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1 Description of ESS pilot

1.1 Scientific case

Obstacles such as dams and other human-made waterworks fragment the habitats and interrupt dispersal routes of many species, including aquatic invertebrates (Grönroos et al., 2013), fish (Barbarossa et al., 2020; Duarte et al., 2021), and plants (Merrit & Wohl, 2005). In addition to this, river dams and other human-made waterworks change the natural flow regimes that support the often highly heterogeneous environments of aquatic and semi-aquatic species in rivers (Poff et al., 2010; Janse et al., 2015) and river floodplains (Kuiper et al., 2014). River dams tend to reduce sediment transportation which is crucial for the formation and maintenance of river deltas. These deltas, in turn, are hotspots of semi-aquatic biodiversity and agricultural productivity because of their fertile soils and proximity to water (Tessler *et al.*, 2015; Schmitt *et al.*, 2021, but see also Nienhuis et al., 2020). At the same time, the reservoirs behind river dams may submerge riparian zones on which many plant and animal species rely (Nilsson & Berggren, 2000) and which may lead to the displacement of human populations (Randell, 2022) which have settled there for the same reasons (i.e. fertile soils and proximity to water). Because of this mix of negative consequences, it is perhaps no surprise that dam removal is an explicit target in the EU Nature Restoration Plan (see section 3.1.1), which aims for the restauration of at least 25,000 km of free-flowing rivers. River dams, however, also are important in the less developed countries, and are welcomed as a source of renewable energy (i.e. hydropower) when combatting climate change (Winemiller *et al.*, 2016). Decision making regarding the placement or removal of river dams thus, ultimately, involves a consideration of *the multiple simultaneous impacts of river dams*, e.g., on green energy production, (aquatic) habitat connectivity, and sedimentation processes. The aim of this pilot is, therefore, to contribute to a decision framework that helps to weigh the pros (i.e., in terms of energy production) and cons of (different types of) individual river dams and their placement within a river basin (e.g., as in Schmitt et al., 2018). As pointed out in the Requirements Baseline (BIOMONDO D1.1 RequirementsBaseline v2.1.pdf), EO is a suitable tool to improve the global information basis for assessments of such effects and associated trade-offs.

In the scope of BIOMONDO Pilot 3, we explored the possibilities for combining EO data and biodiversity modelling for monitoring and assessing the impact of dam construction and removal on:

1) habitat connectivity and dispersal routes of fish species

2) water quality and downstream sedimentation processes

For the first objective (i.e. impact on habitat connectivity and dispersal routes), we studied whether there are differences between individual dams in the extent to which they fragment the habitat of ~10.000 fish species across all river dams belonging to an entire drainage system. We related these findings to the amount of electricity produced by each of these dams and estimated the extent to which they are placed optimally (i.e. minimal impact on connectivity relative to the amount of electricity they produce). For the other objective we focussed on the impacts of four pre-selected river dams that belong to the same drainage system.

1.2 Science/Policy Traceability Matrix

The BIOMONDO Science/Policy Traceability Matrix (SPTM) lists six major drivers related to the decline of freshwater biodiversity, including pollution and eutrophication, habitat changes, invasive species, climate change impact, overexploitation, and effects resulting to driver interaction or unknown drivers. Pilot 3 is aiming to explore one of five objectives that aim to assess habitat change related impacts. It addresses all three pilot objectives for this domain (Figure 1).

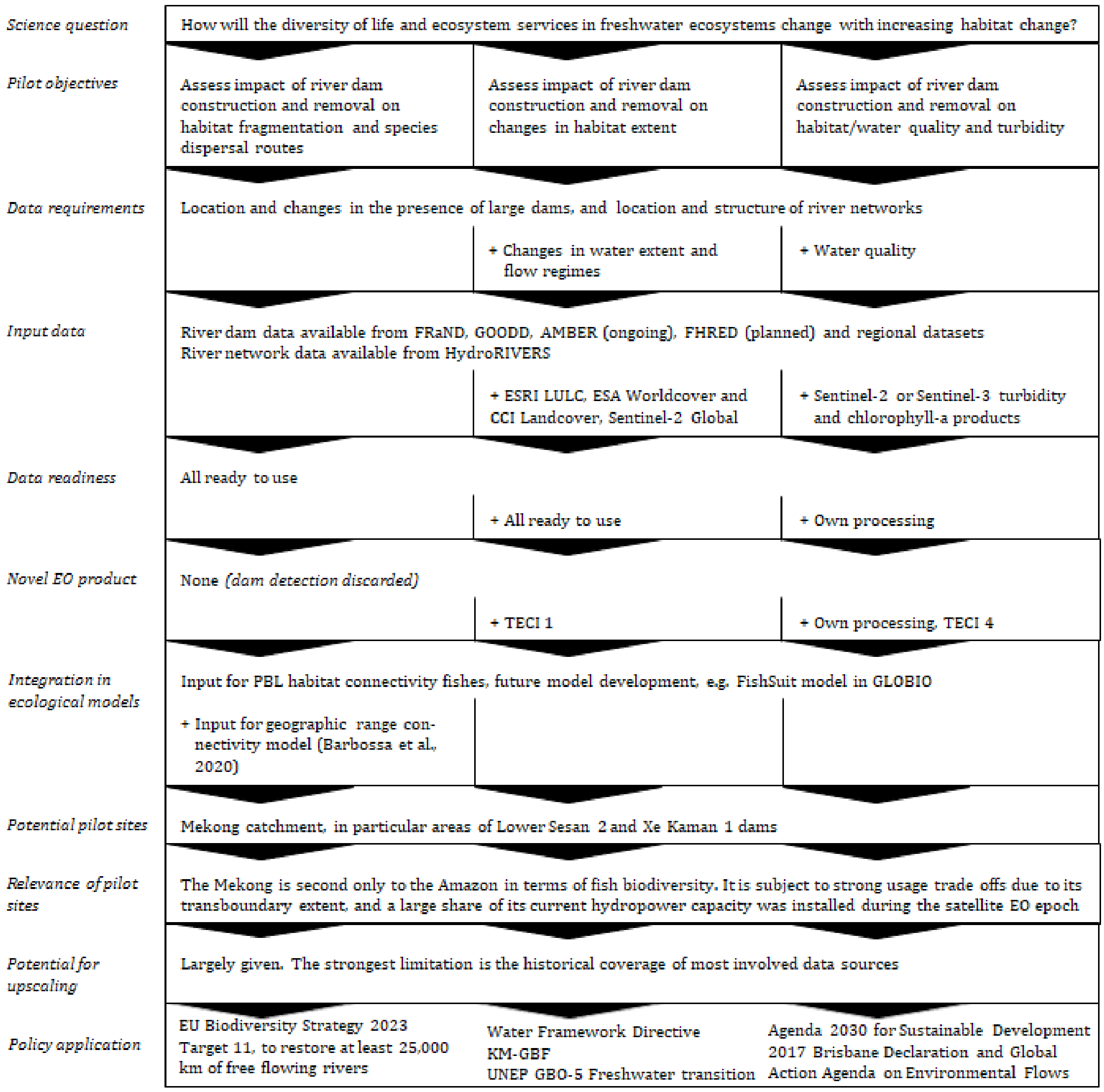

Figure 1 Graphical summary of the Science/Policy Traceability Matrix for pilot study 3 (modified from BIOMONDO WP1 SPTM). Information given for Data requirements and below represents common requirements for all objectives in the top row, and objective specific requirements just below.

1.3 Test site – Mekong catchment

The Mekong Basin is a large river system that flows through six countries in Southeast Asia: China, Myanmar, Thailand, Laos, Cambodia, and Vietnam (Figure 2). The basin has a total extent of 795,000 km² and is home to one of the most diverse freshwater ecosystems in the world, with over 1,300 fish species, many of which are found nowhere else on Earth. The Mekong Basin is also home to a variety of other aquatic species, including amphibians, reptiles, crustaceans, and molluscs. The number of hydropower plants in the catchment is increasing quickly since the 1990s, with more than 150 dams completed today, and more than 50 dams in planning, most of them in Laos.

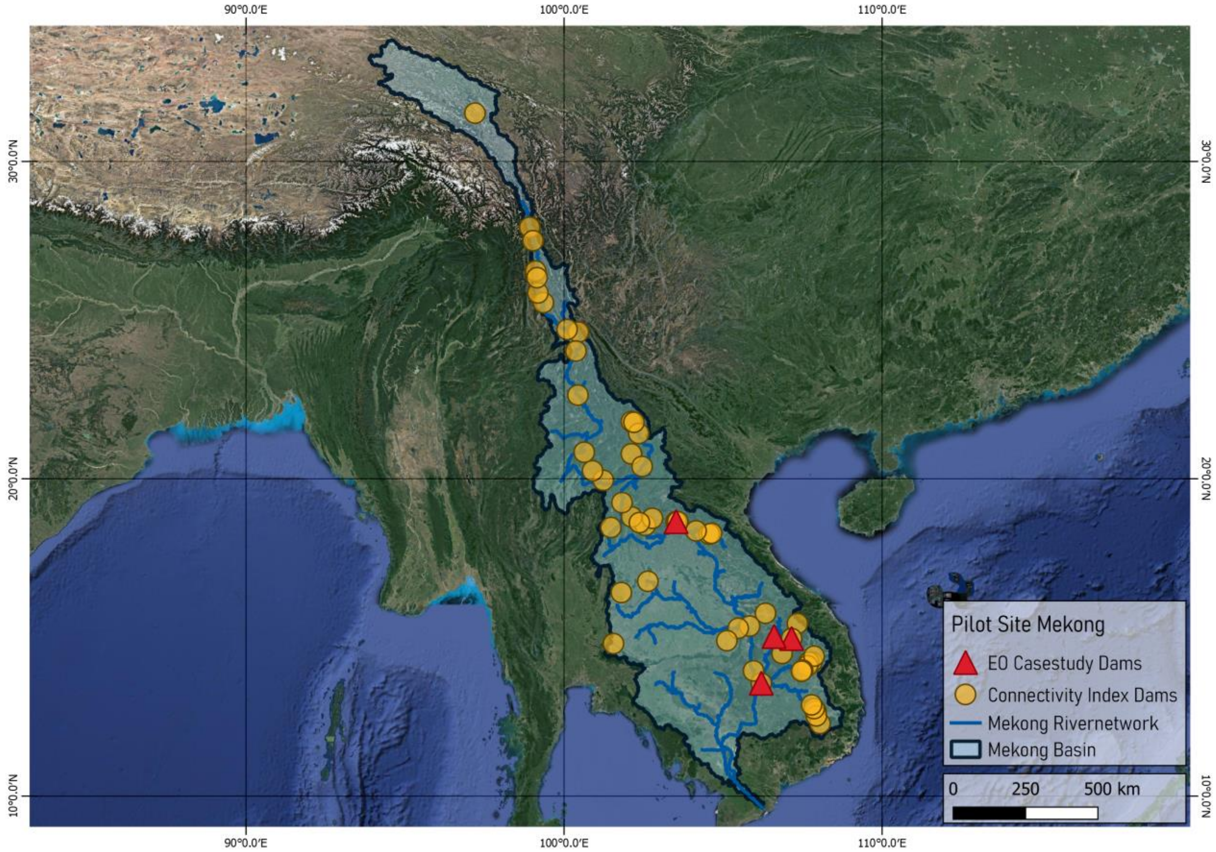

Figure 2 Pilot site Mekong catchment.

The basin's freshwater ecosystems provide a wide range of ecosystem services, such as water purification, flood control, and nutrient cycling, they are a major food source, and the Mekong delta is one of south-east Asia's main economic centres. Management and conservation of the Mekong River basin is implemented at national and international (e.g., Mekong River Commission MRC, Greater Mekong Subregion GMS Program by the Asian Development Bank) level, and various non-governmental organizations (e.g., IUCN, ICEM, WWF) pursue major activities in the region. According to GMS, about 115,000 km^2 or 15% of the catchment area fall within one of almost 200 protected are-as.

To determine the impact of individual river dams on connectivity, we used species range data from IUCN and point occurrence records from multiple sources (see Barbarossa et al., 2020). For the Mekong basin this included the geographical ranges of 783 lotic fish species. We used the dam data (n=107) from Schmitt et al. (2019), which includes info on location, status (Existing, Planned or under Construction), commercial operation date, installed capacity, and dam height. The species ranges were referenced to Hydro-BASINS (HB) subbasins (Pfaffstetter level 12). With the Pfaffstetter level 12 we used the highest level of spatial definition available, i.e., the smallest sub-basin units. Each of the sub-basins carries information on the connectivity to the next downstream sub-basin, which allows to determine the total connected area within a main hydrologic basin.

Dams falling within a sub-basin were georeferenced to the downstream boundary of that sub-basin so that isolated patches were a collection of HB sub-basin units.

Four dams in the Mekong catchment were selected for detailed investigations of EO water quality parameters which were processed for the surrounding area of the dams. Table 1 shows the selected dams and their properties.

Table 1 Selection of Dams for Pilot 3, ordered from west to east (See Figure 2)

Dam	**Operating since**	**Height**	**River**	***country***
Nam Ngiep 1	Sep. 2019	167m	Ngiep	Laos
Lower Se San 2	Dec. 2018	75m	Se San	Cambodia
Xe-Pian, Xe-Namnoy	Dec. 2019	74m	Sekong	Laos
Xe Kaman 1	Dec. 2017	120m	Xe Kaman	Laos

1.4 Methods

1.4.1 River connectivity and pareto front optimization

We studied historical and upcoming changes in river connectivity following a procedure described in Barbarossa *et. al.* (2020). This procedure results in an assessment of the degree of geographic range fragmentation of fish species across the entire Mekong basin, expressed as a connectivity index (CI) (range 0-1) where 1 represents a range that is fully connected and smaller values indicating less connectivity. This method explicitly takes the geographic range of ~10,000 fish species into account which tend to be limited to subsets of entire river basins and provides a unique value for each of these species. As such, it is thus more tailored towards studies of biodiversity (it is a metric of the extent to which the habitats of fish species are fragmented) and differs from metrics that estimate the extent to which rivers are 'free-flowing' (e.g. Grill et al. 2019) which are more oriented towards hydrological processes.

While the work in Barbarossa *et. al.* (2020) focusses on the combined impact of all (present and future) river dams on entire basins (including the Mekong) and makes a comparison between different basins across the globe, we focus on the impact of individual river dams within the Mekong basin, the differences between them, and compare these impacts with the gains in energy production associated with each dam. More specifically, we did this by:

1. tracking the historical changes in habitat connectivity and energy production (i.e. cumulative installed capacity) each time a new dam was placed since the 1960s. This allowed us to get a quick idea whether and when dams were placed at relatively 'optimal' locations in terms of energy production vs. impact on habitat connectivity and when this was not the case, i.e. whether past decisions have been

relatively optimal in terms of impact on connectivity and gains in terms energy production or not.

2. performing a computer experiment in which individual dams were removed in order to find out which dams have the largest impact on habitat connectivity as a part of the present-day configuration of river dams.
3. the usage and calculation of a new metric (i.e. inclusion probability in the optimal pareto front) that attempts to simultaneously weigh the (negative) impact of individual river dams on connectivity and the (positive) impact on energy production (Giagkiozis & Fleming, 2014).

While it might be hard to revers past decisions, these methods may serve as a proof of concept for/first step towards the application of these types of metrics when assessing the (combined) impacts of future (planned) dams. As a first attempt towards simultaneously weighing the pros and cons of river dams, we determined the extent to which existing or planned river dams deviate from the pareto optimal set (Giagkiozis & Fleming, 2014). This is a model generated optimal distribution (in our case of dams across the Mekong River basin) that takes multiple objectives into account. We determined such an optimal set when considering the energy produced and the impact of river dams on habitat connectivity. The ideal dam would have a minimal impact on connectivity while producing the maximum possible amount of green energy. The extent to which existing and planned river dams correspond to this ideal was determined by determining each dam's inclusion probability in the optimal pareto front. A high inclusion probability corresponds, in this case, to dams that (likely) are close, while a low inclusion probability to dams that are far away from this ideal situation. When planning new dams, you would thus want to choose a location where the inclusion probability is high, while dam removal would be most beneficial at locations where the inclusion probability is low. Our optimization procedure can be expanded to include other impacts of river dams such as those on river water quality, sediment transport or land cover.

1.4.2 Water quality parameters and retrieval

Sediment-laden water is turbid and has a different colour than clear water. By analysing satellite images of the river, we detected changes in water colour and turbidity that may be indicative of changes in sediment transport before and after the placement of river dams. The C2RCC (Doerffer and Schiller, 2007, Brockmann et al., 2016) algorithm was used and shows robust performance under a range of water and atmospheric conditions, including extremely absorbing and extremely scattering water. A limitation of C2RCC is that the method assumes that the water reflectivity matches the spectra that were present in the neural network training set. C2RCC is a coupled algorithm because it calculates both atmospherically corrected water reflections and the water constituents. In the context of BIOMONDO, C2RCC is used as a coupled algorithm for Sentinel-2 applying the C2X-COMPLEX nets. These neural networks were trained with a dataset representing optical models of complex water bodies, covering the properties of inland waters and their concentration ranges for chlorophyll-a concentration and turbidity. The novelty of this method within the BIOMONDO project is the application of the C2RCC with C2X-Complex nets to the unknown Mekong River waters. The C2X-Complex net was trained with sampled data from inland waters of Germany and never tested for the high turbid und unknown waters within the monsoon season in Asia and the Mekong. The application of the C2RCC with C2X-Complex nets proved to be very reliable for the volatile river water constituents. The Forel-Ule (FU) color index has been calculated to assess the watercolor within the Mekong and its side arms. The FU scale was initially developed as a color index that would allow the visual classification of the watercolor (Wernand and Van Der Woerd, 2010) and divides water reflectance spectra into 21 color classes from dark blue to yellowish-brown. We used the FU approach to investigate the hypotheses that the watercolor changes due to the increasing number of dams in the Mekong basin, resulting in reduced sediment transportation (Schmitt et al., 2018).

To investigate the impacts on the river water quality we determined the Forel Ule (FU) value. Forel Ule values of 0-5 correspond to turbidity values of 0-20 FNU and is increasing with Forel Ule values from 16-21 corresponding to values of >100 FNU. Four dams were selected as a primary case study based on Schmitt et al., 2018 for further investigation. We studied temporal (i.e., monthly) changes in water quality in the subbasins of these river dams and performed transect analysis (comparing different years) that included river parts down and upstream of the dam.

1.5 Expert consultations

The main findings of BIOMONDO pilot 3 were discussed with various scientific and policy experts. Table 2 provides an overview of the consultation meetings held for the assessment of our main findings.

Table 2 List of experts providing feedback on the main findings of pilot 2. *Meeting was simultaneously a consultation for the Horizon Europe SOS-Water project but featured BIOMONDO material and feedback.

Name	Institution	Meeting dates
Arjen Haag	Deltares	5 June 2023
Rafael Schmitt	Stanford Univ.	14 November 2022*
Philip Minderhoud	Wageningen Univ.	20 June 2023
Nam Nguyen Trung	SIWRP	23 June 2023*
Lam Dang Thanh	SIWRP	23 June 2023*
Advisory Board • María Vallejos • Erin Hestir • Lisa Rebelo • Ole Seehausen	 Univ. Buenos Aires UC California, Merced IWMI /DE Africa Univ. Bern	 Maternity leave 30 Aug 2023 30 Aug 2023 7 Sept 2023

2 Scientific impact

2.1 Main findings and contribution to current knowledge level

2.1.1 River connectivity

Concerning the two first pilot objectives (see Figure 1), the assessment of river dam construction and removal on habitat fragmentation and species dispersal routes, and on habitat extent, we focused on the testing and evaluation of the connectivity model by Barbarossa et al. (2020). We tested the impact of individual dams on the large-scale connectivity by calculating historic decrease in habitat connectivity as new dams were placed, the associated increase in energy production, and the combined (historical) changes in energy production and (overall, i.e. averaged across all fish species) habitat connectivity since the 1960s. (Figure 3). The results show that around the years 1994 and 2019 large reductions occurred in habitat connectivity while the gains in energy production were relatively small suggesting a less-than-optimal placement of river dams. Around the year 2010, on the other hand, a relatively large increase in energy production was obtained while the impact on habitat connectivity was relatively small suggesting that dam placement during this period was much more optimal. These differences suggest that the extent to which dams are placed optimally in terms of their impact on habitat connectivity when compared to gains in energy production could have played a larger role in past decision-making processes.

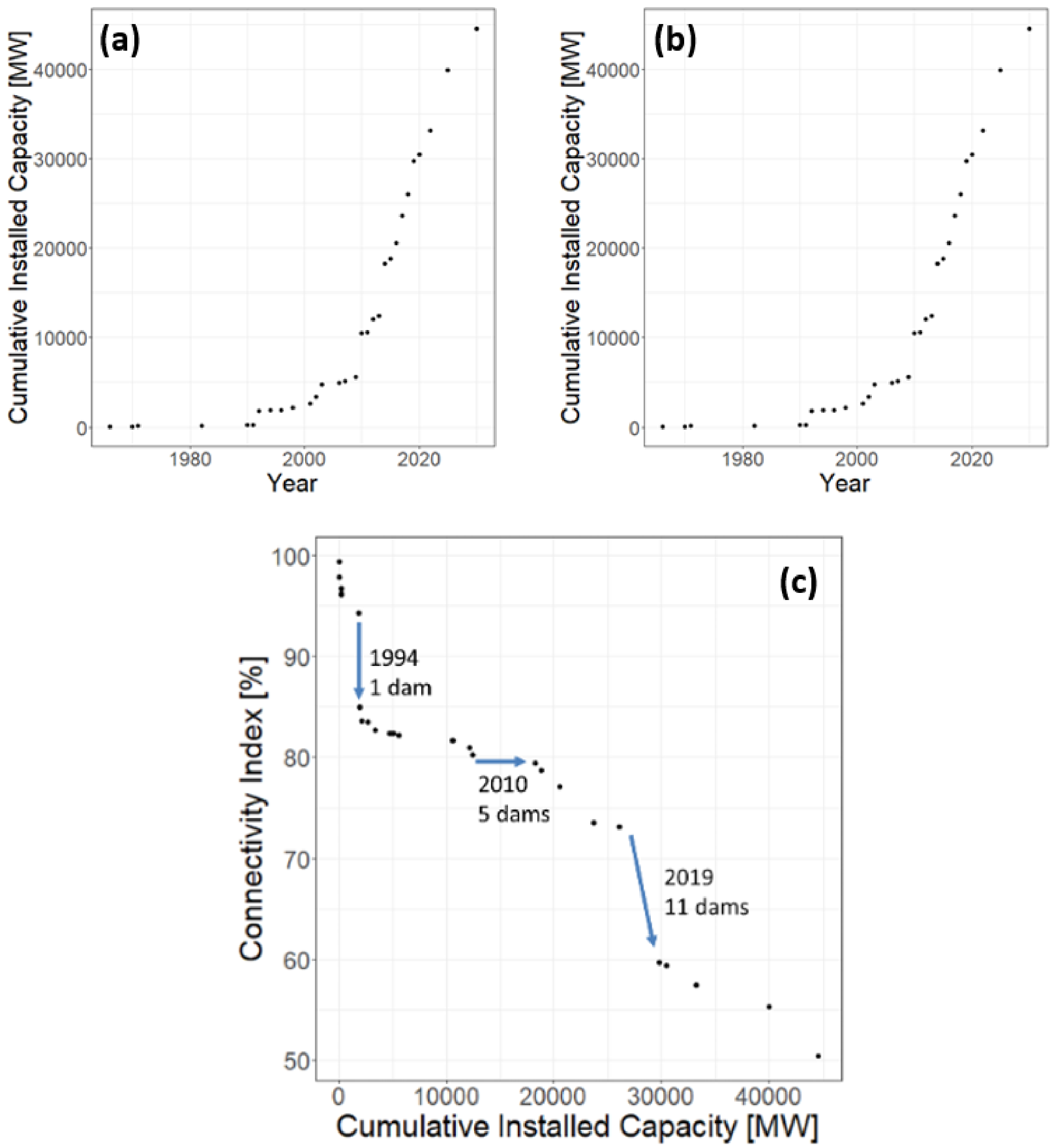

Figure 3 Historic decrease in overall (i.e. averaged across all fish species) habitat connectivity as new dams were placed in the Mekong delta since the 1960s (panel a), the associated increase in energy production (i.e. cumulative installed capacity, panel b), and the combined (historical) changes in energy production and habitat connectivity (panel c). These are new results obtained for BIOMONDO.

The impact of dams may differ between fish species that complete their lifecycle in freshwater (i.e., non-diadromous species) and fish species that migrate between freshwater and marine environments (i.e., diadromous species). Specific connectivity measures were, therefore, adopted for diadromous and non-diadromous fish species, following a procedure co-developed by members of BIOMONDO and described in Barbarossa et al. (2020).

Our results from the experiment in which we removed individual dams from the current set of dams revealed large differences between river dams. We found the highest (positive) impact of dam removal on the overall habitat connectivity for both diadromous and non-diadromous species for the Don-Sahong dam. Another high-impact dam is the Pak-Mun dam (for non-diadromous species), and the Xayaburi dam. The electricity production between these dams varies greatly and is estimated to be 260, 136, and 1.260 MW for the Don-Sahong, Pak-Mun, and Xayaburi dam, respectively. Results for the inclusion probability in the optimal pareto front therefore showed notable differences between these dams (i.e. 9, 3, and 41% respectively). Even though these three dams all have a very high impact on habitat connectivity, the probability that the Don-Sahong and Pak-Mun dam are part of a distribution of dams that is optimal in terms of impact on connectivity and energy production is much lower when compared to the Xayaburi dam, mainly because this dam produces a lot more energy. These and many more metrics were presented in the BIOMONDO viewer that made it possible to look up information on individual dams (Figure 4). We showed this viewer to the listed experts who were positive about its potential as a tool to support decision making although the presentation could be simplified substantially and could be combined with other existing decision support tools (e.g., STIMSON, 2023; SERVIR, 2023) for the Mekong.

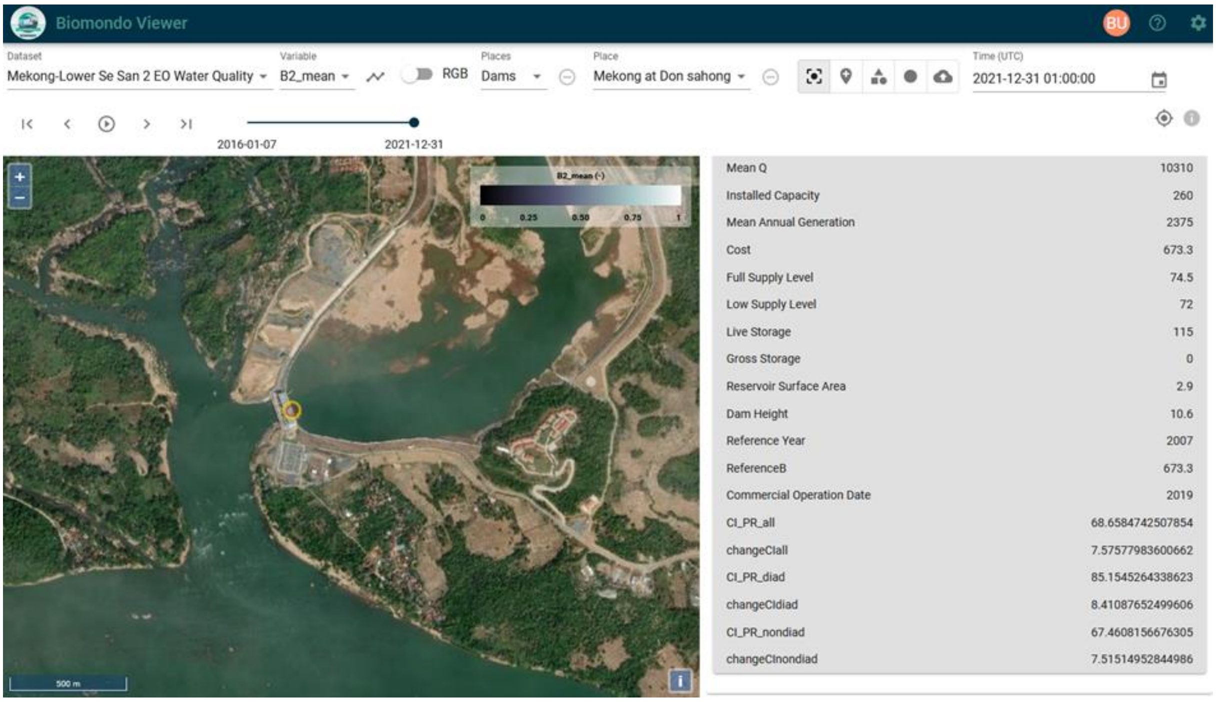

Figure 4 Information on an individual dam as presented in the BIOMONDO viewer.

2.1.2 River turbidity and sediment transport

Sediment transport is an essential ecosystem service of the Mekong River, since the whole river delta region depends on the supply of suspended sediments, most importantly to compensate coastal erosion. Previous research facilitated estimates of sediment transport based on simulated bed-load transport (i.e., sand and gravel fractions; Schmitt et al., 2019). But the total sediment transport is estimated to be 30-100 times the bedload (Schmitt et al., 2016), which means that this estimation approach is subject to high uncertainty. Accordingly, Rafael Schmitt recommended that we try to improve these estimates using EO estimates of sediment transport at the surface. This objective is further pursued by Eawag in the scope of the Horizon Europe project SOS-Water, in collaboration with Vietnam's Southern Institute of Water Resource Planning (SIWRP), based on initial results from BIOMONDO. Note that for a river with a composition and optical properties that are strongly dominated by TSM, we use the quantities TSM (i.e., particle concentration), turbidity (i.e., particle side-scattering) and Secchi depth (i.e. inverse attenuation, mostly by particles) interchangeably.

We first performed a validation study, and then verified if the product's spatio-temporal variations confirm their suitability for the present use case. Retrievals of water quality parameters in rivers are still much less common than in coastal areas or lakes, and plenty of in situ reference measurements are available from the Mekong River Commission. These measurements' data and metadata (e.g. location accuracy) quality is however subject to rather high uncertainty, and careful selection of reference locations and samples is key (Markert et al., 2018). In our preliminary analysis, the EO based time series generated matched the ground measurements well (Figure 5), while the matchup performance was somewhat worse than in the analysis by Markert et al. (2018) in the Google Earth Engine. Additional in situ measurements provided by SIWRP in the scope of SOS-Water enabled further comparisons in which the retrieval accuracy by Markert et al. (2018) was met and excelled.

By regularly producing turbidity or TSM products of the Mekong catchment and coupling instantaneous near-surface particle loading from these products with the flow velocity obtained in hydrodynamic models, we could significantly improve the assessment of sediment transport alterations. Sediment transport is a key variable, because it maintains the productivity of rice fields and the geomorphological genesis of the Mekong delta, it is a key habitat variable for aquatic organisms, and it affects the long-term productivity of hydropower reservoirs as increase in sediment trapping can reduce the storage capacity. Currently, sediment flux estimates are based on the basal transport component, which is an output variable of hydrological models (e.g., Schmitt et al., 2016), but represents only-5-10% of the vertically integrated sediment transport. Therefore, constraining the transport with a basal and a superficial component from EO could strongly improve the estimates.

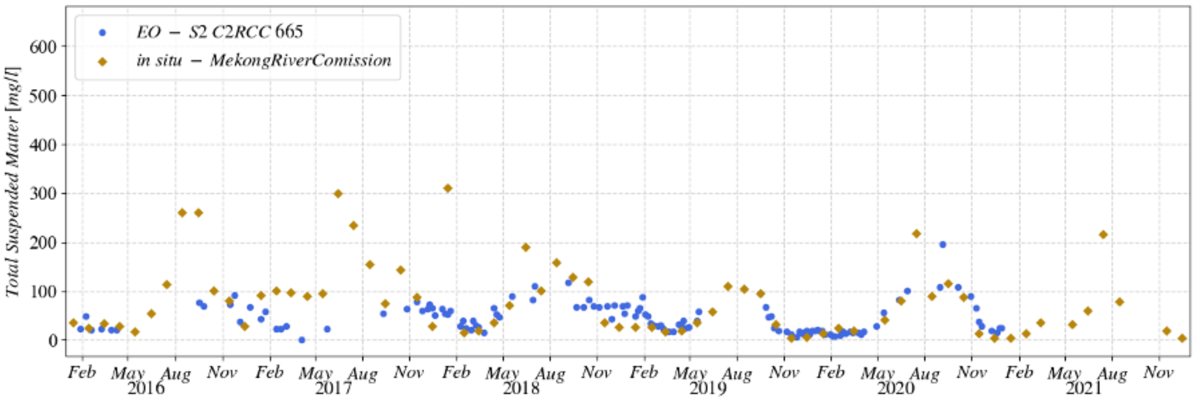

Figure 5 Time series validation for the Savannakhet dam in Laos and TSM estimates from EO, using in situ measurements available from the Mekong River Commission's data portal (MRC, 2023).

The very small-scale variability observed in EO TSM products suggests that they could even be the basis of spatial assessments of dam sedimentation, which, e.g., in the case of Lower Se San 2 occurs mostly at the upper end of the reservoir. Related to altered TSM concentration, we could also see a clear change in water colour in consequence of dam construction. Figure 5 shows the water colour (FU) of the Lower Se San 2 downstream river water. The heatmap shows that for the years 2018-2020 the colour was more blueish compared to the earlier year. The first turbine for the Lower Se San 2 began producing electricity in December 2017. It is assumed that with the operational start of the dam the sediment transport decreased, which also decreased the brownish colour of the water. The Forel Ule values of 0-5 correspond to turbidity values of 0-20 FNU and is increasing with Forel Ule values from 16-21 corresponding to values of >100 FNU.

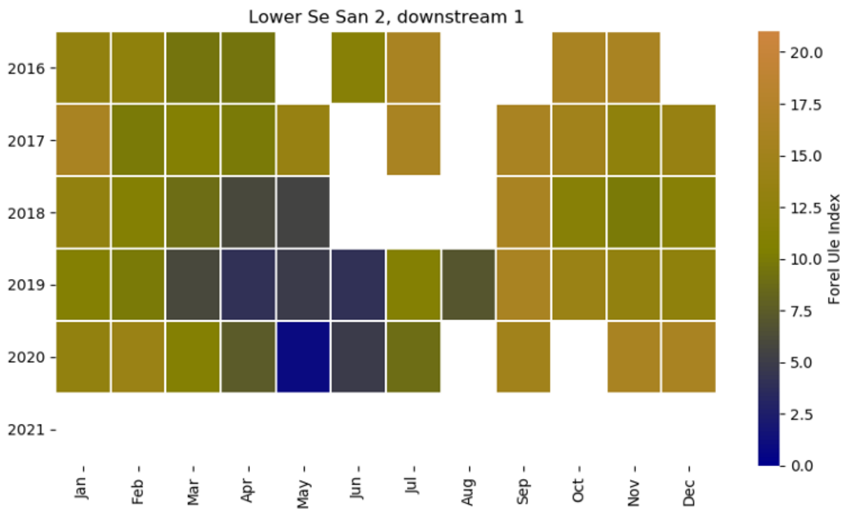

Figure 6 Changing water colour in the Mekong River at a selected station downstream of Lower Se San 2. The dam began production in Nov. 2017 and was officially opened in Dec. 2018.

Given the strong climatic seasonality in monsoon regions, and in response to a request by Arjen Haag, we also assessed the S2 data availability for the selected test sites. We found that across the four reservoirs and two years we investigated, seasonal data gaps affect four to eight consecutive months per year. During these months, usually around April to September, only scattered pixels pass the cloud masking (Figure 7). Contrariwise, up to seven observations per month are available during the dry season. This lack of observations during the rainy seasons is a severe and limitation for optical Earth observation of river catchments in many subtropic regions, including, e.g., the Congo basin (Ruppen et al., 2023). An increased observation frequency using additional satellite missions such as Landsat-8 and 9 might add occasional cloud-free observations, and missions with earlier overpass times might also mitigate the cloudiness. Regional cloud cover assessments with geostationary satellite images are needed to quantify to what degree these measures could mitigate the seasonal data scarcity.

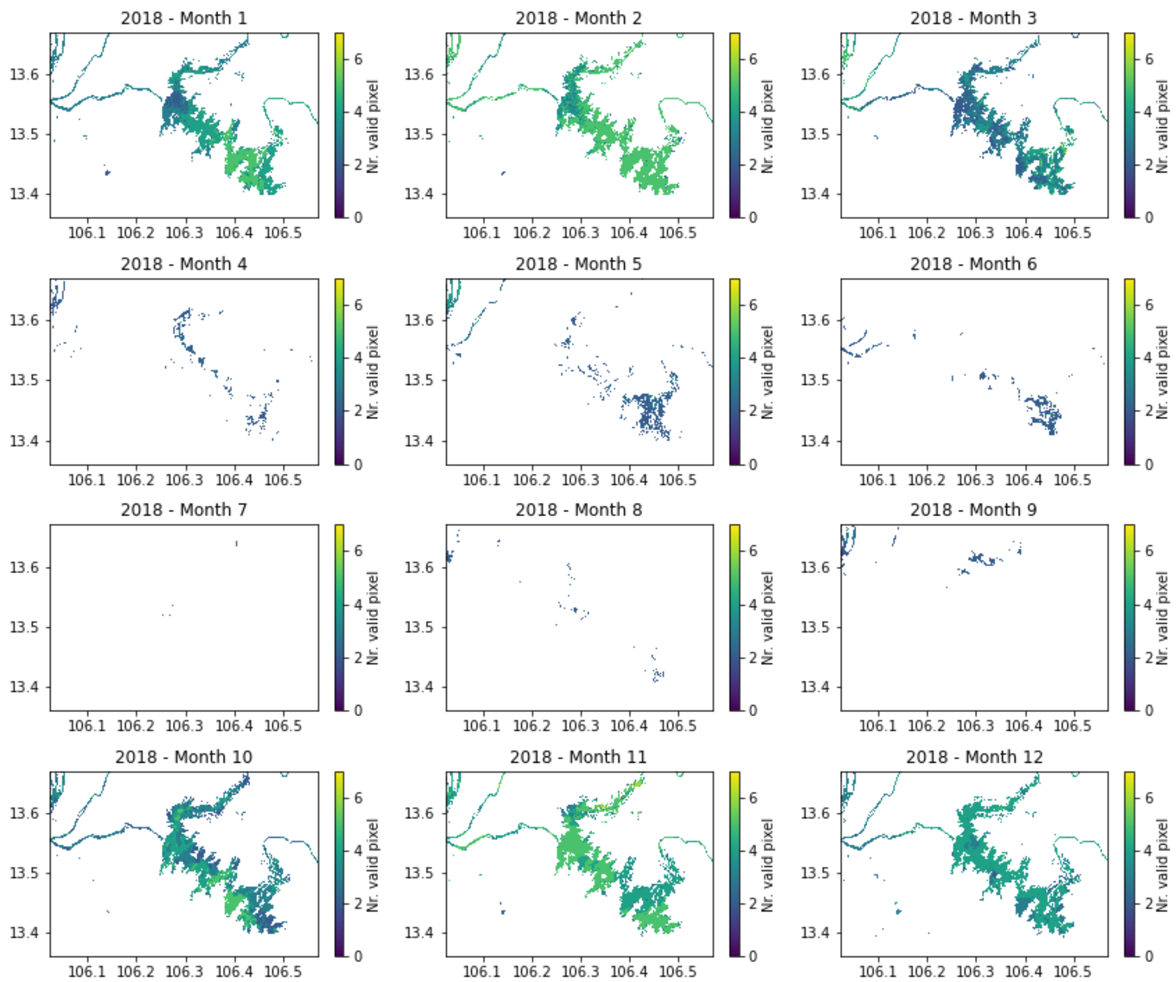

Figure 7 Number of monthly valid observations for the Lower Se San 2 reservoir in 2018.

In synthesis, we found that the information content accessible from EO can facilitate a wide range of information needs related to the construction and removal of river dams. We presented a trade-off between energy production and basin connectivity (Figure 3), but EO products could contribute sediment transport as another usage dimension with oftentimes conflicting requirements. However, after presenting the BIOMONDO Viewer, we were also recommended to more carefully tailor information portals to certain user's individual competences and requirements, following the guiding principle 'less is more'.

2.2 Effects of river dams on freshwater biodiversity

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2019 Global Assessment explicitly states that inventories in freshwater ecosystems and wetlands are lacking and constitute a 'knowledge gap' (IPBES, 2019, Appendix 4). It is, perhaps, thus no surprise that it remains challenging to attribute the rapid decline of biodiversity in freshwater ecosystems (Sala et al., 2000) to any specific cause including the impacts of hydropower and dam constructions, both upstream and downstream. Especially, since freshwater ecosystems are impacted by a wide range of anthropogenic drivers. However, there are some studies that have reviewed the effects and make recommendations for remedial actions (Vörösmarty et al.; 2010, Liermann et al., 2012; Gracey et al., 2016).

Gracey et al., (2016) summarise the main three impact pathways as, freshwater habitat alterations, water quality degradation and land use change. Negative impacts are likely to both terrestrial and aquatic biodiversity in the river basins. Reservoirs cause ecological impacts due to loss of terrestrial habitat due to land flooding, with resultant increases in evaporation from the reservoir, which leads to reduced discharge as well as greenhouse gas emissions from reservoirs (Dorber et al., 2020; Räsänen et al., 2018).

As summarised in the report Hydropower pressure on European rivers: The story in numbers. (ASF, 2019) "Impacts on freshwater ecosystems range from river fragmentation, which prevents the free movement of organisms, to severe modification of river flow and temperature regimes and to dramatic reductions in sediment transport, resulting in a loss in ecosystem services and biodiversity."

There is urgent need to know how to best improve dam placement, constructions and associated water management to enable establishment of more sustainable hydropower dams and reservoirs with less carbon emissions and negative effects on freshwater biodiversity.

2.2.1 Connectivity and fragmentation

In the Living Planet Index for freshwater migratory fish (Deinet et al., 2020), it is reported that globally, migratory freshwater fish have declined by an average of 76% and that average declines have been more pronounced in Europe (-93%).

Fragmentation of both terrestrial and aquatic ecosystems – impedes organisms (both small and big) dispersal and migration, which leads to reduced genetic diversity, diminishing the potential to adapt to changing environmental conditions and increasing local extinction risk. Fragmentation is the biggest cause of decline in freshwater biodiversity according to Vörösmarty et al. (2010). Specifically, dams restrict or even prevent passage in the upstream direction, and they can increase fish mortality associated with downstream passage through turbines. Gracey et al. (2016) highlighted that dam density, reflected in fragmentation indices for "freshwater habitat alteration", is a significant unquantified threat to aquatic biodiversity. It is, however, known that the specific geographic nature of freshwater ecosystems limits species dispersal more than in terrestrial or marine habitats for two reasons: 1) there is little exchange of organisms between river basins which are isolated from each other (Leuven et al., 2009) and 2) dispersal is constrained by the dendritic (tree-like) structure and directional flow of river networks (Hänfling & Weetman, 2006; Carrara et al., 2012; Wubs et al. 2016). The limited ability of freshwater species to reach sites via dispersal as a consequence of these limitations (Shurin & Smith, 2006) reduces biodiversity (Shurin et al., 2000; Irz et al., 2004). The effects of human-induced habitat fragmentation can thus be expected to be particularly severe for freshwater ecosystems and because fragmentation in dendritic river networks creates habitat patches that are smaller and more varied in size when compared to terrestrial landscapes (Fagan, 2002; Fuller et al., 2015).

The seasonal nature of river dynamics requires a level of temporal resolution to capture changes to which EO based products can contribute valuable information. Hence, coverage of biodiversity impacts by hydropower developments could be improved by providing time steps that represent seasonal ecological water demands.

2.2.2 Water quality and sediment loads

Hydropower operations can profoundly affect water quality variables such as temperature, nutrients, organic matter, turbidity, and dissolved oxygen content (Gracey et al., 2016).

A substantial reduction of nutrient rich sediments to deltas and oceans in the global north has been reported by Dethier et al. (2022), who demonstrated the value of a satellite remote sensing approach (based on the full Landsat 5 and 7 archive) for estimating suspended sediment concentration (SSC) and suspended sediment flux in 414 major rivers across the globe. It was pointed out that the technique can be updated and refined as additional in situ measurements are added to the calibration datasets and new satellites improve the monitoring coverage of Earth's surface. In addition, "the near-real-time" assessment of sediment transport by rivers can help inform policy decisions through direct observation of extant and historical conditions". Interestingly, this approach may not only be valuable to monitor the impacts of river dams on sediment transport. Other anthropogenic factors, e.g. deforestation, may also strongly affect (erosion and) sedimentation processes (Nienhuis et al., 2020) and may be studied with similar methods.

The downstream effects on sedimentation are of great interest. Findings by (Kondolf et al., 2014, Schmitt et al., 2018) provide estimates on the reduction in the sediment loads reaching the Mekong delta bringing profound consequences on the productivity of the river and persistence of the delta landform itself. Prior to the late 20th century, the Mekong delta received 140 to 160 million metric tons of sediment annually from the Mekong River basin. More than half, and percentage increasing every year, of this is now being trapped in upstream reservoirs. The delta is one of the world's largest deltas and dependent on the sediment transport and it averages less than 1 m above sea level and is therefore vulnerable to subsidence and coastal erosion (Schmitt et al. 2019).

Thermally sensitive species groups can be impacted or disappear completely when turbine water is drawn from either an epilimnetic or a hypolimnetic water layer in the reservoir and released downstream (Gracey et al., 2016). There can also be exacerbated effects of climate change via introduction and proliferation of invasive species. Future EO based temperature comparisons may contribute to monitoring these changes.

In addition, eutrophic conditions because of nutrient-laden sediments trapped in reservoirs can, in warmer months or with climate change, lead to algae blooms, which will likely be visible in EO based timeseries of changes in chlorophyll-a concentration.

2.3 Potential for large-scale application

2.3.1 Up-scaling river connectivity analyses

The key unit to calculate habitat connectivity are HydroBASINS subbasins (Pfaffstetter level 12) to which the species ranges are referenced, and which can be observed from space (based on elevation data obtained in 2000 by NASA's Shuttle Radar Topography Mission (SRTM)). Each of these sub-basins, in turn, carries information on the connectivity to the next downstream sub-basin, which allows to determine the total connected area within a main hydrologic basin. Specifically, for the here used connectivity model, we consider a main limitation that the effect of parallel river branches is not accounted for in the model and that the shape of these basins changes when dams are placed. Further improvement/inclusion of this information may strongly affect our results, e.g., for the Pak-Mun dam. As a part of our work for BIOMONDO we explored whether it is possible to update the HydroBASINS level 12 watersheds such that they are touched by the reservoir of each dam which, indeed, seems to be possible (Figure 8).

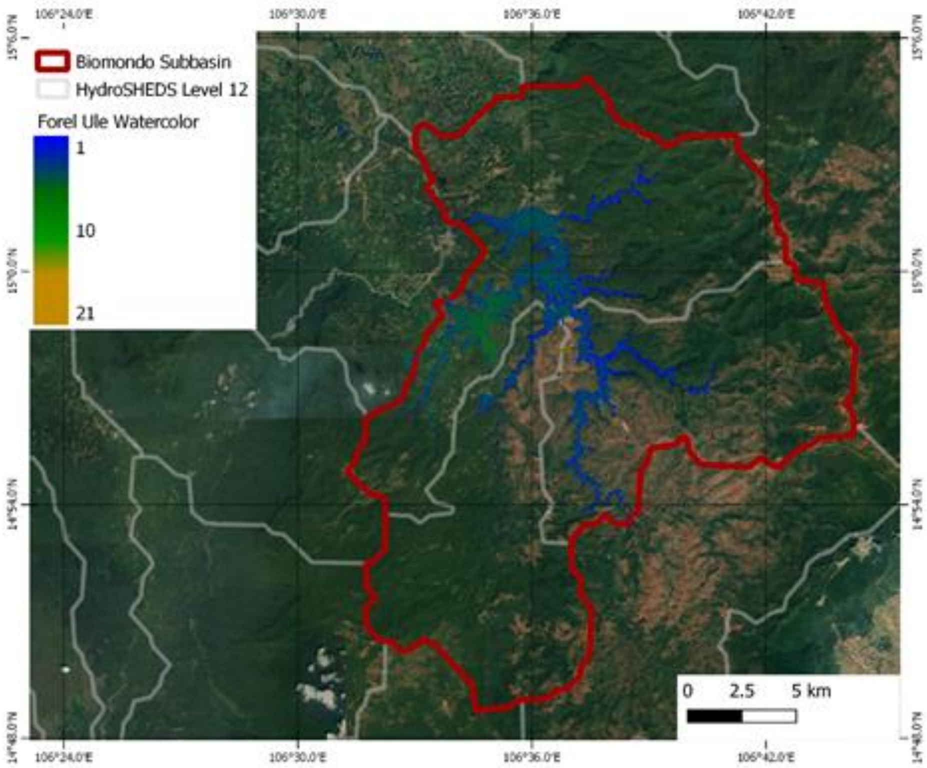

Figure 8 Updated HydroBASINS level 12 watershed such that it is touched by the reservoir of each dam.

The quality and accuracy of hydrological base data is crucial for this use case, which, in turn, requires most accurate Digital Elevation Models. According to Arjen Haag, WWF is therefore currently working on an update to the HydroBASINS dataset. Likewise, the accurate detection and inventory of dams has some potential for improvement, given that all available datasets differ slightly. Better insights on the dynamic component of the catchments' hydrology, e.g., obtaining information on ecologically appropriate dam operation practice, could be obtained from water extent and level data. The most comprehensive current information service is based on altimetry data on one hand, and on water level derivatives from EO (Sentinel-1/Sentinel-2) and water extent estimates on the other hand (STIMSON, 2023). In the context of the EU Horizon Europe project SOS-Water, FutureWater Netherlands is currently working to improve altimeter products specifically for the Mekong catchment, and they plan to incorporate SWOT data in the future.

Upscaling to a global level, i.e., applying our methods to all river basins worldwide, is in principle feasible for river-dam caused changes in connectivity. In particular, because the information needed to determine this, e.g. the geographical ranges of fish species, dam location and status, commercial operation date, installed capacity, and dam height, and HydroBASINS subbasins, are available on a global level. Similarly, the assessment of the trade-offs, e.g. using the optimal pareto front, between impacts of individual river dams on connectivity and energy production is likely possible on a global scale. There is no reason to assume that further updates to HydroBASINS data (as discussed in section

2.2) is not possible on a global scale and ongoing efforts towards such improvements (e.g., by WWF) already seem to take place on a global level. The identification of parallel branches and the precise location of river dams (also mentioned in section 2.2) from EO data may, depending on the properties of these dams and branches (e.g. their width) may require some form of automatization (e.g. machine learning) when applying this on a global level.

2.3.2 Up-scaling river turbidity and sediment transport analyses

Comprehensive river water quality datasets from either in situ measurements or EO are scarce. In the case of EO, global water quality products for reservoirs and lakes are available (ESA Lakes CCI, Copernicus Global Land Service) but no such dataset exists for rivers. Building such datasets would for most rivers require high spatial resolution, namely S2 data, and artifacts due to natural deviation, manmade constructions, shoreline effects and similar challenges will likely require advanced post-processing or manual labour. Additionally, rivers exhibit significant spatial and temporal heterogeneity in water quality. The impact of dams on water quality can vary significantly across different river systems, and it is essential to validate satellite-based water quality assessments with ground-based data for accuracy. All these aspects make it a significantly more resource and time-intensive task than is the case with existing global lake datasets. The costs associated with it could be prohibitive, limiting the ability to conduct a comprehensive global assessment. The feasibility of basin-scale assessments seems much better in this context.

By implementing basin-scale assessments across the world, we can also improve the focus on regionally specific socio-economic and ecological issues and trade-offs. For example, hydropower production and sediment transport are in focus for the Mekong, but in the Rhine basin agricultural and industrial water abstraction and pollution are the top priority management challenges. Such an improved focus can help policymakers and researchers understand broader patterns and trends that may not be evident from global assessments or smaller scale analyses. Sentinel 2 and other satellites offer a cost-effective means for such kind of water quality assessments, especially in remote or inaccessible regions. It could also provide near-real-time data, allowing for the continuous tracking of water quality changes.

As mentioned in section 2.2 one of the main effects on aquatic and semi-aquatic species diversity is related to changes in water temperature. To be able to monitor these with EO based product could enable increased knowledge and support to decision making for catchment management (e.g. prioritisation for protection and restoration). Currently the spatial resolution of globally available thermal datasets (LSWT) is too low for most rivers stretches and smaller reservoirs. In the near future several thermal missions with high spatial resolution are planned for launch, e.g., Trishna, the NASA Surface Biology and Geology Mission (SBG) and the Copernicus Land Surface Temperature Monitoring Mission (LSTM), see also details in BIOMONDO_IAR_Pilot_2_v2.1.docx.

Future activities concerning water management at catchment scale should also focus on the integration of new developments with existing tools. There is already a range of EO and other data services for the Mekong catchment (e.g. Stimson's dam monitor, NASA SERVIR) and the design of complementary, interoperable and serviceable tools would strongly benefit from participatory development processes. Such processes require common goals and dedicated resources, hence larger management and coordination efforts.

3 Policy impact

3.1 Relevant policies, goals and targets

Water is essential for all natural ecosystems, for biodiversity, climate regulation and human health including ecosystem services that also provide potable water, food and energy supply. Hence, links between the extent and condition of freshwater ecosystems such as rivers and their connectivity and free flows are reflected in policies on sustainability and biodiversity as well as in recent calls and research funding opportunities that stress links between water, energy, health, climate and biodiversity.

River dams contribute to water security, energy supply, and flood protection but also fragment habitats of freshwater species and sometimes severely affect the ecosystems of wetlands and downstream deltas (Barbarossa et al., 2020).

The results and products derived for Pilot 3 have potential to support several current policies and strategies and their related monitoring frameworks. For the policy Impact Assessment Report, the EU 2030 Biodiversity Strategy (EC, 2021) and targets of the new Nature Restoration Plan, the Water Framework Directive (European Commission, 2014), the 2030 Agenda for Sustainable Development (UN GA, 2015) and Kunming-Montreal Global Biodiversity Framework (KM-GBF) (CBD, 2022a and 2022b) are highly relevant.

Other biodiversity frameworks and strategies, organisations and initiatives that we deem could benefit from the Pilot 3 results include and are also outlined and include:

- UNEP GBO-5 Freshwater transition (CBD, 2020b)
- Brisbane Declaration and Global Action Agenda on Environmental Flows 2017 (Arthington et al., 2018)
- IUCN, Ramsar and WWF

Commitments on biodiversity were made by different stakeholders at the UN 2023 Water Conference in March 2023. Dagmar Kaljariko, Policy Officer, EC, DG ENV, stressed the importance of addressing the Water-Biodiversity Nexus and that the EU is to significantly increase the rate of restoration of rivers in line with the objectives of the WFD and the EU 2030 Biodiversity Strategy as part of the commitments. The EU is also to work with UNEP on a replicable and scalable comprehensive management approach to revalue, restore and reconnect watersheds including rivers, lakes and wetlands and other surface and ground water ecosystems, i.e. an integrated approach to protecting aquatic ecosystems and to support national and regional water managers. As described below the EU Biodiversity Strategy goes a bit further than the WFD with specific targets related to connectivity and restoration of rivers to free flowing. We see that the Pilot 3 results on connectivity and water quality (turbidity and chlorophyll-a) can provide spatially explicit information on trade-offs between energy production and connectivity issues that affect biodiversity.

In the following sections (3.1.1 to 3.1.5) the main policies and strategies relevant to Pilot 3 are summarised and can be viewed as an update to the descriptions in the BIOMONDO Requirements baseline document (BIOMONDO_D1.1_RequirementsBaseline_v2.1.pdf).

The BIOMONDO Experimental datasets are described in 3.2 for context. Section 3.3 outlines a policy relevant show case with examples of Pilot 3 results and ideas of how these results can be used in practice to support management decisions and inform policy. In section 3.4 the potential policy utility and impact of the Pilot 3 results are assessed and described in relation to the added value for related biodiversity strategies and monitoring frameworks. It focuses on the usefulness for current policies and how the results respond to biodiversity policy priorities. We also describe how the products and results could be used for decision support, development of indicators and revision of monitoring guidelines.

3.1.1 EU 2030 Biodiversity Strategy & Nature Restoration Law

In the EU Biodiversity Strategy for 2030 (EC, 2021), the EU and its Member States have committed to implement more than 100 actions by 2030. The EU Nature Restoration Plan constitutes one part of these actions and includes "Target 11 - At least 25,000 km of free-flowing rivers are restored." The EU's legal framework on water is ambitious but implementation is lagging. Greater efforts are needed to restore freshwater ecosystems and the natural functions of rivers to achieve the objectives. This can be done by removing or adjusting barriers that prevent the passage of migrating fish and improving the flow of water and sediments. To help make this a reality, at least 25,000 km of rivers will be restored into free-flowing rivers by 2030 through the removal of primarily obsolete barriers and the restoration of floodplains and wetlands.

In a similar way to the targets of the Kunming-Montreal Global Biodiversity Framework (see section 3.1.4), the EU BD strategy also has targets to legally protect 30 % of EU's land and sea areas, and for at least 30% of EU habitats to reach favourable conservation status by 2030 (Target 1 and Target 4). Target 12 aims at a 50% reduction in the number of Red List species threatened by invasive alien species. In addition, several specific missions are planned as part of the Green Deal to support the EU BD Strategy, e.g. Mission Starfish, which "provides a systemic approach to reducing human pressures, including pollution and climate change, on oceans, seas, coastal and inland waters and a significant step towards restoring their ecosystem functions" (Bieroza et al., 2021). It includes five objectives and 17 measurable targets to be achieved by 2030 of which freshwater quality is covered by target 3 (30% of EU waters are fully protected), 5 (re-naturalise rivers and waters) and 7–9 (zero plastic litter, zero eutrophication and zero spill).

The EU Nature Restoration Law is a key element of the EU 2030 Biodiversity Strategy, which calls for binding targets to restore degraded ecosystems, particularly those with the most potential to capture and store carbon and to prevent and reduce the impact of natural disasters. A proposal for a regulation on nature restoration was put forward to EU member states in June 2022 and it was narrowly passed in July 2023. It can be seen as very important for aligning EU policies and one of the Restoration law specific targets, relate directly to river connectivity. Restoration measures related to river ecosystems (5-9) as listed in (EU nature restoration regulation, Annex VII, in progress) include:

- 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 riverbeds and lakes and lowland watercourses by e.g., removing artificial bed fixation, optimising substrate composition, improving or developing habitat cover.
- Restore natural sedimentation processes.
- Establish riparian buffers, e.g., riparian forests, buffer strips, meadows or pastures.

The targets and indicators of the Biodiversity Strategy have been examined by the KCEO Deep Dive initiative (Camia et al., 2023) from the perspective of existing supporting datasets and including future needs for developments. The Deep Dive specifically explores the use of Earth Observation (EO) products and services to support EU biodiversity policies. For Target 11 of the Biodiversity Strategy the datasets that are listed to support its monitoring include the Copernicus CLMS Water Bodies and HRL Water and Wetness as well as the GSWE (Global Surface Water Explorer) for indicator "Fraction of the stream network that is dams-free" and GSWE and CLMS CLC+ Backbone and for the "Connectivity Status Index (CSI), (Grill et al., 2019). This metric is an indicator of the extent to which hydrological flows, i.e. along four dimensions: longitudinal (between up- and downstream), lateral (to floodplain and riparian areas), vertical (to groundwater and atmosphere) and temporal (based on seasonality of flows), are unaltered by humans and is, unlike the method in Barbarossa et al. (2020), not a direct metric of the extent to which habitats/geographic ranges of individual fish species are fragmented. The comments associated with these datasets makes it clear that they can "contribute" to the indicators if coupled with other information although some issues remain that relate to the user requirements for temporal resolution, frequency of updates and latency.

3.1.2 Water Framework Directive

Waters must achieve good ecological and chemical status, to protect human health, water supply, natural ecosystems and biodiversity (European Commission, 2014).

The Water Framework Directive (WFD), adopted and implemented in 2000, is the main EU directive for member states reporting on the ecological condition of European surface and ground waters. It is based on the natural river basin approach to manage water and to improve the status. The status comprises the quality of the biological community, the hydromorphological characteristics and the physico-chemical characteristics of water bodies.

The WFD obliges Member States to formulate river basin management plans (RBMPs) to safeguard each of the 110 river basin districts, 40 of which are international and cross borders, covering about 60 % of EU territory. These are the key tools for implementing the WFD. They are drawn up after extensive public consultation and are valid for a six-year period. Currently the 3rd RMBP cycle is being reported.

The WFD points out the multitude of human activities that uses water to generate and sustain economic growth and prosperity include farming, commercial fishing, energy production, manufacturing, transport and tourism as well as being central to natural ecosystems and climate regulation. Many of these are related to the water flows of rivers. The EU has more than 100 000 surface water bodies and 80 % of them are rivers.

The same river can consist of different water bodies since the status of the water may change over time and on its way from the source to the sea; hydromorphological changes (e.g. effects on connectivity) from hydropower plants – dams, weirs and other obstacles are seen as one of the main reasons for many water bodies in Europe not reaching "good ecological status" (ASF, 2019).

After the "fitness check" (policy evaluation) of the WFD in 2020 (European Commission, 2020), the actuality and importance of the directive was confirmed, including "the widely applicable non-deterioration principle", "the (binding) cross-references to the WFD's objectives in other EU policies" and "the Directives' monitoring requirements". Nevertheless, there is scope for improvement relating to its role in supporting implementation and enforcement. The WFD is seen as a very important legislation that can provide tools for the new EU Nature Restoration Law and implementations via the RBMPs.

The EEA assessment (EEA, 2018) of status and pressures on European waters identified that the more than 25 000 hydropower plants in Europe were "one of the main drivers affecting status of rivers and resulting in loss of connectivity, altered water flow and sediment transport". This report points to a need to increase efficiency at existing hydropower sites and building new hydropower plants to achieve renewable energy targets but that it is important for EU policies promoting hydropower to be compatible with the objectives of the WFD and consider impacts on water bodies.

Several other EU directives are closely related to WFD and are relevant to work on river connectivity and environmental effects from hydropower on ecosystems and biodiversity, such as the Marine Strategy Framework Directive (2008), the Floods Directive (2007), the Groundwater Directive (2006), the Bathing Water Directive (2006), the Drinking Water Directive (1998), the Urban Wastewater Directive (1991), the Nitrates Directive (1991) and of course the EU 2030 Biodiversity Strategy.

Pilot 3 results and products related to connectivity and water quality parameters such as turbidity could, if produced for European river stretches, provide inputs into RMBPs and assessments of the WFD including updates to guidelines.

3.1.3 Agenda 2030 for Sustainable Development

The connectivity status of rivers worldwide is highly relevant to all policies dealing with water extent, scarcity, distribution and quality. Grill et al. (2019) highlighted that "The international community is committed to protecting and restoring rivers under Agenda 2030 for Sustainable Development, which calls on all countries to track, at a national scale, the spatial extent and condition of water-related ecosystems." This is described in the UN Water Integrated Monitoring Guide for SDG 6, Clean water and sanitation (UN WATER, 2018). Specifically target indicators 6.4.2 – Level of water stress: freshwater withdrawal as a proportion of available freshwater resources and 6.6.1 – Change in the extent of water-related ecosystems over time, were identified as needing better support information that is spatially explicit and continuous over time.

At the midterm review of the SDGs in 2023 a strategic guide was published to accelerate progress on SDG6 and deliver on the outcomes of the UN 2023 Water Conference, including the Water Action Agenda (United Nations, 2023). The report summarizes the global water crisis and progress on SDG 6 at the halfway point of Agenda 2030. "*It conveys UN-Water's vision for the second part of the 2030 Agenda and presents actionable* *policy recommendations to Member States on how to achieve SDG 6 by 2030 by using the SDG 6 Global Acceleration Framework. This includes how water policy and governance can interact with other SDGs for greater impact and communicates how the UN system can support the implementation of the second half of the "Water Action Decade" and the Water Action Agenda*".

3.1.4 Kunming-Montreal Global Biodiversity Framework (KM-GBF)

The aim of the Kunming-Montreal Global Biodiversity Framework (KM-GBF), with its developing monitoring framework of targets and indicators, is halting and reversing the loss of biodiversity, sustaining water-related ecosystem services, and supporting SDG 6 and the other Sustainable Development Goals. The KM-GBF is recognising freshwaters ecosystems as a realm of its own in addition to terrestrial, coastal and marine ecosystems. The final KM-GBF includes four goals for 2050 that are supported by 23 targets, which aim to be completed by 2030 (CBD, 2022a and 2022b).

The aim of Goal A and some of its targets and headline indicators are of most relevance to Pilot 3. The first eight targets aim specifically at reducing threats to biodiversity. Target 2 stipulates that by 2030, 30% of degraded ecosystems in each realm are under effective restoration and Target 3 that by 2030, at least 30% of all ecosystems in each realm are effectively conserved and managed. In addition, Target 10 ensures that areas under agriculture, aquaculture, fisheries and forestry are managed sustainably. In addition, Target 6 – Reduce rates of introduction and establishment of invasive alien species by 50 per cent has strong links to Target 8 – Minimize the Impacts of Climate Change on Biodiversity and Build Resilience. Examples of headline indicators for Goal A include A.1 Red List of Ecosystems and A.2 Extent of natural ecosystems.

In August 2023, Guidance notes for each of the 2030 Targets were published, that will be updated periodically. The main purpose of the material is to provide an overview of each target and to serve as a resource for national target setting exercises and high-lighting implications as well as identifying adopted indicators to monitor progress.

Like the EU 2030 Biodiversity strategy target the new targets of the KM-GBF (goal A) stipulate a 30% restoration target by 2030 for freshwater ecosystems and hopefully the new monitoring framework will help achieving this (CBD, 2022b). There is potential for EO-based products and time series to support such restoration targets by providing improved knowledge on freshwater connectivity issues and sedimentation processes and to help monitor effects of restoration actions, including both positive and negative effects on freshwater biodiversity as well as improving the status of current dam datasets.

To achieve the KM-GBF goals GEO BON (Gonzalez et al., 2023) has proposed the establishment of global biodiversity observing system (GBIOS) and identified four key components that are needed to bridge the main science-policy gaps:

1. biodiversity observations guided by policy needs;
2. observations coordinated to form monitoring programmes designed to rapidly detect change and attribute causes for biodiversity change;
3. observations that inform models to project biodiversity change and the loss of ecological and evolutionary resilience; and

4. frequent assessments derived from monitoring to provide policy options to guide action.

The data and products of Pilot 3 show potential to support the second and fourth key components by providing EO based time series products that can facilitate accurate monitoring and assessments of changes to parameters and variables related to biodiversity. As mentioned above, these products show potential to provide specific information on changes to connectivity and sediment transport, and water quality that can affect hydrogeomorphology and conditions of freshwater ecosystems and thereby the habitats of many species and the biodiversity.

3.1.5 Other relevant policies and strategies

The **UNEP GBO-5** (CBD, 2020a) key components of the Sustainable Freshwater Transition (or actions) are closely related to the main drivers of biodiversity loss of freshwater ecosystems and these need to be implemented across all levels of society. Integration of environmental flows into water management is specifically mentioned in the **GBO-5 – Inland Water Highlights** as a key action. Referencing the Aichi Target 15 – Ecosystem restoration and resilience", it is noted that dam removals for river flow restoration have increased exponentially since 1950s. However, the stated restoration goal of 15 per cent of degraded ecosystems by 2020, was not achieved and only limited progress was made.

A policy with more detailed specifics for rivers, is the **Brisbane Declaration and Global Action Agenda on Environmental Flows 2017,** (Arthington et al. 2018). It is a further development building on the 2007 version of the declaration that was formulated during the 10th International River symposium and International Environmental Flows Conference held in Brisbane, Australia, which was endorsed by 800 delegates from more than 50 countries. Environmental flows describe the quantity, timing, and quality of water flows required to sustain aquatic ecosystems and the human livelihoods and well-being that depend on these ecosystems and mimic natural flows (WWF, 2020). It is pointed out that environmental flows (e-flows) are linked to the SDG goals and targets as they contribute to improvements in the production of freshwater and estuarine foods such as fisheries (14.2), thereby contributing indirectly to SDGs 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 8 (decent work and economic growth), SDG 12 (sustainable management and efficient use of natural resources) and SDG 16 (peaceful and inclusive societies for sustainable development, and access to justice for all). Environmental flows can be affected by global warming/climate change and are therefore relevant to SDG 13. Environmental water requirements such as river connectivity and environmental flows and their importance for wetlands has also been highlighted and stressed by **Ramsar (2015) and IUCN (2012**).

In 2022, **WWF** – US and Greater-Mekong and Confluvio conducted a free-flowing rivers assessment of the Lower Mekong basin (Free Flowing Rivers project, 2022). The project results include an updated GIS geodatabase, and river maps with metrics from pressure indices such as degree of fragmentation, regulation, sediment loss, road and urban development, and water abstraction from rivers, and a weighted connectivity status index (CSI) based on the pressure indices. A Free-flowing status report, a Free-flowing rivers toolbox and tutorial documents are also part of the results. The methodology to derived the CSI is described in Grill et al. (2019). Results of Pilot 3, which provide alternative approaches, can potentially be included or linked to further develop and enhance such tools and improve the basis for decisions related to river connectivity issues.

Another report (ASF, 2019) commissioned by WWF, RiverWatch, GEOTA and EuroNatur, provides an inventory of hydropower in the whole of Europe, and overlays them with Europe's protected areas. Over 20% of existing powerplants are located in protected areas such as national parks and Natura 2000 area. It also showed that in addition to the existing hydropower plants there are over 8 000 being planned of which 28% are in protected areas. The recommendations to tackle associated problems include prevention of new hydropower projects in the last remaining free-flowing or intact rivers, planning of additional hydropower plants should be reconsidered including regards changing discharges due to climate change, focus should be on refurbishment and renovation to increase efficiency (e.g. license renewal/prolongation should require restoration efforts and mitigation of environmental impacts and integrated river and catchment approaches are essential to assess dams also in the neighbourhood of protected areas. WWF recommends strongly limiting establishment of new hydropower and advocate for strong river connectivity targets in the EU nature restoration law.

An example of a European national initiative to contribute to sustainable water resource management beneficial for biological diversity has been instigated by the Swedish authorities (SEPA, SWAM) who are funding six projects and syntheses (2023–2026) on the impact of hydropower and other dams on society, landscapes, ecosystems, and species (Swedish Environmental Protection Agency, 2023). The Swedish government recently developed a national 20-year plan (NAP). The aim is to increase knowledge to facilitate implementation of the NAP for Modern Environmental Conditions for Hydropower, including reviewing hydropower plant licenses with the aim to modernize environmental regulations for the hydropower sector. The projects include Water at Risk (WaR) – restoration of water connectivity and Quantifying impacts of dams and dam removal on riverine systems.

3.2 BIOMONDO Experimental dataset

The datasets available for building show cases and methods for viewing the data and products stored in the BIOMONDO Freshwater Laboratory are introduced below and in BIOMONDO_D2.4_ExperimentalDatasets_v1.0.pdf.

For Pilot 3, the experimental datasets presented and discussed with the Early Adopters consist of:

- Land Cover Class from EO
- Water occurrence, change and seasonality from EO
- Chlorophyll-a concentration, water colour, Secchi Depth and turbidity from EO
- Model calculated river connectivity metrics
- Total Suspended Solids from in-situ measurements

All produced EO based and modelled datasets have been included in the BIOMONDO Freshwater Lab. The lab allows the user to work with and combine different information sources to analyse and compare model output with observations made in-situ or by Earth Observation. The central part of the BIOMONDO Freshwater Laboratory is the BIOMONDO Viewer and its functionalities. The Viewer enables easy access, visualization of and to work with the experimental datasets, and it was essential for the demonstration and consultation sessions. The Viewer also serves as good demonstration and show case of how the results and outputs of the ESS Pilots could be integrated into decision systems on the management side, either as external web-based tool or by integrating data in the organisations existing systems. Figure 9 shows the Viewer and gives an example of the water colour dataset at the Lower Se San 2 dam and that time series can be generated and analysed for any location (orange dot) or region defined by the user.

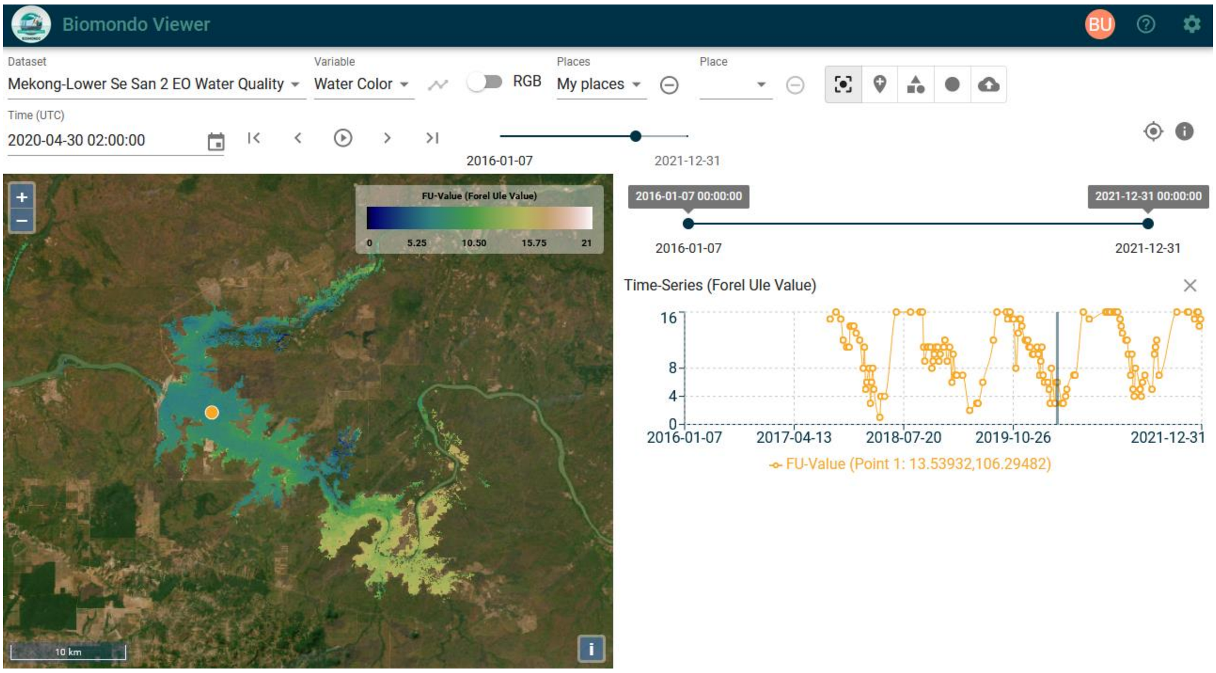

Figure 9 BIOMONDO Viewer showing water colour at the Lower Se San 2 dam on the 30th April 2020.

To facilitate the interpretation and support the scientific and policy discussions, EO and model data from Lower Se San 2 were compiled to show case how EO data can contribute to the analysis of impacts of dam constructions. To provide the Early Adopters with a possibility to compare data sets, the parameters generated by the model per dam were also made available in the viewer. This corresponds to the modelled and analysed impact on the connectivity of individual dams, which was studied by determining the impact of the removal of a single dam (from a set including existing dams and dams that are currently under construction) on the average connectivity of all. The effect on the Connectivity Index (CI) per dam is provided via the BIOMONDO Viewer (Figure 10) and differentiated between the effect of fragmentation for non-diadromous and diadromous fish species, assuming the most downstream dam to affect the connectivity of diadromous fish species to a much higher extent.

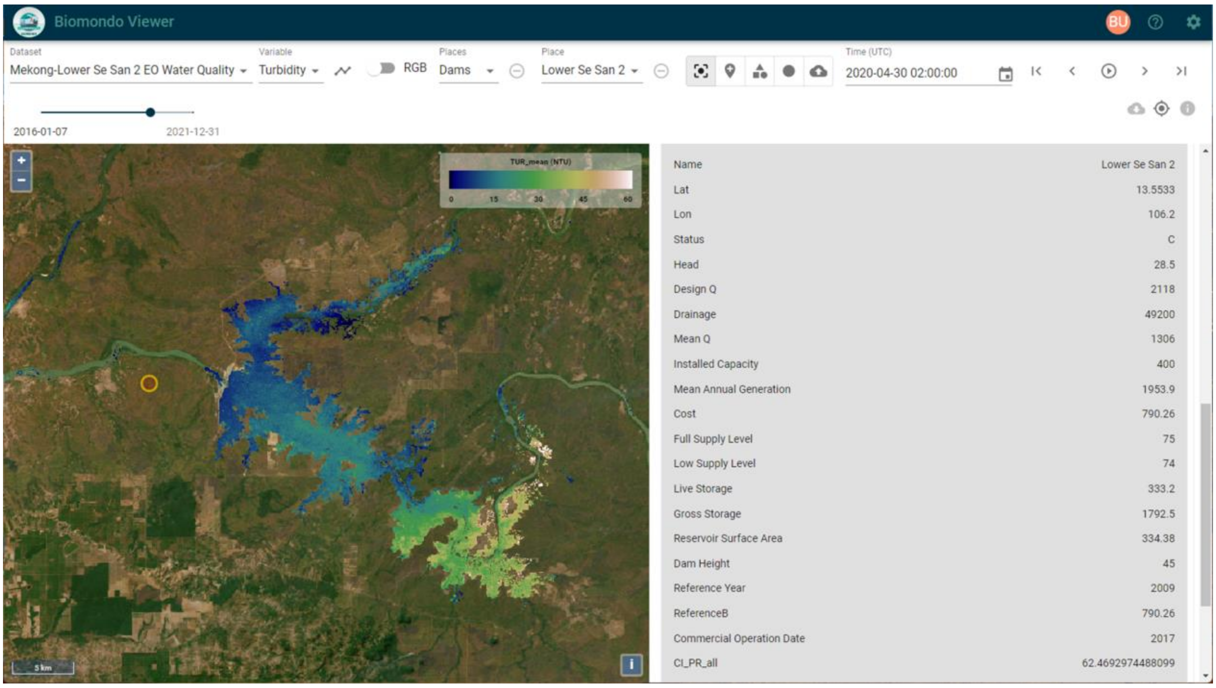

Figure 10 To allow for a further exploration of the multiple simultaneous effects of individual dams' key information was made available in the viewer. CI_PR = Connectivity Index Post Removal.

In addition, thematic ecosystem change indices (TECIs) that provide information on the extent and intensity of changes in ecosystems has been developed and demonstrated to the Early Adopters. The developed TECIs for Pilot 3 are based on the analysis of the datasets for each dam (Table 1) and are designed to capture land use or water quality changes. TECIs can support the interpretation of big datasets and provide valuable information for understanding the drivers and impacts of ecosystem change.

The experimental datasets, the EO based products and TECI examples were presented in consultation meetings (see Table 2) to discuss and assess the impact and utility for policy in general and to inform the showcase presented in section 3.3 below.

3.3 Pilot 3 Show case – Towards EO supported water quality assessments for regulated and exploited rivers

This showcase addresses the impact on natural flow regimes and habitats of aquatic and semi-aquatic species in rivers and river floodplains by obstacles such as dams and other human-made waterworks that alter and interrupt the dispersal routes. Other effects of dams on biota occur via water quality deterioration and reduction of sediment transport to coastal wetlands.

These multiple, simultaneous effects of river dams, including differences in the effects between different types of dams, are not well understood. As discussed in the previous chapters the results of Pilot 3 can contribute to closing some of the scientific knowledge gaps. In this chapter we show case how some of the results and products can support relevant policy priorities and biodiversity monitoring frameworks and how they can be integrated in decision support systems for improved management with the aim to contribute to sustainable water resource management beneficial for biological diversity.

3.3.1 Policy context and information needs

The Pilot 3 results are relevant for several policy targets and goals, as presented in section 3.1 and further discussed in 3.4, i.e. in relation to EU 2030 Biodiversity Strategy and its restoration targets (e.g. free flowing rivers) and EU Nature restoration law (e.g. restore natural sedimentation processes), the WFD (updates to guidelines) with inputs to RBMPs, but also to goals of global frameworks (SDG's and KM-GBF) connected to clean energy, climate, clean water and biodiversity of terrestrial and freshwater ecosystems.

During the expert consultations it was highlighted that the BIOMONDO Viewer could serve as a decision support tool for stakeholders working on different management aspects of the Mekong by providing easy access to time series of EO based products. By visualising and investigating changes in those variables that strongly affect the living conditions of the freshwater species living in the Mekong, attribution of biodiversity changes can be made. This has been highlighted as a requirement to achieve the KM-GBF goals (Gonzalez et al., 2023) and to monitor progress towards targets. As described in section 3.1.4, one of the key components is to ensure that observations are coordinated to form monitoring programmes that are designed to rapidly detect change and attribute causes for biodiversity change. EO products provided through global (e.g. GBIOS) or regional (e.g. BMCC) observation systems have this potential.

As described in Chapter 2, the effects of hydropower dams cause disturbances to both terrestrial and aquatic ecosystems, as well as to coastal river deltas, and research show a range of negative effects. EO derived products that show basin wide variations in sediment transport could also greatly enhance understanding of hydrodynamic processes and help to facilitate an independent data basis and contextualize in situ monitoring to clarify multi-faceted changes in water quality in the presence of conflicting user interests, e.g. renewable energy requirements on the one hand and protection and restoration of biodiversity on the other.

3.3.2 EO based water quality information

In this show case we exemplify the usefulness of the BIOMONDO experimental datasets (section 3.2) from three different perspectives related to monitoring of water quality in rivers and reservoirs in connection with dam constructions, i.e., identifying habitat changes, analysis of sediment transport and anomaly detection in big datasets. This in turn has potential to improve understanding of the drivers involved and impacts on ecosystem and biodiversity changes.

Identification of habitat changes – impacts of dam constructions

EO and model data from Lower Se San 2 were compiled to show case how EO data can contribute to the analysis of impacts on habitat by dam constructions. Figure 11 shows EO turbidity from two dates corresponding to the situation before and after dam construction. Both upstream and downstream effects can be visualised with remote sensing images. The image to the left in Figure 11 shows the Mekong River at the Lower se San dam as a white stream indicating high turbidity values and the image to the right shows low turbidity values (dark blue) upstream of the dam and in the reservoir itself. Sediment and water constituents such as chlorophyll-a, cause changes in the water colour and turbidity and strongly influence the light climate and hence living conditions of many species, including shifts between planktonic and benthic primary production and are key to nutrient transport from river systems to the sea. EO products on sediment loads can also indirectly inform estimates of sediment transport by constraining hydrodynamic models with sediment concentrations at the surface (Schmitt et al., 2016). Effects on the water colour (Forel Ule values) derived from satellite data over time is described in 2.1.2 and shown in Figure 6.

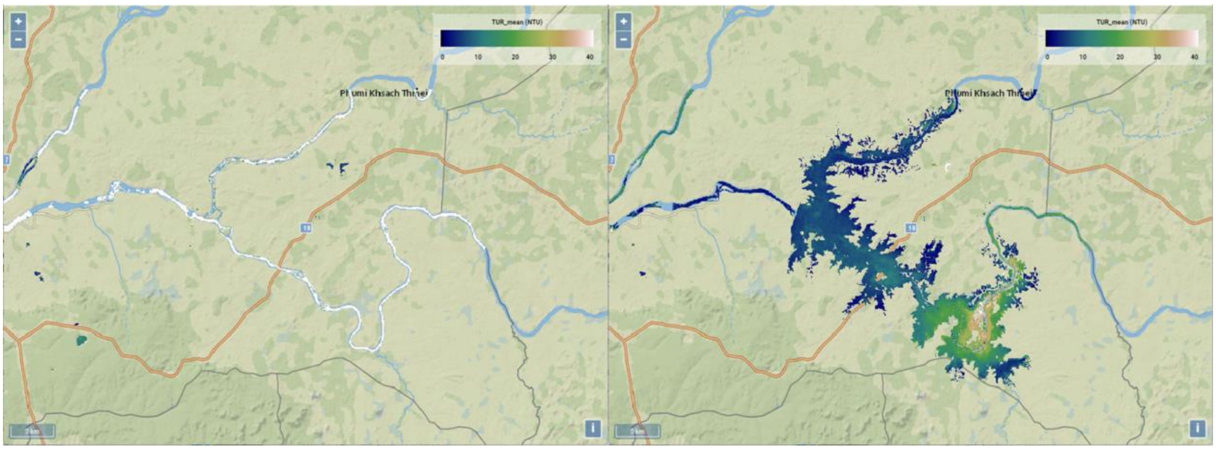

Figure 11 Turbidity maps over Lower Se San 2 before (2017-01-01) and after (2019-03-02) the dam construction.

Sediment transport – EO turbidity transect analysis

EO data provides an incomparable spatial and temporal coverage and river transects can be created and used to study changes in sediment transport over time. A transect analysis was performed at Lower Sea San 2 and included river parts down and upstream of the dam (Figure 12*)* for several years. The results show a large variability along the transect and between the years and can support the regional experts in the interpretation and understanding of the impact on the water quality by the dam and from its regulation. The plot was created to showcase how the experimental datasets can be presented, aggregated, and visualised. The final format and data selection is then dependant on the season of interest, research question or management needs.

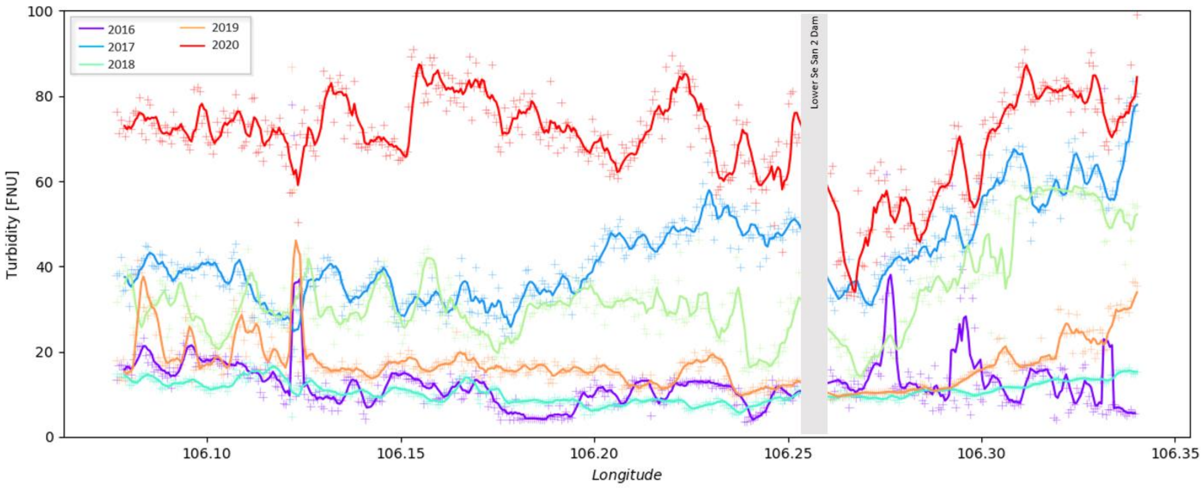

Figure 12 Yearly median turbidity transect analysis at Lower Se San 2 for several years. The grey box shows the area of the dam, the upstream river is on the right side of the grey box and the downstream river is to the left.

Anomaly detection – TECIs for anomaly detection

TECIs that provide information on the extent and intensity of changes in ecosystems has been developed and demonstrated to the Early Adopters. They can support the interpretation of big datasets and provide valuable information for understanding the drivers and impacts of ecosystem change, including changes in riverine and dam water quality. The developed TECIs for Pilot 3 (TECI 1 – Land use change and TECI 4 – Water quality) are based on the analysis of the EO datasets listed per dam (see Table 1) and are designed to capture land use and water quality changes. Figure 13 shows an example of the water quality data for Lower Se San 2 dam reservoir in spring for 2016-2021. The spring of 2018 corresponds to higher TECI-4 scores compared to the other years, indicating high probabilities that this year has higher certainties of anomalies. This is in line with effects of dam construction and opening 2017-2018.

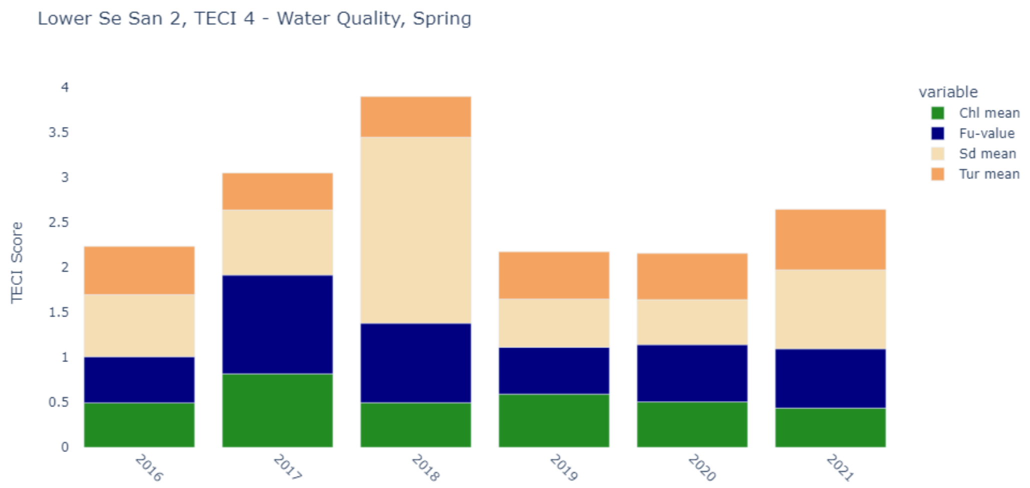

Figure 13 TECI 4 Water Quality score for the Lower Se San 2 dam reservoir in spring 2016-2021.

In Figure 14, another example related to TECI 4 – Water Quality, here for the reservoir of the dam Xe-Pian Xe-Namnoy, shows an increased score for the summer 2018, driven mainly by turbidity. This is in line with the dam collapse in the summer of 2018, when the dam in southern Laos suffered a catastrophic failure that resulted in severe flooding and widespread damage. On July 23, heavy rainfall caused the dam to overflow and collapse, releasing a massive amount of water downstream. The flooding caused significant damage to nearby villages and infrastructure, including homes, roads, and bridges. According to official reports, more than 40 people were killed, and thousands were displaced. This demonstrates that the TECI score can indicate high impacts on biodiversity due to extreme events and what parameters dominate the anomaly.

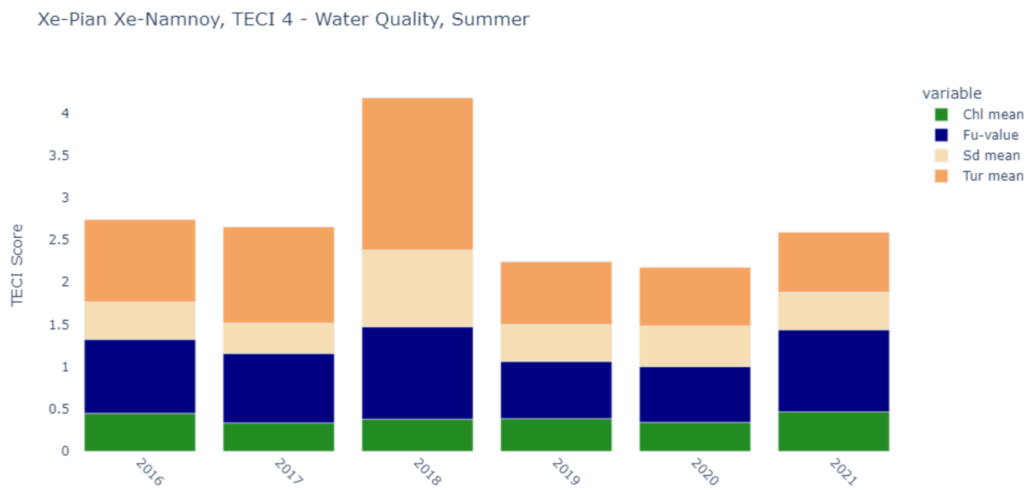

Figure 14 TECI 4 Water Quality score for the Xe-Pian Xe Namnoy dam reservoir in summer.

Altogether, the EO products and the viewer and tools can support decision making by making spatially and temporally continuous data on water quality of a large river and reservoirs easily accessible and provide possibilities for interpretation and attribution of changes to freshwater ecosystems.

3.4 Assessment of policy utility and impact

Results of Pilot 3 were presented to the Early Adopters (section 1.5) but only limited feedback regarding the utility and potential policy impact could be solicited as the experts were mainly involved with scientific issues. However, it was suggested that the results could provide additional information to existing decision support system used by natural resources managers operating in the Mekong basin (see section 2.1.1) and that the BIOMONDO Viewer, if kept simple and adapted to user needs, could be used as a decision support system in its own right.

Improved knowledge of historical and current sediment fluxes up- and downstream of reservoirs including unexpected events such as dam breaks can be used by both catchment managers and policymakers. Innovative combinations of time series of EO data with hydrological and connectivity modelling can provide explicit spatial information of differences throughout a river basin and its subbasins including changes over time. This type of information can be used to compare and mitigate impacts of existing hydropower and reservoir, support planning and prioritisation of new establishments and provide input to development of indicators for policy targets and goals.

The results of Pilot 3 also have potential to support resource managers working to preserve biodiversity by providing spatially explicit information on connectivity needed to identify extent of free-flowing river stretches and prioritise restoration of degraded river sections and through time series of EO based sediment estimates monitor impact on sediment loads from mitigation actions.

The combinations of EO based products and modelling results can also support development of spatially explicit optimisation and planning tools that account for several objectives and help stakeholders and decision makers to develop a shared view of problems and solutions for managing environmental resources and negotiating policies (Lange et al. 2018).

From a policy perspective Pilot 3 results are relevant for several different policy frameworks, as most biodiversity related strategies include specific goals related to freshwater quantity and freshwater quality, as well as river network connectivity.

The KCEO Deep Dive identified two indicators for Target 11 – "25 000 km of free-flowing rivers" of the **EU Biodiversity Strategy**. For indicator "Fraction of the stream network that is dams-free", the results of Pilot 3 have potential to support monitoring of effects from restoration efforts with specific aims for sediment transport and water quality. For the other Target 11 indicator, the "Connectivity status index (CSI)", which is a complex index made up of a weighted average of six pressure indices, the EO products derived in Pilot 3, and especially time series of turbidity, should be able to contribute although we need to look at the current alternative methodologies in some detail to assess the applicability further.

In addition, river basin management plans (RBMPs) are required by the **WFD** for European rivers but are also being developed for many rivers around the world. The findings of Pilot 3 show how specific information supported by EO based time series can improve the understanding of historic effects of dams on connectivity and sedimentation and provide valuable input to determine mitigation actions and to prioritise further infrastructure developments, preservation of environmental flows and protection of remaining free-flowing rivers and river stretches as well as indicating areas suitable for preservation of biodiversity.

EO-based products and time series have potential to support also the restoration targets (2 and 3) of the **KM-GBF** by providing improved knowledge on freshwater connectivity issues and sedimentation processes with the aim to help monitor effects of restoration actions, including both positive and negative effects on freshwater biodiversity.

Environmental flows, as mentioned in section 3.1.5, are based on 5 components (Harwood et al. 2017, Arthington et al. 2018); hydrology, geomorphology, biology, water quality and connectivity. EO based information products and results derived in Pilot 3 that improve the understanding of connectivity issues will help inform the science of environmental flow and key actions of the **GBO-5 Inland Water Highlights and Freshwater transition** and support monitoring of the **SDG** water related goals and targets.

Updates to the spatial location of dams based on EO assessments can be provided as we found that quite a few of the dams are not placed in correct position and some are missing. The results can therefore provide improvements to the global reservoirs and dams dataset (Lehner, 2011; Liermann et al. 2012; Global Dam Watch, 2023). Updates to the dam datasets also have implications for SDG Indicator 6.6.1 (Change in the extent of water-related ecosystems over time) and its Sub-Indicator 1.3 (spatial extent and change of reservoirs).

The present multitude of EO based projects and tools in the Mekong demonstrates that EO is an excellent data source to inform authorities, but even more so NGOs, because they need spatially consistent information that they cannot expect to get from ground sampling data. It is especially important where such data could jeopardize national or regional interests.

In the case of the Mekong, it seems that the basin-wide trade-offs are largely driven by the optimization of hydropower production. This task lacks a dynamic component that can classify 'green' from harmful operations. Without this component, EO based assessments are likely to fall short of details, which favour the use of ground observations. In the long term, EO should be able to fill this gap, i.e. with high resolution microwave sensors that are not limited by clouds.

When it comes to hydrodynamic processes downstream of dams and reservoirs, especially in the Mekong delta, nature-based solutions (NBS) aiming to trap sediment to support protection and restoration of mangroves, have been suggested to combat sea level rise, land subsidence and land loss. Schmitt & Minderhoud (2023) notes that the dependence on sediment supply has been largely overlooked and it was suggested in the Early Adopter consultations with the BIOMONDO team that EO derived products that show basin wide variations in sediment transport could greatly enhance understanding of hydrodynamic processes in the delta and support NBS for improvements to biodiversity and livelihoods of people.

In summary, the results from Pilot 3 provide examples of combinations of EO based products and modelling results, which if further improved (see section 2.3.2), can support the development of indicators for policy targets, both European and global. They can also be used as bases for decision making related to dam placement and regulation as well as basin and delta management for benefits for biodiversity and ecosystem services. We therefore conclude that the results and products as described in Chapter 2 and exemplified in the show case can contribute to decision making, biodiversity management and conservation by integration in already existing decisions support systems or inclusion in next generation support systems.

The findings of Pilot 3 can support resource managers working to:

- assess impacts of dam/hydropower developments
- determine least impact establishments
- determine priorities for protection, mitigation and monitoring of effects of such measures
- preserve ecosystem functioning and biodiversity through maintaining connectivity
- monitor river connectivity and water quality
- support updates to sometimes inconsistent global data sets on dams, especially small dams (Liermann, 2012), and connectivity related parameters including historic changes.

Placement of new dams with altered dam regulation regimes and/or removal of old dams and other obstacles to free-flowing rivers will be considered with growing urgency by most countries as part of trying to work towards sustainability. This includes balancing demands for greater proportion of renewable energies and mitigation measures to ensure protection and restoration of ecosystems to halt and reverse biodiversity loss. The importance of EO based timeseries of the water and land parameters that affect changes to freshwater ecosystems and which the Pilot 3 results demonstrate will therefore undoubtably only increase.

4 References

4.1 Scientific Papers

Baran, E., Larinier, M., Ziv, G. and Marmulla, G., 2011. *Review of the fish and fisheries aspects in the feasibility study and the environmental impact assessment of the proposed Xayaburi Dam on the Mekong mainstream*. WWF Greater Mekong, Phnom Penh (Cambodia).

Barbarossa, V., Schmitt, R.J.P., Huijbregts, M.A.J., Zarfl, C., King, H. & Schipper, A.M., 2020. *Impacts of current and future large dams on the geographic range connectivity of freshwater fish worldwide.* Proc. Natl. Acad. Sci. U. S. A., 117, 3648–3655.

Brockmann, C., Doerffer, R., Peters, M., Stelzer, K., Embacher, S., Ruescas, A.B., 2016. *Evolution of the C2RCC Neural Network for Sentinel 2 and 3 for the Retrieval of Ocean Colour Products in Normal and Extreme Optically Complex Waters.* Proc. ESA Living Planet Symposium. ESA/ESRIN, Prague, Czech Republic.

Carrara, F., Altermatt, F., Rodriguez-Iturbe, I. & Rinaldo, A., 2012. *Dendritic connectivity controls biodiversity patterns in experimental metacommunities*. Proc. Natl. Acad. Sci. U. S. A., 109, 5761–5766.

Dethier, E. N., Renshaw, C. E. and Magilligan, F.J., (2022). *Rapid changes to global river suspended sediment flux by humans*. Science 376, 1447–1452. DOI: 10.1126/science.abn7980.

Doerffer, R., Schiller, H., 2007. *The MERIS Case 2 water algorithm*. Int. J. Remote Sens. 28, 517–535. https://doi.org/10.1080/01431160600821127.

Dorber, M., Arvesen, A., Gernaat, D. et al., 2020. *Controlling biodiversity impacts of future global hydropower reservoirs by strategic site selection.* Sci Rep 10, 21777 (2020). https://doi.org/10.1038/s41598-020-78444-6.

Duarte, G., Segurado, P., Haidvogl, G., Pont, D., Ferreira, M.T. & Branco, P., 2021. *Damn those damn dams: Fluvial longitudinal connectivity impairment for European diadromous fish throughout the 20th century.* Sci. Total Environ., 761, 143293.

Fagan, W.F., 2002. *Connectivity, fragmentation, and extinction risk in dendritic metapopulations.* Ecology, 83, 3243–3249.

Fuller, M.R., Doyle, M.W. & Strayer, D.L., 2015. *Causes and consequences of habitat fragmentation in river networks. Ann*. N. Y. Acad. Sci., 1355, 31–51.

Giagkiozis, I., Fleming, P. J., 2014. *Pareto Front Estimation for Decision Making*. Evol Comput 2014; 22 (4): 651–678. doi: https://doi.org/10.1162/EVCO_a_00128

Gonzalez, A., Vihervaara, P., Balvanera, P., ... Torrello, C. Z., 2023. *A global biodiversity observing system to unite monitoring and guide action.* Nat Ecol Evol 7, 1947–1952 (2023) https://doi.org/10.1038/s41559-023-02171-0.

Gracey, E.O. & Verones, F., 2016. *Impacts from hydropower production on biodiversity in an LCA framework—review and recommendations.* Int J Life Cycle Assess 21, 412–428. https://doi.org/10.1007/s11367-016-1039-3

Grill, G., Lehner, B., Thieme, M., ... Zarfl, C., 2019. *Mapping the world's free-flowing rivers.* Nature 569, 215–221 (2019). https://doi.org/10.1038/s41586-019-1111-9

Grönroos, M., Heino, J., Siqueira, T., Landeiro, V.L., Kotanen, J., Bini, L.M., 2013. *Metacommunity structuring in stream networks: roles of dispersal mode, distance type, and regional environmental context*. Ecol. Evol., 3, 4473–4487.

Harwood, A., Johnson, S., Girard, I., Richard, S., Wick, J., Locke, A., Wendling, G. and Hatfield, T. 2017. *Guidance on Assessing and Reporting Cumulative Impacts of Water Withdrawal on Environmental Flow Needs.* Consultant's report prepared for the Canadian Council of Ministers of the Environment by Ecofish Research Ltd., GW Solutions Inc. and Locke and Associates, February 27, 2017.

Hänfling, B. & Weetman, D., 2006. *Concordant genetic estimators of migration reveal anthropogenically enhanced source-sink population structure in the river sculpin, Cottus gobio.* Genetics, 173, 1487–1501.

Irz, P., Argillier, C. & Oberdorff, T., 2004. *Native and introduced fish species richness in French lakes: local and regional influences.* Glob. Ecol. Biogeogr., 13, 335–344.

Janse, J. H., Kuiper, J. J., Weijters, M. J., Westerbeek, E. P., Jeuken, M. H. J.L., Alkemade, R., Mooij, W.M., Verhoeven, J.T.A., 2015. *GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems*, Environmental Science & Policy, 48: 99-114.

Kondolf, G. M., Rubin, Z. K., and Minear, J. T., 2014. *Dams on the Mekong: Cumulative sediment starvation*, Water Resour. Res., 50, 5158–5169, doi:10.1002/2013WR014651.

Kuiper, J. J., Janse, J. H., Teurlincx, S., Verhoeven, J. T., Alkemade, R., 2014. *The impact of river regulation on the biodiversity intactness of floodplain wetlands*. Wetlands Ecology and Manage-ment, 22(6), 647-658.

Lange, K., Meier, P., Trautwein, C., Schmid, M., Robinson C. T., Weber, C., Brodersen, J., 2018. *Basin-scale effects of small hydropower on biodiversity dynamics.* Front Ecol Environ 2018; 16(7): 397–404, doi:10.1002/fee.1823.

Lehner, B., Reidy Liermann, C., Revenga,, C., Vörösmarty, C., Fekete, B., Crouze,t P., Doell, 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.* Frontiers in Ecology and the Environment. 10.1890/100125.

Leuven, R.S.E.W., van der Velde, G., Baijens, I., Snijders, J., van der Zwart, C., Lenders, H.J.R., et al., 2009. *The river Rhine: a global highway for dispersal of aquatic invasive species.* Biol. Invasions, 11, 1989.

Liermann, C. R., Nilsson, C., Robertson, J., Ng, R. Y., 2012, *Implications of Dam Obstruction for Global Freshwater Fish Diversity*, BioScience, Volume 62, Issue 6, June 2012, Pages 539–548, https://doi.org/10.1525/bio.2012.62.6.5

Markert, K.N.; Schmidt, C.M.; Griffin, R.E.; Flores, A.I.; Poortinga, A.; Saah, D.S.; Muench, R.E.; Clinton, N.E.; Chishtie, F.; Kityuttachai, K., et al., 2018. *Historical and Operational Monitoring of Surface Sediments in the Lower Mekong Basin Using Landsat and Google Earth Engine Cloud Computing*. Remote Sens. 2018, 10, 909.

Merritt, D.M. & Wohl, E.E., 2006. *Plant dispersal along rivers fragmented by dams.* River Res. Appl., 22, 1–26.

Nienhuis, J. H., Ashton, A. D., Edmonds, D. A., Hoitink, A. J. F., Kettner, A. J., Rowland, J. C., & Törnqvist, T. E., 2020. *Global-scale human impact on delta morphology has led to net land area gain.* Nature, 577(7791), 514-518.

Nilsson, C., & Berggren, K., 2000. *Alterations of riparian ecosystems caused by river regulation.* BioScience, 50(9), 783-792.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., ... & Stromberg, J. C., 1997. *The natural flow regime.* BioScience, 47(11), 769-784.

Randell, H., 2022. *The challenges of dam-induced displacement: Reducing risks and rethinking hydropower.* One Earth, 5(8), 849-852.

Ruppen, D., Runnalls, J., Tshimanga, R.M., Wehrli, B., and Odermatt, D., 2023. *Optical remote sensing of large-scale water pollution in Angola and DR Congo caused by the Catoca mine tailings spill.* Int. J. Appl. Earth Obs. Geoinformation 118, 103237.

Räsänen, T. A., Varis, O., Scherer L., Kummu, M., 2018. *Greenhouse gas emissions of hydropower in the Mekong River Basin. Environ.* Res. Lett. 13 034030, DOI 10.1088/1748-9326/aaa817.

Sala, O. E., Chapin, F. S., Armesto, J. J. … Wall, D. H., 2000. *Global biodiversity scenarios for the year 2100.* Science 287: 1770–1774. https://www.science.org/doi/10.1126/science.287.5459.1770.

Schmitt, R. J. P., Bizzi, S., and Castelletti, A., 2016. *Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity.* Water Resour. Res., 52, 3941–3965.

Schmitt, R. J. P., Bizzi, S., Castelletti, A., Kondolf, G. M., 2018. *Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong*. Nature Sustainability, 1(2), 96-104.

Schmitt, R. J.P., Bizzi, S., Castelletti, A., Opperman, J. J., & Kondolf, G. M., 2019. *Planning dam portfolios for low sediment trapping shows limits for sustainable hydropower in the Mekong*. Science advances, 5(10), eaaw2175.

Schmitt, R. J., Giuliani, M., Bizzi, S., Kondolf, G. M., Daily, G. C., & Castelletti, A., 2021. *Strategic basin and delta planning increases the resilience of the Mekong Delta under future uncertainty.* Proceedings of the National Academy of Sciences, 118(36), e2026127118.

Schmitt, R.J.P. & Minderhoud, P.S.J., 2023. *Data, knowledge, and modeling challenges for science-informed management of river deltas.* One Earth 6(3):216-235, Cellpress, https://doi.org/10.1016/j.oneear.2023.02.010.

Shurin, J.B., Havel, J.E., Leibold, M.A. & Pinel-Alloul, B., 2000. *Local and regional zooplankton species richness: A scale-independent test for saturation.* Ecology, 81, 3062–3073

Shurin, A. & Smith, S., 2006. *Room for one more? Evidence for invisibility in ecological communities*. In: Conceptual ecology and invasion biology: reciprocal approaches to nature.

Tessler, Z. D., Vörösmarty, C. J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J. P., & Foufoula-Georgiou, E., 2015. *Profiling risk and sustainability in coastal deltas of the world.* Science, 349(6248), 638-643.

Trottier, G., Turgeon, K., Boisclair, D., Bulle, C, Margni, M., 2022. *The impacts of hydropower on freshwater macroinvertebrate richness: A global meta-analysis.* PLoS One. (8):e0273089. doi: 10.1371/journal.pone.0273089. PMID: 35980987; PMCID:PMC9387867.

Wernand, M.R., van der Woerd, H.J., 2010. *Spectral analysis of the Forel-Ule Ocean colour comparator scale*. J. Eur. Opt. Soc. - Rapid Publ. Vol 5 2010.

Vörösmarty, C., McIntyre, P., Gessner, M., Dudgeon, D., Proussevitch, A., Green, P., Glidden, S., Bunn, S., Sullivan, C., Reidy Liermann, C. & Davies, P., 2010. *Global Threats to Human Water Security and River Biodiversity.* Nature. 468. 334. 10.1038/nature09549.

Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Sáenz, L., 2016. *Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong.* Science, 351(6269), 128-129.

Wubs, E.R.J., Fraaije, R.G.A., de Groot, G.A., Erkens, R.H.J., Garssen, A.G., Kleyheeg, E., et al., 2016. *Going against the flow: a case for upstream dispersal and detection of uncommon dispersal events.* Freshw. Biol., 61, 580–595.

4.2 Websites

European Commission (2020). *Fitness check of the Water Framework Directive and the Floods Directive*, Directorate-General for Communication, accessed 20 December 2023, https://commission.europa.eu/publications/fitness-check-water-framework-directive-and-floods-directive_en.

Free Flowing Rivers project (2022). *Mekong River Connectivity Assessment and Toolbox*. Confluvio, accessed 20 December 2023, https://www.confluvio.com/project/connectivity-in-the-mekong-region.

Global Dam Watch (2023). *Curated global dam and reservoir data for all*. King's College London, accessed 20 December 2023, http://www.globaldamwatch.org/.

MRC, 2023. *Mekong River Commission Information Services*. https://portal.mrcmekong.org/.

SERVIR (2023). *Decision support tools*. Asian Disaster Preparedness Center accessed 20 December 2023, https://servir.adpc.net/tools?page=1 .

STIMSON (2023). *Mekong Dam Monitor*. The Henry L. Stimson Center accessed 20 December 2023, https://www.stimson.org/project/mekong-dam-monitor.

Swedish Environmental Protection Agency (2023). *Environmental Impact of Hydropower*. Swedish Environmental Protection Agency, accessed 20 December 2023, https://www.naturvardsverket.se/en/international/research/the-environmental-research-fund/research-efforts-community/environmental-impact-of-hydropower/.

United Nations (2023). *Water Action Agenda*. United Nations Department of Economic and Social Affairs, accessed 20 December 2023, https://sdgs.un.org/partnerships/action-networks/water.

UN Water (2018). *Integrated Monitoring Guide for SDG 6*. UN Water, accessed 20 December 2023, http://www.unwater.org/publications/integrated-monitoring-guide-SDG-6.

WWF (2020). Environmental Flows. World Wildlife Fund Canada, accessed 20 December 2023, https://wwf.ca/wp-content/uploads/2020/03/Environmental-Flows.pdf.

4.3 Policy and strategy references

Arthington, A.H., Bhaduri, A., Bunn, S.E., Jackson, S.E., Tharme, R.E., Tickner, D., Young, B., Acreman, M., Baker, N., Capon, S., Horne, A.C., Kendy, E., McClain, M.E., Poff, N.L., Richter, B.D. and Ward S., 2018. *The Brisbane Declaration and Global Action Agenda on Environmental Flows*. Front. Environ. Sci. 6:45. https://doi.org/10.3389/fenvs.2018.00045

ASF, 2019. *Hydropower pressure on European - The story in numbers,* Atlantic Salmon Federation. Canada. https://policycommons.net/artifacts/2082140/hydropower-pressure-on-european/2837438/ CID: 20.500.12592/d8m7mw.

Bieroza, M. Z., Bol, R. & Glendell, M., 2021. *What is the deal with the Green Deal: Will the new strategy help to improve European freshwater quality beyond the Water Framework Directive*? Science of The Total Environment, Volume 791, 2021, 148080, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.148080.

Camia, A., Gliottone, I., Dowell, M., Gilmore, R., Coll, M., Skidmore, A., Chirici G., Caimi, C., Brink, A., Robuchon, M., Ferrario, I., 2023. *Earth Observation in Support of EU Policies for Biodiversity - A deep-dive assessment of the Knowledge Centre on Earth Observation*. Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/185588, JRC132908.

CBD, 2020a. *Global Biodiversity Outlook 5*. Montreal. https://www.cbd.int/gbo/gbo5/publication/gbo-5-en.pdf

CBD, 2020b. *GBO-5 Inland Water Highlights*, https://www.cbd.int/waters/doc/gbo5-inlandwaters-en.pdf

CBD, 2022a. *Kunming-Montreal Global Biodiversity Framework.* United Nations Biodiversity Conference COP15/CP-MOP10/NP-MOP4. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf.

CBD, 2022b. *Monitoring framework for the Kunming-Montreal global biodiversity framework.* Montréal: CBD. https://www.cbd.int/doc/c/179e/aecb/592f67904bf07dca7d0971da/cop-15-l-26-en.pdf.

Deinet, S., Scott-Gatty, K., Rotton, H., Twardek, W. M., Marconi, V., McRae, L., Baumgartner, L. J., Brink, K., Claussen, J. E., Cooke, S. J., Darwall, W., Eriksson, B. K., Garcia de Leaniz, C., Hogan, Z., Royte, J., Silva, L. G. M., Thieme, M. L., Tickner, D., Waldman, J., Wanningen, H., Weyl, O. L. F., Berkhuysen, A., 2020. *The Living Planet Index (LPI) for migratory freshwater fish - Technical Report.* World Fish Migration Foundation, The Netherlands.

EEA, 2018. *European waters Assessment of status and pressures 2018*. European Environment Agency Report No. 7, ISBN: 978-92-9213-947-6, doi:10.2800/303664, https://www.eea.europa.eu/publications/state-of-water

European Commission, Directorate-General for Environment, 2014*. The EU Water Framework Directive*. Publications Office, https://data.europa.eu/doi/10.2779/75229

European Commission, Directorate-General for Environment, 2021. *EU biodiversity strategy for 2030 – Bringing nature back into our lives.* Publications Office of the European Union, 2021, https://data.europa.eu/doi/10.2779/677548.

Harwood, A., Johnson, S., Richter, B., Locke, A., Yu, X. and Tickner, D., 2017*. Listen to the river: Lessons from a global review of environmental flow success stories*, WF-UK, Woking, UK. Access via https://wwfint.awsassets.panda.org/downloads/listen_to_the_river.pdf

IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES secretariat, Bonn, Germany. 1148 pages. https://doi.org/10.5281/zenodo.3831673 https://ipbes.net/global-assessment

IUCN, 2012. *The Importance of Assessing the Water Needs of Wetlands in Order to Preserve Their Ecological Functions*. Motion M087, Congress Document WCC-2012-9.6. World Conservation Congress. https://portals.iucn.org/library/sites/library/files/documents/WCC-5th-002.pdf

Maes, J., Teller, A., Erhard, M., Conde, S., Vallecillo Rodriguez, S., Barredo Cano, J.I., Paracchini, M., Malak, D.A., Trombetti, M., Vigiak, O., Zulian, G., Addamo, A., Grizzetti, B., Somma, F., Hagyo, A., Vogt, P., Polce, C., Jones, A., Carré, A. and Hauser, R., 2021. *EU Ecosystem Assessment, Summary for* *policy makers,* EUR 30599 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-40834-5, doi:10.2760/881115, JRC123783.

Moersberger, H., Martin, J.G.C., Junker, J., Georgieva, I., Bauer, S., Beja,P., Breeze, T., Brotons, L., Bruelheide, H., Fernández, N., Fernandez, M., Jandt, U., Langer, C., Lyche Solheim, A., Maes, J., Moreira, F., Pe'er, G., Santana, J., Shamoun-Baranes, J., Smets, B., Valdez, J., McCallum, I., Pereira, H.M., Bonn, A., 2022. *Europa Biodiversity Observation Network: User and Policy Needs Assessment.* EuropaBON/German Centre of Biodiversity Research (iDiv), Leipzig.

Ramsar, 2015. *Call to action to ensure and protect the water requirements of wetlands for the present and the future*. In Resolution XII.12, 12th Meeting of the Conference of the Parties to the Convention on Wetlands (Ramsar). https://www.ramsar.org/sites/default/files/documents/library/ramsar_cop12_conference_report_e_0.pdf

UN GA, 2015. *Transforming our world: the 2030 Agenda for Sustainable Development.* UN Resolution 70/1, 21 October 2015. http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

United Nations, 2023. *Blueprint for Acceleration: Sustainable Development Goal 6 Synthesis Report on Water and Sanitation 2023.* https://www.un-ilibrary.org/content/books/9789210026444