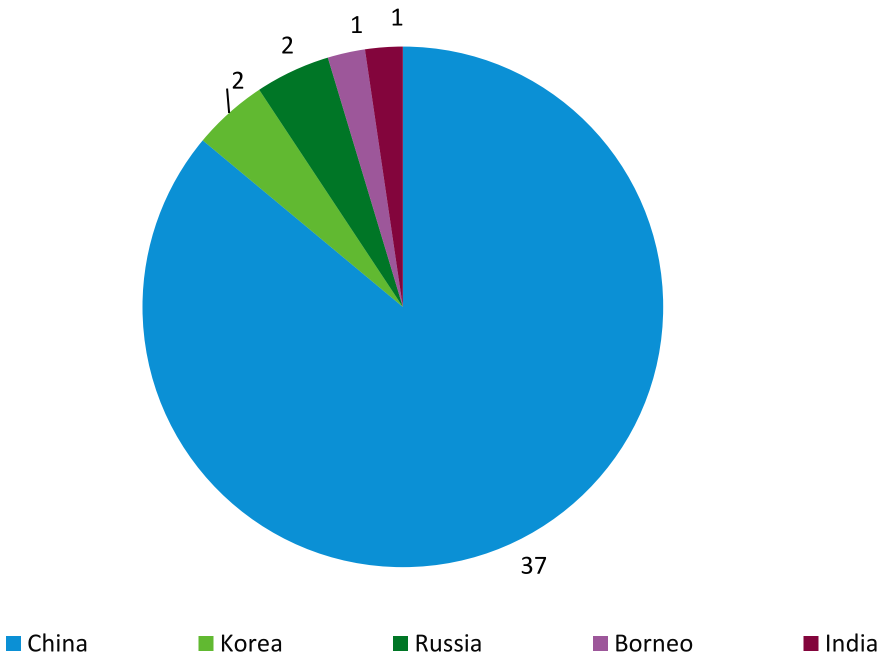
Figure 5: Numbers of studies included for subcategory 1.1 “Europe” and its subcategories



UK = United Kingdom

Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

Figure 6: Numbers of studies included for subcategory 1.2 “Asia” and its subcategories



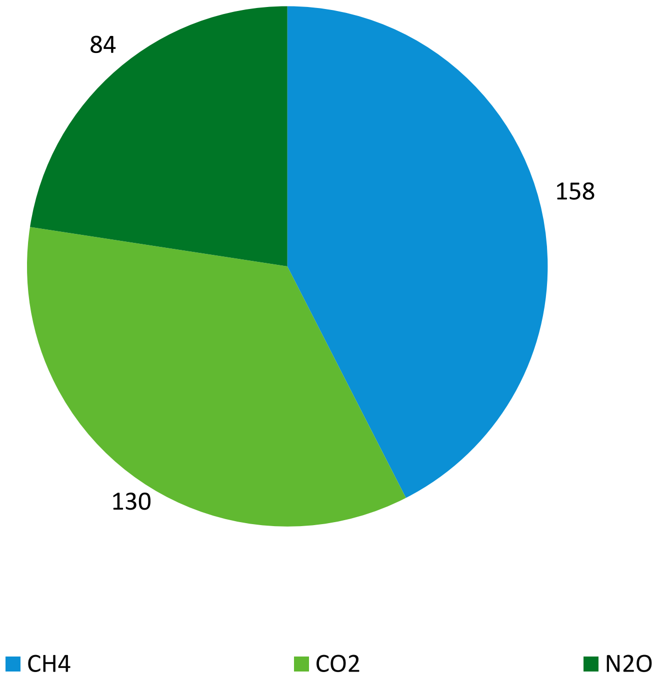
Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

Among the studies from Asia, 37 out of 43 were from China (Figure 6). For North America, the studies are distributed as follows: United States of America 22 references, Canada 9 references and one reference each for Puerto Rico and Panama. Only three studies were found for the continent of South America. For both Africa and Australia & Oceania, two studies were found, respectively.

The evaluation of category 2 "Landscape" showed that only comparatively few works could be clearly categorised. A total of 23 references could be clearly assigned to the lowlands (or the waters of the lowlands), while 6 investigations are dedicated exclusively to waters in mountainous landscapes.

Category 3 “GHG species” constitutes mostly of references that worked on CH_4 (158), followed by CO_2 (130) and N_2O (84), see Figure 7, however, many studies focused on more than one GHG.

Figure 7: Numbers of studies included for category 3 “GHG species” and its subcategories



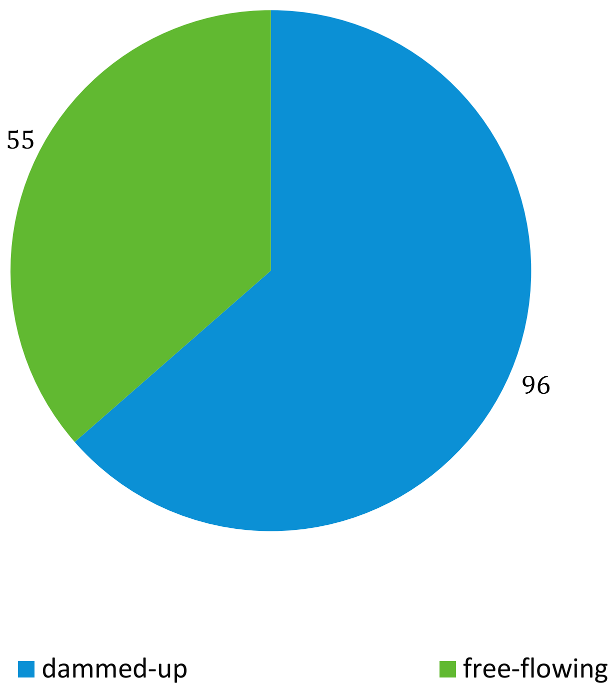
Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

For category 4 “Pressure type”, the subcategories “Dams, barriers and locks” (128), “Diffuse sources” (70) and “Hydrological alteration” (61) yielded the highest numbers of references. For this review, anthropogenic types of pressure on inland waters were classified in accordance with the WFD reporting. For further descriptions of the pressure types, see Chapter 5.

In category 5 “Flowing type”, the majority of references deals with effects of dammed/impounded water bodies (96) compared to free-flowing waters (55) (Figure 8). Category 6 “Water body type” is dominated by references dealing with artificial water bodies (125), reservoirs/dams (122) and rivers (121). In general, a high diversity of all possible water body types and classifications with regard to naturalness or anthropogenic genesis/modification is recognisable in the studies (Figure 9).

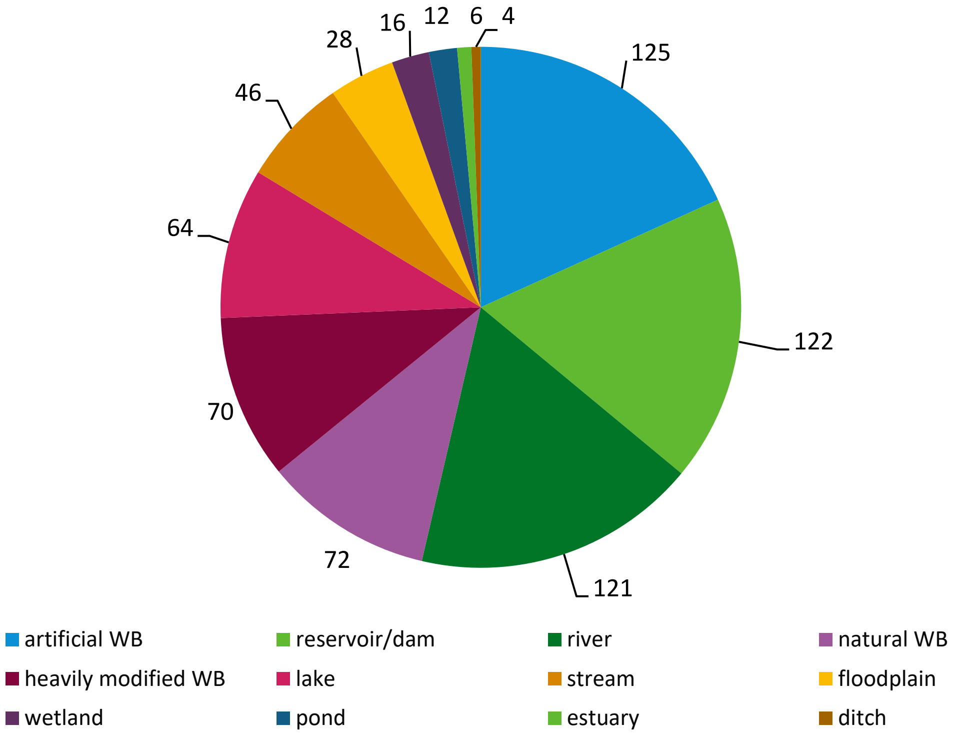
In connection with the type of study (category 7), a high number of studies are in-situ studies (107), i.e. the acquisition of measurement data has high priority here. A total of 76 studies are based on modelling applications (44) and conceptual or statistical approaches (32). As many as 73 papers are based on a review process (Figure 10).

Figure 8: **Numbers of studies included for category 5 “Flowing type” and its subcategories**



Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

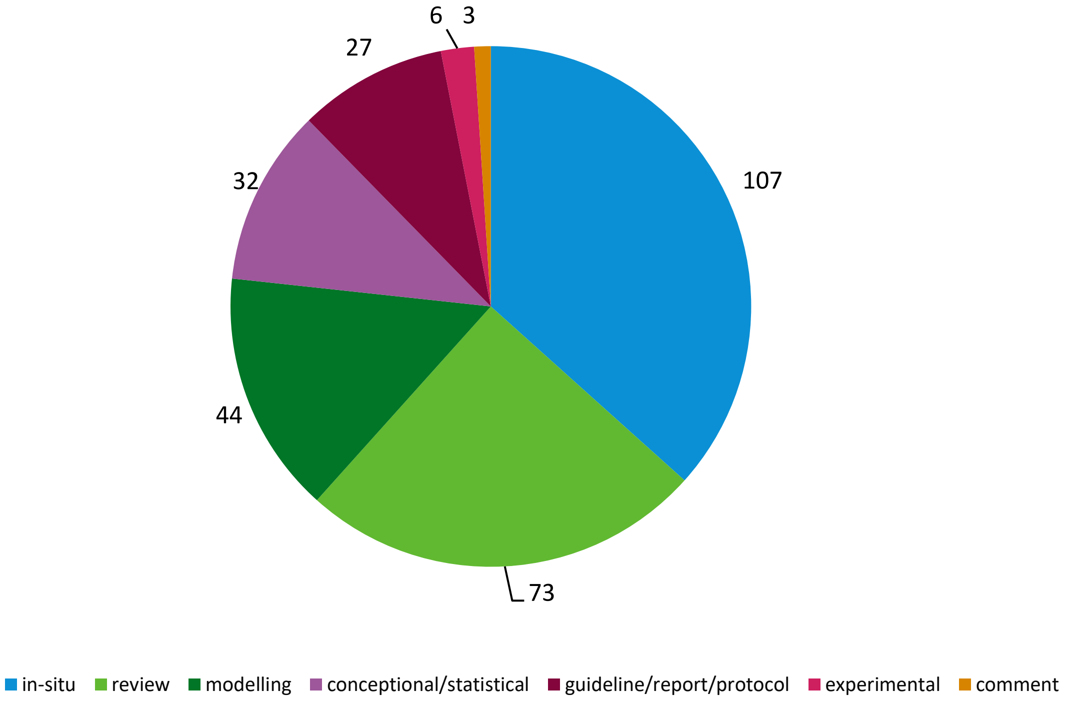
Figure 9: Numbers of studies included for category 6 "Water body type/terrestrial area type" and its subcategories



WB = water body

Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

Figure 10: Numbers of studies included for category 7 "Type of study" and its subcategories



Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

Categories 8 “Measures included” (21 references) and 9 “Not GHG-related” (53 references) were not further divided into subcategories. References in category 9 “Not GHG-related” and 10 “Element” were included due to their general nature on the topics of ecosystem functioning, health and potential effects of perturbations such as by anthropogenic pressures.

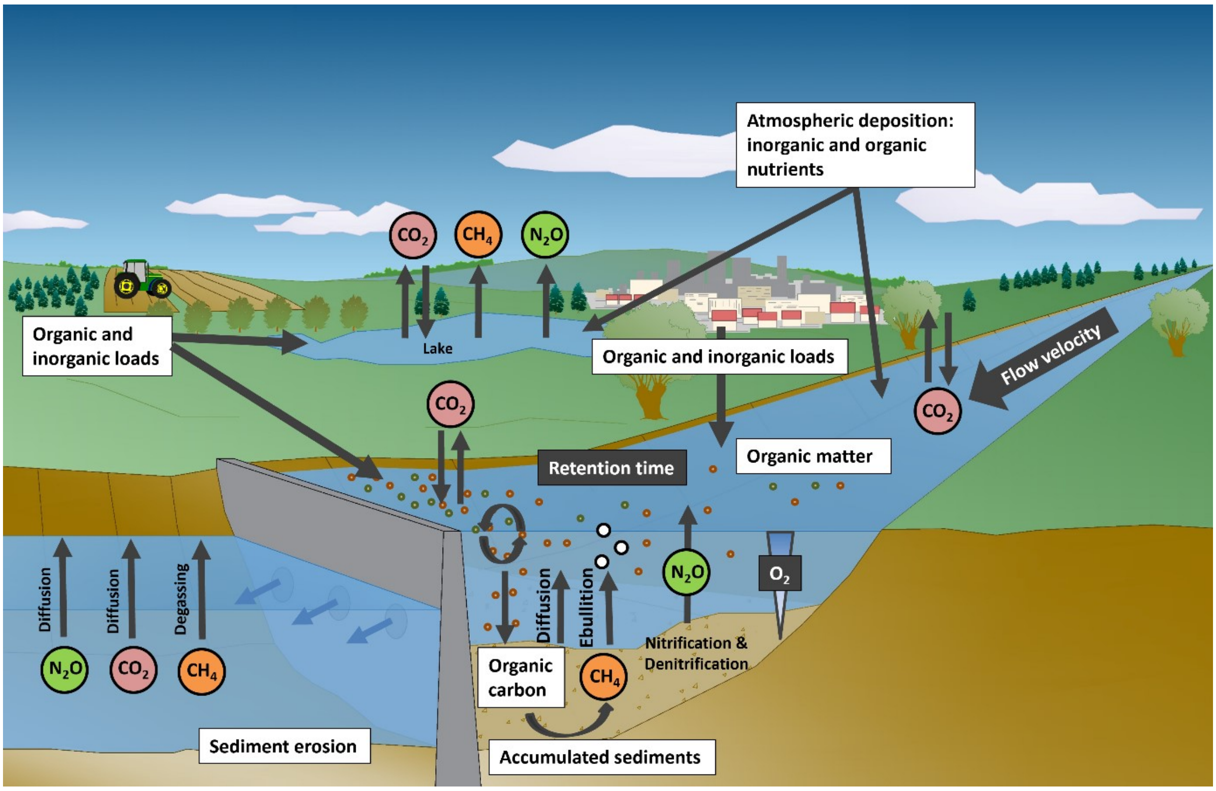
Category 10 „Element“ was established as a supplementary category for category 9 „Not GHG-related“ in order to sort by elements (C, N, P) that are discussed in the respective studies. Within category 10, 16 references deal with C-, 12 with N- and 8 with P-related topics.

5 Impacts of anthropogenic pressures on the C cycle and GHG emissions

5.1 Selection of relevant pressure types

Anthropogenic pressures on the C cycle and GHG emissions display a wide variety of impacts with different consequences. A schematic overview of the relevant processes in heavily modified or artificial water bodies using the example of rivers with barriers and their effects on GHG production is shown in Figure 11.

Figure 11: Scheme of CO_2, CH_4 and N_2O cycling in heavily modified or artificial water bodies using the example of rivers with barriers



Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

The pressure types analysed in this review are in accordance with the WFD and MSFD reporting system of the German Working Group on water issues of the Federal States and the Federal Government (LAWA 2022). The relevant pressure types for this review are (partly with subcategories):

- Substance loads from point and diffuse sources (Chapter 5.2)
  - a) Input of organic matter into the aquatic environment (Chapter 5.2.1)
  - b) Input of inorganic substances into the aquatic environment and subsequent production of organic matter (Chapter 5.2.2)
- Hydromorphological pressures (Chapter 5.3)
  - a) Dams, barriers and locks (Chapter 5.3.1)

b) Reservoirs (due to their high importance as a separate category) (Chapter 5.3.2)

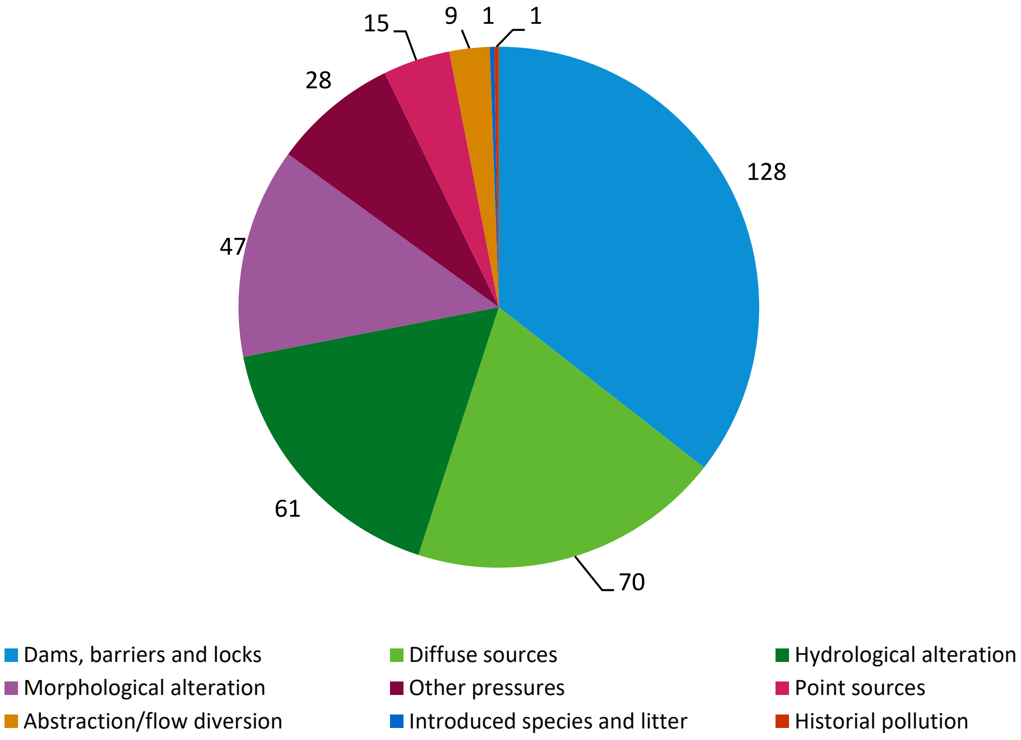
c) Hydrological alterations (Chapter 5.3.3)

d) Morphological alterations (Chapter 5.3.4)

- Other pressures (Chapter 5.4)

A total of 194 studies was identified with regard to an analysis or description of relevant pressures. Figure 12 shows the numbers of studies researched and analysed, broken down by the pressure types used in the meta-analysis.

Figure 12: **Number of studies included for category 4 "Pressure type" of the meta-analysis, broken down by subcategory**



Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

Note: Reservoirs are included in the category "Dams, barriers and locks".

The largest group are 128 studies that identify dams, barriers and locks (including reservoirs) as the cause of increased GHG releases. This is followed by 70 studies on diffuse sources of organic and inorganic pollution, 61 studies that address hydrological alterations and 47 studies that address morphological alterations as a cause. Other causes are analysed or emphasised to a lesser extent. The sub-category "Other pressures" was assigned to studies that deal with the effects of climate change or specific physical backgrounds, which resulted in 28 studies.

Table A1 (see Appendix) provides a complete overview of the studies recognised as relevant for the category "type of pressure". This includes the 194 studies mentioned, which are listed in the table in alphabetical order according to the first author. The following information is used for labelling: Subcategories of pressure types, water body type/floodplain, water body type according to WFD (AWB = artificial water body, HMWB = heavily modified water body, NWB = natural water body) and type of study (e.g. in situ, review, modelling, ...).

5.2 Substance loads from point and diffuse sources

In brief

Substance inputs from various point and diffuse sources are the major ecological threat to all types of inland waters. The most important anthropogenic sources of organic and inorganic substances originating from point and diffuse sources are:

- Wastewater treatment plants (WWTPs)
- Soil erosion due to agricultural activities
- Use of fertilizers

Overall, the unnaturally high input of organic and inorganic substances leads to a high internal production of organic matter within inland waters and thus, to eutrophication. Additionally, the high availability of substrates was shown to fuel the production of the climate-relevant GHGs CO_2, CH_4 and N_2O.

For instance, CO_2 and CH_4 emissions in a WWTP effluent were found to be enhanced by a factor of 1.2 and 8.6, respectively (Alshboul et al. 2016). In general, the input of nutrients from urban wastewater is estimated to increase by a factor of 2.5 to 3.5 between 2000 and 2050 (Van Drecht et al. 2009).

Modelling increasing P loads revealed that lentic waters will emit 30 - 90 % more CH_4 over the next century (Beaulieu et al. 2019). Regarding all GHGs addressed in this review, a continued global increase of eutrophication could result in a 5 - 40 % increase of the GHG effect (DelSontro et al. 2018).

5.2.1 Input of organic matter into the aquatic environment

Organic matter (OM) is often categorised and quantified as dissolved organic matter (DOM) and particulate organic matter (POM). The exchange between these pools is highly dynamic and plays a major role for the OM cycling in marine and freshwater ecosystems, such as for interactions with aquatic organisms or the bioavailability of pollutants (Wei et al. 2016). Additionally, the origin of OM is distinguished between allochthonous (external, land-derived) and autochthonous (internal production via photosynthesis) sources.

The major anthropogenic point source of OM into aquatic ecosystems is effluent from wastewater treatment plants (WWTPs, e.g. Brown et al. 2023). In urban areas, this highly OM-enriched water is discharged into streams and rivers where it fuels the microbial production of GHG by providing organic substrates (e.g. Alshboul et al. 2016; Brown et al. 2023; Park et al. 2023). Alshboul et al. (2016) investigated the CO_2 and CH_4 concentrations in effluents of WWTPs and receiving streams in Germany. They found that downstream of the WWTPs, concentrations of CO_2 and CH_4 were enhanced, resulting in increased emissions of both gases by a factor of 1.2 and 8.6, respectively. Additionally, the CH_4 concentration in the effluent was linearly correlated with the organic load (Alshboul et al. (2016). Park et al. (2023) point out that cities and urban centres in particular act as hotspots for substance inputs and are therefore relevant for increased downstream production and release of GHGs. On a global scale, wastewater has been found to have the strongest impact on ecosystem functions such as food web complexity and net ecosystem production of rivers and streams compared to other human stressors such as agriculture, urbanisation, habitat loss, nutrient enrichment and flow regulation (Brauns et al. 2022).

Regarding diffuse sources, soils are the main natural source of OM to freshwater ecosystems (e.g. Wilkinson et al. 2013; Rasilo et al. 2017; Zhu et al. 2022). Due to anthropogenic activities such as agriculture, including the ploughing of arable land, large areas of bare soil are permanently and systematically eroded, so that high amounts of organic material are transported into aquatic ecosystems via wind or rainwater run-off. Additionally, characteristics of the adjacent watersheds like intensity of human activities or their geological conditions were identified to have a significant effect on the receiving water bodies (e.g. DelSontro et al. 2018; León-Palmero et al. 2020). After reaching inland waters, the OM is either buried in sediments, transported to the ocean or, most relevant for this review, processed and transferred to the atmosphere mainly as CO_2 and CH_4 (e.g. Lapierre et al. 2013; Harmon, 2020). Globally, it is estimated that 25 % – 44 % of riverine terrestrial C is respired and emitted to the atmosphere (Harmon, 2020).

A second pathway for diffuse OM input is via lateral transport within the soil/sediment of water bodies, e.g. via polluted groundwater. Rasilo et al. (2017) found that the oversaturation of CO_2 in boreal streams originated mainly from the mineralization of soil-derived DOC and CH_4. This mineralization is usually highest within the so-called hyporheic zone which refers to the upper sediment layer of freshwater ecosystems. However, high OM concentrations also within the water column were found to be highly relevant for the production of GHG, leading to increased GHG emissions (e.g. Kumar et al. 2023a).

The review from Harmon (2020), dealing with C fluxes to and from inland waters, illustrates the complexity of multifactorial effects on aquatic ecosystems. As one example, Harmon (2020) describes how the quantity and quality of DOC influences several factors. For instance, the amount of DOC has an influence on the penetration depth of solar radiation, which in turn influences the water temperature and primary production and thus, potentially also the uptake or production of GHG. Adding to this, West et al. (2012) showed that the source of DOC plays a critical role for the CH_4 production. Thereby, DOC derived by algae fuelled higher CH_4 production rates compared to terrestrial DOC (West et al. 2012), which was likely due to a higher quality of algae-derived DOC (defined as containing more labile and thus, easily degradable C).

5.2.2 Input of inorganic substances into the aquatic environment and subsequent production of organic matter

Unnaturally high inputs of inorganic substances like N- and P-containing nutrients into aquatic environments lead to a highly intensified production of organic matter (primary production), called eutrophication. This anthropogenically induced process is a prominent global issue that is responsible for a wide variety of ecological problems, e.g. a reduction of the NO_3^- uptake efficiency by autotrophic organisms in agriculturally influenced waters by 347 % (Brauns et al. 2022), ultimately resulting in a worsened quality status of the majority of water bodies. Due to the increased production of organic matter, the remineralisation of this matter requires more oxygen than is produced during its build-up, so that hypoxia is one of the major consequences that can finally increase the production of GHG (e.g. Beaulieu et al. 2019; Xiao et al. 2021; Zhang et al. 2021). With regard to CH_4, modelling increasing nutrient loads (total P) led to the conclusion that global CH_4 emissions from lentic waters (lakes and reservoirs) will increase by 30-90 % over the next century (Beaulieu et al. 2019). For all GHGs (CO_2, CH_4 and N_2O), DelSontro et al. (2018) estimated that a global increase of eutrophication could translate to a 5–40 % increase of the GHG effect.

The most important point source of nutrients such as NO_3^-, NH_4^+ and phosphate (PO_4^{3-}) is again the effluent of WWTPs. Thus, water bodies in urban landscapes were commonly revealed as hotspots of GHG production and emission (e.g. Li et al. 2020; Zhang et al. 2021; Brown et al. 2023; Park et al. 2023). Globally, the input of nutrients from urban wastewater is estimated to increase by a factor of 2.5 to 3.5 between 2000 and 2050 (Van Drecht et al. 2009). Wang et al. (2021) investigated the C and N concentrations, as well as the C:N ratio of wastewater-receiving lakes and rivers and found high concentrations of both elements with low C:N ratios. Generally, low C:N ratios are beneficial for a higher N_2O yield by denitrification (Quick et al. 2019). This was confirmed by Wang et al. (2021) who found a stimulating effect of low C:N ratios on the accumulation of N_2O during denitrification in wastewater-influenced urban inland waters in China.

Regarding all GHGs discussed in this review, a study by Zhang et al. (2021) found that Chinese urban rivers emitted 14, 7 and 2 times more N_2O, CH_4 and CO_2 than non-urban rivers, while the flux magnitudes showed a reverse order, where highest emissions derived from CO_2, followed by CH_4 and N_2O. Similar values were estimated for an urbanized river system in Ecuador, where a water quality change from “acceptable” to “very heavily polluted” resulted in increased GHG concentrations by up to 10 times for CO_2 and CH_4, respectively, and by 15 times for N_2O (Ho et al. 2022).

With regard to diffuse sources of inorganic substances, the input of nutrients from agricultural activities is by far the most important source leading to increased GHG emissions, as revealed by many studies (e.g. Borges et al. 2018; Hao et al. 2021; Pu et al. 2021; Wu et al. 2023; Schödel 2024). Within an agricultural river network in China, widespread and permanent supersaturations of CO_2 and CH_4 were found which were positively correlated with nutrient loading due to N fertilizer input (Xiao et al. 2021). For a highly polluted, temperate estuary in Germany (Elbe estuary), N_2O emissions were found in all seasons, with the highest emissions occurring in winter, coinciding with highest DIN loads, and in the Port of Hamburg (Schulz et al. 2023). The average flux was calculated to be 39.9 µmol N_2O m^{-2} d^{-1}, which corresponds to 6.4 kg N_2O ha^{-1} a^{-1}. Converted to GWP_{100}, this corresponds to approximately 1.75 t CO_2eq ha^{-1} a^{-1}, with approximately three times this amount being released in the Port of Hamburg. Despite decreasing DIN inputs over the years, N_2O emissions did not decrease simultaneously (Schulz et al. 2023). This finding indicates that even after the reduction of external nutrient inputs. The internal pollution of aquatic systems is a major long-term threat that is likely to continue.

Due to the stimulation of primary production by nutrient inputs, chlorophyll-a concentrations, as bioindicator for phytoplankton growth, were identified to be good predictors of GHG emissions, especially of CH_4 and N_2O (DelSontro et al. 2018; Beaulieu et al. 2019). This was, for instance, confirmed for Chinese lakes, in which chlorophyll-a, but also total organic carbon (TOC) concentrations were revealed as key factors of GHG emissions (Kumar et al. 2023a). In general, it was estimated that eutrophic shallow lakes emit approximately 49 % more CH_4 than non-eutrophic shallow lakes (Li et al. 2021).

However, few studies revealed that increased nutrient inputs can also lead to unexpected effects. Although Wang et al. (2023a) reported positive correlations of dissolved CO_2 concentrations (pCO_2) with different N and P species in urban rivers, high CO_2 concentrations did not result in high CO_2 fluxes. The reason for comparatively low CO_2 fluxes despite high CO_2 concentrations was a low gas exchange rate between the water and air that was driven by low water velocities and wind speeds (Wang et al. 2023a). Two studies on CO_2 emissions from eutrophic lakes revealed that eutrophication can, despite the increase of CH_4 emissions as expected, lead to reduced CO_2 emissions (Balmer & Downing 2011; Sun et al. 2021). This combination of lowered CO_2 and increased CH_4 emissions was the result of an intensified primary production that firstly led to a higher uptake of CO_2, but secondly to a higher production of CH_4 due to a larger pool of

OM, serving as substrate for remineralisation (Sun et al. 2021). Concerning N_2O, Webb et al. (2019) reported widespread N_2O undersaturations in eutrophic farm reservoirs. Lowest N_2O concentrations in these artificial water bodies were found during algal blooms and stratification of the water column, likely due to temporary hypoxic or anoxic conditions (Webb et al. 2019). These examples illustrate the importance of considering multifactorial ecological effects on an individual basis which is necessary due to specific conditions e.g. related to the water body type.

5.3 Hydromorphological pressures

In brief

Hydromorphological alterations such as

- the construction of dams, barriers and reservoirs
- impaired flow regimes and
- changes of physical drivers

result in a fundamental destruction of the natural structural conditions of inland waters. This destruction leads to altered biogeochemical conditions that strongly influence the spatio-temporal extent and intensity of biological processes. Natural ecosystem services such as the uptake of GHGs, the retention of nutrients or the burial of substances are reduced, entirely lost or even reversed, resulting in elevated GHG emissions from inland waters.

A comparison of boreal lakes and reservoirs revealed 10x higher GHG fluxes from reservoirs (Tranvik et al. 2009). On a global scale, reservoirs are estimated to account for around 1 % of anthropogenic GHG emissions (Li et al. 2022), where the contribution of CH_4 is likely the highest (Deemer et al. 2016).

Consideration of drawdown areas raises global CO_2 emissions of reservoirs by 53 % (Keller et al. 2021). This results in an increase of CO_2 emissions of inland waters by 6 – 10 % (Marcé et al. 2019; Keller et al. 2020).

5.3.1 Dams, barriers and locks

Globally, the number of dams is estimated to be > 1 million (Lehner et al. 2011). For Europe, the Amber Barrier Atlas already includes ~630,000 dams and barriers (AMBER Consortium 2020). Thus, considering this estimation for Europe and the fact that many small-scale dams and barriers are not considered yet, the actual global number is expected to be much higher. The main purpose for building dams and barriers is flood control, electricity generation by hydropower, irrigation, water supply, aquaculture, environmental services, recreational activities and navigation (Ion & Ene 2021). Although large dams and barriers have a larger effect on the local scale, small water retention structures (SWRS) are estimated to play a significant global role due to being the most common type of water retention structure that causes river fragmentation (Gómez-Gener et al. 2018). SWRS are defined as impoundments with an impounded area of $<0.1\ km^2$ and a volume of $<0.2\ km^3$ (Lehner et al. 2011). They cover only 3.8 % of the global reservoir surface area but represent 99.5 % of the global number of reservoirs (Downing et al. 2006; Lehner et al. 2011).

The main impacts of dams and barriers on watercourse and floodplain ecosystems include (e.g. Brunotte et al. 2009; European Commission 2018; Günther-Diringer et al. 2021; Naumann 2022; Mehl et al. 2015, 2022a, b; Knott et al. 2023):

- Interruption of ecological continuity for aquatic organisms (ascending and descending), death and injury of individual animals during descent in turbines of run-of-river power plants, interruption of continuity for solids and disruption of sediment dynamics
- Displacement and disturbance, barriers to migration and dispersal of protected species
- Hydrological changes, i.e. changes of the ecological flow regime, transformation of free-flowing stretches into lakes or stretches with significantly reduced flow velocity and altered hydrodynamic behaviour, drying out of diversion stretches and thus considerable habitat losses for species of running waters, changes of the flow regime by the establishment of hydropower plants
- Changes in river morphology and riverine habitats
- Changes in the hydrodynamics of the groundwater, the flooding regime in the floodplains, the watercourse, the floodplain structure and habitats and thus negative consequences for the floodplain ecology and the floodplain condition leading to habitat losses
- Water chemical changes, changes of the material and energy balance (including temperature regime) of the running waters and floodplains with consequences for trophic levels, food chains, habitats and the introduction of invasive species.

The transport of sediment is relevant for particulate organic matter, which is transported in flowing waters primarily in suspension, as suspended solids. The material can be living (especially plankton) or dead (decaying remains of plants and animals or already decomposed sludge-like particles). Organic matter is often also bound to inorganic particles, e.g. silt and clay particles.

For sediment transport, which includes debris, stones, sand, silt and clay particles and organic solids, taking place as bedload and suspended sediment transport, the grain size of the solids is of great importance. Whether and which grain sizes are transported or deposited depends on the hydrodynamic conditions. Suspended solids are kept in suspension by the turbulence of the flow, whereby the upward impulses counteract the settling of the particles.

However, if the decisive hydraulic parameters such as flow velocity, bed shear stress and turbulence fall below a certain limit value, the solids are deposited (DWA-M 525). In natural watercourses, these are cross-section widenings, bends and reductions in gradient. In watercourses with barriers and the resulting artificial enlargement of the cross-section, the flow velocity, bed shear stress and turbulence drop to minimal values, so that massive sediment deposits occur in the headwaters of the barriers.

With regard to GHGs, these sediment deposits play a crucial role for their production. Globally, all dams are estimated to trap approximately 30 % of sediment flow to the coast (Gough et al. 2018). Due to the accumulation of organic matter, the microbial production of CO_2, CH_4 and N_2O is fuelled and results in an increased release of GHGs from the sediment (e.g. Maavara et al. 2020b). Since most studies focused on sediment deposits and their effects on GHGs in the context of reservoirs, a detailed description is given in Chapter 5.3.2.

The abovementioned hydraulic parameters not only play a crucial role on the sedimentation of particles, but also on the microbial processing of organic matter up- and downstream of a dam. By comparing the up- and downstream conditions, it was found that the water residence time, being higher in lentic zones (upstream) led to a higher biomass production and also to a higher microbial OC processing compared to lotic zones (downstream) (Proia et al. 2016).

Overall, the construction of dams and barriers displays a major perturbation for aquatic ecosystems, turning formerly lotic areas into lentic ones. Globally, Grill et al. (2019) estimated that very long (> 1,000 km) rivers are most threatened by fragmentation, with only 36 % remaining free-flowing over their entire length. In another study, Grill et al. (2015) calculated that 48 % of the global river volume is moderately to severely impacted by fragmentation and regulation. As a future scenario, this share could rise to 93 % by 2030 (Grill et al. 2015). Concerning streams and rivers worldwide, a study by Van Cappellen & Maavara (2016) estimated that more than 50 % are impacted by barriers, crossing one or more dams before reaching the ocean and that this share could rise up to 90 % by 2030. In Europe, barriers constitute significant pressures for about 20 % of surface water bodies and are one of the main reasons for failing to reach good ecological status (European Environment Agency 2021).

According to a study by Mehl et al. (2023b), hydropower plants in Germany have a statistically significant, negative (worsening) impact on 18 of 32 investigated parameters of the ecological status of watercourses according to (1) the WFD and (2) the classification of the morphological conditions of watercourses. One case study of a barrage in the River Main and its potential effects on CH_4 emissions is described below.

A case study on the GHG impact of barrages

Currently, there are 7,156 hydropower plants in Germany (Eichhorn et al. 2019). For example, 37 run-of-river hydropower plants are located in the River Main. For one of the barrages combined with a hydropower plant in the lower reaches of the River Main, called “Kleinostheim”, Lorke & Burgis (2018) determined an average emission value of 282 mg CH_4 m^{-2} d^{-1} as the sum of diffusion and ebullition, based on representative measurements, but without measuring the outgassing at or downstream of the barrage/hydropower plant. This case study is not representative but is used hereinafter to illustrate the importance of the topic.

The barrage Kleinostheim is 15.004 km long (Wikipedia 2024). Cartographically, a centre width of approximately 120 m can be estimated. This results in a relevant water area impacted by the barrage of approximately 180 ha. Based on the above-mentioned value from Lorke & Burgis (2018), including an increase of 9 % for the outgassing downstream of the barrage (standardised approach according to IPCC 2019, UBA 2023a), this results in a CH_4 emission of the barrage of approximately 202,000 kg a^{-1} or 202 t a^{-1}. Converted to CO_2 equivalents (by a factor of 27, see Table 2), this corresponds to 5,454,000 kg CO_2eq a^{-1} or 5,454 t CO_2eq a^{-1}.

On the other hand, the Kleinostheim hydropower plant generates approximately 52,000 MWh of electricity per year (BUND 2009). With the official value of the average GHG emission of German electricity generation (498 g CO_2eq kWh^{-1} for 2022 including pre-impoundment emissions, UBA 2023c), this leads to an avoided emission of approximately 25,896,000 kg CO_2eq a^{-1} or 25,896 t CO_2eq a^{-1}. This means that CH_4 outgassing from the barrage alone accounts for around 21 % of the emissions avoided by the hydropower plant (CO_2 and N_2O would also have to be considered). It should be noted that in 2020, the average emission value for the German electricity generation was lower compared to 2022, denoted as 369 g CO_2eq kWh^{-1} (UBA 2023c). The increase is the result of the recently increased use of coal as an energy source for electricity production. This means that with a growing share of energy generation from renewable energies and thus, a decreasing mean emission value, the effect-reducing share of GHG releases from the barrage would continue to grow in the sense of a trade-off.

If the GHG emissions of the barrage Kleinostheim are divided by its annual electricity yield, the calculated value is approximately 105 g CO_2eq kWh^{-1} as the primary energy-related emission factor of electricity generation from hydropower. By contrast, UBA (2023d) states a value of 2,659 g CO_2eq

kWh^{-1}, which is approximately 40 times lower and definitely shows that there is an enormous need for investigation.

Conclusion: If the cause for the existence of dams is elsewhere, e.g. for use as a waterway such as on the River Main, then hydropower plants will generally be seen as a positive energy solution. However, if hydropower plants are the only or the main cause for the construction of dams and barriers, the resulting increase in GHG emissions reduces their value for otherwise relevant electricity generation with low GHG emissions. Previous approaches seem to underestimate the magnitude, possibly even greatly.

5.3.2 Reservoirs

Reservoirs feature some unique characteristics, which is why this type of water body is discussed separately in this review. The following three factors are considered to be decisive with regard to the magnitude of GHG production and emission in reservoirs (e.g. Deemer et al. 2016; Chanudet et al. 2020):

1. Altitude (representative of temperature)
2. Mean water residence time
3. Eutrophication level (N and P concentrations)

Due to the temperature dependence of biogeochemical processes, the GHG release quantities in reservoirs will generally be greater in summer than in winter, as well as higher in the tropics than in boreal/polar regions (e.g. Barros et al. 2011; Deemer et al. 2016). Globally, GHG emissions from reservoirs are estimated to account for 1 % of anthropogenic emissions (Li et al. 2022), where the highest contribution originates from CH_4 emissions (Deemer et al. 2016). Compared to natural lakes, which are also known to be significant GHG emitters, boreal reservoirs show 10x higher GHG fluxes (Tranvik et al. 2009). Although most reservoirs were identified to be sources of GHGs, Deemer et al. (2016) reported that up to 16 % of all reservoirs were net sinks for CO_2 and N_2O. This highlights the complexity of GHG production and release within reservoirs and illustrates the need for more investigations.

CH_4 releases are generally higher in the transition zone between the inflowing river and the reservoir than in the other littoral or pelagic zones (Maeck et al. 2013; Chanudet et al. 2020), which can be simply explained by the sedimentation of POM caused by the decreasing transport force of the water towards the dam. The river loses its transport capacity and has to release its suspended material to the sediment, so that sediments with a high proportion of organic matter accumulate (Sobek et al. 2012).

The water depth of the reservoirs also appears to play a major role. The GHG release of large reservoirs is not comparable with that of smaller reservoirs. In particular, a fundamentally different size and shape or morphology as well as different hydrological and hydrodynamic conditions play a decisive role here (e.g. Schilder et al. 2013; Chanudet et al. 2020). Obviously, the long residence time of water in deeper, higher-volume reservoirs favors the accumulation of GHGs in deep water, increases the release to the atmosphere by diffusion, reduces the release by bubble transport and increases the release to downstream areas (Chanudet et al. 2020). However, deeper reservoirs can also emit less GHGs than shallow ones, e.g. if CO_2 is consumed by phytoplankton (Shi et al. 2023).

Generally, elongated water residence times stimulate phytoplankton growth and thus, can strongly influence GHG emissions and nutrient dynamics (Chen et al. 2020). Usually, reservoirs were found to serve as nutrient sinks, at least during the first years, due to enhanced biogeochemical turnover and burial of organic matter and P species. Studies by Harrison et al. (2009), Maavara et al. (2020b) and Yan et al. (2022) calculated various retention efficiencies for N and P which can directly impact downstream areas (Van Cappellen & Maavara 2016; Maavara et al. 2020a). Over time, reservoirs can potentially turn into nutrient and GHG sinks, as was observed for CH_4 in old reservoirs due to the ongoing input and sedimentation of organic matter and its remobilisation (Sobek et al. 2012; Descloux et al. 2017).

Since reservoirs are comparable with lakes regarding their morphology, a comparison of these two water body types appears reasonable. For instance, Schilder et al. (2013) found that the gas exchange coefficient (diffusion coefficient) of CO_2 and CH_4 differs within lakes, which should also have significance for reservoirs. They found the highest values in the lake centre, indicating that the use of single-point measurements is not appropriate for whole-lake (or reservoir) extrapolations.

In cascades of flow-through reservoirs, Shi et al. (2023) found an increase in GHG release downstream, which, with usually decreasing organic pollution due to the retention effect of the upper reservoirs, speaks in favor of gas transport across the reservoirs. Additionally, not only the transport of GHGs can increase downstream emissions in cascade reservoirs, but also the accumulation of sediments that are trapped between the reservoirs. This trapping was found to increase the nutrient cycling and also the release of nutrients (Chen et al. 2020; Wang et al. 2023b).

Reservoirs not only affect downstream areas which receive less amounts of water, but also their upstream riparian areas, called “drawdown areas”. These areas are characterised by changing water levels and temporary dry periods due to water level fluctuations. A study by Shi et al. (2020) found that a hydropower plant in the Mekong River intensified water level fluctuations in the reservoir, ultimately leading to higher denitrification rates at the land-water interface of riparian zones. Concerning GHGs, accelerated microbial processes in the drawdown areas can also lead to a higher production and release (Jin et al. 2016; Marcé et al. 2019), such as in marshes (Chen et al. 2009) and wetlands (Jin et al. 2023). This was supported by Keller et al. (2021) who showed that drawdown areas are hotspots for CO_2, releasing large amounts of CO_2 that, if considered, would increase the global CO_2 emissions of reservoirs by 53 %. If the GHG release from these temporary dry sediments is considered, the global CO_2 emissions of inland waters would increase by 6 % –10 % (Marcé et al. 2019; Keller et al. 2020).

Since CH_4 is emitted via various pathways and is the most important GHG in the context of reservoirs, most studies focused on this particular GHG. As described in Chapter 3.2, CH_4 can be released into the atmosphere via diffusion, ebullition, plant-mediated transport and degassing.

Diffusion, for instance, can lead to an efficient CH_4 oxidation within the sediment or the water column, resulting in overall lower CH_4 emissions, while ebullition leads to an increase of the total CH_4 flux (Harrison et al. 2017). With regard to the type of reservoir, a comparison of run-of-river and storage reservoirs revealed that run-of-river and generally shallow reservoirs with short water residence times experience higher ebullition fluxes, while CH_4 emissions in storage reservoirs are dominated by diffusion (Chanudet et al. 2020). Higher ebullition fluxes in shallower water bodies are a result of the lower hydrostatic pressure and its influence on the cohesive strength of sediments. This strength varies as a function of the organic content and the pore pressure, where a higher organic matter content is associated with a higher cohesive strength and thus, a reduced bubble release (Joyce et al. 2003; Harrison et al. 2017). Concerning the overall occurrence of the different emission pathways, ebullition was identified to be the most relevant process for most reservoirs, contributing approximately 65 % to the total CH_4 flux (Deemer et al. 2016; Johnson et al. 2021). Degassing is the process of CH_4 release due to rapidly changing pressure conditions. This emission pathway is exclusively important in the context of water passing through turbines of hydroelectric reservoirs. These turbines are usually located near the bottom of the reservoir. When water is spilled out of the turbines, the pressure change, as well as possibly accumulated CH_4 from the hypolimnion lead to the release of CH_4 via degassing downstream of the dam. The importance of degassing e.g. after the flushing of a reservoir is still under debate but was already found to be able to contribute large amounts to the total CH_4 emissions (Harrison et al. 2021; Lessmann et al. 2023), especially if the spillway is located near the reservoir bottom so that potentially hypoxic/anoxic and thus CH_4-rich water is discharged. Thus, CH_4 emissions via degassing were previously highly underestimated and can account for up to 45 % higher GHG emissions if included (Harrison et al. 2021).

Many studies focus primarily on the reporting of CH_4 emissions, e.g. the national GHG inventory report of Germany (UBA, 2023a) reports only CH_4 emissions from flowing and standing artificial waters. Thus, the significance of the release of N_2O from reservoirs is probably still underestimated. This was, for instance, illustrated by Lauerwald et al. (2019) who reported that reservoirs account for 53 % of the N_2O emissions from lentic freshwater water bodies, although they account for only 9 % of the global standing water surface area. For a French, 85 years old reservoir, Descloux et al. (2017) showed that N_2O emissions, converted into CO_2 equivalents, accounted for around a third of the CH_4 emissions recorded. However, due to non-existing studies on simultaneously quantifying up- and downstream N_2O emissions of reservoirs, Descloux et al. (2017) were unable to compare their results to other reservoirs. Generally, the NO_3^- concentration was found to be a good predictor to estimate N_2O emissions (Deemer et al. 2016).

5.3.3 Hydrological alterations

Some of the below-mentioned hydrological pressures are already discussed directly or indirectly in the other sub-chapters of Chapter 5, as overlaps can hardly be avoided due to the high level of complexity.

Hydrological changes represent a significant group of pressures with regard to anthropogenically increased or altered GHG releases for the following reasons:

1. The input of organic substances and inorganic nutrients into inland waters is predominantly linked to hydrological processes.
2. Transport, storage and remobilisation of organic substances, nutrients and also GHGs within water bodies and water systems depend on hydrological, hydrodynamic and hydrostatic conditions.
3. Hydrological processes, usually in combination with other factors, provide a decisive physical framework for biogeochemical processes in inland waters.

The anthropogenic hydrological alterations mainly concern the following aspects, which are therefore also responsible for changes and, in particular, an increase in GHG release (adapted from Mehl et al. 2014):

- Catchment area characteristics (relevant characteristics for run-off formation and concentration such as land use, vegetation cover, sealing, soil drainage, etc.)
- Catchment size, shape and structure/water network formation (artificial overpasses, canal connections, creation of artificial lakes, changes in drainage direction, e.g. as a result of mining)
- Quantity management measures (input, abstraction, transfer)
- Morphological measures including water maintenance measures (morphological alterations, infrastructures, technical flood protection measures), see Chapter 5.3.4

- Dam and reservoir effect (retention, abstraction, hydropeaking, solids removal), see Chapters 5.3.1 and 5.3.2
- Changes in wetlands/floodplains, see Chapter 5.3.4

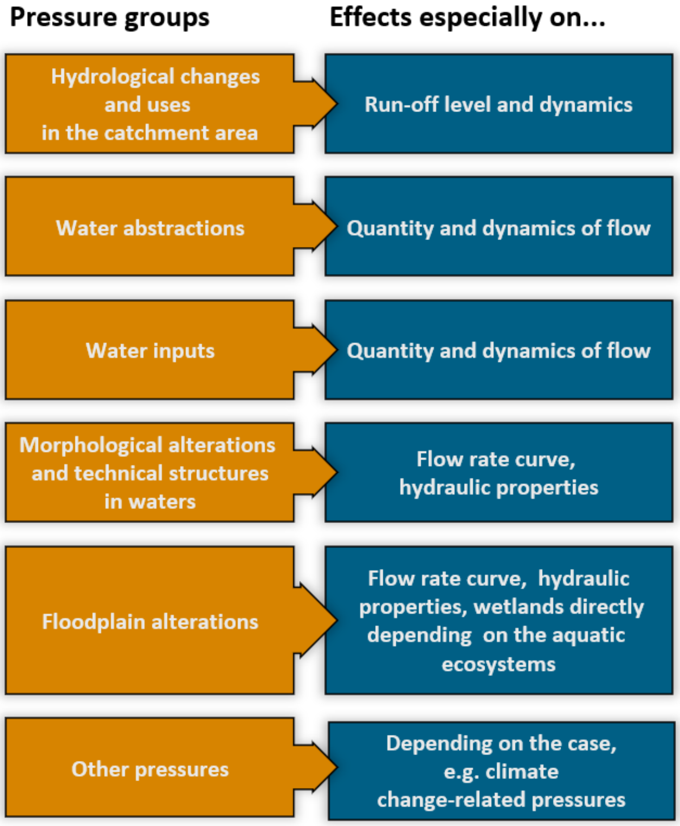
A summarised presentation of the pressure groups, the main hydrological impacts of the pressures and the correlations with the parameters of the hydrological regime according to Annex V WFD and/or German Ordinance of Surface Waters (OGewV) are also shown in Figure 13.

The impacts of land use and changes in discharge were already examined by many studies (e.g. Sanches et al. 2019; Hao et al. 2021; Valiente et al. 2022; Battin et al. 2023). For instance, Borges et al. (2018) found that a combination of decreased freshwater discharge and increased agricultural land use led to an increase of riverine CO_2, CH_4 and N_2O concentrations in a large European river (the Meuse, Belgium).

Generally, water level fluctuations likely have the strongest impact on riparian zones, in which large areas are subject to frequently changing drying-rewetting cycles. For river-connected wetlands, Jin et al. (2023) found that water level fluctuations had a direct impact on the vegetation cover, where, for instance, the *Phragmites* zone increased in the flooding period by approximately 28 %, whereas *Carex* and *Phalaris* decreased by approximately 43 %. Additionally, highest CH_4 and N_2O fluxes occurred during flooding and on bare mud sites (without vegetation) (Jin et al. 2023). A similar pattern was observed by Machado dos Santos Pinto et al. (2020) who reported that along a hydrological gradient, CO_2 and CH_4 emissions were highest in frequently flooded areas compared to non-flooded and rarely-flooded areas. These studies demonstrate that changing hydrological conditions are highly stimulating on biogeochemical processes and thus, the production and emission of GHGs. Leng et al. (2021) even speculated that changing hydrological conditions could have a greater impact on future CH_4 emissions compared to warming.

Within standing waters such as lakes and reservoirs, internal hydrological conditions, potentially being altered due to anthropogenic activities, were identified to influence the storage and release of GHGs. In a small eutrophic lake in Switzerland, water column stratification and mixing had a major impact on the turbulent diffusivity, where a higher diffusivity represents a higher mixing and more CH_4 being oxidised, while a lower diffusivity lead to a greater proportion of CH_4 storage within the hypolimnion (Vachon et al. 2019). Thus, if water level fluctuations or the size of the water surface area are modified, these changes can likely influence the storage and emission of GHGs.

Figure 13: Pressure groups and their major hydrological effects on inland waters according to Annex V WFD and/or German Ordinance of Surface Waters (OGewV), adapted from Mehl et al. (2015)



Source: Own illustration, biota – Institut für ökologische Forschung und Planung GmbH.

5.3.4 Morphological alterations

Alterations to the natural morphology of inland waters are based on measures that primarily serve to "improve" the hydraulic capacity of the watercourses, to stabilise navigation or to "improve" the receiving water for agricultural purposes. The following measures are primarily involved:

- River straightening (higher flow velocity, less sediment accumulation, less turbulence, less oxygen penetration into the sediment)
- Deepening of rivers (potential stratification of deeper areas, changes of conditions within near-bottom layers with direct effects on biological processes)
- Changes in transverse and longitudinal profile (e.g. homogenization of river beds, less surfaces for the accumulation of biofilms)
- Changes in the substrates
- Construction of pipework

In principle, such anthropogenic measures lead to the destruction of the original structural conditions of the water bodies and to the elimination of the original ecological continuity of the watercourse systems through artificial structures (e.g. weirs, but also dams, barriers, locks and reservoirs) and the resulting changes of physical conditions.

Due to river straightening, for instance, buffer zones along the river bed are disconnected from the river and no longer able to provide their ecosystem function as sinks for nutrients (e.g. Walton et al. 2020). Ultimately, this results in the loss of these habitats which was found to significantly inhibit food web complexity and net ecosystem productivity (Brauns et al. 2022).

Additionally, river straightening increases the flow velocity and leads to a decreased water retention time that limits the efficiency of biological processes. With regard to GHGs, changes of the turbulence directly alter their release into the atmosphere, where a high turbulence leads to high emissions and vice versa (e.g. Liu et al. 2017). Due to this higher turbulence and gas transfer velocities, streams were found to emit higher quantities of GHGs than rivers (e.g. Alin et al. 2011). In the Elbe River, a comparison of different river areas (midstream vs. groyne fields) revealed that more turbulent areas such as between groynes are characterized by higher gas transfer velocities that lead to much higher CH_4 emissions (Bussmann et al. 2022; Koschorreck et al. 2023). Regarding the effect specifically on CH_4 emissions, for instance, physical drivers such as gas transfer velocity, elevation and river slope were found to be the most relevant ones (Rocher-Ros et al. 2023).

In addition, the morphological changes intentionally or unintentionally lead to changes in riparian wetlands/floodplains, such as loss of area/volume due to embankment, morphological changes, direct hydrological regulation measures in the floodplain, in particular drainage, changes in roughness due to use, lowering of the groundwater table and reduction of exfiltration into surface waters. For Europe, Christiansen et al. (2020) estimated that up to 90 % of all European floodplains are degraded due to hydromorphological pressures. According to this, it can be assumed that e.g. a reduced nutrient retention in floodplains could lead to higher nutrient availabilities in the adjacent water body and thus, to a higher GHG production.

5.4 Other pressures

Within this category, studies dealing with physical pressures and being related to climate change are summarised.

Physical drivers, such as gas transfer velocity, elevation, river slope or meteorological factors are responsible for a wide variety of effects on biological and chemical processes. Temperature is undoubtedly one of the main controlling factors on all processes that are responsible for the production of GHGs. For instance, a direct comparison of physical versus biological factors on CH_4 dynamics in shallow lakes revealed that physical drivers appeared to be more important (Baliña et al. 2022). According to a study by Aben et al. (2017), each temperature increase by 1°C could result in 6 % –20 % more CH_4 originating from ebullition in freshwaters. The importance on sediment characteristics and their storage capacity was reported by Van Bergen et al. (2019) who found that the sediment CH_4 release was mainly driven by temperature. Additionally, they found that ebullition increased exponentially above a threshold of 15°C. Another study by Marotta et al. (2014) also reported that warming will increase sedimentary CH_4 and CO_2 production in lakes by up to 61 %.

However, also biological factors were identified to have an impact on GHG emissions. Aben et al. (2022b) conducted a mesocosm experiment where the climate warming effects of different plant types (algae, free-floating and submerged plants) on GHG emissions were tested. It was demonstrated that GHG fluxes differed depending on the dominant plant type, where the response was strongest for free-floating plants. The authors concluded that an anticipated shift from submerged plants to an algae- or free-floating-dominated system due to warming could lead to an increase of GHG emissions.

As one consequence of climate change, shifts in precipitation patterns are predicted. Multiple studies showed that precipitation in general and thus, also shifting patterns, can influence the production and release of GHGs. The most obvious effect is that water routes are altered which makes the local catchment hydrology and land use even more important to consider (Battin et al. 2023). However, also the global importance of changing hydrological conditions on river flows was already revealed (Gudmundsson et al. 2021). A study by Sinha et al. (2017) reported that eutrophication will increase during the 21st century as a result of changing precipitation patterns. Deemer et al. (2016) found that precipitation is generally a good predictor for CO_2. Concerning CH_4, precipitation was identified to have a significant effect on partial pressure, diffusion and ebullition in floodplain ponds of the Three Gorges Reservoir (Miller et al. 2019). Furthermore, also drought events will likely have a major influence on GHG emissions. Gómez-Gener et al. (2015) conducted a combined in situ and modelling study on hot spots of C emissions during a summer drought. The results of their model show that extreme drying would increase the surface area of their study site by approximately 4 times and thus, would double the CO_2 emissions. Besides affecting the biogeochemical processing in inland waters, also their abundance and distribution will be changed due to changing precipitation and run-off patterns, as was described for lakes by Tranvik et al. (2009).

Another predicted consequence of climate change is that storms are likely to occur more often and more intense. Together with changing hydrological patterns and water routes, storms will likely enhance nutrient losses from land into inland waters where the GHG production is ultimately fuelled (Beaulieu et al. 2019).

6 Quantification options of GHG emissions

6.1 Representative in situ measurements

The basis for any quantification of GHG release from landscape components, such as inland waters, is to conduct reliable in situ measurements using the best measurement methods currently available. GHG release or uptake is usually determined by using chambers with a defined volume and exposure time, in which the concentration development over time is measured. Measurements should be carried out at a sufficient number of different locations and times of the year to capture both the spatial and temporal variability of emissions from a water body (UNESCO/IHA GHG Measurement Guidelines for Freshwater Reservoirs 2010 (Goldenfum 2010), IPCC 2019). Both data of GHG measurements and on boundary conditions should be recorded in a process-oriented time cycle and over a sufficient period of time in order to minimise meteorological, hydrological and also water management and load-relevant influences on the homogeneity of the data as far as possible. However, it must be noted that an appropriate monitoring strategy would be highly time-consuming and cost-intensive.

The following technical approaches are used in particular to determine gas concentrations in the field:

- Gas chromatographic systems with a barrier discharge ionisation detector and an electron capture detector
- Systems using laser absorption
- Photoacoustic systems with dew point control
- Infrared spectrometer (vibrational spectroscopy using Fourier transformation)

When measuring and balancing the release of GHGs from inland waters, it is important to record all transfer pathways from the water body to the atmosphere. It should also be considered in the subsequent analysis that dissolved gas drifts with flowing waters and thus, is sometimes only released elsewhere, i.e. on the adjacent flow path and not close to the area of its production. The following pathways in the sense of GHG transfer from water bodies into the atmosphere can be differentiated (e.g. Sanches et al. 2019, see also Figure 2, Figure 3 and Figure 11):

1. Release through rising gas bubbles (ebullition),
2. Diffusive gas exchange at the water surface,
3. Degassing downstream, and
4. Emission via emerse macrophytes.

In addition to the internal processes and conditions within water bodies, atmospheric and meteorological parameters (especially air pressure and wind speed) also play a major role for diffusive gas exchange.

The degassing that takes place in reservoirs and hydropower plants in particular can be estimated as the difference between the concentration of dissolved gas when the water enters the reservoir or dammed area and the concentration of dissolved gas downstream, multiplied by the outlet flow (IPCC 2019). The diffusive emission can either be measured directly or estimated using a mass balance approach (Goldenfum 2010). Typically, diffusive fluxes are estimated using near-surface concentrations in combination with a thin boundary layer model for most systems (see Deemer et al. 2016), using floating chambers or, if necessary, by eddy flux measurements (IPCC 2019). Ebullitive fluxes of CH_4 are estimated using inverted funnel traps and echo sounders. For the joint detection of ebullitive and diffusive CH_4 fluxes, floating chambers or eddy flux techniques or a combination of the available methods are commonly used (IPCC 2019).

For large bodies of water, very accurate measurements of emissions can also be achieved by installing eddy covariance systems with suitable gas sensors that are continuously measuring throughout the year (Lorke & Burgis 2018). The eddy covariance method is a direct micrometeorological measurement method for quantifying turbulent gas exchange. The average volume of air passing a measuring point is measured in relation to the vertical wind speed, the direction of movement and the gas concentration or density over a specific measuring interval in order to record the fluctuations. Studies in which this method was used are, for instance, Spank et al. (2017) and Hounshell et al. (2023).

GHGs can now also be measured with relatively high precision from space (e.g. Engram et al. 2020; Ai et al. 2022). For example, data from the Copernicus Sentinel-5P satellite, NASA's Orbiting Carbon Observatory (OCO-2), the Chinese space agency's TanSat mission and the Japanese space agency's Gosat-2 mission can be used (ESA 2020). However, the mixture of gases from different areas of origin makes it difficult to carry out a causal, spatially differentiated analysis. Copernicus-Sentinel-5, for example, is a spectrometer for trace gases in the ultraviolet, visible, near and short-wave infrared range that achieves a resolution of 7.5 km x 7.5 km (DLR 2024). For the spatial level of inland waters, this can therefore currently only be properly interpreted for large lakes.

If in situ data are available for inland waters, they are only representative for the respective location, usually a rather small area of water, and the corresponding measurement period. These data have to be regionalised, i.e. transferred from a type of point information to area-based information (interpolation and extrapolation). Given the high complexity of GHG release processes and the high degree of individuality of water bodies, even simple regional analogy methods are very difficult. The most important step is therefore the transition to statistical analyses and, above all, statistical models (Chapter 6.2). To ensure this, the following factors in particular should be taken into account to adequately characterise the boundary conditions, in addition to recording the measured values and safeguarding against measurement errors:

- Hydrometric characteristics (e.g. water body area, volume, depth ratios, age of reservoirs)
- Hydrological characteristics (discharge, residence time, flow velocity)
- Level of current (or historical) organic and inorganic pollution of the water bodies or from the catchment area, especially for TOC as well as P and N compounds
- Physical-chemical conditions of the water
- Meteorological conditions
- Special anthropogenic influences: structures, watercourse maintenance regime
- Sediment properties (geological, physical, chemical, biological)

It is noteworthy that for chlorophyll-a, which indicates the trophic and thus the water body's internal primary production, as well as for particular organic C or calcium carbonate concentration measurements, the use of satellites is strongly improving (e.g. Balch et al. 2005; Deemer et al. 2016; Clay et al. 2019; Hu et al. 2019), which also opens up opportunities for data integration, at least for larger inland waters.

6.2 Statistical models

Assessment of statistical models

Statistical models are internationally widely used to quantify GHG emissions. The quality of statistical models is highly dependent on the database that is used for their validation. A broad and representative database enables a more accurate identification of relationships between GHG emissions and their influencing factors within specific water body types.

Extrapolations based on statistical models will only be reliable and reasonable if all general water body types and their characteristic conditions are included into the model. Currently, the available database does not seem to be appropriate to reliably predict GHG emissions of each water body type. Thus, estimated global GHG emissions for all inland waters are likely highly uncertain.

Statistical models are used to fundamentally analyse the properties of the measurement data and to transfer these properties as a method of spatial transfer or regionalisation. Before obtaining the corresponding statistical parameters, however, the measurement data should be checked for possible errors (inconsistency) and possible regime changes (inhomogeneity) and, if necessary, adjusted, e.g. by removing outliers.

The quality of such models depends crucially on the quality and quantity of measurement and observation data. The best possible compliance with the requirements for representative data described in Chapter 6.1 therefore plays a central role.

Due to their ease of use, statistical models are internationally widely used to quantify GHG emissions (e.g. Deemer et al. 2016; Harrison et al. 2017; Aho et al. 2023). Many models are based on regression relationships with decisive influencing factors as regressors, so-called multiple regression equations (e.g. Karlsson et al. 2021), or other multivariate statistical models (e.g. Prairie et al. 2021). For CH_4 emissions from reservoirs, the well-known, empirical Greenhouse Gas Reservoir Tool (G-res) model according to Prairie et al. (2017) can be used, which enables a relatively simple estimation by considering reservoir-specific data (reservoir morphometry, littoral areas, and local climate data including air temperature and solar radiation).

The above-mentioned data on the boundary conditions (Chapter 6.1) could also be used to initially establish a type series: GHG release types of inland waters, e.g. by using multivariate statistical methods such as cluster analyses, among others. Each type would then be adequately characterised and identified by a typical GHG emission behaviour (e.g. mean or median, range of GHG release per time unit).

Statistical models also include the methodology according to the default method of the Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019), which was used by UBA (2023a) for the estimation of German GHG emissions from flowing and standing artificial waters.

However, there is (of course) a warning against applying derived statistical models to unknown water body types that have not yet been included in the models without closer scrutiny. For example, Chanudet et al. (2020) found that estimation functions for the GHG release of large reservoirs cannot be transferred to smaller reservoirs, mainly due to different morphological and hydrodynamic characteristics.

6.3 Stochastic models

By applying stochastic methods, random measurement data (in the sense of statistical samples) are related to probabilities so that probability-describing, stochastic models can be derived.

Stochastic models can be used to generate artificial time series that predict possible future processes and trends. In this respect, values simulated in this way can differ significantly from existing observations or measurement data in terms of size, temporal sequence, duration and other process characteristics.

As the meta-analysis shows, the use of stochastic models does not yet appear to play a role in connection with the release of GHGs from inland waters. One study who dealt with this kind of model is Beaulieu et al. (2016). This speaks in favour of the still very limited and uncertain database.

6.4 Deterministic models

In contrast, deterministic models as a transfer method are based on known or hypothetical physical (mathematical), chemical or biological laws. With the same model drive, the same results are always generated, i.e. there is unambiguity, which fundamentally distinguishes the models from stochastic models that work with probability distributions. Deterministic models for GHG release estimation are often based on water quality models including calibration data, such as Ho et al. (2021).

According to the meta-analysis, this group of models does not yet play a major role in the spatially comprehensive balancing of GHG release. The main reason for this is that input data and model parameters would have to be available in very high temporal and spatial resolution for corresponding models, but this will be difficult to achieve.

6.5 Mixed, stochastic-deterministic models

Mixed models, which combine stochastic and deterministic approaches as favourably as possible, are a fourth group of models. It is assumed that "safe" physical, chemical or even biological processes can be modelled deterministically, while stochastic model routines are dedicated to the question of uncertainty or probability. Ho et al. (2021), for example, combine a deterministic model approach (water quality modelling) with fuzzy model approaches for risk assessment of GHG production in an urbanized river system.

According to the meta-analysis, this group of models is also not yet of great importance, but its importance is expected to increase.

6.6 Conclusions

In order to obtain a larger and improved database on GHG release from inland waters in Germany, particularly with regard to accounting approaches, the above-mentioned options should first be utilised as a two-tiered approach as follows:

Tier 1: Representative measurements of GHG emissions

- ► Establishment of a measurement programme for GHG monitoring from inland waters that is representative for a diversity of water bodies and pressures; this should be done for all natural, artificial and heavily modified inland waters, water body types and across all scales
- ► Alignment of the measurement programme to all pathways of GHG transfer from water to atmosphere
- ► Due to the great importance of floodplains as C sinks, their inclusion in the monitoring programme should also be considered, as reciprocal effects of C transport between rivers and floodplains are to be expected

- Recording of key process-triggering and process-controlling factors (boundary conditions), such as hydrometric, hydrological, physico-chemical and meteorological data, as well as data on the organic and inorganic load situation
- Co-use of types of water bodies and floodplains (water body types according to OGewV, floodplain types according to Koenzen 2005) and the associated morphological, hydrological, geological and pedological conditions
- Collection of both GHG measurement data and data on the boundary conditions in a process-oriented time cycle and over a sufficient period of time in order to minimise meteorological, hydrological, water management and load-relevant influences on the homogeneity of the data as far as possible

Tier 2: Statistical analysis and modelling of GHG emissions

- Use of statistical analysis methods for the measurement data
- Including data on the boundary conditions or factors to be influenced for the transfer to statistical models, e.g. multiple regression models
- Alternative multivariate statistical methods such as cluster analyses; determination of typical GHG emission behaviours for different water body types (e.g. mean value or median, range of GHG release per time unit)
- Use of statistical methods to consider the GHG release of river basins

7 Potential mitigation measures to reduce GHG emissions of inland waters

7.1 Selection of relevant measure types

Many restoration measures that lead to an improvement of the ecological status of inland waters also have a high potential for reducing GHG emissions (e.g. Wang et al. 2022b; Kumar et al. 2023a). In this respect, synergies can be utilised here that are necessary in terms of the efficiency and cost-effectiveness of environmental protection measures (e.g. SRU 2020; Albert et al. 2022a, b).

The watercourse network in Germany covers more than 500,000 km; around a quarter of the watercourses have a catchment area of at least 10 km^2 and are therefore subject to reporting under the WFD. Of the more than 12,000 lakes in Germany, 738 lakes have a lake surface area of at least 50 ha and are therefore also subject to WFD reporting requirements (data from Völker et al. 2022). According to the WFD, there are requirements to achieve good status or good potential for the water bodies subject to reporting. The following focus on types of measure is based on the system of key types of measure (KTM) for the WFD and MSFD reporting of the German Working Group on water issues of the Federal States and the Federal Government. As also done for the relevant pressure types on the C cycle and GHG emissions (Chapter 5), LAWA (2022) is used as basis for this chapter. However, the KTMs described here are also summarised or differentiated on a case-by-case basis if this appears appropriate with regard to GHG emissions and important measures.

A qualitative or even quantitative assessment of the types of measures in terms of their contribution to GHG emission reduction is not possible at this generalised level. However, the potential reduction effects are very likely to be very effective for functionally suitable and spatially comprehensive measures. Consequently, strong synergies between water and nature conservation, soil protection and climate protection can be achieved.

7.2 Reduction of organic pollution and inorganic nutrient pollution of waters

7.2.1 Description of the measures and their physical and biogeochemical effects

98 % of German water bodies (water bodies subject to reporting under the WFD) are significantly polluted from diffuse sources. Significant point sources of substance inputs are also relevant for 32 % of water bodies (Völker et al. 2022). In addition, there is substance pollution of groundwater, which also has an indirect effect on surface waters. 42 % of groundwater bodies experience significant pollutant inputs from diffuse sources, 6 % of water bodies from point sources (Völker et al. 2022).

The measure type “reduction of organic pollution and inorganic nutrient pollution of water bodies” comprises several KTMs of LAWA (2022):

- Construction or upgrades of wastewater treatment plants
- Advisory services for agriculture (note: with the aim of reducing agricultural emissions, e.g. as a result of fertilisation)
- Upgrades or improvements of industrial wastewater treatment plants (including farms)

- Measures to reduce sediment from soil erosion and surface run-off

From a water protection perspective, the KTMs are primarily aimed at improving the oxygen balance of waters and reducing the consequences of eutrophication for inland, coastal and marine waters. This is therefore aimed at achieving benefits in terms of improving the ecological status of water bodies in accordance with the WFD and MSFD.

A reduction of organic pollution and inorganic nutrient pollution of inland waters by means of the above KTMs represents the primary approach to reducing GHG emissions from waters because it addresses a major anthropogenic cause of pollution (e.g. Wang et al. 2022b; Kumar et al 2023a).

This means that the supply of organic and inorganic matter for the GHG production in inland waters has to be reduced, in the best case to a near-natural level. From then on, GHG emissions would approach natural conditions, whereby the gradual reduction of historical pollution would generally set the framework for the level and speed of adaptation.

7.2.2 Benefits in terms of GHG emission reduction

Whether as organic material from the catchment area or as a result of primary production within the water bodies, less organic matter means less C in inland waters. Organic matter that does not end up in the water bodies would naturally be degraded to CO_2 elsewhere. In this respect, there is probably no decisive advantage associated with a reduction in organic pollution of water bodies in terms of CO_2 release alone, but there is a major advantage with regard to CH_4, which is significantly more harmful to the climate.

Particularly in lentic waters, the input of organic matter also leads to sediment accumulation and to siltation, primarily in the deep zones as well as in shallow, current-, wave- and wind-protected bank areas. This accumulation of organic material can therefore also represent permanent C storage, e.g. as a preliminary stage in the development of peatlands (Succow & Joosten 2001).

Concerning N_2O, unpolluted or only slightly anthropogenically polluted surface waters are apparently often undersaturated with N_2O and therefore represent a temporary N_2O sink, as Aho et al. (2023) found for North American inland waters. In their study, they used (a) observational data from 34 streams, rivers, and lakes monitored by the US National Ecological Observatory Network and (b) an existing global process-based model of N_2O emissions from inland waters. In this respect, the reduction of water pollution by organic substances and eutrophication-relevant inorganic nutrients, especially P and N compounds, also leads to a reduction in N_2O emissions, as was shown for instance by Wang et al. (2022b), and possibly even to the recovery of water bodies as a sink for N_2O. Based on a meta-analysis of the global literature in the context of N_2O emissions, Schödel (2024) concludes that the anthropogenically increased N_2O emissions from inland waters must be reduced primarily through measures to reduce nitrogen emissions from agriculture and warns of a further global increase in these emissions.

7.3 Improving longitudinal continuity

7.3.1 Description of the measures and their physical and biogeochemical effects

Improving longitudinal continuity is a type of measure aimed at improving the continuity of water bodies in accordance with Annex V of the WFD. To this end, the pressures are assessed with regard to the migration possibilities of aquatic fauna and the transport of sediment. Barriers therefore play a strongly negative role for the ecological conditions of watercourses and their floodplains (see Chapter 5.3). There are around 215,000 transverse structures in Germany's watercourses subject to WFD reporting requirements alone (Völker et al. 2022). These range from small structures (e.g. bed sills, drops) to large weirs or even dams.

From the perspective of water protection, flood protection and floodplain development, the numerous small run-of-river power plants and the associated barriers in Germany, which are insignificant in terms of energy production, should also be fundamentally called into question (Mehl et al. 2023b). For the EU, the proposal for a regulation of the European Parliament and the Council on the restoration of nature ("Nature Restoration Law", European Commission 2022a) provides a legal basis for the removal of river barriers so that 25.000 km of free-flowing rivers are to be re-established in the EU by 2030.

Not only are hydropower plants very critical from an ecological point of view, they also only play a subordinate role in terms of energy production, are very abundant and often constitute the only reason for single-purpose barriers in rivers. The release of highly climate-damaging GHGs should consistently be seen as a trade-off for the supposedly climate-neutral generation of electricity from hydropower plants (Chapter 5.3).

Measures to only achieve ecological continuity such as fish passes are not appropriate to achieve a reduction of GHG emissions due to altered physical conditions through barriers. Therefore, only measures that aim to completely or at least significantly reduce the hydrodynamic barrier effect can be effective in terms of GHG release reduction (Chapter 5.3.1). Consequently, it is essential to at least dismantle the barriers and harmonise the longitudinal and transverse profile to near-natural conditions. The anthropogenic fragmentation should therefore be adapted in favour of a near-natural longitudinal gradient. At the same time, such measures are also the most ecologically favourable, so that high synergies between water protection, nature conservation and climate protection can be achieved here (EEB 2023, see also e.g. Oetken & Sundermann, 2018; Mehl et al. 2022a, b; Naumann 2022).

7.3.2 Benefits in terms of GHG emission reduction

The improvement of longitudinal continuity can make a decisive contribution to reducing artificial accumulation areas for organic substances and the associated anoxic conditions in the sediments. This would shift the GHG releases of CH_4 and N_2O more into the direction of CO_2, which is less harmful to the climate, even with the same organic load. The more river restoration measures (see Chapter 7.4) are taken in parallel, the greater this effect is likely to be.

This is confirmed by the examined studies. For example, CH_4 release rates increase with sedimentation rates in dammed watercourses (Sobek et al. 2012; Maeck et al. 2013; Lorke & Burgis 2018; Marcon et al. 2023), so that, conversely, a reduction in sediment accumulation lowers CH_4 release rates. This is also increasingly important because the relevant microbial activity increases strongly (and non-linearly) with rising water temperature (e.g. DelSontro et al. 2016). In this respect, the general increase in air and water temperatures due to climate change and the more frequent and longer periods of extreme heat (IPCC 2023) will lead to a further aggravation, which can be counteracted by improving longitudinal continuity.

7.4 River restoration

7.4.1 Description of the measures and their physical and biogeochemical effects

86 % of German surface water bodies are affected by flow regulation and morphological changes (Völker et al. 2022), meaning that extensive measures are required. River restoration is included

in the KTM "Improving hydromorphological conditions of water bodies" according to LAWA (2022). The following measures in particular are addressed with this type of measure:

- Formation of near-natural longitudinal and transverse profiles including natural pool-riffle sequences, insofar as this does not already concern measures for improving longitudinal continuity (Chapter 7.3)
- Near-natural course development, i.e. different degrees of winding, river bifurcations etc. typical of the rivers
- Input of site-typical bed substrates
- Input or allowance of deadwood
- Supporting self-dynamic structural elements, e.g. pools, islands, longitudinal and transverse banks
- Near-natural bank formation
- Supporting site-typical riparian vegetation
- Realising near-natural heterogeneous flow conditions

7.4.2 Benefits in terms of GHG emission reduction

Relevant restoration measures lead to an enormously increased atmospheric oxygen input in comparison to non-naturally restored waters (Schwoerbel 1964, 1967; Uhlmann 1988; Schönborn 1992). As a result, the decomposition of organic substances through increased oxic conditions is more likely to produce CO_2 and the release of CH_4 and N_2O is substantially reduced.

On the other hand, the measures lead to an enormous increase in biologically active areas, so that the degradation processes of biological self-cleaning are maximised (Spellman & Drinan 2001; Vagnetti et al. 2003). In addition, the deposition of particulate-bound organic substances in areas characterised by currents is reduced, so that the risk of anoxic sludge deposits is minimised.

In general, a near-natural water body structure strengthens biocomplexity and also leads to more complex food webs and thus higher incorporation of inorganic and organic nutrients into the biomass, so that the permanent storage of C is enhanced.

7.5 Reconnecting rivers to floodplains

7.5.1 Description of the measures and their physical and biogeochemical effects

Two thirds of the original floodplains along Germany's major rivers and streams are no longer available as natural floodplains due to flood protection dikes, but also partly as a result of watercourse development (BMU/BfN 2021). Of the remaining (recent) floodplains, only around 9 % can be assessed as very or slightly changed in terms of their ecological status (BMU/BfN 2021). In principle, the conditions in Germany's smaller watercourses are similar: many watercourses have lost their natural habitat and the remaining watercourses are often not in good ecological status. However, a systematic assessment and a comprehensive overview are lacking which can certainly be characterised as a deficit in the assessment requirements of the WFD.

Reconnecting rivers to floodplains, e.g. by allowing flooding in riparian areas to occur again, is therefore also part of the KTM "Improving hydromorphological conditions of water bodies" according to LAWA (2022). The reconnection of the floodplains creates the following physical and biogeochemical benefits:

- Deposition of organic matter in the floodplains during floods, thus export of organic matter from the river into the floodplain and consequently accumulation of C in the floodplain soils, as well as sequestration via mineralisation and the resulting increased supply of inorganic nutrients in the floodplain vegetation, permanently especially in the woody and forest vegetation
- Creation of near-natural groundwater and flooding regimes in the floodplains as a basis for soils with a high organic content and/or peatlands
- Temporary increase in bioactive areas and spaces for biological self-purification (decomposition of organic substances)

7.5.2 Benefits in terms of GHG emission reduction

Consequently, benefits in terms of GHG emission reduction also arise from this type of measure. Both C accumulation in the soil and indirect accumulation in the floodplain vegetation promote C storage that contributes to GHG reduction. In addition, the self-purification capacity is also increased during periods of flooding, so that more CO_2 is produced and the release of the more climate-damaging GHGs CH_4 and N_2O is reduced (Wang et al 2022b).

On the other hand, in floodplains with a high organic content or even peaty floodplains, the increase in groundwater levels and/or flooding offers the possibility of reduced GHG release and more C sequestration in the soil (Scholz et al. 2012; Mehl et al. 2013; Tiemeyer et al. 2020; UBA 2023a). Inorganic and organic nutrient inputs (in the case of mineralization) also lead to increased biomass formation as part of photosynthesis in the floodplain vegetation, which acts as a relatively permanent C store in the root zone and in the woody plants. In the case of herbaceous vegetation and the leaves of trees, however, storage is only temporary (limited to the growing season).

7.6 Improvements in flow regime and/or establishment of ecological flows

7.6.1 Description of the measures and their physical and biogeochemical effects

The improvement of the flow regime or the creation of ecological flows corresponds to the same KTM according to LAWA (2022).

Natural hydrological and associated geohydrological and hydrodynamic processes form the basis of functional geoecological structures and processes in watercourses and their floodplains, which provide the abiotic framework for the wildlife (Ward 1989; Richter et al. 1997; Thoms 2006). Above all, they are necessary to maintain a self-sustaining biocomplexity in the watercourse systems (Thorp et al. 2006). The re-establishment of natural flow dynamics and variability in anthropogenically modified watercourse systems thus form an essential basis for functional biogeochemical processes (Chapter 3) and for the natural aquatic and floodplain flora and fauna (Merot et al. 2006; Seidel et al. 2017).

Hydrological conditions play a key role in understanding all ecosystems dependent on the hydrological regime. The "paradigm of environmental flow" is fundamentally accepted as a reference, whereby five essential components of the natural run-off regime are emphasised (Poff et al. 1997): (1) magnitude, (2) frequency, (3) duration, (4) timing and (5) rate of change of hydrological conditions. The hydrological regime therefore also forms a supporting assessment approach of the WFD, which in Germany is mapped in particular via a method of the German Working Group on water issues of the Federal States and the Federal Government (Mehl et al. 2015).

Previous applications of the methodology according to Mehl et al. (2015) at the federal state level have shown the following results, among others:

- In Saxony-Anhalt, 2 water bodies were classified as very good and 95 as good, while 216 were classified as not good; the main deficits are modifications/utilisation in the catchment area (pressure group A), morphological alterations (pressure group D) and floodplain alterations (pressure group E) (Mehl et al. 2010; Hoffmann et al. 2010).
- In Mecklenburg-Western Pomerania, 120 watercourse water bodies were classified as good, but 737 as not good; the main reasons for the „not good“ classification of the watercourse water bodies are deficits in pressure groups A (modifications/utilisation in the catchment area), D (morphological alterations) and E (floodplain alterations) as well as pressures due to the removal of natural basin drainage areas (pressure group F) (Biota 2014); in contrast, 13 of the lake water bodies in Mecklenburg-Western Pomerania were categorised as very good, 122 as good and only 61 water bodies as not good (Biota 2014).
- In Baden-Württemberg, only 12 water bodies were classified as good, while 163 were classified as not good; the main reasons for this are relatively high pressures in pressure groups D (morphological alterations) and E (floodplain alterations), but also deficits in pressure groups A (modifications/utilisation in the catchment area) and C (water discharges) (Schönrock et al. 2021).
- In Saxony, only 42 water bodies could be classified as good, while 516 water bodies were classified as not good, 12 of which were even classified as bad; in Saxony, too, it is mainly morphological alterations (pressure group D) and floodplain alterations (pressure group E) that are the cause, and land use (pressure group A) also has a negative impact on the result (report in preparation).

Measures to improve the flow regime include in particular:

- Reduction of water abstraction and associated adverse hydrological phenomena, e.g. intensification of low flows, changes in material transport processes (erosion, transport and accumulation of substances)
- Reduction of anthropogenic rainwater discharges and associated adverse hydrological consequences, e.g. run-off peaks and hydraulic stress in waters
- Imitation of the natural ecological discharge at diversion structures (at dams and other water reservoirs)

7.6.2 Benefits in terms of GHG emission reduction

Measures of this type can re-establish the flow regime to more natural conditions or even achieve them. The fundamental advantage for the reduction of GHG emissions is that, as a rule, more stable discharge conditions occur and more functional biocoenoses can be maintained. More stable biocoenoses feature a stronger self-purification capacity with regard to organic pollution and greater incorporation of inorganic and organic nutrients. This is associated with a temporary or permanent removal of nutrients by the ecosystem, leading to a reduction of GHG production.

In watercourses, a more stable (higher) low-flow can improve the input of atmospheric oxygen, shifting the biogeochemical conditions for the decomposition of organic matter in favour of the release of CO_2. A higher low water flow would also influence the material transport processes in the water systems. More organic material could already be degraded in the open water and would not be deposited in the sediment, reducing the risk of anaerobic conditions in areas with low flow velocities. This would fundamentally reduce the risk of releasing the particularly climate-damaging gases CH_4 and N_2O.

7.7 Natural water retention measures

7.7.1 Description of the measures and their physical and biogeochemical effects

Natural water retention measures correspond to the same KTM according to LAWA (2022). Water retention measures include in particular those implemented in the hydrological catchment area, including:

- Wetland and peatland restoration measures
- Water retention in forests by blocking drainage paths
- Removal or limitation of artificial surface drainage measures (drainage, ditch drainage)
- Run-off attenuation measures, e.g. interruption of run-off paths by hedges
- Technical retention measures in urban areas, e.g. rainwater retention basins
- Measures to increase local infiltration (thus slowing down run-off through increased base flow/groundwater flow)
- Development of near natural or artificial retention areas, e.g. by relocating dykes, constructing or establishing flood retention basins or polders

7.7.2 Benefits in terms of GHG emission reduction

Corresponding measures initially also lead to improvements in the flow regime or to the establishment of ecological flows with the associated benefits in terms of GHG emission reduction (see Chapter 7.6).

It is very important that water retention measures also contribute to the retention of organic substances and inorganic nutrients, which reduces the pressure on inland waters accordingly. This is particularly evident in the case of wetland and peatland restoration measures, where the measures can achieve an accumulation and relatively permanent removal of C, N and P (Walton et al. 2020; Zak et al. 2022; Zou et al. 2022). The retention efficiencies of wetland buffer zones were estimated to be 43 % for total N and 21 % for total P (Walton et al. 2020).

7.8 Overview of the effectiveness of the measure types

The different types of measures have different levels of effectiveness. They range from always effective to effective only under specific conditions. All measures that lead to a reduction in direct organic pollution and inorganic nutrient inputs with the associated internal production of organic matter in waters can be regarded as generally effective in terms of reducing GHG release from inland waters.

For many of the above-mentioned impacts of anthropogenic pressures on the C cycle and GHG emissions, it is clear that, due to the significantly higher climate damage compared to CO_2, measures aiming to reduce the release of CH_4 and N_2O from inland waters should primarily be focussed on.

In individual cases, however, the relative effectiveness of GHG-reducing measures depends especially on the following aspects:

- Natural characteristics, in particular geological and pedological conditions (e.g. proportion of peatlands), gradients, hydrogeological conditions, proportion of standing water bodies, water network density (watercourses)
- Size and type of water bodies and floodplains (water body types according to OGewV, floodplain types according to Koenzen 2005) and associated morphological, hydrological, geological and pedological conditions
- Utilisation-related anthropogenic pollution situation in the hydrological catchment area and in the water system (organic substances, inorganic nutrients)
- Existing (historical) organic pollution, accumulated in sediments

In general, the scope of the measures and the achievable reduction in relation to the magnitude of the anthropogenic GHG release from inland waters plays a major role, which can be analysed by water body stretches/areas or catchment areas.

An orientating assessment of the effectiveness of the types of measures to reduce GHG release from inland waters as described above is provided in Table 5.

Table 5: Effectiveness of types of measures to reduce GHG release from inland waters

Three-class evaluation based on the meta-analysis (low, moderate, high)

Measure types	Effectiveness in reducing the release of CO_2	Effectiveness in reducing the release of CH_4	Effectiveness in reducing the release of N_2O
Reduction of organic pollution and inorganic nutrient pollution of water bodies	high	high	high
Improving longitudinal continuity *(only measures aimed at completely or at least significantly reducing the hydrodynamic barrier effect)*	low	high	high
River restoration	moderate - high	moderate - high	moderate
Reconnecting rivers to floodplains (C storage in floodplains, especially in peatlands)	moderate - high	moderate - high	moderate
Improvements in flow regime and/or re-establishment of a functional water balance/hydrological regime	low	moderate - high	low - moderate
Natural water retention measures	moderate - high	moderate - high	moderate - high

8 Conclusions

8.1 Key findings

The most important messages of this study can be summarised as follows:

- The significance of GHG release (CO_2, CH_4, N_2O) from inland waters is currently not sufficiently quantifiable but should be considered comparatively high. This is due to their natural function as a preflood of runoff from land areas, so that large quantities of organic and inorganic substances are concentrated and biologically processed. On a global scale, Lauerwald et al. (2023b) estimate the contribution of inland waters to global CH_4 emissions at around 20 %. The proportions of CO_2 and N_2O are not yet known.

- The meta-analysis revealed that the greatly increased GHG release compared to natural conditions is of anthropogenic origin. A stronger anthropogenic pressure therefore stimulates a higher GHG production and release.

- The primary cause of enhanced GHG emissions is organic pollution of water bodies, which is often caused by high inorganic nutrient inputs (especially P and N) which stimulate high primary production. N inputs also increase the probability of increased N_2O release. The continuing organic pollution of German inland waters is evident. Inorganic pollution is still very high, as demonstrated by the results of the national reporting for WFD and MSFD implementation (Völker et al. 2022).

- In artificial waters, the currently altered hydromorphological/hydraulic conditions have a negative impact on the release of GHGs, particularly CH_4 and N_2O, as demonstrated by the meta-analysis; in particular, the release is the result of a strong tendency to accumulate organic matter in the sediment with simultaneous oxygen deficiency.

- In natural and heavily modified water bodies as defined by the WFD, the various anthropogenic changes to the water bodies and their mostly disconnected floodplains (morphological, hydrological, etc.) have a pollution-increasing effect, which primarily leads to reduced self-purification processes (organic pollution), intensifies trophic phenomena and also promotes increased accumulation of organic matter in the sediment with simultaneous oxygen deficiencies (see above; this is also confirmed by the meta-analysis). Dams and barriers, which enable the accumulation of organic matter over long spatial distances due to altered hydraulic conditions, appear to be particularly negative.

- If hydropower plants are the single purpose of building dams and barriers, the resulting increase in GHG release reduces their value for electricity generation with low GHG release. This shows that, from the point of view of water protection, it is not only the ecologically highly negative consequence of these structures that need to be taken into account (e.g. European Commission 2022a; EEB 2023), but also the acceptance of increased GHG releases from waters due to anthropogenic activities needs to be tackled.

- The analysis of the types of pollution for anthropogenically increased GHG emissions shows that there is a considerable overlap with the causes of pressures in the field of water protection, which is why the pressure type system can be used in particular in connection with WFD implementation and was also used here to analyse the international studies. Practically all GHG-related pressures are also pressures that are relevant for water protection (water management and nature conservation).

- The real extent of GHG release from German inland waters currently appears to be significantly underestimated in the national GHG inventory (UBA 2023a). This is supported by the following gaps in the current report (see Table 414 in UBA 2023a): a) no data and balances on the release of CO_2 from all categories of inland waters, b) no data and balances on the release of the particularly climate-damaging N_2O from all categories of inland waters, c) no data and balances on the release of CH_4 from standing and flowing waters, which are of natural origin (according to the WFD definitions, this includes natural and heavily modified water bodies), d) no data and balances on the release of CH_4 from standing and flowing artificial waters which were constructed less than 20 years ago. However, for artificial waters on organic soils (drainage ditches, standing artificial waters), UBA (2023a) offers emission estimates at least for CH_4 without an age limit; for peat extraction areas (in the sense of wetlands), UBA (2023a) provides emission estimates for CO_2, CH_4 and N_2O.

- According to IPCC (2019), the emission factors used in UBA (2023a) for the sole CH_4 release considered (for water bodies on mineral soils) also only represent global average values and are subject to large uncertainties (see also Saunois et al. 2020; Rosentreter et al. 2021), which makes it clear that the current estimation of German GHG release balances for the categories of standing and flowing artificial waters more than 20 years old should be considered uncertain.

- Furthermore, the approach used in UBA (2023a) to determine mean emission factors depending on the trophic status of the water bodies is pragmatically appropriate (reduction/other scaling of the default values according to IPCC 2019). The data basis used for this approach (according to Hoehn et al. 2009) is undisputedly technically appropriate. However, whether it is really representative of the diversity of water types and their pollution situation, and whether it is still sufficiently up-to-date, should at least be critically scrutinised. In any case, the data set is not representative of small waters in the landscape.

- Despite the argument of the current lack of data availability or missing emission factors, the IPCC's (2019) technical recommendation not to include GHG emissions from natural waters (initially) in the national GHG inventories for international reporting, which was also followed by the German report (UBA 2023a), should be critically scrutinised. IPCC (2019) also initially only includes an "obligation" to assess CH_4 release apart from water bodies on organic soils. According to the WFD definitions, water bodies with a natural origin are either natural or heavily modified. For both categories together, more than 90 % of the German water bodies do not achieve the "good ecological status" required by the WFD (based on the water bodies formed; Völker et al. 2022), which indicates significant anthropogenic GHG pollution. A total area of "only" 89,000 ha of artificial water bodies in Germany (on mineral soils; accounting for 14 % of the total area of inland waters; to a certain extent considered in UBA 2023a) contrasts with a significantly larger area of 572,083 ha of natural water bodies (data from UBA 2023a), which were not considered, clearly illustrating the problem.

- Overall, there is a considerable lack of knowledge in Germany with regard to the release of GHGs from inland waters (as well as on a global scale, see Lauerwald et al. 2023a, b). Relevant data are also important for the assessment of complex pressures on water bodies and with regard to synergies of measures (in particular WFD, MSFD, EU restoration law, EU birds and habitats directives), which emphasises the urgency of improving the state of knowledge, as well as the database.

8.2 Open research questions

Two central topics are the focus of national and international research needs:

1. The necessary improvement of the state of knowledge on the most important GHG emissions from inland waters as an essential part of the analysis, balancing and evaluation of anthropogenic GHG pollution as a driver of global climate change.
2. On the basis of improved knowledge, an appropriate implementation and evaluation of the GHG issue in connection with the objectives and measures of water protection (water management and nature conservation).

The following research tasks were identified:

- There is a great need for action in Germany with regard to a suitable measurement strategy for the release of GHGs (CH_4, N_2O and CO_2) from inland waters and for the development of reliable transfer functions for balancing (in the form of emission factors, see also Lauerwald et al. 2023a, b). Schödel (2024) is also in favour of more (permanent) measurement campaigns under very different framework conditions with regard to N_2O, which in her opinion is underestimated in terms of climate policy. Tian et al. (2020) see the need for N_2O measurements to improve the quality of existing models through validation.

- In this respect, the aim is to obtain sufficient measurement data on GHG release for inland waters in Germany according to the standards of (1) spatial and temporal representativeness, (2) reflection of the diversity of water types and the main parameters influencing GHG release (morphometry, hydrology, etc.) and (3) coverage of the different pollution situations (internal and external).

- A sampling strategy geared towards representativeness is therefore necessary for all types of inland waters (flowing waters, lakes, canals, harbour basins, reservoirs, ditches, small water bodies/standing waters, etc.) and the corresponding water categories according to the WFD (natural, heavily modified inland waters), preferably with the help of a profound statistical approach (relevant parameters must be defined in advance, their respective significance must also be assessed in advance, see Goldenfum 2010; IPCC 2019).

- Important parameters are in particular hydrometric characteristics (e.g. water body area, volume, depth ratios, age of reservoirs), hydrological characteristics (discharge, residence time, flow velocity), degree of current (or historical) organic and inorganic pollution of the water bodies or from the catchment area, in particular for TOC, P and N compounds, physicochemical conditions of the water, meteorological conditions, special anthropogenic influences: Structures, water maintenance regime, sediment properties (geological-soil, physical, chemical, biological), e.g. in the case of reservoirs also the depth of abstraction and the type of stratification and circulation.

- The measurement procedures/methods for quantifying GHGs should be standardised or, if necessary, intercalibrated for uniform data and assessments throughout Germany. Measurements should be carried out over a complete annual cycle to increase accuracy, as the dynamics of GHG release are highly temperature-sensitive (IPCC 2019); measurements over several years may even be appropriate under exceptional meteorological/hydrological conditions.

- Four pathways in terms of the transfer of GHGs from water bodies to the atmosphere should be adequately considered: (1) release through upwelling gas bubbles, (2) diffusive gas exchange at the water surface, (3) degassing downstream and (4) emission via emersed macrophytes.

- In the short/medium term, it is necessary to obtain reliable (statistical) transfer functions as a basis for well-founded estimates (emission factors for appropriate water body types with regard to key parameters/characteristics and organic and inorganic loads). In the medium/long term, the derivation of deterministic and/or mixed stochastic-deterministic models can help to improve the transfer approaches.
- Regular comparisons with the default approaches of the IPCC and possibly other internationally recommended approaches are advisable. Conclusions should be drawn for all levels of application, possibly depending on the scale (tiered approach). Data bases and methods of the IPCC can be influenced/improved with convincing national results (including corresponding publications).
- Natural climate protection ("Natural Climate Protection Action Programme", BMUV 2023a) in inland waters and their floodplains is essentially based on water protection measures (WFD). Nature-based water protection solutions (Albert et al. 2022a, b) are predominantly also climate protection measures (and in many cases also climate adaptation measures). The corresponding synergies could be demonstrated and evaluated, also in terms of multiple target fulfilment and cost-effective implementation (see e.g. Mehl et al. 2023a).
- The great importance of GHG release from water bodies and floodplains should also be taken into account when assessing ecosystem services in terms of the natural retention of GHGs (Scholz et al. 2012; Mehl et al. 2013, 2020; Podschun et al. 2018a; Mehl 2021; Von Keitz et al. 2022). Existing methods should continuously be developed further as knowledge of the scientific basis increases (Podschun et al. 2018b; Gerner et al. 2023).
- Effect monitoring of implemented measures in accordance with the types of measures under the WFD/LAWA (2022) with regard to GHG release and an evaluation of effectiveness (e.g. also taking transport processes into account) is advisable in order to arrive at improved assessment approaches and valid data for public relations work. To this end, it is also advisable to investigate the interactions of GHG release/binding in water bodies and floodplains (especially peatlands). This includes the search for correlations and synergies with regard to the C and nutrient balance between water bodies and recent floodplains, differentiated according to water body and floodplain types.

9 List of references[1]

Aben, R., Barros, N., van Donk, E., Frenken, T., Hilt, S., Kazanjian, G., Lamers, L., Peeters, E., Roelofs, J., de Senerpont Domis, L., Stephan, S., Velthuis, M., van de Waal, D., Wik, M., Thornton, B., Wilkinson, J., DelSontro, T. & Kosten, S. (2017): Cross continental increase in methane ebullition under climate change. In: *Nature communications* 8 (1), p. 1682. https://doi.org/10.1038/s41467-017-01535-y.

Aben, R., Oliveira Junior, E., Carlos, A., van Bergen, T., Lamers, L. & Kosten, S. (2022a): Impact of plant species and intense nutrient loading on CH_4 and N_2O fluxes from small inland waters: An experimental approach. In: *Aquatic Botany* 180, p. 103527. https://doi.org/10.1016/j.aquabot.2022.103527

Aben, R., Velthuis, M., Kazanjian, G., Frenken, T., Peeters, E., van de Waal, D., Hilt, S., Senerpont Domis, L. de, Lamers, L. & Kosten, S. (2022b): Temperature response of aquatic greenhouse gas emissions differs between dominant plant types. In: *Water research* 226, p. 119251. https://doi.org/10.1016/j.watres.2022.119251

Aho, K. S., Maavara, T., Cawley, K. M. & Raymond, P. A. (2023): Inland waters can act as nitrous oxide sinks: Observation and modeling reveal that nitrous oxide undersaturation may partially offset emissions. In: *Geophysical Research Letters*, 50, e2023GL104987. https://doi.org/10.1029/2023GL104987

Ai, Y., Huang, T., Duan, C., Di Huang, Gong, Y. & Cheng, H. (2022): Knowledge domain of greenhouse gas emissions from hydropower reservoirs: Hotspots, frontiers and future perspectives. In: *Frontiers in Environmental Science* 10. https://doi.org/10.3389/fenvs.2022.1055891

Albert, C., Schröter, B., Brillinger, M., Henze, J., Guerrero, P., Gottwald, S., Haase, D., Herrmann, S., Mehl, D., Nicols, C., Ott, E., Schmidt, S. & Sommerhäuser, M. (2022a): Naturbasierte Lösungen in Flusslandschaften entwickeln, Chancen für Menschen und Natur nutzen. In: *Naturschutz und Landschaftsplanung* 54 (03), pp. 12-19. https://doi.org/10.1399/NuL.2022.03.01

Albert, C., Schröter, B., Brillinger, M., Kelly, T., Ott, E. & Schmidt, S. (2022b): Naturbasierte Lösungen in Flusslandschaften entwickeln: Wie kann eine erfolgreiche Planung gelingen? In: *Korrespondenz Wasserwirtschaft* 15 (3), pp. 157–162. https://doi.org/10.3243/kwe2022.03.002

Alin, S., Rasera, M., Salimon, C., Richey, J., Holtgrieve, G., Krusche, A. & Snidvongs, A. (2011): Physical controls on carbon dioxide transfer velocity and flux in low-gradient river systems and implications for regional carbon budgets. In: *Journal of Geophysical Research* 116, G01009. https://doi.org/10.1029/2010JG001398

Alshboul, Z., Encinas-Fernández, J., Hofmann, H. & Lorke, A. (2016): Export of dissolved methane and carbon dioxide with effluents from municipal wastewater treatment plants. In: *Environmental Science & Technology* 50 (11), pp. 5555–5563. https://doi.org/10.1021/acs.est.5b04923

Amani, M., Schiller, D. von, Suárez, I., Atristain, M., Elosegi, A., Marcé, R., García-Baquero, G. & Obrador, B. (2022): The drawdown phase of dam decommissioning is a hot moment of gaseous carbon emissions from a temperate reservoir. In: *Inland Waters* 12 (4), pp. 451–462. https://doi.org/10.1080/20442041.2022.2096977

AMBER Consortium (2020): The AMBER Barrier Atlas. A Pan-European database of artificial instream barriers. Version 1.0 June 29th 2020. https://amber.international/european-barrier-atlas/

Ansari, J., Davis, M., Anderson, S., Eivazi, F. & Bardhan, S. (2023): Greenhouse Gas Emissions from Row Crop, Agroforestry, and Forested Land Use Systems in Floodplain Soils. In: *Water, Air & Soil Pollution,* 234 (4). https://doi.org/10.1007/s11270-023-06227-6

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[1] The list of references also includes studies that were collected for the meta-analysis but are not mentioned within the chapters of this review.

Audet, J., Carstensen, M., Hoffmann, C., Lavaux, L., Thiemer, K. & Davidson, T. (2020): Greenhouse gas emissions from urban ponds in Denmark. In: *Inland Waters* 10 (3), pp. 373–385. https://doi.org/10.1080/20442041.2020.1730680

Aufdenkampe, A., Mayorga, E., Raymond, P., Melack, J., Doney, S., Alin, S., Aalto, R. & Yoo, K. (2011): Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. In: *Frontiers in Ecology and the Environment* 9 (1), pp. 53–60. https://doi.org/10.1890/100014

Balch, W. M., Gordon, H. R., Bowler, B. C., Drapeau, D. T. & Booth, E. S. (2005): Calcium carbonate measurements in the surface global ocean based on Moderate-Resolution Imaging Spectroradiometer data. In: *Journal of Geophysical Research* 110, C07001. https://doi.org/10.1029/2004JC002560

Baliña, S., Sánchez, M. & Del Giorgio, P. (2022): Physical Factors and Microbubble Formation Explain Differences in CH_4 Dynamics Between Shallow Lakes Under Alternative States. In: *Frontiers in Environmental Science* 10, Article 892339. https://doi.org/10.3389/fenvs.2022.892339

Balmer, M. & Downing, J. (2011): Carbon dioxide concentrations in eutrophic lakes: undersaturation implies atmospheric uptake. In: *Inland Waters*, 1:2, pp. 125-132. https://doi.org/10.5268/IW-1.2.366

Barros, N., Cole, J., Tranvik, L., Prairie, Y., Bastviken, D., Huszar, V., Del Giorgio, P. & Roland, F. (2011): Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. In: *Nature Geoscience* 4 (9), pp. 593–596. https://doi.org/10.1038/ngeo1211

Battin, T., Lauerwald, R., Bernhardt, E., Bertuzzo, E., Gener, L., Hall, R., Hotchkiss, E., Maavara, T., Pavelsky, T., Ran, L., Raymond, P., Rosentreter, J. & Regnier, P. (2023): River ecosystem metabolism and carbon biogeochemistry in a changing world. In: *Nature* 613, pp. 449–459. https://doi.org/10.1038/s41586-022-05500-8

Battin, T., Luyssaert, S., Kaplan, L., Aufdenkampe, A., Richter, A. & Tranvik, L. (2009): The boundless carbon cycle. In: *Nature Geoscience* 2 (9), pp. 598–600. https://doi.org/10.1038/ngeo618

Bauwe, A., Neumann, D. & Lennartz, B. (2019): Einfluss des Klimawandels auf Abfluss und Phosphoraustrag. In: *Korrespondenz Wasserwirtschaft* 12 (3), pp. 166–171. https://doi.org/10.3243/kwe2019.03.006

Beaulieu, J., DelSontro, T. & Downing, J. (2019): Eutrophication will increase methane emissions from lakes and impoundments during the 21st century. In: *Nature communications* 10 (1), p. 1375. https://doi.org/10.1038/s41467-019-09100-5

Beaulieu, J., McManus, M. & Nietch, C. (2016): Estimates of reservoir methane emissions based on a spatially balanced probabilistic-survey. In: *Limnology and Oceanography* 61, pp. S27–S40. https://doi.org/10.1002/lno.10284

Beaulieu, J., Shuster, W. & Rebholz, J. (2010): Nitrous oxide emissions from a large, impounded river: the Ohio River. In: *Environmental science & technology* 44 (19), pp. 7527–7533. https://doi.org/10.1021/es1016735

Bednařík, A., Blaser, M., Matoušů, A., Hekera, P. & Rulík, M. (2017): Effect of weir impoundments on methane dynamics in a river. In: *Science of the total environment* 584-585, pp. 164–174. https://doi.org/10.1016/j.scitotenv.2017.01.163

Benjankar, R., Tonina, D., McKean, J., Sohrabi, M., Chen, Q. & Vidergar, D. (2018): Dam operations may improve aquatic habitat and offset negative effects of climate change. In: *Journal of environmental management* 213, pp. 126–134. https://doi.org/10.1016/j.jenvman.2018.02.066

Berga, L. (2016): The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. In: *Engineering* 2 (3), pp. 313–318. https://doi.org/10.1016/J.ENG.2016.03.004

Best, J. (2019): Anthropogenic stresses on the world’s big rivers. In: *Nature Geoscience* 12 (1), pp. 7–21. https://doi.org/10.1038/s41561-018-0262-x

Bhullar, G., Iravani, M., Edwards, P. & Venterink, H. (2013): Methane transport and emissions from soil as affected by water table and vascular plants. In: *BMC Ecology* 13, 32. https://doi.org/10.1186/1472-6785-13-32

Biota (2014): Klassifizierung des Wasserhaushalts von WRRL-relevanten Wasserkörpern und deren Einzugsgebieten in Mecklenburg-Vorpommern. Biota – Institut für ökologische Forschung und Planung GmbH im Auftrag des Landesamtes für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern, 117 p. https://www.wrrl-mv.de/static/WRRL/Dateien/Dokumente/Service/Dokumente/2014_Wasserhaushalt_Klassifizierung_MV.pdf

Bižić, M., Klintzsch, T., Ionescu, D., Hindiyeh, M., Y., Günthel, M., Muro-Pastor, A., Eckert, W., Urich, T., Keppler, F. & Grossart, H.-P. (2020): Aquatic and terrestrial cyanobacteria produce methane. In: *Science Advances* 6. https://doi.org/10.1126/sciadv.aax5343

BMUV (2023a): Federal Action Plan on Nature-based Solution for Climate and Biodiversity. – Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection) [ed.], 88 p. https://www.bmuv.de/fileadmin/Daten_BMU/Pools/Broschueren/ank_publikation_en_bf.pdf (December 19, 2023)

BMUV (2023b): Nationale Wasserstrategie. Kabinettsbeschluss vom 15.03.2023. Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection) [ed.], 120 p. https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Binnengewaesser/nationale_wasserstrategie_2023_bf.pdf (December 19, 2023)

BMVI/BMU (2020): Bundesprogramm „Blaues Band Deutschland“. Modellprojekte als ökologische Trittsteine an den Bundeswasserstraßen. Federal Ministry of Transport and Digital Infrastructure (Bundesministerium für Verkehr und digitale Infrastruktur – BMVI) and Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit – BMU) [eds.], 28 p. https://www.blaues-band.bund.de/Projektseiten/Blaues_Band/DE/SharedDocs/Downloads/BBD_Modellprojekte.pdf;jsessionid=D2D5B66F59EA121AD362B4A3F574B089.live11311?__blob=publicationFile&v=6 (December 19, 2023)

Booth, M., Urbanic, M., Wang, X. & Beaulieu, J. (2021): Bioturbation frequency alters methane emissions from reservoir sediments. In: *Science of the total environment* 789, p. 148033. https://doi.org/10.1016/j.scitotenv.2021.148033

Borges, A., Darchambeau, F., Lambert, T., Bouillon, S., Morana, C., Brouyère, S., Hakoun, V., Jurado, A., Tseng, H.-C., Descy, J.-P. & Roland, F. (2018): Effects of agricultural land use on fluvial carbon dioxide, methane and nitrous oxide concentrations in a large European river, the Meuse (Belgium). In: *Science of the total environment*, pp. 342–355. https://doi.org/10.1016/j.scitotenv.2017.08.047

Borges, A., Darchambeau, F., Teodoru, C., Marwick, T., Tamooh, F., Geeraert, N., Omengo, F., Guérin, F., Lambert, T., Morana, C., Okuku, E. & Bouillon, S. (2015): Globally significant greenhouse-gas emissions from African inland waters. In: *Nature Geoscience* 8 (8), pp. 637–642. https://doi.org/10.1038/ngeo2486

Brauns, M., Allen, D., Boëchat, I., Cross, W., Ferreira, V., Graeber, D., Patrick, C., Peipoch, M., von Schiller, D. & Gücker, B. (2022): A global synthesis of human impacts on the multifunctionality of streams and rivers. In: *Global change biology* 28 (16), pp. 4783–4793. https://doi.org/10.1111/gcb.16210

Breznikar, A. (2023): Rewetting effects on nutrient cycling and export dynamics in coastal peatlands of the Southern Baltic Sea. Doctoral thesis, Universität Rostock. 116 p.

Brion, N., Billen, G., Guezennec, L. & Ficht, A. (2000): Distribution of nitrifying activity in the Seine River “France” from Paris to the estuary. In: *Estuaries* 23(5), pp. 669–682. https://doi.org/10.2307/1352893

Brown, A., Bass, A., Skiba, U., MacDonald, J. & Pickard, A. (2023): Urban landscapes and legacy industry provide hotspots for riverine greenhouse gases: A source-to-sea study of the River Clyde. In: *Water research* 236, p. 119969. https://doi.org/10.1016/j.watres.2023.119969

Brown, A., Lespez, L., Sear, D., Macaire, J.-J., Houben, P., Klimek, K., Brazier, R., Van Oost, K. & Pears, B. (2018): Natural vs anthropogenic streams in Europe. History, ecology and implications for restoration, river-rewilding and riverine ecosystem services. In: *Earth-Science Reviews* 180, pp. 185-205. https://doi.org/10.1016/j.earscirev.2018.02.001

Brunotte, E., Dister, E., Günther-Diringer, D., Koenzen, U. & Mehl, D. (2009): Flussauen in Deutschland. Erfassung und Bewertung des Auenzustandes. In: *Schriftenreihe Naturschutz und biologische Vielfalt* 87, 141 p. https://www.bfn.de/publikationen/schriftenreihe-naturschutz-biologische-vielfalt/nabiv-heft-87-flussauen-deutschland

BUND (2009): Bund Naturschutz in Bayern e. V. Anhang 1 zur Stellungnahme des Bund Naturschutz zur 3. Phase Öffentlichkeitsbeteiligung WRRL in Bayern, Analyse der Wasserkraftnutzung in Bayern. Abschätzung der Anteile FGE Donau und FGE Rhein (Maingebiet). Konsequenzen für die Berücksichtigung im Bewirtschaftungsplan und im Maßnahmenprogramm der WRRL. https://www.bund-naturschutz.de/fileadmin/Bilder_und_Dokumente/Themen/Natur_und_Landschaft/Gew%C3%A4sser_in_Bayern/WRRL/BN_Anhang%201%20Wasserkraft_WRRL_300609.pdf (February 25, 2024)

Bussmann, I., Koedel, U., Schütze, C., Kamjunke, N. & Koschorreck, M. (2022): Spatial Variability and Hotspots of Methane Concentrations in a Large Temperate River. In: *Frontiers in Environmental Science* 10, Article 833936. https://doi.org/10.3389/fenvs.2022.833936

Caspers, H. & Karbe, L. (1967): Vorschläge für eine saprobiologische Typisierung der Gewässer. In: *Internationale Revue der gesamten Hydrobiologie* 52, pp. 145-162

Chanu, T., Nag, S., Koushlesh, S., Devi, M. & Das, B. (2022): Greenhouse Gas Emission from Inland Open Water Bodies and Their Estimation Process: An Emerging Issue in the Era of Climate Change. In: *Agricultural Sciences* 13 (02), pp. 290–306. https://doi.org/10.4236/as.2022.132020

Chanudet, V., Gaillard, J., Lambelain, J., Demarty, M., Descloux, S., Félix-Faure, J., Poirel, A. & Dambrine, E. (2020): Emission of greenhouse gases from French temperate hydropower reservoirs. In: *Aquatic Sciences* 82 (3). https://doi.org/10.1007/s00027-020-00721-3

Chen, H., Wu, Y., Yuan, X., Gao, Y., Wu, N. & Zhu, D. (2009): Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir. In: *Journal of Geophysical Research* 114, D18301. https://doi.org/doi:10.1029/2009JD012410

Chen, K., Yang, S., Roden, E., Chen, X., Chang, K.-Y., Guo, Z., Liang, X., Ma, E., Fan, L. & Zheng, C. (2023): Influence of Vertical Hydrologic Exchange Flow, Channel Flow, and Biogeochemical Kinetics on CH_4 Emissions From Rivers. In: *Water Resources Research* 59 (12), Article e2023WR035341. https://doi.org/10.1029/2023WR035341

Chen, Q., Shi, W., Huisman, J., Maberly, S., Zhang, J., Yu, J., Chen, Y., Tonina, D. & Yi, Q. (2020): Hydropower reservoirs on the upper Mekong River modify nutrient bioavailability downstream, In: *National Science Review* 7 (9), pp. 1449 1457. https://doi.org/10.1093/nsr/nwaa026

Christiansen, T., Azlak, M., Ivits-Wasser, E., Globevnik, L., Snoj, L., Scholz, M., Schulz-Zunkel, C., Henle, K., Schmedtje, U., Kampa, E., Birk, S., Kail, J., Januschke, K., Völker, J. & Lyche-Solheim, A. (2020): Floodplains: a natural system to preserve and restore. EEA Report 24/2019. Office for Official Publications of the European Communities, Luxembourg, 54 pp. https://doi.org/10.2800/431107

Cierjacks, A., Kleinschmit, B., Babinsky, M., Kleinschroth, F., Markert, A., Menzel, M., Ziechmann, U., Schiller, T., Graf, M. & Lang, F. (2010): Carbon stocks of soil and vegetation on Danubian floodplains. In: *Journal of Plant Nutrition and Soil Science* 173 (5), pp. 644–653. https://doi.org/10.1002/jpln.200900209

CITEPA (Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique) (2022): Rapport National d'Inventaire pour la France au titre de la Convention cadre des Nations Unies sur les Changements Climatiques et du Protocole de Kyoto (National Greenhouse Gas Inventory France - Emissions from 1990 to 2020). 959 p. https://www.citepa.org/fr/activites/inventaires-des-emissions/ccnucc

Clay, S., Pena, A., DeTracey, B. & Devred, E. (2019): Evaluation of satellite-based algorithms to retrieve chlorophyll-a concentration in the Canadian Atlantic and Pacific Oceans. In: *Remote Sensing* 11 (22), 2609. https://doi.org/10.3390/rs11222609

Cole, J., Prairie, Y., Caraco, N., McDowell, W., Tranvik, L., Striegl, R., Duarte, C., Kortelainen, P., Downing, J., Middelburg, J. & Melack, J. (2007): Plumbing the Global Carbon Cycle: Integrating Inland Waters into the Terrestrial Carbon Budget. In: *Ecosystems* 10 (1), pp. 171–184. https://doi.org/10.1007/s10021-006-9013-8

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A. & Joosten, H. (2011). Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. In: *Hydrobiologia* 674, pp. 67-89. https://doi.org/10.1007/s10750-011-0729-x

Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Risquez Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J. & Vignati, E. (2023): GHG emissions of all world countries. Publications Office of the European Union, Luxembourg. JRC134504. https://doi.org/10.2760/953332

D'Ambrosio, S. & Harrison, J. (2022): Measuring CH_4 Fluxes From Lake and Reservoir Sediments: Methodologies and Needs. In: *Frontiers in Environmental Science* 10, Article 850070. https://doi.org/10.3389/fenvs.2022.850070

D'Ambrosio, S. & Harrison, J. (2021): Methanogenesis exceeds CH_4 consumption in eutrophic lake sediments. In: *Limnology and Oceanography Letters* 6 (4), pp. 173–181. https://doi.org/10.1002/lol2.10192

Deblois, C., Demarty, M., Bilodeau, F. & Tremblay, A. (2023): Automated CO_2 and CH_4 monitoring system for continuous estimation of degassing related to hydropower. In: *Frontiers in Environmental Science* 11, Article 1194994. https://doi.org/10.3389/fenvs.2023.1194994

Deemer, B., Harrison, J. & Whitling, E. (2011): Microbial dinitrogen and nitrous oxide production in a small eutrophic reservoir: An in situ approach to quantifying hypolimnetic process rates. In: *Limnology and Oceanography* 56 (4), pp. 1189–1199. https://doi.org/10.4319/lo.2011.56.4.1189

Deemer, B., Harrison, J., Li, S., Beaulieu, J., DelSontro, T., Barros, N., Bezerra-Neto, J., Powers, S., Dos Santos, M. & Vonk, J. (2016): Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis. In: *Bioscience* 66 (11), pp. 949–964. https://doi.org/10.1093/biosci/biw117

DelSontro, T., Beaulieu, J. & Downing, J. (2018): Greenhouse gas emissions from lakes and impoundments: upscaling in the face of global change. In: *Limnology and oceanography letters* 3, pp. 64–75. https://doi.org/10.1002/lol2.10073

DelSontro, T., Boutet, L., St-Pierre, A., del Giorgio, P., Prairie, Y. (2016): Methane ebullition and diffusion from northern ponds and lakes regulated by the interaction between temperature and system productivity. In: *Limnology & Oceanography* 61, pp. S62-S77. https://doi.org/10.1002/lno.10335

DelSontro, T., McGinnis, D., Sobek, S., Ostrovsky, I. & Wehrli, B. (2010): Extreme methane emissions from a Swiss hydropower reservoir: contribution from bubbling sediments. In: *Environmental science & technology* 44 (7), pp. 2419–2425. https://doi.org/10.1021/es9031369

Descloux, S., Chanudet, V., Serça, D. & Guérin, F. (2017): Methane and nitrous oxide annual emissions from an old eutrophic temperate reservoir. In: *Science of the total environment* 598, pp. 959–972. https://doi.org/10.1016/j.scitotenv.2017.04.066

DLR (Deutsches Zentrum für Luft- und Raumfahrt e. V.) (2024): Sentinel-5. https://www.d-copernicus.de/daten/satelliten/satelliten-details/news/sentinel-5/?tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=85a0fa176e851eed437cc711bf758129 (February 12, 2024)

Doretto, A., Piano, E. & Larson, C. (2020): The River Continuum Concept: lessons from the past and perspectives for the future. In: *Canadian Journal of Fisheries and Aquatic Sciences* 77 (11), pp. 1853–1864. https://doi.org/10.1139/cjfas-2020-0039

Downing, J., Prairie, Y., Cole, J., Duarte, C., Tranvik, L., Striegl, R., McDowell, W., Kortelainen, P., Caraco, N., Melack, J. & Middelburg, J. (2006): The global abundance and size distribution of lakes, ponds, and impoundments. In: Limnology and Oceanography 51(5), pp. 2388-2397. https://doi.org/10.4319/lo.2006.51.5.2388

DWA-M 525: Sedimentmanagement in Fließgewässern: Grundlagen, Methoden, Fallbeispiele. Merkblatt. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V. – DWA [ed.], November 2012, 165 p. https://shop.dwa.de/media/a0/fd/ef/1674733290/DWA-M_525_Vor_2023.pdf

EEB (2023): European Environmental Bureau. Openletter: NGO reply to the European Commission on the role of hydropower in the deployment of renewable energies in Europe. https://eeb.org/wp-content/uploads/2023/10/ngo-open-letter-hydropower_20-10-2023-1.pdf (November 23, 2023)

Ehlert, T., Neukirchen, B. & Hausmann, B. (2018): Perspektiven einer nachhaltigen Auenentwicklung. In: *Natur und Landschaft* 93 (2), pp. 59-63. https://doi.org/10.17433/2.2018.50153545.59-63

Eichhorn, M., Scheftelowitz, M., Reichmuth, M., Lorenz, C., Louca, K., Schiffler, A., Keuneke, R., Bauschmann, M., Ponitka, J., Manske, D. & Thrän, D. (2019): Spatial Distribution of Wind Turbines, Photovoltaic Field Systems, Bioenergy, and River Hydro Power Plants in Germany. In: *Data* 4, 29. https://doi.org/10.3390/data4010029

Emmer, I. & Couwenberg, J. (2017): Methodology for Rewetting Drained Temperate Peatlands: Verified Carbon Standard Methodologies, VM0036, Version 1.0, 81 S., https://verra.org/methodology/vm0036-methodology-for-rewetting-drained-temperate-peatlands-v1-0/ (April 25, 2022)

Engram, M., Walter Anthony, K., Sachs, T., Kohnert, K., Serafimovich, A., Grosse, G. & Meyer, F. (2020): Remote sensing northern lake methane ebullition. In: *Nature Climate Change* 10 (6), pp. 511–517. https://doi.org/10.1038/s41558-020-0762-8

ESA (The European Space Agency) (2020): Klares Bild aus dem All: Satelliten messen Treibhausgasemissionen. https://www.esa.int/Space_in_Member_States/Austria/Klares_Bild_aus_dem_All_Satelliten_messen_Treibhausgasemissionen (February 12, 2024)

European Climate Law: Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (Official Journal of the EC L 243/1, 09.07.2021)

European Commission (2018): Guidance on the requirements for hydropower in relation to Natura 2000. European Commission, 83 p. https://www.natura2000.fr/sites/default/files/references_bibliographiques/hydro_final_may_2018_final.pdf (February 25, 2024)

European Commission (2022a): Proposal for a Regulation of the European Parliament and of the Council on nature restoration, COM (2022)304 final. https://eur-lex.europa.eu/legal-content/EN/TXT/DOC/?uri=CELEX:52022PC0304 (December 22, 2023)

European Commission (2022b): WFD Descriptive Reporting Guidance. 419 p. https://cdr.eionet.europa.eu/help/WFD/WFD_715_2022/Guidance%20documents/WFD%20Descriptive%20Reporting%20Guidance.pdf (December 04, 2023)

European Environment Agency (2018): Why should we care about floodplains. Publications Office. 9 p. https://data.europa.eu/doi/10.2800/548993 (December 04, 2023)

European Environment Agency (2020): Trends and drivers of EU greenhouse gas emissions. 32 p. https://doi.org/10.2800/19800 (December 04, 2023)

European Environment Agency (2021): Tracking barriers and their impacts on European river ecosystems. Briefing no. 30/2020. https://doi.org/10.2800/359938 (December 04, 2023)

European Environment Agency (2023): Annual European Union greenhouse gas inventory 1990-2021 and inventory report 2023. 752 p. https://www.eea.europa.eu/publications/annual-european-union-greenhouse-gas-2 (December 04, 2023)

Fischler, S. (2019): Treibhausgasemissionen von Speicherseen. Bachelorarbeit, Universität Innsbruck, 135 p. https://diglib.uibk.ac.at/download/pdf/3484329.pdf (December 04, 2023)

Garack, S., Wollrab, S., Jähnig, S., Günther, K., Berger, S., Neubert, M., Albrecht, J., Friedrichs-Manthey, M., Sauer, A. & Kirillin, G. (2022): Entwicklung der ökologischen Beschaffenheit von Oberflächengewässern im Klimawandel. In: *Korrespondenz Wasserwirtschaft* 15 (2), pp. 98-107. https://doi.org/10.3243/kwe2022.02.003

Gattenlöhner, U., Bender, M. & Bär Lamas, M. (2022): Blitzlichtstudie "Seen und Klimawandel". Auswirkungen des Klimawandels und daraus resultierenden Änderungen von Temperaturen, Niederschlagsmengen und Niederschlagsverteilungen auf Seen, Kleingewässer und Feuchtgebiete in Deutschland. In: *BfN-Schriften* 624, 87 p. https://doi.org/10.19217/skr624

Gerner, N., Albert, C., Dehnhardt, A., Fenske, M., Mehl, D., Pusch, M., Schneider, P., Siegel, K. & Tschöpe, M. (2023): Der Einsatz von Ökosystemleistungsbewertungen als unterstützendes Instrument im Gewässerschutz. Beitrag der DWA-Arbeitsgruppe GB-10.4. In: *Korrespondenz Wasserwirtschaft* (16), pp. 651-655, https://doi.org/10.3243/kw2023.10.001

GHG Protocol Team (2023): GHG Protocol guidance on uncertainty assessment in GHG inventories and calculating statistical parameter uncertainty. https://ghgprotocol.org/sites/default/files/2023-03/ghg-uncertainty.pdf (December 04, 2023)

Global Monitoring Laboratory (2024): Trends in CO_2, CH_4, N_2O. https://gml.noaa.gov/ccgg/trends/ (Mai 02, 2024)

Goldenfum, J. A. (2010): GHG Measurement Guidelines for Freshwater Reservoirs. The International Hydropower Association (IHA) (ed.), 38 p. https://cdn.prod.website-files.com/64f9d0036cb97160cc26feba/64f9d0036cb97160cc270fe8_GHG%20Measurement%20Guidelines%20for%20Freshwater%20Reservoirs.pdf

Gómez-Gener, L., Gubau, M., Schiller, D. von, Marcé, R. & Obrador, B. (2018): Effect of small water retention structures on diffusive CO_2 and CH_4 emissions along a highly impounded river. In: *Inland Waters* 8 (4), pp. 449–460. https://doi.org/10.1080/20442041.2018.1457846

Gómez-Gener, L., Obrador, B., Schiller, D. von, Marcé, R., Casas-Ruiz, J., Proia, L., Acuña, V., Catalán, N., Muñoz, I. & Koschorreck, M. (2015): Hot spots for carbon emissions from Mediterranean fluvial networks during summer drought. In: *Biogeochemistry* 125 (3), pp. 409–426. https://doi.org/10.1007/s10533-015-0139-7

Gough, P., Fernández Garrido, P. & Van Herk, J. (2018): Dam Removal: A viable solution for the future of our European rivers. Dam Removal Europe. https://damremoval.eu/wp-content/uploads/2019/03/DRE-policy-Report-2018-digitaal-010319.pdf (November 15, 2023)

Grill, G., Lehner, B., Lumsdon, A., MacDonald, G., Zarfl, C. & Reidy Liermann, C. (2015): An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. In: *Environmental Research Letters* 10 (1), p. 15001. https://doi.org/10.1088/1748-9326/10/1/015001

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, M., Meng, J., Mulligan, M., Nilsson, C., Olden, J., Opperman, J., Petry, P., Reidy Liermann, C., Sáenz, L., Salinas-Rodríguez, S., Schelle, P., Schmitt, R., Snider, J., Tan, F., Tockner, K., Valdujo, P., van Soesbergen, A. & Zarfl, C. (2019): Mapping the world's free-flowing rivers. In: *Nature* 569 (7755), pp. 215–221. https://doi.org/10.1038/s41586-019-1111-9

Grinham, A., O'Sullivan, C., Dunbabin, M., Sturm, K., Gale, D., Clarke, W. & Albert, S. (2022): Drivers of Anaerobic Methanogenesis in Sub-Tropical Reservoir Sediments. In: *Frontiers in Environmental Science* 10, Article 852344. https://doi.org/10.3389/fenvs.2022.852344

Grossart, H.-P., Frindte, K., Dziallas, C., Eckert, W. & Tang, K. (2011): Microbial methane production in oxygenated water column of an oligotrophic lake. In: *Proceedings of the National Academy of Sciences of the United States of America* 108 (49), pp. 19657–19661. https://doi.org/10.1073/pnas.1110716108

Gruca-Rokosz, R. (2020): Quantitative Fluxes of the Greenhouse Gases CH_4 and CO_2 from the Surfaces of Selected Polish Reservoirs. In: *Atmosphere* 11 (3), p. 286. https://doi.org/10.3390/atmos11030286

Gudmundsson, L., Boulange, J., Do, H., Gosling, S., Grillakis, M., Koutroulis, A., Leonard, M., Liu, J., Müller Schmied, H., Papadimitriou, L., Pokhrei, Y., Seneviratne, S., Satoh, Y., Thiery, W., Westra, S., Zhang, X. & Zhao, F. (2021): Globally observed trends in mean and extreme river flow attributed to climate change. In: *Science* 371, pp. 1159–1162. https://doi.org/10.1126/science.aba3996

Günthel, M., Klawonn, I., Woodhouse, J., Bižić, M., Ionescu, D., Ganzert, L., Kümmel, S., Nijenhuis, I., Zoccarato, L., Grossart, H.-P. & Tang, K. (2020): Photosynthesis-driven methane production in oxic lake water as an important contributor to methane emission. In: *Limnology and Oceanography* 65 (12), pp. 2853–2865. https://doi.org/10.1002/lno.11557

Günther-Diringer, D., Berner, K., Koenzen, U., Kurth, A., Modrak, P., Ackermann, W., Ehlert, T. & Heyden, J. (2021): Methodische Grundlagen zum Auenzustandsbericht 2021: Erfassung, Bilanzierung und Bewertung von Flussauen. In: *BfN-Skripten* 591, 57 p. https://doi.org/10.19217/skr591

Hansen, C., Matson, P. & Griffiths, N. (2023): Diversity in reservoir surface morphology and climate limits ability to compare and upscale estimates of greenhouse gas emissions. In: *Science of the total environment* 893, p. 164851. https://doi.org/10.1016/j.scitotenv.2023.164851

Hansen, C., Pilla, R., Matson, P., Skinner, B., Griffiths, N. & Jager, H. (2022): Variability in modelled reservoir greenhouse gas emissions: comparison of select US hydropower reservoirs against global estimates. In: *Environmental Research Communications* 4 (12), p. 121008. https://doi.org/10.1088/2515-7620/acae24

Hao, X., Ruihong, Y., Zhuangzhuang, Z., Zhen, Q., Xixi, L., Tingxi, L. & Ruizhong, G. (2021): Greenhouse gas emissions from the water-air interface of a grassland river: a case study of the Xilin River. In: *Scientific reports* 11 (1), p. 2659. https://doi.org/10.1038/s41598-021-81658-x

Harmon, T. (2020): Carbon gas flux to and from inland waters: support for a global observation network. In: *Limnology* 21 (3), pp. 429–442. https://doi.org/10.1007/s10201-020-00623-1

Harrison, J., Deemer, B., Birchfield, M. & O'Malley, M. (2017): Reservoir Water-Level Drawdowns Accelerate and Amplify Methane Emission. In: *Environmental science & technology* 51 (3), pp. 1267–1277. https://doi.org/10.1021/acs.est.6b03185

Harrison, J., Maranger, R., Alexander, R., Giblin, A., Jacinthe, P.-A., Mayorga, E., Seitzinger, S., Sobota, D. & Wollheim, W. (2009): The regional and global significance of nitrogen removal in lakes and reservoirs. In: *Biogeochemistry* 93 (1-2), pp. 143–157. https://doi.org/10.1007/s10533-008-9272-x

Harrison, J., Prairie, Y., Mercier-Blais, S. & Soued, C. (2021): Year-2020 Global Distribution and Pathways of Reservoir Methane and Carbon Dioxide Emissions According to the Greenhouse Gas From Reservoirs (G-res) Model. In: *Global Biogeochemical Cycles* 35 (6), Article e2020GB006888. https://doi.org/10.1029/2020GB006888

Hartmann, J., Günthel, M., Klintzsch, T., Kirillin, G., Grossart, H.-P., Keppler, F. & Isenbeck-Schröter, M. (2020): High Spatiotemporal Dynamics of Methane Production and Emission in Oxic Surface Water. In: *Environmental science & technology* 54 (3), pp. 1451–1463. https://doi.org/10.1021/acs.est.9b03182

He, C., Qi, R., Feng, H., Zhao, Z., Wang, F., Wang, D., Wang, F., Chen, X., Zhang, P., Li, S. & Yi, Y. (2023): Spatio-temporal variations and dominated environmental parameters of nitrous oxide (N_2O) concentrations from cascade reservoirs in southwest China. In: *Environmental science and pollution research international* 30 (46), pp. 102547–102559. https://doi.org/10.1007/s11356-023-29502-9

Heger, A., Becker, J., Vásconez Navas, L. & Eschenbach, A. (2021): Factors controlling soil organic carbon stocks in hardwood floodplain forests of the lower middle Elbe River. In: *Geoderma* 404, p. 115389. https://doi.org/10.1016/j.geoderma.2021.115389

Hilt, S., Grossart, H.-P., McGinnis, D. & Keppler, F. (2022): Potential role of submerged macrophytes for oxic methane production in aquatic ecosystems. In: *Limnology and Oceanography* 67 (S2). https://doi.org/10.1002/lno.12095

Ho, L., Jerves-Cobo, R., Barthel, M., Six, J., Bode, S., Boeckx, P. & Goethals, P. (2022): Greenhouse gas dynamics in an urbanized river system: influence of water quality and land use. In: *Environmental science and pollution research international* 29 (25), pp. 37277–37290. https://doi.org/10.1007/s11356-021-18081-2

Ho, L., Jerves-Cobo, R., Eurie Forio, M., Mouton, A., Nopens, I. & Goethals, P. (2021): Integrated mechanistic and data-driven modeling for risk assessment of greenhouse gas production in an urbanized river system. In: *Journal of environmental management* 294, p. 112999. https://doi.org/10.1016/j.jenvman.2021.112999

Hoehn, E., Riedmüller, U., Eckert, B., Tworeck, A. & Leßmann, D. (2009): Abschlussbericht zum LAWA-Projekt „Ökologische Bewertung von künstlichen und erheblich veränderten Seen sowie Mittelgebirgsseen anhand der biologischen Komponente Phytoplankton nach den Anforderungen der EU-Wasserrahmenrichtlinie - Bewertungsmodul für Mittelgebirgsseen und Verfahrensanpassungen für Baggerseen, pH-neutrale Tagebauseen, Talsperren und Sondertypen im Tiefland“. Projekt-Nr: O 3.06, Fribourg, 106 p. https://www.gewaesserfragen.de/pdfs/Abschlbericht_LAWA_O3_06_Feb_09.pdf

Hoffmann, T. G., Mehl, D., Weiland, M. & Mühlner, C. (2010): HYDREG – Ein Verfahren zur Natürlichkeitsbewertung des hydrologischen Regimes der Oberflächenwasserkörper gemäß EU-WRRL. 2. Methoden und Ergebnisse. In: *KW Korrespondenz Wasserwirtschaft* 3 (9), pp. 474-484. https://doi.org/10.3243/kwe2010.09.003

Holgerson, M. & Raymond, P. (2016): Large contribution to inland water CO_2 and CH_4 emissions from very small ponds. In: *Nature Geoscience* 9 (3), pp. 222–226. https://doi.org/10.1038/ngeo2654

Holzner, M. (2023): Kleine Wasserkraft und Gewässerstrukturentwicklung seit 1850 aufgezeigt am Beispiel der Isen in Oberbayern. In: *Wasserwirtschaft* 11, pp. 37–42. http://doi.org/10.1007/s35147-023-1925-0

Hounshell, A., D’Acunha, B., Breef-Pilz, A., Johnson, M., Thomas, R. & Carey, C. (2023): Eddy Covariance Data Reveal That a Small Freshwater Reservoir Emits a Substantial Amount of Carbon Dioxide and Methane. In: *Journal of Geophysical Research: Biogeosciences* 128 (3), Article e2022JG007091. https://doi.org/10.1029/2022JG007091

Hu, C., Feng, L., Lee, Z., Franz, B. A., Bailey, S. W., Werdell, P. J. & Proctor, C. W. (2019): Improving satellite global chlorophyll a data products through algorithm refinement and data recovery. In: *Journal of Geophysical Research: Oceans* 124 (3), pp. 1524-1543. https://dx.doi.org/doi:10.1029/2019JC014941

Hutchins, R., Casas-Ruiz, J., Prairie, Y. & Del Giorgio, P. (2020): Magnitude and drivers of integrated fluvial network greenhouse gas emissions across the boreal landscape in Quebec. In: *Water research* 173, https://doi.org/10.1016/j.watres.2020.115556

International Hydropower Association (2022): Hydropower Status Report 2022 – Sector trends and insights. 52 p. https://assets-global.websitefiles.com/64f9d0036cb97160cc26feba/64f9d0036cb97160cc2714ce_IHA202212-status-report-02.pdf (December 01, 2023)

Ion, I. & Ene, A. (2021): Evaluation of Greenhouse Gas Emissions from Reservoirs: A Review. In: *Sustainability* 13 (21), p. 11621. https://doi.org/10.3390/su132111621

IPCC (2019): 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change [Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. & Federici, S. (eds)]. Published: IPCC, Switzerland. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html (December 21, 2023)

IPCC (2021): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

IPCC (2023): Sections. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)], IPCC, Geneva, Switzerland, pp. 35–115. https://doi.org/10.59327/IPCC/AR6-9789291691647

Jacinthe, P., Filippelli, G., Tedesco, L. & Raftis, R. (2012): Carbon storage and greenhouse gases emission from a fluvial reservoir in an agricultural landscape. In: *CATENA* 94, pp. 53–63. https://doi.org/10.1016/j.catena.2011.03.012

Jensen, S., Webb, J., Simpson, G., Baulch, H., Leavitt, P. & Finlay, K. (2022): Seasonal variability of CO_2, CH_4, and N_2O content and fluxes in small agricultural reservoirs of the northern Great Plains. In: *Frontiers in Environmental Science* 10, Article 895531. https://doi.org/10.3389/fenvs.2022.895531

Jin, H., Yoon, T., Lee, S.-H., Kang, H., Im, J. & Park, J.-H. (2016): Enhanced greenhouse gas emission from exposed sediments along a hydroelectric reservoir during an extreme drought event. In: *Environmental Research Letters* 11 (12), p. 124003. https://doi.org/10.1088/1748-9326/11/12/124003

Jin, Q., Liu, H., Xu, X., Zhao, L., Chen, L., Chen, L., Shi, R. & Li, W. (2023): Emission dynamics of greenhouse gases regulated by fluctuation of water level in river-connected wetland. In: *Journal of environmental management* 329, p. 117091. https://doi.org/10.1016/j.jenvman.2022.117091

Johnson, M., Matthews, E., Bastviken, D., Deemer, B., Du, J. & Genovese, V. (2021): Spatiotemporal Methane Emission From Global Reservoirs. In: *Journal of Geophysical Research: Biogeosciences* 126 (8), Article e2021JG006305. https://doi.org/10.1029/2021JG006305

Joyce, J.& Jewell, P. (2003): Physical Controls on Methane Ebullition from Reservoirs and Lakes. In: *Environmental & Engineering Geoscience* 9 (2), pp. 167–178, https://doi.org/10.2113/9.2.167

Karlsson, J., Serikova, S., Vorobyev, S., Rocher-Ros, G., Denfeld, B. & Pokrovsky, O. (2021): Carbon emission from Western Siberian inland waters. In: *Nature communications* 12 (1), p. 825. https://doi.org/10.1038/s41467-021-21054-1

Keller, P., Catalán, N., Schiller, D. von, Grossart, H.-P., Koschorreck, M., Obrador, B., Frassl, M., Karakaya, N., Barros, N., Howitt, J., Mendoza-Lera, C., Pastor, A., Flaim, G., Aben, R., Riis, T., Arce, M., Onandia, G., Paranaíba, J., Linkhorst, A., Del Campo, R., Amado, A., Cauvy-Fraunié, S., Brothers, S., Condon, J., Mendonça, R., 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., Finlayson, C., Melita, M., Oliveira Junior, E., Muniz, C., Gómez-Gener, L., Leigh, C., Zhang, Q. & Marcé, R. (2020): Global CO_2 emissions from dry inland waters share common drivers across ecosystems. In: *Nature communications* 11 (1), p. 2126. https://doi.org/10.1038/s41467-020-15929-y

Keller, P., Marcé, R., Obrador, B. & Koschorreck, M. (2021): Global carbon budget of reservoirs is overturned by the quantification of drawdown areas. In: *Nature Geoscience* 14 (6), pp. 402–408. https://doi.org/10.1038/s41561-021-00734-z

Knott, J., Müller, M., Pander, J. & Geist, J. (2023): Bigger than expected: Species- and size-specific passage of fish through hydropower screens. In: *Ecological Engineering* 188, p. 106883. https://doi.org/10.1016/j.ecoleng.2022.106883

Koenzen, U. (2005): Fluss- und Stromauen in Deutschland. Typologie und Leitbilder. – Ergebnisse des F+E-Vorhabens „Typologie und Leitbildentwicklung für Flussauen in der Bundesrepublik Deutschland“ des Bundesamtes für Naturschutz, FKZ: 803 82 100. In: *Angewandte Landschaftsökologie* 65, 327 p. https://www.bfn.de/sites/default/files/2021-09/BfN_AL%C3%96_65_screen_final.pdf

Koenzen, U., Kurth, A. & Günther-Diringer, D. (2021): Auenzustandsbericht 2021. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit – BMU) and Federal Agency for Nature Conservation (Bundesamt für Naturschutz – BfN) [eds.], 71 p. https://www.bfn.de/sites/default/files/2021-04/AZB_2021_bf.pdf (December 19, 2023)

Konold, W. (2023): Querbauwerke in Fließgewässern: Aus einem anderen Blickwinkel betrachtet. In: *Wasserwirtschaft* 113 (11), pp. 33–36. https://doi.org/10.1007/s35147-023-1926-z

Kool, D. M., Dolfing, J., Wrage, N. & Van Groenigen, J. W. (2011): Nitrifier denitrification as a distinct and significant source of nitrous oxide from soil. In: *Soil Biology and Biochemistry* 43(1), pp. 174–178. https://doi.org/10.1016/j.soilbio.2010.09.030

Koschorreck, M., Kamjunke, N., Koedel, U., Rode, M., Schuetze, C. & Bussmann, I. (2023): Diurnal versus spatial variability of greenhouse gas emissions from an anthropogenic modified German lowland river. Preprint (in review). In: *Biogeosciences*. https://doi.org/10.5194/bg-2023-176 (December 01, 2023)

Krickov, I., Lim, A., Shirokova, L., Korets, M., Karlsson, J. & Pokrovsky, O. (2023): Environmental controllers for carbon emission and concentration patterns in Siberian rivers during different seasons. In: *Science of the total environment* 859 (Pt 1), p. 160202. https://doi.org/10.1016/j.scitotenv.2022.160202

KSG: Bundes-Klimaschutzgesetz vom 12. Dezember 2019 (BGBl. I S. 2513), zuletzt geändert durch Artikel 1 des Gesetzes vom 18. August 2021 (BGBl. I S. 3905). https://www.gesetze-im-internet.de/ksg/BJNR251310019.html

Kumar, A., Mishra, S., Bakshi, S., Upadhyay, P. & Thakur, T. (2023a): Response of eutrophication and water quality drivers on greenhouse gas emissions in lakes of China: A critical analysis. In: *Ecohydrology* 16 (1), Article e2483. https://doi.org/10.1002/eco.2483

Kumar, A., Chaturvedi, A., Joshi, N., Mondal, R. & Malyan, S. (2023b): Greenhouse gas emissions from hydroelectric reservoirs: mechanistic understanding of influencing factors and future prospect. In: *Environmental science and pollution research international*. https://doi.org/10.1007/s11356-023-25717-y

Kumar, A., Yu, Z.-G., Klemeš, J. & Bokhari, A. (2021): A state-of-the-art review of greenhouse gas emissions from Indian hydropower reservoirs. In: *Journal of Cleaner Production* 320, p. 128806. https://doi.org/10.1016/j.jclepro.2021.128806

Kumar, A., Yang, T. & Sharma, M. (2019): Greenhouse gas measurement from Chinese freshwater bodies: A review. In: *Journal of Cleaner Production* 233, pp. 368–378. https://doi.org/10.1016/j.jclepro.2019.06.052

Langenegger, T., Vachon, D., Donis, D. & McGinnis, D. (2019): What the bubble knows: Lake methane dynamics revealed by sediment gas bubble composition. In: *Limnology and Oceanography* 64 (4), pp. 1526–1544. https://doi.org/10.1002/lno.11133

Lapierre, J.-F., Guillemette, F., Berggren, M. & Del Giorgio, P. (2013): Increases in terrestrially derived carbon stimulate organic carbon processing and CO_2 emissions in boreal aquatic ecosystems. In: *Nature communications* 4, p. 2972. https://doi.org/10.1038/ncomms3972

Lauerwald, R., Allen, G., Deemer, B., Liu, S., Maavara, T., Raymond, P., Alcott, L., Bastviken, D., Hastie, A., Holgerson, M., Johnson, M., Lehner, B., Lin, P., Marzadri, A., Ran, L., Tian, H., Yang, X., Yao, Y. & Regnier, P. (2023a): Inland Water Greenhouse Gas Budgets for RECCAP2: 1. State-Of-The-Art of Global Scale Assessments. In: *Global Biogeochemical Cycles* 37 (5), Article e2022GB007657. https://doi.org/10.1029/2022GB007657

Lauerwald, R., Allen, G., Deemer, B., Liu, S., Maavara, T., Raymond, P., Alcott, L., Bastviken, D., Hastie, A., Holgerson, M., Johnson, M., Lehner, B., Lin, P., Marzadri, A., Ran, L., Tian, H., Yang, X., Yao, Y. & Regnier, P. (2023b): Inland Water Greenhouse Gas Budgets for RECCAP2: 2. Regionalization and Homogenization of Estimates. In: *Global Biogeochemical Cycles* 37 (5), Article e2022GB007658. https://doi.org/10.1029/2022GB007658

Lauerwald, R., Regnier, P., Figueiredo, V., Enrich-Prast, A., Bastviken, D., Lehner, B., Maavara, T. & Raymond, P. (2019): Natural lakes are a minor global source of N_2O to the atmosphere. In: *Global Biogeochemical Cycles* 33, pp. 1564–1581. https://doi.org/10.1029/2019GB006261

LAWA (2022): LAWA-BLANO Maßnahmenkatalog (WRRL, HWRMRL, MSRL). LAWA-Arbeitsprogramm Flussbewirtschaftung. Bund/Länder-Arbeitsgemeinschaft Wasser (German Working Group on water issues of the Federal States and the Federal Government represented by the Environment Ministers Conference), Kleingruppe „Fortschreibung LAWA Maßnahmenkatalog“ “ in Abstimmung mit der LAWA-AO Kleingruppe „Reporting Sheets“, 75 p. https://www.lawa.de/documents/lawa-blano-massnahmenkatalog-standaug2022_1671700851.pdf (November 28, 2023)

Lehner, B., Liermann, C., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J., Rödel, R., Sindorf, N. & Wisser, D. (2011): High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. In: *Frontiers in Ecology and the Environment* 9 (9), pp. 494–502. https://doi.org/10.1890/100125

Leng, P., Kamjunke, N., Li, F. & Koschorreck, M. (2021): Temporal Patterns of Methane Emissions From Two Streams With Different Riparian Connectivity. In: *Journal of Geophysical Research: Biogeosciences* 126 (8), Article e2020JG006104. https://doi.org/10.1029/2020JG006104

León-Palmero, E., Morales-Baquero, R. & Reche, I. (2020): Greenhouse gas fluxes from reservoirs determined by watershed lithology, morphometry, and anthropogenic pressure. In: *Environmental Research Letters* 15 (4), p. 44012. https://doi.org/10.1088/1748-9326/ab7467

Lessmann, O., Fernandez, J., Martinez-Cruz, K. & Peeters, F. (2023): Methane emissions due to reservoir flushing: a significant emission pathway? In: *Biogeosciences* 20, pp. 4057–4068. https://doi.org/10.5194/bg-20-4057-2023

Levasseur, A., Mercier-Blais, S., Prairie, Y., Tremblay, A. & Turpin, C. (2021): Improving the accuracy of electricity carbon footprint: Estimation of hydroelectric reservoir greenhouse gas emissions. In: *Renewable and Sustainable Energy Reviews* 136, p. 110433. https://doi.org/10.1016/j.rser.2020.110433

Li, M. & He, N. (2022): Carbon intensity of global existing and future hydropower reservoirs. In: *Renewable and Sustainable Energy Reviews* 162, p. 112433. https://doi.org/10.1016/j.rser.2022.112433

Li, S., Bush, R., Santos, I., Zhang, Q., Song, K., Mao, R., Wen, Z. & Lu, X. (2018): Large greenhouse gases emissions from China's lakes and reservoirs. In: *Water research* 147, pp. 13–24. https://doi.org/10.1016/j.watres.2018.09.053

Li, X., Yao, H., Yu, Y., Cao, Y. & Tang, C. (2020): Greenhouse gases in an urban river: Trend, isotopic evidence for underlying processes, and the impact of in-river structures. In: *Journal of Hydrology* 591, p. 125290. https://doi.org/10.1016/j.jhydrol.2020.125290

Li, Y., Shang, J., Zhang, C., Zhang, W., Niu, L., Wang, L. & Zhang, H. (2021): The role of freshwater eutrophication in greenhouse gas emissions: A review. In: *Science of the total environment* 768, p. 144582. https://doi.org/10.1016/j.scitotenv.2020.144582

Lima, I., Ramos, F., Bambace, L. & Rosa, R. (2007): Methane Emissions from Large Dams as Renewable Energy Resources: A Developing Nation Perspective. In: *Mitigation and Adaptation Strategies for Global Change* 13 (2), pp. 193–206. https://doi.org/10.1007/s11027-007-9086-5

Lin, P., Du, Z., Wang, L., Liu, J., Xu, Q., Du, J. & Jiang, R. (2023): Hotspots of riverine greenhouse gas (CH_4, CO_2, N_2O) emissions from Qinghai Lake Basin on the northeast Tibetan Plateau. In: *Science of the total environment* 857 (Pt 1), p. 159373. https://doi.org/10.1016/j.scitotenv.2022.159373

Lin, Q., Wang, S., Li, Y., Riaz, L., Yu, F., Yang, Q., Han, S. & Ma, J. (2022): Effects and mechanisms of land-types conversion on greenhouse gas emissions in the Yellow River floodplain wetland. In: *Science of the total environment* 813, p. 152406. https://doi.org/10.1016/j.scitotenv.2021.152406

Liu, J. & Han, G. (2021): Controlling factors of seasonal and spatial variation of riverine CO_2 partial pressure and its implication for riverine carbon flux. In: *Science of the total environment* 786, p. 147332. https://doi.org/10.1016/j.scitotenv.2021.147332

Liu, S., Lu, X., Xia, X., Yang, X. & Ran, L. (2017): Hydrological and geomorphological control on CO_2 outgassing from low-gradient large rivers: An example of the Yangtze River system. In: *Journal of Hydrology* 550, pp. 26–41. https://doi.org/10.1016/j.jhydrol.2017.04.044

Liu, X., Zheng, X., Wu, L., Deng, S., Pan, H., Zou, J., Zhang, X. & Luo, Y. (2022b): Techno-ecological synergies of hydropower plants: Insights from GHG mitigation. In: *Science of the total environment* 853, p. 158602. https://doi.org/10.1016/j.scitotenv.2022.158602

Liu, Y.-X., Abdela, K., Tang, Z.-N., Yu, J.-Y., Zhou, X.-D., Kumar, A. & Yu, Z.-G. (2022a): Impacts of surface water interchange between urban rivers and fish ponds in Chu river of Nanjing, China: A potential cause of greenhouse gas emissions. In: *Frontiers in Environmental Science* 10, Article 1084623. https://doi.org/10.3389/fenvs.2022.1084623

Lorke, A. & Burgis, F. (2018): Methanemissionen aus Oberflächengewässern. Universität Koblenz-Landau. Abschlussbericht zum Kooperationsvorhaben zwischen dem Freistaat Bayern, vertreten durch das Bayerische Landesamt für Umwelt, und der Universität Koblenz-Landau, 49 p. (unpublished project report)

Maavara, T., Akbarzadeh, Z. & van Cappellen, P. (2020a): Global Dam-Driven Changes to Riverine N:P:Si Ratios Delivered to the Coastal Ocean. In: *Geophysical Research Letters* 47 (15), Article e2020GL088288. https://doi.org/10.1029/2020GL088288

Maavara, T., Chen, Q., van Meter, K., Brown, L., Zhang, J., Ni, J. & Zarfl, C. (2020b): River dam impacts on biogeochemical cycling. In: *Nature Reviews Earth & Environment* 1 (2), pp. 103–116. https://doi.org/10.1038/s43017-019-0019-0

Maavara, T., Lauerwald, R., Regnier, P. & van Cappellen, P. (2017): Global perturbation of organic carbon cycling by river damming. In: *Nature communications* 8, p. 15347. https://doi.org/10.1038/ncomms15347

Machado Dos Santos Pinto, R., Weigelhofer, G., Diaz-Pines, E., Guerreiro Brito, A., Zechmeister-Boltenstern, S. & Hein, T. (2020): River-floodplain restoration and hydrological effects on GHG emissions: Biogeochemical dynamics in the parafluvial zone. In: *Science of the total environment* 715, p. 136980. https://doi.org/10.1016/j.scitotenv.2020.136980

Maeck, A., DelSontro, T., McGinnis, D., Fischer, H., Flury, S., Schmidt, M., Fietzek, P. & Lorke, A. (2013): Sediment trapping by dams creates methane emission hot spots. In: *Environmental science & technology* 47 (15), pp. 8130–8137. https://doi.org/10.1021/es4003907

Maeck, A., Hofmann, H. & Lorke, A. (2014): Pumping methane out of aquatic sediments – ebullition forcing mechanisms in an impounded river. In: *Biogeosciences* 11 (11), pp. 2925–2938. https://doi.org/10.5194/bg-11-2925-2014

Mäkinen, K. & Khan, S. (2010): Policy Considerations for Greenhouse Gas Emissions from Freshwater Reservoirs. In: *Water Alternatives* 3 (2), pp. 91-105, https://researchoutput.csu.edu.au/ws/portalfiles/portal/8794229/PostpubPID25320.pdf

Marcé, R., Obrador, B., Gómez-Gener, L., Catalán, N., Koschorreck, M., Arce, M., Singer, G. & von Schiller, D. (2019): Emissions from dry inland waters are a blind spot in the global carbon cycle. In: *Earth-Science Reviews* 188, pp. 240–248. https://doi.org/10.1016/j.earscirev.2018.11.012

Marcon, L., Schwarz, M., Backes, L., Offermann, M., Schreiber, F., Hilgert, S., Sotiri, K., Jokiel, C. & Lorke, A. (2023): Linking Sediment Gas Storage to the Methane Dynamics in a Shallow Freshwater Reservoir. In: *Journal of Geophysical Research: Biogeosciences* 128 (10), Article e2022JG007365. https://doi.org/10.1029/2022JG007365

Marotta, H., Pinho, L., Gudasz, C., Bastviken, D., Tranvik, L. & Enrich-Prast, A. (2014): Greenhouse gas production in low-latitude lake sediments responds strongly to warming. In: *Nature Climate Change* 4 (6), pp. 467–470. https://doi.org/10.1038/nclimate2222

McCrackin, M. & Elser, J. (2011): Greenhouse gas dynamics in lakes receiving atmospheric nitrogen deposition. In: *Global Biogeochemical Cycles* 25 (4). https://doi.org/10.1029/2010GB003897

McGinnis, D., Prairie, Y., Grossart, H.-P. & DelSontro, T. (2023): Editorial: Sources, sinks, and emissions in aquatic systems: the past, present, and future under global change. In: *Frontiers in Environmental Science* 11, Article 1218878. https://doi.org/10.3389/fenvs.2023.1218878

Mehl, D. (2021): Zones alluviales et climat. In: *Le magazine du Forum Biodiversité Suisse HOTSPOT* 43, p. 8, https://portal-cdn.scnat.ch/asset/6a0b560a-a5ef-5576-b943-5755cc4ba8d0/HOTSPOT%2043.2021%20franz%204.5.2021%20WEB.pdf?b=2db03b99-3a1a-5bef-8d05-b6c5acce1ef3&v=26162e0b-5575-567a-b848-aebe4df5dcb3_0&s=UOR9KCyTmlV7CTriwIEGgEcwOyP0qKTox-pUSkAVRUDbcjs06FlIRQ4tsKp8Rg7RpZ0k6awUL5j_ev5ZbWMzV3zlyHo873by0JdOA0MTzuguAT-VDZrwJVL7ndQ0jT5VygHe_ETO24k2AhBmmLQkVSsyrNZE_LoIUHLK00VqUdzoQ

Mehl, D., Hoffmann, T. G. & Iwanowski, J. (2020): Quantifizierung und Bewertung regulativer Ökosystemleistungen: Rückhalt von Treibhausgasen/Kohlenstoffsequestrierung, Hochwasser-, Niedrigwasser- und Sedimentregulation, Bodenbildung in Auen sowie Kühlwirkung der Gewässer und terrestrischen Böden. In: Fischer-Bedtke, C., Fischer, H., Mehl, D., Podschun, S., Pusch, M., Stammel, B. & Scholz, M. [eds.]: River Ecosystem Service Index (RESI) – Methoden zur Quantifizierung und Bewertung ausgewählter Ökosystemleistungen in Flüssen und Auen. In: *Schriftenreihe des Helmholtz-Zentrums für Umweltforschung GmbH,* UFZ-Bericht 2/2020, pp. 77-92, https://hdl.handle.net/10419/266335

Mehl, D., Hoffmann, T. G. & Miegel, K. (2014): Klassifizierung des Wasserhaushalts von Einzugsgebieten und Wasserkörpern – Verfahrensempfehlung. b) Hintergrunddokument. Bund-/Länderarbeitsgemeinschaft Wasser [ed.], Ständiger Ausschuss „Oberirdische Gewässer und Küstengewässer (LAWA-AO), Sächsisches

Staatsministerium für Umwelt und Landwirtschaft, Dresden, 161 p. http://www.laenderfinanzierungsprogramm.de/static/LFP/Dateien/LAWA/AO/o-6-12-verfahrensempfehlung.pdf

Mehl, D., Hoffmann, T. G., Friske, V., Kohlhas, E., Linnenweber, C., Mühlner, C. & Pinz, K. (2015): Der Wasserhaushalt von Einzugsgebieten und Wasserkörpern als hydromorphologische Qualitätskomponentengruppe nach WRRL – der induktive und belastungsbasierte Ansatz des Entwurfs der LAWA-Empfehlung. In: *Hydrologie und Wasserbewirtschaftung* 59 (3), pp. 96-108. https://doi.org/10.5675/HyWa_2015,3_2

Mehl, D., Hoffmann, T. G., Weiland, M. & Mühlner, C. (2010): HYDREG – Ein Verfahren zur Natürlichkeitsbewertung des hydrologischen Regimes der Oberflächenwasserkörper gemäß EU-WRRL. 1. Hintergrund, Zielstellung und Grundlagen. In: *KW Korrespondenz Wasserwirtschaft* 3 (6), pp. 300-304. https://doi.org/10.3243/kwe2010.06.003

Mehl, D., Iwanowski, J., Dehnhardt, A., Püffel, C. & Albert, A. (2022a): Auswirkungen von Handlungsalternativen für Staustufen der Lahn auf Ökosystemleistungen. In: *Wasser und Abfall*, 01-02/2022: pp. 36-43. https://doi.org/10.1007/s35152-022-0728-4

Mehl, D., Iwanowski, J., Dehnhardt, A., Püffel, C. & Albert, A. (2022b): Der Ökosystemleistungsansatz als Grundlage einer Bewertung von Handlungsalternativen im Sinne der WRRL für die Bundeswasserstraße Lahn. In: *Wasser und Abfall*, 01-02/2022, pp. 20-28. https://doi.org/10.1007/s35152-022-0729-3

Mehl, D., Iwanowski, J., Hausmann, B. & Neukirchen, B. (2023a): Ein Verfahren zur Bewertung umweltfachlicher Synergien von Maßnahmen des Nationalen Hochwasserschutzprogramms (NHWSP). In: *BfN-Schriften* 638, 73 p. https://doi.org/10.19217/skr638

Mehl, D., Iwanowski, J., Hoffmann, T. & Pusch, M. (2023b): Einfluss von Wasserkraftanlagen auf den ökologischen Zustand von Fließgewässern in Deutschland. In: *Wasser und Abfall* 11, pp. 35–44. https://doi.org/10.1007/s35152-023-1482-y

Mehl, D., Scholz, M., Schulz-Zunkel, C., Kasperidus, H. D., Born, W. & Ehlert, T. (2013): Analyse und Bewertung von Ökosystemfunktionen und -leistungen großer Flussauen. In: *Korrespondenz Wasserwirtschaft*, 6 (9), pp. 493-499. https://doi.org/10.3243/kwe2013.09.001

Mehl, D., Steinhäuser, A., Kasper, D., Kasperidus, H. D. & Scholz, M. (2012): Treibhausgasemissionen in Flussauen. In: Scholz, M., Mehl, D., Schulz-Zunkel, C., Kasperidus, H. D., Born, W. & Henle, K. [eds.]: Ökosystemfunktionen in Flussauen. Analyse und Bewertung von Hochwasserretention, Nährstoffrückhalt, Treibhausgas-Senken-/Quellenfunktion und Habitatfunktion. In: *Schriftenreihe Naturschutz und biologische Vielfalt*, 124, pp. 85-101. https://doi.org/1029681686

Mendonça, R., Barros, N., Vidal, L., Pacheco, F., Kosten, S. & Roland, F. (2012): Greenhouse Gas Emissions from Hydroelectric Reservoirs: What Knowledge Do We Have and What is Lacking? In: Liu, G. [ed.]: Greenhouse Gases. Emission, Measurement and Management*,* 516 p. https://doi.org/10.5772/32752

Merot, P., Hubert-Moy, L., Gascuel-Odoux, C., Clement, B., Durand, P., Baudry, J. & Thenail, C. (2006): Environmental Assessment. A method for improving the management of controversial wetland. In: *Environmental Management* 37, 2, pp. 258-270. https://doi.org/10.1007/s00267-004-0391-4

Metzger, J., Seidel, C., Jensen, J. & Haimerl, G. (2022): Laufwasserkraftwerke: Differenzierungen, technische Entwicklungen und Perspektiven. In: *Korrespondenz Wasserwirtschaft* 15 (12), pp. 756–762. https://doi.org/10.3243/kwe2022.10.003

Miao, Y., Huang, J., Duan, H., Meng, H., Wang, Z., Qi, T. & Wu, Q. (2020): Spatial and seasonal variability of nitrous oxide in a large freshwater lake in the lower reaches of the Yangtze River, China. In: *Science of the total environment* 721, p. 137716. https://doi.org/10.1016/j.scitotenv.2020.137716

Miao, Y., Sun, F., Hong, W., Fang, F., Yu, J., Luo, H., Wu, C., Xu, G., Sun, Y. & Meng, H. (2022): Greenhouse Gas Emissions from a Main Tributary of the Yangtze River, Eastern China. In: *Sustainability* 14 (21), p. 13729. https://doi.org/10.3390/su142113729

Miller, B., Arntzen, E., Goldman, A. & Richmond, M. (2017): Methane Ebullition in Temperate Hydropower Reservoirs and Implications for US Policy on Greenhouse Gas Emissions. In: *Environmental management* 60 (4), pp. 615–629. https://doi.org/10.1007/s00267-017-0909-1

Miller, B., Chen, H., He, Y., Yuan, X. & Holtgrieve, G. (2019): Magnitudes and Drivers of Greenhouse Gas Fluxes in Floodplain Ponds During Drawdown and Inundation by the Three Gorges Reservoir. In: *Journal of Geophysical Research: Biogeosciences* 124 (8), pp. 2499–2517. https://doi.org/10.1029/2018JG004701

Mohajan, H. (2012): GHG emissions of the USA. In: *Indus Journal of Management & Social Sciences* 6, pp. 132–148. https://mpra.ub.uni-muenchen.de/id/eprint/50670

Mongil-Manso, J., Díaz-Gutiérrez, V., Navarro-Hevia, J., Espina, M. & San Segundo, L. (2019): The role of check dams in retaining organic carbon and nutrients. A study case in the Sierra de Ávila mountain range (Central Spain). In: *Science of the total environment* 657, pp. 1030–1040. https://doi.org/10.1016/j.scitotenv.2018.12.087

MSFD (Marine Strategy Framework Directive): Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Official Journal of the EC L 164/19, 25.06.2008). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0056

Muller, M. (2019). Dams have the power to slow climate change. In: *Nature* 566 (7744), pp. 315–317. https://doi.org/10.1038/d41586-019-00616-w

Mulligan, M., Lehner, B., Zarfl, C., Thieme, M., Beames, P., van Soesbergen, A., Higgins, J., Januchowski-Hartley, S., Brauman, K., Felice, L. de, Wen, Q., Garcia de Leaniz, C., Belletti, B., Mandle, L., Yang, X., Wang, J. & Mazany-Wright, N. (2021): Global Dam Watch: curated data and tools for management and decision making. In: *Environmental Research: Infrastructure and Sustainability* 1 (3), p. 33003. https://doi.org/10.1088/2634-4505/ac333a

Mwanake, R., Gettel, G., Wangari, E., Glaser, C., Houska, T., Breuer, L., Butterbach-bahl, K. & Kiese, R. (2023): Anthropogenic activities significantly increase annual greenhouse gas (GHG) fluxes from temperate headwater streams in Germany. In: *Biogeosciences* 20 (16), pp. 3395–3422. https://doi.org/10.5194/bg-20-3395-2023

National Centre for Emission Management (2019): Poland's National Inventory Report 2019 - Greenhouse Gas Inventory for 1988-2017. National Centre for Emission Management (KOBiZE) at the Institute of Environmental Protection – National Research Institute. 425 p. https://www.kobize.pl/uploads/materialy/materialy_do_pobrania/krajowa_inwentaryzacja_emisji/NIR_POL_2019.pdf (December 06, 23)

National Institute for Public Health and the Environment (2023): National Inventory Report 2023 - Greenhouse gas emissions in the Netherlands 1990–2021. 476 p. https://doi.org/10.21945/RIVM-2023-0052

Natural Earth Data (2023): Downloads. https://www.naturalearthdata.com/downloads/ (December 22, 2023)

Naumann, S. (2022): Aktueller Gewässerzustand und Wasserkraftnutzung. In: *Korrespondenz Wasserwirtschaft* 15 (12), pp. 743–748. https://doi.org/10.3243/kwe2022.12.001

NGOs (2023): Open letter: NGO reply to the European Commission on the role of hydropower in the deployment of renewable energies in Europe. Open letter to Lukasz Kolinski. Brussels, October 20, 2023, https://wwfeu.awsassets.panda.org/downloads/ngo-open-letter-hydropower_25-10-2023.pdf (December 19, 2023)

Ni, J., Wang, H., Ma, T., Huang, R., Ciais, P., Li, Z., Yue, Y., Chen, J., Li, B., Wang, Y., Zheng, M., Wang, T. & Borthwick, A. (2022): Three Gorges Dam: friend or foe of riverine greenhouse gases? In: *National science review* 9 (6), nwac013. https://doi.org/10.1093/nsr/nwac013

Nilsson, C. & Berggren, K. (2000): Alterations of Riparian Ecosystems caused by River Regulation: Dam operations have caused global-scale ecological changes in riparian ecosystems. How to protect river environments and human needs of rivers remains one of the most important questions of our time. In: *Bioscience* 50 (9), pp. 783–792, https://doi.org/10.1641/0006-3568(2000)050[0783:AORECB]2.0.CO;2

Nilsson, C., Reidy, C., Dynesius, M. & Revenga, C. (2005): Fragmentation and flow regulation of the world's large river systems. In: *Science* 308 (5720), pp. 405–408. https://doi.org/10.1126/science.1107887

Oetken, M. & Sundermann, A. (2018): Strategien zur effektiven Renaturierung von Fließgewässern. In: *Korrespondenz Wasserwirtschaft* 11 (3), pp. 142–147. https://doi.org/10.3243/kwe2018.03.002

OGewV: Verordnung zum Schutz der Oberflächengewässer (Oberflächengewässerverordnung – OGewV) vom Juni 2016 (BGBl. I S. 1373). https://www.gesetze-im-internet.de/ogewv_2016/

Page, J., Kåresdotter, E., Destouni, G., Pan, H. & Kalantari, Z. (2021): A more complete accounting of greenhouse gas emissions and sequestration in urban landscapes. In: *Anthropocene* 34, p. 100296. https://doi.org/10.1016/j.ancene.2021.100296

Panique-Casso, D., Goethals, P. & Ho, L. (2024): Modeling greenhouse gas emissions from riverine systems: A review. In: *Water research* 250, p. 121012. https://doi.org/10.1016/j.watres.2023.121012

Park, J.-H., Lee, H., Zhumabieke, M., Kim, S.-H., Shin, K.-H. & Khim, B.-K. (2023): Basin-specific pollution and impoundment effects on greenhouse gas distributions in three rivers and estuaries. In: *Water research* 236, p. 119982. https://doi.org/10.1016/j.watres.2023.119982

Peacock, M., Audet, J., Jordan, S., Smeds, J. & Wallin, M. (2019): Greenhouse gas emissions from urban ponds are driven by nutrient status and hydrology. In: *Ecosphere* 10 (3), Article e02643. https://doi.org/10.1002/ecs2.2643

Peeters, F., Encinas Fernandez, J. & Hofmann, H. (2019): Sediment fluxes rather than oxic methanogenesis explain diffusive CH_4 emissions from lakes and reservoirs. In: *Scientific reports* 9 (1), p. 243. https://doi.org/10.1038/s41598-018-36530-w

Phyoe, W. & Wang, F. (2019): A review of carbon sink or source effect on artificial reservoirs. In: *International Journal of Environmental Science and Technology* 16 (4), pp. 2161–2174. https://doi.org/10.1007/s13762-019-02237-2

Podschun, S. A., Albert, C., Costea, G., Damm, C., Dehnhardt, A., Fischer, C., Fischer, H. Foeckler, F., Gelhaus, M., Gerstner, L., Hartje, V., Hoffmann, T. G., Hornung, L., Iwanowski, J., Kasperidus, H., Linnemann, K., Mehl, D., Rayanov, M., Ritz, S., Rumm, A., Sander, A., Schmidt, M., Scholz, M., Schulz-Zunkel, C., Stammel, B., Thiele, J., Venohr, M., von Haaren, C., Wildner, M. & Pusch, M. (2018a): RESI-Anwendungshandbuch: Ökosystemleistungen von Flüssen und Auen erfassen und bewerten. In: *IGB-Schriftenreihe,* Heft 31/2018, 187 p. https://www.igb-berlin.de/sites/default/files/media-files/download-files/RESI_Anwendungshandbuch.pdf

Podschun, S. A., Thiele, J., Dehnhardt, A., Mehl, D., Hoffmann, T. G., Albert, C., von Haaren, C., Deutschmann, K., Costea, G. & Pusch, M. (2018b): Das Konzept der Ökosystemleistungen - eine Chance für integratives Gewässermanagement. In: *Hydrologie und Wasserbewirtschaftung* 62 (6), pp. 453-468. https://doi.org/10.5675/HyWa_2018.6 _7

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E. & Stromberg, J. C. (1997): The natural flow regime. A paradigm for river conservation and restoration. In: *BioScience* 47, pp. 769-784, https://doi.org/10.2307/1313099

Pönisch, D., Breznikar, A., Gutekunst, C., Jurasinski, G., Voss, M. & Rehder, G. (2023): Nutrient release and flux dynamics of CO_2, CH_4, and N_2O in a coastal peatland driven by actively induced rewetting with brackish water from the Baltic Sea. In: *Biogeosciences* 20(2), pp. 295–323. https://doi.org/10.5194/bg-20-295-2023

Prairie, Y. T., Alm, J., Harby, A., Mercier-Blais. S. & Nahas, R. (2017): The GHG Reservoir Tool (G-res). Technical documentation. Updated version 3.2 (2022-12-19). UNESCO/IHA research project on the GHG status of freshwater reservoirs. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association, 75 p. https://cdn.prod.website-files.com/64f9d0036cb97160cc26feba/64f9d0036cb97160cc270fe1_g-res_technical_document_v2.1.pdf

Prairie, Y., Alm, J., Beaulieu, J., Barros, N., Battin, T., Cole, J., Del Giorgio, P., DelSontro, T., Guérin, F., Harby, A., Harrison, J., Mercier-Blais, S., Serça, D., Sobek, S. & Vachon, D. (2018): Greenhouse Gas Emissions from Freshwater Reservoirs: What Does the Atmosphere See? In: *Ecosystems (New York, N.Y.)* 21 (5), pp. 1058–1071. https://doi.org/10.1007/s10021-017-0198-9

Prairie, Y., Mercier-Blais, S., Harrison, J., Soued, C., Del Giorgio, P., Harby, A., Alm, J., Chanudet, V. & Nahas, R. (2021): A new modelling framework to assess biogenic GHG emissions from reservoirs: The G-res tool. In: *Environmental Modelling & Software* 143, p. 105117. https://doi.org/10.1016/j.envsoft.2021.105117

Proia, L., Schiller, D. von, Gutierrez, C., Casas-Ruiz, J., Gómez-Gener, L., Marcé, R., Obrador, B., Acuña, V. & Sabater, S. (2016): Microbial carbon processing along a river discontinuum. In: *Freshwater Science* 35 (4), pp. 1133–1147. https://doi.org/10.1086/689181

Pu, L., Chen, X., Lu, C., Jiang, L., Ma, B. & Yang, X. (2021): Spatial-Temporal Characteristics of Agricultural Greenhouse Gases Emissions of the Main Stream Area of the Yellow River Basin in Gansu, China. In: *Atmosphere* 12 (10), p. 1296. https://doi.org/10.3390/atmos12101296

Quick, A., Reeder, W., Farrell, T., Tonina, D., Feris, K. & Benner, S. (2019): Nitrous oxide from streams and rivers: A review of primary biogeochemical pathways and environmental variables. In: *Earth-Science Reviews* 191, pp. 224–262. https://doi.org/10.1016/j.earscirev.2019.02.021

Rabaey, J. & Cotner, J. (2022): Pond greenhouse gas emissions controlled by duckweed coverage. In: *Frontiers in Environmental Science* 10, Article 889289. https://doi.org/10.3389/fenvs.2022.889289

Ran, L., Lu, X., Yang, H., Li, L., Yu, R., Sun, H. & Han, J. (2015): CO_2 outgassing from the Yellow River network and its implications for riverine carbon cycle. In: *Journal of Geophysical Research: Biogeosciences* 120 (7), pp. 1334–1347. https://doi.org/10.1002/2015JG002982

Ran, L., Butman, D., Battin, T., Yang, X., Tian, M., Duvert, C., Hartmann, J., Geeraert, N. & Liu, S. (2021): Substantial decrease in CO_2 emissions from Chinese inland waters due to global change. In: *Nature communications* 12 (1), p. 1730. https://doi.org/10.1038/s41467-021-21926-6

Ranganathan, J., Corbier, L., Bhatia, P., Schmitz, S., Gage, P. & Oren, K. (2004): The Greenhouse Gas Protocol: A corporate accounting and reporting standard. World Business Council for Sustainable Development & World Resources Institute (eds.), 116 p. ISBN 1-56973-568-9. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

Rasilo, T., Hutchins, R., Ruiz-González, C. & Del Giorgio, P. (2017): Transport and transformation of soil-derived CO_2, CH_4 and DOC sustain CO_2 supersaturation in small boreal streams. In: *Science of the total environment* 579, pp. 902–912. https://doi.org/10.1016/j.scitotenv.2016.10.187

Ray, N. & Holgerson, M. (2023): High Intra-Seasonal Variability in Greenhouse Gas Emissions From Temperate Constructed Ponds. In: *Geophysical Research Letters* 50 (18), Article e2023GL104235. https://doi.org/10.1029/2023GL104235

Raymond, P., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Dürr, H., Meybeck, M., Ciais, P. & Guth, P. (2013): Global carbon dioxide emissions from inland waters. In: *Nature* 503 (7476), pp. 355–359. https://doi.org/10.1038/nature12760

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F., Gruber, N., Janssens, I., Laruelle, G., Lauerwald, R., Luyssaert, S., Andersson, A., Arndt, S., Arnosti, C., Borges, A., Dale, A., Gallego-Sala, A., Goddéris, Y., Goossens, N., Hartmann, J., Heinze, C., Ilyina, T., Joos, F., LaRowe, D., Leifeld, J., Meysman, F., Munhoven, G., Raymond, P., Spahni, R., Suntharalingam, P. & Thullner, M. (2013): Anthropogenic perturbation of the carbon fluxes from land to ocean. In: *Nature Geoscience* 6 (8), pp. 597–607. https://doi.org/10.1038/ngeo1830

Richter, B., Baumgartner, J., Wigington, R. & Braun, D. (1997): How much water does a river need? In: *Freshwater Biology* 37, pp. 231-249. https://doi.org/10.1046/j.1365-2427.1997.00153.x

Rieger, I., Lang, F., Kleinschmit, B., Kowarik, I. & Cierjacks, A. (2013): Fine root and aboveground carbon stocks in riparian forests: the roles of diking and environmental gradients. In: *Plant and Soil* 370 (1-2), pp. 497–509. https://doi.org/10.1007/s11104-013-1638-8

Robison, A., Wollheim, W., Perryman, C., Cotter, A., Mackay, J., Varner, R., Clarizia, P. & Ernakovich, J. (2022): Dominance of Diffusive Methane Emissions From Lowland Headwater Streams Promotes Oxidation and Isotopic Enrichment. In: *Frontiers in Environmental Science* 9, Article 791305. https://doi.org/10.3389/fenvs.2021.791305

Rocher-Ros, G., Stanley, E., Loken, L., Casson, N., Raymond, P., Liu, S., Amatulli, G. & Sponseller, R. (2023): Global methane emissions from rivers and streams. In: *Nature* 621 (7979), pp. 530–535. https://doi.org/10.1038/s41586-023-06344-6

Romberg, G. (1976): Biologische Selbstreinigung verschmutzter Flüsse. In: *Wärme- und Stoffübertragung* 9, pp. 227–246. https://doi.org/10.1007/BF01003575

Rosentreter, J., Borges, A., Deemer, B., Holgerson, M., Liu, S., Song, C., Melack, J., Raymond, P., Duarte, C., Allen, G., Olefeldt, D., Poulter, B., Battin, T. & Eyre, B. (2021): Half of global methane emissions come from highly variable aquatic ecosystem sources. In: *Nature Geoscience* 14 (4), pp. 225–230. https://doi.org/10.1038/s41561-021-00715-2

Samiotis, G., Pekridis, G., Kaklidis, N., Trikoilidou, E., Taousanidis, N. & Amanatidou, E. (2018): Greenhouse gas emissions from two hydroelectric reservoirs in Mediterranean region. In: *Environmental monitoring and assessment* 190 (6), p. 363. https://doi.org/10.1007/s10661-018-6721-4

Sanches, L., Guenet, B., Marinho, C., Barros, N. & de Assis Esteves, F. (2019): Global regulation of methane emission from natural lakes. In: *Scientific reports* 9 (1), p. 255. https://doi.org/10.1038/s41598-018-36519-5

Santoso, A., Hamilton, D., Schipper, L., Ostrovsky, I. & Hendy, C. (2021): High contribution of methane in greenhouse gas emissions from a eutrophic lake: a mass balance synthesis. In: *New Zealand Journal of Marine and Freshwater Research* 55 (3), pp. 411–430. https://doi.org/10.1080/00288330.2020.1798476

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P. M., Covey, K., Curry, C. L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M. I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K. M., Joos, F., Kleinen, T., Krummel, P. B., Langenfelds, R. L., Laruelle, G. G., Liu, L., Machida, T., Maksyutov, S., McDonald, K. C., McNorton, J., Miller, P. A., Melton, J. R., Morino, I., Müller, J., Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R. J., Peng, C., Peng, S., Peters, G. P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W. J., Rosentreter, J. A., Segers, A., Simpson, I. J., Shi, H., Smith, S. J., Steele, L. P., Thornton, B. F., Tian, H., Tohjima, Y., Tubiello, F. N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T. S., van Weele, M., van der Werf, G. R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q. & Zhuang, Q. (2020): The Global Methane Budget

2000–2017. In: *Earth Syst. Sci. Data* 12, pp. 1561–1623, https://doi.org/https://doi.org/10.5194/essd-12-1561-2020, 2020

Scherer, L. & Pfister, S. (2016): Global water footprint assessment of hydropower. In: *Renewable Energy* 99, pp. 711–720. https://doi.org/10.1016/j.renene.2016.07.021

Schilder, J., Bastviken, D., van Hardenbroek, M., Kankaala, P., Rinta, P., Stötter, T. & Heiri, O. (2013): Spatial heterogeneity and lake morphology affect diffusive greenhouse gas emission estimates of lakes. In: *Geophysical Research Letters* 40 (21), pp. 5752–5756. https://doi.org/10.1002/2013GL057669

Schiller, D. von, Aristi, I., Ponsatí, L., Arroita, M., Acuña, V., Elosegi, A. & Sabater, S. (2016): Regulation causes nitrogen cycling discontinuities in Mediterranean rivers. In: *Science of the total environment* 540, pp. 168–177. https://doi.org/10.1016/j.scitotenv.2015.07.017

Schödel, S. (2024): Metaanalyse – Weltweite Lachgas/N_2O-Quellen. Bilanzierungen, Veränderungen, Berücksichtigung in IPCC-Szenarien. In: *UBA-Texte* 46/2024, 80 p. https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/46_2024_texte_metastudie_lachgas.pdf

Scholz, M., Mehl, D., Schulz-Zunkel, C., Kasperidus, H. D., Born, W. & Henle, K. [eds.] (2012): Ökosystemfunktionen in Flussauen. Analyse und Bewertung von Hochwasserretention, Nährstoffrückhalt, Treibhausgas-Senken-/Quellenfunktion und Habitatfunktion. In: *Schriftenreihe Naturschutz und biologische Vielfalt*, 124, 257 p. https://doi.org/1029681686

Schönborn, W. (1992): Fließgewässerbiologie. Gustav Fischer Verlag, Stuttgart, ISBN 3334603962, 504 p.

Schönrock, S., Hoffmann, T. G., Foy, T. & Mehl, D. (2021): Fachliche Bearbeitung der Wasserhaushaltsklassifizierung der Baden-Württembergischen Flusswasserkörper. Bearbeitung 2019 zur Umsetzung der EG-Wasserrahmenrichtlinie. Landesanstalt für Umwelt Baden-Württemberg (LUBW) [ed.], Karlsruhe, 55 p. https://pudi.lubw.de/detailseite/-/publication/10201-Bearbeitung_2019_zur_Umsetzung_der_EG-Wasserrahmenrichtlinie.pdf

Schulz, G., Sanders, T., Voynova, Y., Bange, H. & Dähnke, K. (2023): Seasonal variability of nitrous oxide concentrations and emissions in a temperate estuary. In: *Biogeosciences* 20 (15), pp. 3229–3247. https://doi.org/10.5194/bg-20-3229-2023

Schwoerbel, J. (1964). Die Bedeutung des Hyporheals für die benthische Lebensgemeinschaft der Fließgewässer. In: *SIL Proceedings, 1922-2010*, 15:1, pp. 215-226. https://doi.org/10.1080/03680770.1962.11895523

Schwoerbel, J. (1967): Das hyporheische Interstitial als Grenzbiotop zwischen oberirdischem und subterranem Ökosystem und seine Bedeutung für die Primär-Evolution von Kleinsthöhlenbewohnern. In: *Archiv für Hydrobiologie (Suppl.)* 33, pp. 1-62

Seidel, M., Langheinrich, U. & Lüderitz, V. (2017): Gewässermorphologische Integrität von Flüssen. Wiederanschluss von Altwässern zur Verbesserung der Lebensbedingungen flusstypischer Arten. In: *Korrespondenz Wasserwirtschaft* 10 (2), pp. 107-111. https://doi.org/10.3243/kwe.2017.02.006

Senbayram, M., Chen, R., Budai, A., Bakken, L. & Dittert, K. (2012): N_2O emission and the $N_2O/(N_2O+N_2)$ product ratio of denitrification as controlled by available carbon substrates and nitrate concentrations. In: *Agriculture, Ecosystems and Environment* 147(1), pp. 4–12. https://doi.org/10.1016/j.agee.2011.06.022

Shi, W., Chen, Q., Zhang, J., Zheng, F., Liu, D., Yi, Q. & Chen, Y. (2020): Enhanced riparian denitrification in reservoirs following hydropower production. In: *Journal of Hydrology* 583, p. 124305. https://doi.org/10.1016/j.jhydrol.2019.124305

Shi, W., Maavara, T., Chen, Q., Zhang, J., Ni, J. & Tonina, D. (2023): Spatial patterns of diffusive greenhouse gas emissions from cascade hydropower reservoirs. In: *Journal of Hydrology* 619, p. 129343. https://doi.org/10.1016/j.jhydrol.2023.129343

Shupe, H. (2022): Carbon stocks and sequestration rates of hardwood floodplain forests along the Middle Elbe River, Germany. Doctoral thesis, Universität Hamburg. 158 p. https://ediss.sub.uni-hamburg.de/bitstream/ediss/10266/1/Disseration_30_05_23.pdf

Silverthorn, T., López-Rojo, N., Foulquier, A., Chanudet, V. & Datry, T. (2023): Greenhouse gas dynamics in river networks fragmented by drying and damming. In: *Freshwater Biology*, Article fwb.14172. https://doi.org/10.1111/fwb.14172

Sinha, E., Michalak, A. & Balaji, V. (2017): Eutrophication will increase during the 21st century as a result of precipitation changes. In: *Science* 357, pp. 405-408. https://doi.org/10.1126/science.aan2409

Sobek, S., DelSontro, T., Wongfun, N. & Wehrli, B. (2012): Extreme organic carbon burial fuels intense methane bubbling in a temperate reservoir. In: *Geophysical Research Letters* 39 (1), Article 2011GL050144. https://doi.org/10.1029/2011GL050144

Song, C., Gardner, K., Klein, S., Souza, S. & Mo, W. (2018): Cradle-to-grave greenhouse gas emissions from dams in the United States of America. In: *Renewable and Sustainable Energy Reviews* 90, pp. 945–956. https://doi.org/10.1016/j.rser.2018.04.014

Soued, C. & Prairie, Y. (2021): Changing sources and processes sustaining surface CO_2 and CH_4 fluxes along a tropical river to reservoir system. In: *Biogeosciences* 18 (4), pp. 1333–1350. https://doi.org/10.5194/bg-18-1333-2021

Spank, U., Hehn, M., Keller, P., Bernhofer, C. & Koschorreck, M. (2017): Measurement of Greenhouse Gas Emissions from Reservoirs. Conference Paper. 20th workshop on physical process in natural waters, Hyytiälä, Finland, 21-25 August 2017. https://www.researchgate.net/publication/319314788_Measurement_of_Greenhouse_Gas_Emissions_from_Reservoirs

Spellman, F. R. & Drinan, J. (2001): Stream Ecology and Self Purification. An Introduction. 2. Edition, London, Taylor & Francis, 261 p. https://www.routledge.com/Stream-Ecology-and-Self-Purification-An-Introduction-Second-Edition/Spellman-Drinan/p/book/9781587160868

SRU (2020): Für eine entschlossene Umweltpolitik in Deutschland und Europa. Umweltgutachten 2020. Sachverständigenrat für Umweltfragen [ed.], 556 p. https://www.umweltrat.de/SharedDocs/Downloads/DE/01_Umweltgutachten/2016_2020/2020_Umweltgutachten_Entschlossene_Umweltpolitik.pdf?__blob=publicationFile&v=2

St. Louis, V., Kelly, C., Duchemin, E., Rudd, J. & Rosenberg, D. (2000): Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere: A Global Estimate. In: *Bioscience* (50-9), pp. 766–775, https://doi.org/10.1641/0006-3568(2000)050[0766:RSASOG]2.0.CO;2

Stanley, E., Casson, N., Christel, S., Crawford, J., Loken, L. & Oliver, S. (2016): The ecology of methane in streams and rivers: patterns, controls, and global significance. In: *Ecological Monographs* 86 (2), pp. 146–171. https://doi.org/10.1890/15-1027

Statista (2023): Statistiken zu Treibhausgas- und CO_2-Emissionen. https://de.statista.com/themen/2442/treibhausgasemissionen (December 27, 2023)

Stein, L. Y. & Yung, Y. L. (2003): Production, isotopic composition and atmospheric fate of biologically produced N_2O. In: *Annual Review of Earth and Planetary Sciences* 31(1), pp. 329–356. https://doi.org/10.1146/annurev.earth.31.110502.080901

Striegl, R., Dornblaser, M., McDonald, C., Rover, J. & Stets, E. (2012): Carbon dioxide and methane emissions from the Yukon River system. In: *Global Biogeochemical Cycles* 26 (4), Article 2012GB004306. https://doi.org/10.1029/2012GB004306

Succow, M. & Joosten, H. [eds.] (2001): Landschaftsökologische Moorkunde. 2nd ed., E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller), Stuttgart, 622 p.

Sun, H., Lu, X., Yu, R., Yang, J., Liu, X., Cao, Z., Zhang, Z., Li, M. & Geng, Y. (2021): Eutrophication decreased CO_2 but increased CH_4 emissions from lake: A case study of a shallow Lake Ulansuhai. In: *Water research* 201. https://doi.org/10.1016/j.watres.2021.117363

Temmink, R., van den Akker, M., Robroek, B., Cruijsen, P., Veraart, A., Kosten, S., Peters, R., Verheggen-Kleinheerenbrink, G., Roelofs, A., van Eek, X., Bakker, E. & Lamers, L. (2021): Nature development in degraded landscapes: How pioneer bioturbators and water level control soil subsidence, nutrient chemistry and greenhouse gas emission. In: *Pedobiologia* 87-88, p. 150745. https://doi.org/10.1016/j.pedobi.2021.150745

Teodoru, C., Nyoni, F., Borges, A., Darchambeau, F., Nyambe, I. & Bouillon, S. (2015): Dynamics of greenhouse gases (CO_2, CH_4, N_2O) along the Zambezi River and major tributaries, and their importance in the riverine carbon budget. In: *Biogeosciences* 12 (8), pp. 2431–2453. https://doi.org/10.5194/bg-12-2431-2015

Thieme, M., Khrystenko, D., Qin, S., Golden Kroner, R., Lehner, B., Pack, S., Tockner, K., Zarfl, C., Shahbol, N. & Mascia, M. (2020): Dams and protected areas: Quantifying the spatial and temporal extent of global dam construction within protected areas. In: *Conservation Letters* 13 (4), Article e12719. https://doi.org/10.1111/conl.12719

Thieme, M., Tickner, D., Grill, G., Carvallo, J., Goichot, M., Hartmann, J., Higgins, J., Lehner, B., Mulligan, M., Nilsson, C., Tockner, K., Zarfl, C. & Opperman, J. (2021): Navigating trade-offs between dams and river conservation. In: *Global Sustainability* 4. https://doi.org/10.1017/sus.2021.15

Thoms, M. C. (2006): Variability in riverine ecosystems. In: *River Research and Applications* 22, pp. 115-121. https://doi.org/10.1002/rra.900

Thorp, J. H., Thoms, M. C. & Delong, M. D. (2006): The riverine ecosystem synthesis: biocomplexity in river networks across space and time. In: *River Research and Applications* 22, pp. 123-147. https://doi.org/10.1002/rra.901

Tian, H., Xu, R., Canadell, J. G, Thompson, R. L., Winiwarter, W., Suntharalingam, P., Davidson, E. A., Ciais, P, Jackson, R. B., Janssens-Maenhout, G., Prather, M. J., Regnier, P., Pan, N., Pan, S., Peters, G. P., Shi, H., ubiello, F. N., Zaehle, S., Zhou, F., Arneth, A., Battaglia, G., Berthet, S., Bopp, L., Bouwman, A. F., Buitenhuis, E. T., Chang, J., Chipperfield, M. P., Dangal, S. R. S., Dlugokencky, E., Elkins, J. W., Eyre, B. D., Fu, B., Hall, B., Ito, A., Joos , F., Krummel, P. B., Landolfi, A., Laruelle, G. G., Lauerwald, R., Li, W., Lienert, S., Maavara, T., MacLeod, M., Millet, D. B., Olin, S., Patra, P. K., Prinn, R. G., Raymond, P. A., Ruiz, D. J., van der Werf, G. R., Vuichard, N., Wang, J., Weiss, R. F., Wells, K. C., Wilson, C., Yang, J. & Yao, Y. (2020): A comprehensive quantification of global nitrous oxide sources and sinks. In: *Nature* 586, pp. 248–256. https://doi.org/10.1038/s41586-020-2780-0

Tiemeyer, B., Freibauer, A., Borraz, E., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Ebli, M., Eickenscheidt, T., Fiedler, S., Förster, C., Gensior, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Laggner, A., Leiber-Sauheitl, K., Peichl-Brak, M. & Drösler, M. (2020): A new methodology for organic soils in national greenhouse gas inventories: Data synthesis, derivation and application. In: *Ecological Indicators* 109, p. 105838. https://doi.org/10.1016/j.ecolind.2019.105838

Tranvik, L. J., Cole, J. J. & Prairie, Y. T. (2018): The study of carbon in inland waters – from isolated ecosystems to players in the global carbon cycle. In: *Limnology and Oceanography Letters* 3, pp. 41–48. https://doi.org/10.1002/lol2.10068

Tranvik, L., Downing, J., Cotner, J., Loiselle, S., Striegl, R., Ballatore, T., Dillon, P., Finlay, K., Fortino, K., Knoll, L., Kortelainen, P., Kutser, T., Larsen, S., Laurion, I., Leech, D., McCallister, S., McKnight, D., Melack, J., Overholt, E., Porter, J., Prairie, Y., Renwick, W., Roland, F., Sherman, B., Schindler, D., Sobek, S., Tremblay, A., Vanni, M., Verschoor, A., von Wachenfeldt, E. & Weyhenmeyer, G. (2009): Lakes and reservoirs as regulators of carbon cycling and climate. In: *Limnology and Oceanography* 54, pp. 2298–2314. https://doi.org/10.4319/lo.2009.54.6_part_2.2298

Tremblay, A. & Bastien, J. (2009): Greenhouse gases fluxes from a new reservoir and natural water bodies in Québec, Canada. In: *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen* 30 (6), pp. 866–869. https://doi.org/10.1080/03680770.2009.11902259

UBA (2021): Treibhausgasminderung um 70 Prozent bis 2030: So kann es gehen! Position. Umweltbundesamt/German Environment Agency (ed.), Dessau-Roßlau, 44 p., https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/21_12_29_uba_pos_treibhausgasminderung_um_70prozent_bf.pdf

UBA (2023a): Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2023. Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990 – 2021. Umweltbundesamt/German Environment Agency (ed.), Dessau-Roßlau, 981 p., https://literatur.thuenen.de/digbib_extern/dn066747.pdf

UBA (2023b): Monitoringbericht 2023 zur Deutschen Anpassungsstrategie an den Klimawandel. Bericht der Interministeriellen Arbeitsgruppe Anpassungsstrategie der Bundesregierung. Umweltbundesamt/German Environment Agency (ed.), Dessau-Roßlau, 368 p., https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/das-monitoringbericht_2023_bf_korr.pdf

UBA (2023c): Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990 - 2022. Umweltbundesamt/German Environment Agency (ed.), Dessau-Roßlau, Climate Change 20/2023, 32 p., https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2022-04-13_cc_15-2022_strommix_2022_fin_bf.pdf

UBA (2023d): Emissionsbilanz erneuerbarer Energieträger. Bestimmung der vermiedenen Emissionen im Jahr 2022. Umweltbundesamt/German Environment Agency (ed.), Dessau-Roßlau, Climate Change 49/2023, 174 p., https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/20231219_49_2023_cc_emissionsbilanz_erneuerbarer_energien_2022_bf.pdf

Uhlmann, D. (1988): Hydrobiologie. Ein Grundriss für Ingenieure und Naturwissenschaftler. 3. Edition, Gustav Fischer Verlag, Jena, 298 p.

Upadhyay, P., Prajapati, S. & Kumar, A. (2023): Impacts of riverine pollution on greenhouse gas emissions: A comprehensive review. In: *Ecological Indicators* 154, p. 110649. https://doi.org/10.1016/j.ecolind.2023.110649

Vachon, D., Langenegger, T., Donis, D. & McGinnis, D. (2019): Influence of water column stratification and mixing patterns on the fate of methane produced in deep sediments of a small eutrophic lake. In: *Limnology and Oceanography* 64 (5), pp. 2114–2128. https://doi.org/10.1002/lno.11172

Vachon, D., Sponseller, R. A. & Karlsson, J. (2020): Integrating carbon emission, accumulation and transport in inland waters to understand their role in the global carbon cycle. In: *Global Change Biology*. https://doi.org/10.1111/gcb.154

Vagnetti, R., Miana, P., Fabris, M. & Pavoni, B. (2003): Self-purification ability of a resurgence stream, In: *Chemosphere* 52 (10), pp. 1781-1795. https://doi.org/https://doi.org/10.1016/S0045-6535(03)00445-4.

Valiente, N., Eiler, A., Allesson, L., Andersen, T., Clayer, F., Crapart, C., Dörsch, P., Fontaine, L., Heuschele, J., Vogt, R., Wei, J., de Wit, H. & Hessen, D. (2022): Catchment properties as predictors of greenhouse gas concentrations across a gradient of boreal lakes. In: *Frontiers in Environmental Science* 10, Article 880619. https://doi.org/10.3389/fenvs.2022.880619

Van Bergen, T., Barros, N., Mendonça, R., Aben, R., Althuizen, I., Huszar, V., Lamers, L., Lürling, M., Roland, F. & Kosten, S. (2019): Seasonal and diel variation in greenhouse gas emissions from an urban pond and its major drivers. In: *Limnology and Oceanography* 64 (5), pp. 2129–2139. https://doi.org/10.1002/lno.11173

Van Cappellen, P. & Maavara, T. (2016): Rivers in the Anthropocene: Global scale modifications of riverine nutrient fluxes by damming. In: *Ecohydrology & Hydrobiology* 16 (2), pp. 106–111. https://doi.org/10.1016/j.ecohyd.2016.04.001

Van Drecht, G., Bouwman, A., Harrison, J. & Knoop, J. (2009): Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. In: *Global Biogeochemical Cycles* 23 (4), Article 2009GB003458. https://doi.org/10.1029/2009GB003458

Vicente, I. de (2021): Biogeochemistry of Mediterranean Wetlands: A Review about the Effects of Water-Level Fluctuations on Phosphorus Cycling and Greenhouse Gas Emissions. In: *Water* 13 (11), p. 1510. https://doi.org/10.3390/w13111510

Villa, J., Smith, G., Ju, Y., Renteria, L., Angle, J., Arntzen, E., Harding, S., Ren, H., Chen, X., Sawyer, A., Graham, E., Stegen, J., Wrighton, K. & Bohrer, G. (2020): Methane and nitrous oxide porewater concentrations and surface fluxes of a regulated river. In: *Science of the total environment* 715, p. 136920. https://doi.org/10.1016/j.scitotenv.2020.136920

Völker, J., Arle, J., Baumgarten, C., Blondzik, K., Frauenstein, J., Hilliges, F., Hofmeier, M., Krakau, M., Mönnich, J., Mohaupt, V., Naumann, S., Osiek, D., Rechenberg, J., Richter, N., Schnäckel, A., Schulte, C., Ullrich, A., & Vette, F. (2022): Water Framework Directive – The status of German waters 2021. Progress and Challenges. Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz – BMUV) and Federal Environment Agency (Umweltbundesamt – UBA) [eds.], Bonn, Dessau, 120 p. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/water-framework-directive-2021_bf.pdf (December 19, 2023)

Von Keitz, S., Mehl, D. & Dehnhardt, A. (2022): Ökosystemleistungen (Ecosystem services). In: Patt, H. [ed.]: Fließgewässer- und Auenentwicklung: Grundlagen und Erfahrungen. Berlin, Springer-Verlag, 3. ed, pp. 138-159, https://doi.org/10.1007/978-3-662-64435-5_3

Vuta, L.-I., Dumitran, G.-E., Tica, E.-I. & Popa, B. (2023): Carbon footprint of Vidraru hydropower development. In: *IOP Conference Series: Earth and Environmental Science* 1136 (1), p. 12061. https://doi.org/10.1088/1755-1315/1136/1/012061

Walton, C., Zak, D., Audet, J., Petersen, R., Lange, J., Oehmke, C., Wichtmann, W., Kreyling, J., Grygoruk, M., Jabłońska, E., Kotowski, W., Wiśniewska, M., Ziegler, R. & Hoffmann, C. (2020): Wetland buffer zones for nitrogen and phosphorus retention: Impacts of soil type, hydrology and vegetation. In: *Science of the total environment* 727, p. 138709. https://doi.org/10.1016/j.scitotenv.2020.138709

Wang, F., Lang, Y., Liu, C.-Q., Qin, Y., Yu, N. & Wang, B. (2019): Flux of organic carbon burial and carbon emission from a large reservoir: implications for the cleanliness assessment of hydropower. In: *Science bulletin* 64 (9), pp. 603–611. https://doi.org/10.1016/j.scib.2019.03.034

Wang, G., Liu, S., Sun, S. & Xia, X. (2023a): Unexpected low CO_2 emission from highly disturbed urban inland waters. In: *Environmental research* 235, p. 116689. https://doi.org/10.1016/j.envres.2023.116689

Wang, G., Xia, X., Liu, S., Zhang, S., Yan, W. & McDowell, W. (2021): Distinctive Patterns and Controls of Nitrous Oxide Concentrations and Fluxes from Urban Inland Waters. In: *Environmental science & technology* 55 (12), pp. 8422–8431. https://doi.org/10.1021/acs.est.1c00647

Wang, X., Chen, Y., Yuan, Q., Xing, X., Hu, B., Gan, J., Zheng, Y. & Liu, Y. (2022a): Effect of river damming on nutrient transport and transformation and its countermeasures. In: *Frontiers in Marine Science* 9, Article 1078216. https://doi.org/10.3389/fmars.2022.1078216

Wang, X., Huang, P., Ma, M., Shan, K., Wen, Z. & Wu, S. (2020): Greenhouse gas emissions from riparian zone cropland in a tributary bay of the Three Gorges Reservoir, China. In: *PeerJ* 8, e8503. https://doi.org/10.7717/peerj.8503

Wang, X., Wang, P., Wang, C., Chen, J., Hu, B., Yuan, Q., Du, C. & Xing, X. (2023b): Cascade damming impacts on microbial mediated nitrogen cycling in rivers. In: *Science of the total environment* 903, p. 166533. https://doi.org/10.1016/j.scitotenv.2023.166533

Wang, X., Yu, L., Liu, T., He, Y., Wu, S., Chen, H., Yuan, X., Wang, J., Li, X., Li, H., Que, Z., Qing, Z. & Zhou, T. (2022b): Methane and nitrous oxide concentrations and fluxes from heavily polluted urban streams: Comprehensive influence of pollution and restoration. In: *Environmental pollution (Barking, Essex: 1987)* 313, p. 120098. https://doi.org/10.1016/j.envpol.2022.120098

Ward, J. V. (1989): The four-dimensional nature of lotic ecosystems. In: *Journal of the North American Benthological Society* 8, pp. 2-8. https://doi.org/10.2307/1467397

Webb, J., Hayes, N., Simpson, G., Leavitt, P., Baulch, H. & Finlay, K. (2019): Widespread nitrous oxide undersaturation in farm waterbodies creates an unexpected greenhouse gas sink. In: *Proceedings of the National Academy of Sciences of the United States of America* 116 (20), pp. 9814–9819. https://doi.org/10.1073/pnas.1820389116

Wei, H., Chen, M., Schlautman, M. A. & Hur, J. (2016): Dynamic exchanges between DOM and POM pools in coastal and inland aquatic ecosystems: A review. In: *Science of The Total Environment* 551–552, pp. 415-428. https://doi.org/10.1016/j.scitotenv.2016.02.031

West, W., Coloso, J. & Jones, S. (2012): Effects of algal and terrestrial carbon on methane production rates and methanogen community structure in a temperate lake sediment. In: *Freshwater Biology* 57, pp. 949-955. https://doi.org/10.1111/j.1365-2427.2012.02755.x

WFD (European Water Framework Directive): Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Official Journal of the EC L 327, 22.12.2000), http://data.europa.eu/eli/dir/2000/60/oj

Wikipedia (2024): Encyclopaedia Wikipedia. Liste der Mainstaustufen. https://de.wikipedia.org/wiki/Liste_der_Mainstaustufen (February 25, 2024)

Wilkinson, G., Pace, M. & Cole, J. (2013): Terrestrial dominance of organic matter in north temperate lakes. In: *Global Biogeochemical Cycles* 27, pp. 43–51. https://doi.org/10.1029/2012GB004453

Wilkinson, J., Bodmer, P. & Lorke, A. (2019): Methane dynamics and thermal response in impoundments of the Rhine River, Germany. In: *Science of the total environment* 659, pp. 1045–1057. https://doi.org/10.1016/j.scitotenv.2018.12.424

Wilson, D., Blain, D., Couwenberg, J., Evans, C., Murdiyarso, D., Page, S., Renou-Wilson, F., Rieley, J., Sirin, A., Strack, M. & Tuittila, E.-S. (2016): Greenhouse gas emission factors associated with rewetting of organic soils. In: *Mires and Peat* 17, pp. 1–28. https://doi.org/10.19189/MaP.2016.OMB.222

Wissenschaftliche Dienste des Deutschen Bundestages (2022): Treibhausgasemissionen der Wasserkraft – Berücksichtigung in der Emissionsbilanz und im Nationalen Treibhausgasinventar. Sachstand, Az.: WD 8-3000-052/22. 9 p. https://www.bundestag.de/resource/blob/916774/149e701025457a6a043ee8270de1226e/WD-8-052-22-pdf-data.pdf (June 21, 24)

Wohl, E., Hall, R., Lininger, K., Sutfin, N. & Walters, D. (2017): Carbon dynamics of river corridors and the effects of human alterations. In: *Ecological Monographs* 87 (3), pp. 379–409. https://doi.org/10.1002/ecm.1261

Wohl, E., Lininger, K. & Scott, D. (2018): River beads as a conceptual framework for building carbon storage and resilience to extreme climate events into river management. In: *Biogeochemistry* 141 (3), pp. 365–383. https://doi.org/10.1007/s10533-017-0397-7

Wu, W., Niu, X., Yan, Z., Li, S., Comer-Warner, S., Tian, H., Li, S.-L., Zou, J., Yu, G. & Liu, C.-Q. (2023): Agricultural ditches are hotspots of greenhouse gas emissions controlled by nutrient input. In: *Water research* 242, p. 120271. https://doi.org/10.1016/j.watres.2023.120271

Wüstemann, H., Bonn, A., Albert, C., Bertram, C., Biber-Freudenberger, L., Dehnhardt, A., Döhring, R., Elsasser, P., Hartje, V., Mehl, D., Kantelhardt, J., Rehdanz, K., Schaller, L., Scholz, M., Thrän, D., Witing, F. & Hansjürgens, B. (2017): Synergies and trade-offs between nature conservation and climate policy: Insights from the ‘‘Natural Capital Germany – TEEB DE” study. In: *Ecosystem Services* 24, p. 187-199. https://doi.org/10.1016/j.ecoser.2017.02.008

Wüstemann, H., Hartje, V., Bonn, A. Hansjürgens, B., Bertram, C., Dehnhardt, A., Döring, R., Doyle, U., Elsasser, P., Mehl, D., Osterburg, B., Rehdanz, K., Ring, I., Scholz, M. & Vohland, K. (2015): Natural Capital and Climate Policy. Synergies and Conflicts. Summary for Decision Makers. Technische Universität Berlin, Helmholtz Centre for Environmental Research Leipzig [eds.], 77 p., https://www.ufz.de/export/data/global/190504_TEEB_DE_Climate_report_summary_Eng.pdf

Xiao, Q., Hu, Z., Hu, C., Islam, A., Bian, H., Chen, S., Liu, C. & Lee, X. (2021): A highly agricultural river network in Jurong Reservoir watershed as significant CO_2 and CH_4 sources. In: *Science of the total environment* 769, p. 144558. https://doi.org/10.1016/j.scitotenv.2020.144558

Xiaocheng, F., Tao, T., Wanxiang, J., Fengqing, L., Naicheng, W., Shuchan, Z. & Qinghua, C. (2008): Impacts of small hydropower plants on macroinvertebrate communities. In: *Acta Ecologica Sinica* 28 (1), pp. 45–52. https://doi.org/10.1016/S1872-2032(08)60019-0

Yan, X., Garnier, J., Billen, G., Wang, S. & Thieu, V. (2022): Unravelling nutrient fate and CO_2 concentrations in the reservoirs of the Seine Basin using a modelling approach. In: *Water research* 225. https://doi.org/10.1016/j.watres.2022.119135

Yan, X., Thieu, V. & Garnier, J. (2021): Long-Term Evolution of Greenhouse Gas Emissions From Global Reservoirs. In: *Frontiers in Environmental Science* 9, Article 705477. https://doi.org/10.3389/fenvs.2021.705477

Yang, L. & Lei, K. (2018): Effects of land use on the concentration and emission of nitrous oxide in nitrogen-enriched rivers. In: *Environmental pollution* 238, pp. 379–388. https://doi.org/10.1016/j.envpol.2018.03.043

Yang, L., Lu, F. & Wang, X. (2014): Measuring Greenhouse Gas Emissions From China's Reservoirs. In: *Eos* 95 (1), pp. 1–12. https://doi.org/10.1002/2014EO010001

Yao, Y., Song, J. & Wei, X. (2022a): The fate of carbon in check dam sediments. In: *Earth-Science Reviews* 224, p. 103889. https://doi.org/10.1016/j.earscirev.2021.103889

Yao, Y., Tian, H., Xu, X., Li, Y. & Pan, S. (2022b): Dynamics and controls of inland water CH_4 emissions across the Conterminous United States: 1860-2019. In: *Water research* 224, p. 119043. https://doi.org/10.1016/j.watres.2022.119043

Zak, D., Maagaard, A. & Liu, H. (2022): Restoring Riparian Peatlands for Inland Waters: A European Perspective. In Elsevier (Ed.): *Encyclopedia of Inland Waters*, pp. 276–287, https://doi.org/10.1016/b978-0-12-819166-8.00127-4

Zhang, L., Liu, Y., Jin, M., Liang, X., Krause, S., Schneidewind, U., Li, Y. & Zhan, H. (2023): Influence of seasonal water-level fluctuations on depth-dependent microbial nitrogen transformation and greenhouse gas fluxes in the riparian zone. In: *Journal of Hydrology* 622, p. 129676. https://doi.org/10.1016/j.jhydrol.2023.129676

Zhang, W., Li, H., Xiao, Q. & Li, X. (2021): Urban rivers are hotspots of riverine greenhouse gas (N_2O, CH_4, CO_2) emissions in the mixed-landscape Chaohu lake basin. In: *Water research* 189, p. 116624. https://doi.org/10.1016/j.watres.2020.116624

Zhang, Y., Su, Y., Li, Z., Guo, S., Lu, L., Zhang, B. & Qin, Y. (2022): Terrigenous organic carbon drives methane dynamics in cascade reservoirs in the upper Yangtze China. In: *Water research* 219, p. 118546. https://doi.org/10.1016/j.watres.2022.118546

Zheng, Y., Wu, S., Xiao, S., Yu, K., Fang, X., Xia, L., Wang, J., Liu, S., Freeman, C. & Zou, J. (2022): Global methane and nitrous oxide emissions from inland waters and estuaries. In: *Global change biology* 28 (15), pp. 4713–4725. https://doi.org/10.1111/gcb.16233

Zhou, X.-D., Kumar, A., Wang, H.-Y., Knorr, K.-H., Chen, Y.-B., Liu, Y.-X., Lin, J.-J., Han, L. & Yu, Z.-G. (2023): Greenhouse gas emissions hotspots and drivers of urban freshwater bodies in areas of the Yangtze River delta, China. In: *Ecohydrology* 16 (2), Article e2498. https://doi.org/10.1002/eco.2498

Zhu, X., Burger, M., Doane, T. & Horwath, W. R. (2013): Ammonia oxidation pathways and nitrifier denitrification are significant sources of N_2O and NO under low oxygen availability. In: *Pnas* 110 (16), pp. 6328–6333. https://doi.org/10.1073/pnas.1219993110

Zhu, Y., Jones, J., Collins, A., Zhang, Y., Olde, L., Rovelli, L., Murphy, J., Heppell, C. & Trimmer, M. (2022): Separating natural from human enhanced methane emissions in headwater streams. In: *Nature Communications* 13, 3810. https://doi.org/10.1038/s41467-022-31559-y

Zou, J., Ziegler, A., Chen, D., McNicol, G., Ciais, P., Jiang, X., Zheng, C., Wu, J., Wu, J., Lin, Z., He, X., Brown, L., Holden, J., Zhang, Z., Ramchunder, S., Chen, A. & Zeng, Z. (2022): Rewetting global wetlands effectively reduces major greenhouse gas emissions. In: *Nature Geoscience* 15 (8), pp. 627–632. https://doi.org/10.1038/s41561-022-00989-0

A Appendix: Overview of the studies included in the meta-analysis for the category "Type of pressure"

Table A1: Overview of the studies included in the meta-analysis for all subcategories of category 4 "Type of pressures" (according to the WFD) in alphabetical order, together with the respective water body type/floodplain, if applicable, and the type of study. AWB = artificial water body, HMWB = heavily modified water body, NWB = natural water body. * denotes studies that are not GHG-related

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Aben et al. (2017)							X		AWB, HMWB, NWB, reservoir/dam, river, lake, stream	Review, Conceptional/statistical, Experimental
Aben et al. (2022a)		X							floodplain	Experimental
Aben et al. (2022b)							X		AWB, lake, pond	Experimental
Ai et al. (2022)				X					AWB, reservoir/dam	Review
Amani et al. (2022)				X					AWB, reservoir/dam	In situ
Ansari et al. (2023)		X							floodplain	In situ
Audet et al. (2020)		X							AWB, pond	In situ
Barros et al. (2011)				X					AWB, reservoir/dam	Review

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Battin et al. (2023)					X	X	X		HMWB, NWB, river	Review
Bauwe et al. (2019)		X			X				NWB, river	Modelling
Beaulieu et al. (2010)	X	X		X					HMWB, river, stream	In situ
Beaulieu et al. (2016)				X					AWB, reservoir/dam	Modelling
Beaulieu et al. (2019)		X		X		X			HMWB, lake	Modelling
Bednarik et al. (2017)				X					AWB, HMWB, floodplain	In situ
Benjankar et al. (2018)				X					AWB, reservoir/dam, stream	Modelling
Berga (2016)				X					AWB, reservoir/dam	Review
Best (2019)*		X	X	X	X	X	X		AWB, HMWB, NWB, reservoir/dam, river, floodplain	Review
Bhullar et al. (2013)					X				wetland	Experimental

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Booth et al. (2021)				X			X		AWB, reservoir/dam	In situ
Borges et al. (2018)		X			X				HMWB, river	In situ
Brauns et al. (2022)*	X	X			X	X			HMWB, river, stream	Review, Conceptional/statistical
Brown et al. (2018)					X	X		X	AWB, NWB, stream	Review
Brown et al. (2023)	X	X			X		X		HMWB, river	In situ
Bussmann et al. (2022)		X		X		X			HMWB, river	In situ
Chanu et al. (2022)				X			X		AWB, HMWB, NWB, reservoir/dam, river, lake, stream, wetland, estuary	Review
Chanudet et al. (2020)		X		X					AWB, reservoir/dam	In situ
Chen et al. (2023)						X			NWB, river	Modelling

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
D'Ambrosio and Harrison (2021)		X							AWB, NWB, lake	Review
D'Ambrosio and Harrison (2022)				X					NWB, lake	Review
Deblois et al. (2023)				X					AWB, reservoir/dam	Guideline/protocol/report
Deemer et al. (2011)		X		X					AWB, HMWB, reservoir/dam, lake	In situ
Deemer et al. (2016)				X					AWB, reservoir/dam	Review
DelSontro et al. (2010)				X					AWB, reservoir/dam, lake	In situ
DelSontro et al. (2018)		X		X					AWB, NWB, reservoir/dam, lake	Modelling
Descloux et al. (2017)		X		X					AWB, reservoir/dam	In situ
European Environment		X			X	X			Floodplain	Guideline/protocol/report

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Agency (2018)										
Fischler (2019)				X					AWB, reservoir/dam, lake	Review
Garack et al. (2022)					X		X		(surface waters)	Review, conceptional/statistical
Gattenlöhner et al. (2022)					X		X		Lake, stream, wetland	Review, conceptional/statistical
Gómez-Gener et al. (2015)				X	X	X			AWB, NWB, reservoir/dam, river, stream	In situ
Gómez-Gener et al. (2018)				X	X				AWB, NWB, reservoir/dam, river	In situ
Grill et al. (2015)*				X		X			AWB, reservoir/dam, river	Modelling
Grinham et al. (2022)			X	X					AWB, reservoir/dam	In situ
Gruca-Rokosz (2020)		X		X		X			AWB, reservoir/dam	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Gudmundsson et al. (2021)					X		X		River	Modelling
Hansen et al. (2022)				X					AWB, reservoir/dam	Modelling
Hansen et al. (2023)				X	X	X			AWB, reservoir/dam, river	Conceptional/statistical
Hao et al. (2021)	X	X			X				AWB, reservoir/dam, river, lake, wetland	In situ
Harmon (2020)	X	X		X	X	X	X		AWB, HMWB, NWB, reservoir/dam, river, lake, stream, estuary	Review, Conceptional/statistical
Harrison et al. (2009)*		X		X					AWB, NWB, reservoir/dam, lake	Modelling
Harrison et al. (2017)				X	X				AWB, reservoir/dam, river, lake	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Harrison et al. (2021)				X					AWB, reservoir/dam	Modelling
He et al. (2023)				X		X			AWB, reservoir/dam	In situ
Heger et al. (2021)*					X				Floodplain	In situ
Ho et al. (2021)	X	X			X				HMWB, river	Modelling
Ho et al. (2022)		X			X				HMWB, river	In situ
Holzner (2023)*				X		X			HMWB, river	Conceptional/statistical
Hounshell et al. (2023)				X		X			AWB, reservoir/dam	In situ
International Hydropower Association (2022)				X					AWB, reservoir/dam	Guideline/protocol/report
Ion and Ene (2021)				X					AWB, reservoir/dam	Review, Modelling
Jacinthe et al. (2012)		X		X	X				AWB, HMWB, reservoir/dam, river, stream	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Jensen et al. (2022)		X		X		X			AWB, reservoir/dam	In situ
Jin et al. (2016)				X	X				AWB, reservoir/dam	In situ
Jin et al. (2023)				X	X				AWB, reservoir/dam, river	In situ
Johnson et al. (2021)				X					AWB, reservoir/dam	Review, Modelling
Joyce et al. (2003)			X	X					AWB, reservoir/dam	In situ
Karlsson et al. (2021)							X		NWB, lake, stream, pond	In situ
Keller et al. (2020)			X		X				AWB, NWB, reservoir/dam, river, lake, stream, floodplain, wetland	In situ
Keller et al. (2021)				X		X			AWB, reservoir/dam	Modelling
Knott et al. (2023)*				X					HMWB, river	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Konold (2023)*				X		X			HMWB, river, stream, floodplain	Conceptional/statistical
Koschorreck et al. (2023)				X		X			HMWB, river	In situ
Kumar et al. (2019)				X					AWB, NWB, reservoir/dam, lake	Review
Kumar et al. (2021)				X					AWB, reservoir/dam	Review
Kumar et al. (2023a)		X							NWB, lake	Review, Conceptional/statistical
Kumar et al. (2023b)				X					AWB, reservoir/dam	Review, Guideline/protocol/report
Langenegger et al. (2019)		X							NWB, lake	Conceptional/statistical, Modelling
Lapierre et al. (2013)		X							NWB, river, lake, wetland	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Lehner et al. (2011)*				X					AWB, reservoir/dam, river	Modelling, Conceptional/statistical
León-Palmero et al. (2020)		X		X		X			AWB, reservoir/dam	In situ
Lessmann et al. (2023)				X			X		AWB, HMWB, reservoir/dam, river	In situ
Levasseur et al. (2021)				X					AWB, reservoir/dam, river, floodplain	Conceptional/statistical, Modelling
Li and He (2022)				X					AWB, reservoir/dam	Review
Li et al. (2018)				X					AWB, NWB, reservoir/dam, lake	Review
Li et al. (2020)	X			X		X	X		AWB, HMWB, NWB, reservoir/dam, river, lake, stream, wetland	In situ, Review

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Li et al. (2021)		X		X					AWB, HMWB, NWB, reservoir/dam, river, lake, stream	Review, Conceptional/statistical
Lima et al. (2007)				X					AWB, reservoir/dam	Review
Lin et al. (2022)		X			X				HMWB, river, floodplain, wetland	In situ
Liu et al. (2017)					X				HMWB, river	Modelling
Liu et al. (2022a)	X		X		X				AWB, HMWB, river, pond	In situ
Liu et al. (2022b)				X		X			AWB, reservoir/dam	In situ, Conceptional/statistical
Lorke and Burgis (2018)		X		X					AWB, HMWB, reservoir/dam, river, lake, stream	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Maavara et al. (2017)*				X					AWB, HMWB, reservoir/dam, river	Modelling
Maavara et al. (2020a)*				X					AWB, HMWB, reservoir/dam, river	Modelling
Maavara et al. (2020b)*				X					AWB, HMWB, reservoir/dam, river	Review
Machado Dos Santos Pinto et al. (2020)					X				NWB, river, floodplain	In situ
Maeck et al. (2013)				X					AWB, reservoir/dam, river	In situ
Maeck et al. (2014)				X			X		AWB, HMWB, reservoir/dam, river	In situ
Mäkinen and Khan (2010)*				X					AWB, reservoir/dam	Review, Conceptional/statistical, Guideline/protocol/report

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Marcé et al. (2019)			X	X	X	X			AWB, HMWB, NWB, reservoir/dam, river, lake, stream, pond	Review
Marcon et al. (2023)				X					AWB, HMWB, reservoir/dam, river	In situ
Marotta et al. (2014)							X		NWB, lake	In situ
McCrackin and Elser (2011)		X							NWB, lake	In situ
McGinnis et al. (2023)		X		X		X			AWB, HMWB, NWB, reservoir/dam, river, lake, stream, floodplain, wetland, estuary	Review
Mehl et al. (2023b)*				X	X	X			AWB, HMWB, river, stream	Review, Conceptional/statistical

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Mendonca et al. (2012)				X		X			AWB, reservoir/dam	Review
Metzger et al. (2022)*			X	X					HMWB, river	Review, Guideline/protocol/report
Miao et al. (2020)		X							HMWB, lake	In situ
Miller et al. (2017)				X	X	X			AWB, reservoir/dam, river	In situ
Miller et al. (2019)				X	X				AWB, reservoir/dam, river, floodplain	In situ
Mongil-Manso et al. (2019)*		X		X			X		AWB, reservoir/dam	In situ
Mulligan et al. (2021)*				X					AWB, reservoir/dam	Guideline/proprotor/report
Mwanake et al. (2023)	X	X							NWB, stream	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Naumann (2022)*				X	X	X			AWB, HMWB, reservoir/dam, river, stream	Review, Conceptional/statistical, Guideline/protocol/report
Ni et al. (2022)				X					AWB, reservoir/dam, river	In situ
Nilsson and Berggren (2000)*				X		X			AWB, HMWB, reservoir/dam, river, floodplain	Review
Nilsson et al. (2005)*				X					AWB, reservoir/dam, river	Review, Conceptional/statistical
Page et al. (2021)		X							HMWB, river, lake, stream	Conceptional/statistical
Park et al. (2023)		X		X	X	X			AWB, NWB, reservoir/dam, river	In situ
Peacock et al. (2019)		X			X	X			AWB, pond	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Peeters et al. (2019)				X					AWB, NWB, reservoir/dam, lake	Modelling, Conceptional/statistical
Phyoe et al. (2019)				X					AWB, reservoir/dam	Review
Prairie et al. (2018)				X					AWB, reservoir/dam	Review
Prairie et al. (2021)				X					AWB, reservoir/dam	Modelling
Proia et al. (2016)*				X					AWB, HMWB, reservoir/dam, river	In situ
Pu et al. (2021)		X							HMWB, river	In situ
Ran et al. (2015)		X							HMWB, river	In situ
Ran et al. (2021)				X		X			AWB, NWB, reservoir/dam, river, lake, stream	Review, Conceptional/statistical
Ray and Holgerson (2023)					X	X			AWB, pond	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Raymond et al. (2013)				X					AWB, NWB, reservoir/dam, river, lake, stream	Review
Regnier et al. (2013)	X	X							(surface waters)	Review
Rieger et al. (2013)*				X					NWB, Floodplain	In situ
Rocher-Ros et al. (2023)		X			X	X	X		HMWB, NWB, river, stream	Modelling, Conceptional/statistical
Rosentreter et al. (2021)		X		X	X	X			AWB, HMWB, NWB, reservoir/dam, river, lake, stream, wetland, estuary	Review
Samiotis et al. (2018)				X	X				AWB, reservoir/dam	In situ
Santoso et al. (2021)		X							NWB, lake	In situ, Modelling
Scherer and Pfister (2016)*				X	X				AWB, reservoir/dam	Conceptional/statistical, Modelling

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Schiller et al. (2016)*				X					AWB, NWB, reservoir/dam, river	In situ
Schulz et al. (2023)		X				X			HMWB, river	In situ
Seidel et al. (2017)*						X			HMWB, river, floodplain	Guideline/protocol/report
Shi et al. (2020)*				X	X				AWB, reservoir/dam, river, floodplain	In situ
Shi et al. (2023)				X	X	X			AWB, reservoir/dam, river	In situ
Silverthorn et al. (2023)				X	X				AWB, reservoir/dam, river	Review
Sobek et al. (2012)				X					AWB, reservoir/dam, lake	In situ
Song et al. (2018)			X	X					AWB, reservoir/dam	Review
Soued et al. (2021)				X					AWB, reservoir/dam	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Spank et al. (2017)				X	X				AWB, reservoir/dam	In situ
St. Louis et al. (2000)				X					AWB, reservoir/dam	Review, Modelling
Sun et al. (2021)		X							NWB, lake	In situ
Teodoru et al. (2015)		X		X					AWB, HMWB, reservoir/dam, river	In situ
Thieme et al. (2020)*				X					AWB, reservoir/dam	Review
Thieme et al. (2021)*				X					AWB, reservoir/dam, river	Conceptional/statistical
Tiemeyer et al. (2020)					X				(soils)	Modelling
Tranvik et al. (2009)		X		X	X		X		AWB, HMWB, reservoir/dam, lake	Review
Tremblay and Bastien (2009)				X					AWB, NWB, reservoir/dam, river, lake, stream	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Umweltbundesamt (2023)	X	X		X	X				AWB, HMWB, NWB, reservoir/dam, river, lake, stream, ditch	Modelling, Guideline/protocol/report
Upadhyay et al. (2023)		X							HMWB, NWB, river	Review
Vachon et al. (2019)		X							NWB, lake	In situ, Modelling
Valiente et al. (2022)		X			X				AWB, NWB, lake, wetland	In situ, Modelling
Van Bergen et al. (2019)		X				X	X		AWB, pond	In situ
Van Cappellen et al. (2016)*				X					AWB, HMWB, reservoir/dam, river	Review
Van Drecht et al. (2009)*	X								(surface waters)	Modelling
Vicente (2021)					X		X		NWB, wetland	Review
Villa et al. (2020)				X	X				HMWB, river	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Vuta et al. (2023)				X					AWB, reservoir/dam	In situ
Walton et al. (2020)*		X			X				NWB, river, stream,, floodplain, wetland	Review, Conceptional/statistical
Wang et al. (2019)				X					AWB, reservoir/dam	Modelling
Wang et al. (2020)		X		X	X	X			AWB, reservoir/dam, river, floodplain	In situ
Wang et al. (2021)	X								NWB, river, lake	In situ
Wang et al. (2022a)				X					AWB, HMWB, reservoir/dam, river	Review
Wang et al. (2022b)		X							HMWB, stream	In situ
Wang et al. (2023a)	X	X					X		HMWB, river, lake	In situ
Wang et al. (2023b)*				X	X				AWB, reservoir/dam	In situ
Webb et al. (2019)		X			X	X			AWB, pond	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Wilkinson et al. (2019)				X			X		AWB, HMWB, reservoir/dam, river	In situ
Wilson et al. (2016)					X				(surface waters)	Review, Conceptional/statistical, Guideline/protocol/report
Wissenschaftliche Dienste des Bundestages (2022)				X					AWB, reservoir/dam, river	Review
Wohl et al. (2017)				X	X	X			HMWB, river, floodplain	Conceptional/statistical, Modelling
Wu et al. (2023)		X	X		X	X			AWB, HMWB, river, ditch	In situ
Xiao et al. (2021)		X							AWB, HMWB, reservoir/dam, river, lake, stream, pond, ditch	In situ
Xiaocheng et al. (2008)*				X	X				HMWB, river	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Yan et al. (2021)		X		X					AWB, reservoir/dam	Review
Yan et al. (2022)		X		X					AWB, reservoir/dam	Modelling
Yang et al. (2014)				X					AWB, reservoir/dam	Review
Yang et al. (2018)		X							HMWB, river	In situ
Yao et al. (2022a)		X					X		AWB, HMWB, NWB, reservoir/dam, river, lake	Modelling
Yao et al. (2022b)*				X					AWB, reservoir/dam	Review
Zak et al. (2022)*		X							HMWB, wetland	Review
Zhang et al. (2021)		X							HMWB, NWB, river	In situ
Zhang et al. (2022)		X		X					AWB, reservoir/dam, river	In situ

Reference	Point sources	Diffuse sources	Abstraction/flow diversion	Dams, barriers and locks	Hydrological alteration	Morphological alteration	Other pressures	Historical pollution	Water body or terrestrial area type	Type of study
Zheng et al. (2022)				X					AWB, HMWB, NWB, reservoir/dam, river, lake, stream, estuary	Review
Zhou et al. (2023)	X	X		X	X				AWB, reservoir/dam, river, lake	In situ
Zou et al. (2022)					X	X	X		HMWB, wetland	Conceptional/statistical