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Abschlussbericht
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Titel: **CONNECT - Connectivity and coherence of lake ecosystems in space and time**

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Federführendes Leibniz-Institut:
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Executive Summary

The aim of CONNECT was to study how lake-to-lake connectivity drives seasonal biological coherence along river-connected lakes. Following phytoplankton transport and development along lake chains necessitates data at high spatial and temporal resolution. CONNECT combined various methods ranging from water sampling and lab measurements to high-frequency *in situ* sondes and near to far remote sensing (RS). Furthermore, connectivity and its effect on signal transport was tested under controlled conditions in experimental lakes using the IGB LakeLab facility. An international interdisciplinary expert network was successfully established with the mission to exchange and transfer knowledge between disciplines of aquatic and terrestrial ecologists and inland water RS experts. Besides publications in scientific journals, CONNECT raised public attention in the media through press releases, online articles (IGB web site), social media, public TV and radio.

The CONNECT project started in May 2018, followed by a Kick-off meeting hosted by IGB-Stechlin in June 2018, where the project organisation was discussed and agreements on data organisation, publication and sharing were formulated. Monthly Jour-fixe secured regular information flow between all CONNECT partners and external collaborators. During the first year the core postdoc team was hired. The field campaign was prepared by selecting lakes of different connectivity, trophic state and morphometry, and sampling permissions from local, regional and governmental authorities were acquired. The field campaign started in May 2019 by monitoring 19 lakes located in the Upper Havel river system, the Feldberger Lake District and Lake Stechlin.

Buoys equipped with multi-probes for high-frequency *in situ* measurements of biological, physical and chemical parameters were installed in the lakes. Synchronised with overflights of Sentinel 2 a,b satellites, sampling campaigns were conducted every 5 weeks during the vegetation period from May to November 2019, and from April to October 2020. Measurements included multiprobe depth profiles, reflectance and radiance with hand held devices, GHG profiles and flux with mobile gas flux chambers. Water samples were taken for laboratory analyses of algae pigment composition, inherent optical properties, nutrients, and plankton community composition. Three extra field campaigns were conducted in parallel with airborne hyperspectral imaging and GHG flux measurements for ground-truthing methodologies.

To compare the effects of extreme weather events on strong versus weak connected lake systems and the signal transport along lake chains, two large-scale enclosure experiments were conducted in the IGB LakeLab, one in summer 2019 on the influence of water retention time on lake systems, and a second in summer 2021 on combined effects of browning and nutrients on optical properties of water by different constituents. Both experiments involved an international interdisciplinary team of experts on RS, ecology and meta-ecosystems, most funded by the Transnational Access (TA) program of the EU project AQUACOSM. CONNECT-partners joined during the experiments to conduct an extra field campaign involving airborne hyperspectral imaging and measurements of *in situ* reflectance profiting from special equipment of the TA users not regularly available to the CONNECT team.

The CONNECT team hosted several workshops, organised special sessions on national and international conferences to discuss topics on aquatic connectivity, RS of inland water, meta-ecosystem concepts, GHG dynamics and presented results from field and experimental studies. This effectively promoted international collaboration by interdisciplinary exchange, specifically by connecting concepts in aquatic and terrestrial ecology with RS and experimental mesocosm-based approaches. First results from the CONNECT field campaign are published and several manuscripts are in revision and preparation, while active collaboration tackling different aspects of the collected data is on-going. Data acquired in CONNECT have thereby contributed to evaluate and improve inland water reflectance products such as chlorophyll spatial distribution in lakes.

Extending the collaborations in CONNECT to a wider international expert network effectively advanced processing of RS data for inland waters. For example, data from the extra campaign on Lake Stechlin in 2019 were used for ground-truthing an algorithm for DESIS data through

collaboration with DLR. Additional researchers joined the field and experimental campaigns to add aspects such as water isotopes, fungal parasites and algae toxins to the overall scope of the study. CONNECT has resulted in further lasting values by enabling innovative methodology and construction of new instruments (e.g. automatic GHG flux chambers, mini-mutispectrometers). In conclusion, the interdisciplinary network was successfully established and the gathered field and experimental data provide a valuable basis for understanding connected lake systems and thus help to improve current management of river-connected lake ecosystems under future climate change.

1. Achievement of objectives and milestones

The CONNECT project successfully established an interdisciplinary network with CONNECT partners involving experts from aquatic and terrestrial ecology, greenhouse gas (GHG) dynamics and remote sensing (RS) of inland waters to tackle connectivity of lake systems and detect coherence patterns of river-connected lakes. This network was extended through national and international workshops, meetings, congresses and the conduction of two LakeLab experiments involving international experts via EU-funded AQUACOSM Transnational Access (TA), thus fostering state-of-the-art research and collaboration. CONNECT started in May 2018 and all milestones were shifted accordingly. The core team of four postdocs was involved in planning and conduction of field campaigns and experimental studies in the LakeLab 2019, while a fifth postdoc joined the team in 2021 for the second LakeLab experiment. One postdoc joined the team shortly for modelling aspects and another for part-time for assistance in image-based plankton analyses. Overall, 7 postdocs, 4 students and 1 technical assistant were employed (some part-time or short-term), and 4 Master and 2 Bachelor theses were completed.

The Kick-off meeting (Milestone 1) was hosted by IGB in June 2018 with 15 participants bringing together the CONNECT partners, introducing the project, its 3 work-packages (WPs) and the expertise from each partner. The **field campaign (WP1)**, a preliminary design of the **LakeLab mesocosm experiment (WP2)**, and the work-flow on **Data management (WP3)** including data collection and analyses, Q/C, standardisation, data sharing and modelling by initiating a Confluence information page, metadata and data sheets, CONNECT data policy, etc. were discussed and implemented accordingly. The CONNECT project lead (PI's Berger and Wollrab), set up a Jour fixe for monthly exchange on the project status, for advice from partners, and to foster interdisciplinary collaboration.

Goal of the **field campaign (WP1)** was to study how lake-to-lake connectivity drives seasonal biological coherence in lake chains and to investigate how lake depth and mixing pattern modulate the effects of lake-to-lake connectivity on coherence. Therefore, 19 lakes in (or close to) the Upper Havel river-lake system (Baltic lake district) were chosen to cover a wide connectivity gradient and include shallow and deep lakes. The lakes combine connected relatively deep, stratified, lakes along the Upper Havel river system (Zotzensee, Vilzsee, Labussee, Kl. Pälitzsee, Gr. Pälitzsee, Ellbogensee, Röblinsee, Stolpsee, Gr. Lychensee), connected shallow lakes entering the Upper Havel river system (Zierker See, Useriner See, Woblitzsee, Gr. Labussee, Priepertsee), weak connected, deep lakes in the Feldberg area (Breiter Luzin, Schmaler Luzin, Feldberger Haussee) and the almost disconnected Lake Stechlin (Ogashawara et al. 2020, 2021; Xiao et al. 2020; Aichner et al. 2022).

To cover full vegetation seasons and get all necessary permissions for buoy installation and samplings, the lake campaign started only in spring 2019 with samplings every 5 weeks and continuous multiprobe-based measurements of sensors deployed at the buoys. The field campaign ended in late fall 2020 (samplings) and in spring 2021 (continuous probe measurements). Extra field campaigns with CONNECT partners and additional experts were conducted in the area including airborne hyperspectral measurements of Lake Stechlin via airplane, drones and near RS devices in parallel with high frequency measurements by *in-situ* probes, enabling cross-comparison of data for the Q/C process. First results from the field campaign highlighted the importance of ground-truthing RS products with i*n situ* and lab measurements (Ogashawara et al. 2020, 2021, Aichner et al. 2022).

Due to the delayed start of the field campaign, the **Workshop 1 (Milestone 2)** for inter-calibration of selected *in situ* and RS tools and initialisation of high frequency measuring campaigns was partly achieved in the Summer Workshop 2019 **(Workshop 2**, **Milestone 2, 4)** held during the first LakeLab experiment (WP2). In November 2020 an online **Data Workshop** was held (originally planned at ZALF) to exchange expertise on data analysis and advanced statistics with specific focus on processing and ground-truthing of optical RS data **(Milestone 2, 4).** According to the data management plan all data are saved on a server hosted by IGB and metadata were recorded including samplings and data handling. The open sessions **(Milestone 3, 6)** originally planned in 2018 and 2019, were shifted to 2021 due to COVID-19 related postponement of conferences. A special session on "connecting in-situ

sensor networks and RS to understand the complex ecology of aquatic landscapes" was organised by the project lead at the annual ASLO conference in 2021 (virtual) bringing together interdisciplinary experts and leading to fruitful discussions.

Objective of the **LakeLab experiment (Milestone 5, WP2)** conducted in August 2019 was to simulate a pulse nutrient input into lake chains comparable to an extreme weather event such as storm with heavy rain, to investigate effects on lakes along lake chains of different connectivity strength. After the addition of nutrients and deep mixing, the water retention times in the lake chains were experimentally manipulated with a newly-designed pump system simulating water exchange times prevalent in the connected Havel lakes, ranging from 30 days to 1 year. At the start of the experiment a Summer Workshop (WS2) was organised with CONNECT partners and international experts participating in the LakeLab experiment via TA through the AQUACOSM project. Interdisciplinary collaboration with national and international experts from Germany, Austria, Spain, The Netherlands, USA, and Australia covered research fields from process-based aquatic ecology to RS and hydrological modelling and preliminary results from the first LakeLab experiment.

The final symposium **(Milestone 7)** within a special session on **"**connectivity of aquatic ecosystems" was organised at the SIL conference in Berlin 2022, bringing together limnologists and meta-community ecologists as well as the RS community. Overall, **results from CONNECT** have been presented at several national and international conferences such as ICEI in Jena 2018, LPS in Milano 2019, ASLO (virtual) 2021, WRW in Tulcea 2021, LPS in Bonn 2022, SIL in Berlin 2022, DGL in Konstanz 2022. Furthermore, invited oral presentations and workshops offering training opportunities for aquatic ecologists on the use of RS products have been organised as part of the Global Lake Observatory Network (GLEON) where a RS focus group has been established under the lead of Dr. Ogashawara (CONNECT postdoc) and Dr. Cillero (collaborative CONNECT partner and AQUACOSM TA user). In addition, results from CONNECT have been presented at governmental events (e.g. Gewässersymposium MV), regional information meetings, and reported to water authorities, local communities and stakeholders.

CONNECT already led to eleven publications, two on the evaluation of RS derived products on water quality based on data collected in CONNECT (Ogashawara et al. 2020, 2021) and new methods of GHG measurements (Xiao et al. 2021), and eight on optical measurements where CONNECT personnel was involved and co-funding was acknowledged. An essay providing a best practice guide on use of RS products for aquatic ecologists has been developed based on available expertise in the CONNECT consortium (Ogashawara et al. *in revision*). Due to COVID-19 pandemic related delays in data analyses and processing, the synthesis paper on the field campaign will be submitted in fall 2023 (**Milestone 8,** partly reached). One data paper has been published (Aichner et al. 2022), several manuscripts on different aspects of the field campaign and the LakeLab experiments are in preparation. Compared to the original financial plan, budget was partly shifted and invested in personal by reducing travel budget (due to COVID-19 pandemic related cancellation of WS at ZALF, ASLO conference in Spain, and virtual meetings instead), by moving publication costs (IGB is DEAL member), by reducing consumables (support from IGB and AQUACOSM), and by moving investment budget (support from BMBF and IGB).

2. Activities and obstacles

The success of the cross-disciplinary CONNECT project was achieved by attracting a highly competent, complimentary and collaborative postdoc team. One postdoc on RS, ground-based spectrometers started in May 2018, a second postdoc on chemistry and phytoplankton began in July 2018, a third postdoc on GHG fluxes and eddy covariance joined in January 2019, and a fourth postdoc on RS and bio-optical modelling completed the core team in April 2019. Two part-time postdocs on image-based phytoplankton analyses and modelling joined the team in 2021, and one part-time postdoc joined in 2022 assisting in data analysis and modelling. Many international students and collaboration partners enlarged the network. Monthly Jour-fixe were effectively used to exchange expert information and foster collaboration among the CONNECT project partners (IGB, TUM, FUB, DLR, HZG, ZALF, GFZ), except (IOW).

The project leaders initiated the preparation for the CONNECT field campaign in the area of BB and MV, followed up by the first two postdocs in organising lake specific data requests from authorities, contacting governmental, regional and local authorities, and local fishermen for permissions to sample and install permanent buoys with sensors. As the study lakes are distributed among two federal states Brandenburg (BB) and Mecklenburg-Vorpommern (MV) including official waterways and lakes with special restrictions due to nature conservation law, this process involved numerous governmental, regional and local authorities, and took longer than expected. The low-cost buoys were constructed and installed in 18 lakes except Lake Stechlin where the LakeLab and a monitoring buoy exist as monitoring platforms.

Instrumentation, including multiparameter probes were acquired with support from BMBF and IGB to measure biological, chemical and physical parameters and estimate the algal biomass via chlorophyll-a. The PI and postdoc team prepared the labs for nutrients analyses, IOPs, phytoplankton pigments (HPLC) and other parameters. Manual and automatic GHG flux chambers and mini-spectrometers were developed and built, although the final constructions were delayed due to COVID-19 pandemic related delays of material delivery, and could not be deployed on all buoys. However, GHG flux chambers and minispectrometers were installed in a subset of lakes in 2020 and used in the LakeLab experiment 2021 (JOMEX-CONNECT, funded by AQUACOSM). IGB team members participated in a motorboat driving course to acquire a licence for inland waters. The field campaign time plan, Sentinel 2 series overpasses, parameter lists, technician availability, boat and car reservations were prepared.

WS1 was postponed due to the delayed start of CONNECT and extensive preparations for the field campaign. Instead, a Summer Workshop in 2019 and a Data Workshop in November 2020 were held to discuss data processing, results and publications. Preparation for the LakeLab Experiment in summer 2019 by the **IGB team** started in April 2019. According to the experimental design, 24 LakeLab enclosures were connected to each other to form six chains of 4 enclosures. To simulate different water retention times, a computer system to regulate different water exchange regimes was implemented. The laboratories were prepared and equipment was shipped for visiting scientists from Europe, USA and Australia. The LakeLab experiment was conducted in August 2019 with in total 60 participants, all coordinated by the IGB-team and partly supported by AQUACOSM. The Summer Workshop (WS2) in August 2019 prepared by IGB in collaboration with partners (TUM, FUB, DLR, HZG, ZALF) was held in parallel with the LakeLab experiment 2019. The second LakeLab experiment conducted in August 2021 on the effect of nutrients and browning on optical properties of water, was joined by international scientists from Europe, Asia, and USA, all supported by AQUACOSM TA.

FUB took care of the technical aspects and logistics of flights including planning, permissions, data acquisition and conduction of 2 Cessna flights and one glider flight. The overflights with the motor glider ASK16 for airborne eddy-covariance measurements of GHG exchange was conducted on 24 August 2019, and one test flight in May 2019. **GFZ** co-organised airborne eddy covariance measurements, software development, data processing and hyperspectral instrument for Cessna overflight incl. data processing. Common efforts on one flight campaign on 26 July 2019 (IGB, FUB, GFZ) and another flight campaign on 22 August 2019 (IGB, FUB, TUM, GFZ) were achieved. **TUM** performed in-situ reflectance measurements during flight campaign 22 August 2019 and during field campaign August 2019. **DLR** gave important scientific advice on chlorophyll-a retrieval from satellite data and offered additional hyperspectral data from DESIS. **ZALF** assisted with exchange of expertise on data analysis and **HZG** with exchange of instruments and expert knowledge.

The start of the field campaign in 2020 was heavily hit by the COVID-19 pandemic. Special permissions on many levels were needed to continue the samplings, further hindered by limited access to boats, cars and especially laboratory. However, due to support by the IGB-administration a (restricted) field campaign could continue. Although a cost neutral prolongation was given to CONNECT, not all data analysis could be finished within this time frame. In part this was due to delays in lab analysis caused by the COVID-19 pandemic, but also due to limitations in workforce, especially for team members with young children and care taker duties. Furthermore, one of our postdocs got another position before the end of the project. This position was refilled but still came at a delay to pigment and plankton analysis.

Results and successes

Publications

The CONNECT project was presented at several national and international conferences with at least 8 posters and 23 talks. Furthermore, the CONNECT team members were invited to give oral presentations at national and international conferences and workshops (at least 5 talks). Three research articles and one data article using data from the CONNECT field campaigns have been published (Ogashawara et al. 2020, 2021, Xiao et al. 2021, Aichner et al. 2022), eight research articles were published on optical measurements where CONNECT personnel was involved and co-funding by CONNECT was acknowledged, two manuscripts are currently in revision*, and several publications are in preparation.* Reports to the Oberhavel authorities based on core parameters measured in Lake Stechlin and in the enclosures during the CONNECT LakeLab experiment in August 2019 were delivered. The CONNECT project was presented to the public in several media such as press releases, blogs, internet articles, radio / TV reports.

Scientific events

The IGB team organised several scientific events to bring together the CONNECT partners, establish a collaborative network of international experts on aquatic ecology, terrestrial ecology, biogeochemistry, and RS of inland water, organise field campaign and LakeLab experiments, data organisation, sharing and publication plans, and exchange ideas and expert knowledge by: CONNECT Kick-off meeting in June 2018, CONNECT Summer-Workshop in August 2019, Fall 2019 meeting with the Space Science group at FU Berlin (Prof. Dr. Fischer), Data Workshop in November 2020, and Data meeting on the JOMEX-CONNECT experiment in August 2022. In addition, a meeting in January 2020 was organised bringing together experts involved in data collection and processing of airborne hyperspectral measurements and eddy-covariance analysis of airborne gas flux measurements with the CONNECT core team. Finally, a special session on “Connecting in-situ sensor networks and RS to understand the complex ecology of aquatic landscapes” was organised by the project lead at the ASLO conference 2021 (virtual) and the final symposium in combination with a special session on “Connectivity of aquatic ecosystems” was organised at the SIL conference in Berlin 2022.

Completed qualification work

Two Bachelor Thesis and three Master Thesis have been conducted within CONNECT.

Transfer

Interdisciplinary scientific transfer of expertise and knowledge among the CONNECT partners was achieved by monthly meetings (Jour-fixe), specific topic-oriented meetings, and was expanded to international collaborations through the Summer Workshop in Stechlin and the Data Workshop (online). The CONNECT Workshops linked scientific disciplines to industry (SMEs) by participants in the AQUACOSM TA program during the LakeLab experiments connected to the WS2. Many activities in CONNECT were transferred to the public by press releases in newspapers, blogs, the IGB website, and TV and radio reports.

3. Equal opportunities, career development and internationalisation

The five postdoc positions were advertised internationally and followed equal opportunity measures by specifically encouraging female scientists to apply. The application and hiring process was accompanied by IGB's equal opportunity officer and workers’ council. The CONNECT core postdoc team consisted of two male and two female scientists. In the last year of the project one female postdoc shifted position and a male postdoc joined the team (part-time). Two male postdocs and one female PhD student were co-funded by CONNECT contributing to image-based plankton analyses and modelling. The CONNECT project was led by two female scientists and accompanied by six male senior scientists. Three Bachelor students (two female, one male), and two Master students (one female, one male) joined the project. Additionally, three student helpers (two female and one male) and one male technician assisted during the project. The CONNECT project shows an equal distribution of gender. The CONNECT team also covered international diversity (Brazil, France, USA, Thailand, The

Netherlands, India, Canada, Germany). Furthermore, many international scientists joined the LakeLab experiments. CONNECT supported the career of early career researchers resulting in two postdocs that successfully attained permanent jobs, and one being successful at retrieving EU funding (e.g. WaterForCE, AquaINFRA) and more (GeoAquaWatch).

Structures and collaboration

The IGB team and colleagues collaborated in the CONNECT project and shared expertise in various fields of aquatic ecology and related research, such as plankton ecology, hydrology, river ecology, microbiology, biogeochemisty, bio-optical modelling and mesocosm-based experimentation. The collaborative CONNECT partners covered expertise in connected landscape ecology, meta-ecosystem concepts, statistical approaches, and data management tools (ZALF), GHG measurements (FUB). Collaboration with GFZ and the University of Innsbruck enabled airborne (motor glider) GHG measurements of inland waters, data analyses and statistics. RS and chlorophyll retrieval of inland water was scientifically and methodologically supported by CONNECT partners DLR, HZG, TUM. Furthermore, CONNECT fostered international and interdisciplinary collaboration during LakeLab experiments by visiting guest scientists with expertise in RS of coastal areas, including drone flights by SMEs, light and attenuation detection, connectivity and related food web processes of ecosystems. Methodological collaboration in instrument inter-calibration and new near RS technology (self-build mini-spectrometers) was supported by HZG and UFZ.

4. Quality assurance

All CONNECT partners and international collaborating colleagues followed the regulations of good scientific practice including data management and publication guidelines for data collected within CONNECT. All raw data were stored on separate IGB servers. Data requests from external scientists were archived including data sharing agreements. Upon publication of scientific results, the corresponding data have been and will be made publicly available.

5. Additional resources

Additional own resources in personal costs (salaries) contributed by all CONNECT partner institutes (excluding Helmholtz institutes) encompassed 84 person month in total, whereof the majority of 72 months (381.600 EUR) were provided by IGB, 8 person month (46.000 EUR) by FUB, and 2 person month each by ZALF (11.400 EUR) and TUM (11.400 EUR). Own material resources of IGB comprised 868.000 EUR in total including multiparameter sondes, radiometer, consumables, TA related costs (no salaries), motorboat driving license, spectrometers, LakeLab maintainance, sondes calibration, and buoy parts.

6. Outlook

Data gathered in CONNECT demonstrate the importance to use correct algorithms for different inland water types to implement RS in future water quality management. A combination of RS with high frequency *in situ* instrumentation and regional high-resolution near real time data, AI-based phytoplankton classification and possibly -omics - could gain more precise and faster information on algae bloom developments and different algae groups including toxic cyanobacteria blooms. This would facilitate regional-scale monitoring and management of lakes and rivers. The results of CONNECT, on how lake connectivity enables downstream-transport of nutrients and phytoplankton along river-connected lakes can help to recognise influential lakes in lake chains for successful management. Challenges such as bottom reflection in shallow lakes and ponds still need to get solved and weather independent spectral measurements and instrumentation need to be developed. Additionally, improved data analysis and processing of data collected by motor gliders and automatic GHG flux chambers as well as the image-based plankton is needed to enable fast and accurate forecasting bloom events and related changes in ecosystem functions.