New Emphasis on Water Clarity as Socio-Ecological Indicator for Urban Water – a short illustration

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Abstract
Water clarity is quantified for more than 200 years by the visibility of a disk lowered under water. The perspective on water transparency, however, changed since the early days of limnology from being a physical parameter of optical water property to an ecological indicator tracking algal turbidity due to man-made nutrient addition (eutrophication), identifying an overall success of sustained lake restoration in the late 60ies to 80ies or ecosystem health in recent time. Whatever the many different interpretations for good or bad water visibility have been found across the 130-year history in limnology, water transparency today gained new attention since natural assets such as ponds, lakes, floodplain waters, streams or rivers became a popular design element in modern urban planning aimed at human well-being in densely populated cities. Water visibility, also called water transparency, which can be used as criterion for water quality, but ideally should be backed by further ecosystem measurements in aquatic science, is also used to judge the recreational use of blue-green urban spaces by public awareness. In the recent study about oxbow lake Alte Donau in Vienna, we identified critical values of water transparency in view of lake science and human judgment. With lake restoration, the increase of water transparency to 1.5m Secchi depth was accompanied by a trophic shift from eutrophic algal turbidity to mesotrophic condition of macrophyte dominated clear water state. This critical Secchi depth of 1.5m corresponds further to a "littoral lake bottom view" satisfying bathing aesthetics by human perception. A further increase of water transparency to at least 3.5m, however, is found by empirical lake measurements for supporting sustained growth of bottom-dwelling macrophytes (*Chara* species) at the expense of tall growing *Myriophyllum spicatum*. The latter requires underwater cutting as this near surface canopy building macrophyte is causing nuisance for recreational purposes. Thus, a water transparency (Secchi depth > 3.5m) allowing the growth of underwater near-sediment meadows of Charophytes is recommended for stabilizing sustained lake restoration, but exceeds by far the requirements of water transparency that is satisfying people's awareness judging good water quality by bathing aesthetics. We conclude, that water transparency is the only common limnological parameter that the public can use by human perception for assessing water quality or a progress of a lake restoration. A good status of water transparency close to ecosystem reference conditions attracts public awareness to take advantage of various ecosystem

services enhancing well-being in urban life – it thus offers a great opportunity to the public to raise socio-ecological consciousness concerning urban green-blue spaces.

1. Introduction

Man-made ecosystem degradation accelerated in recent decades (Crutzen 2002; Dalby 2016) and became most obvious in urban areas. The Danubian floodplain in Vienna is threatended by simplification of the ecosystem structure (Sanon et al. 2012; Haidvogl et al. 2013; Hohensinner 2019), biodiversity loss (e.g., Funk et al. 2009; Hein et al. 2016), and overusing natural systems for recreation purposes (e.g., Arnberger and Eder 2012). Alte Donau, a former river stretch of the Danube River, is the most well studied urban lake in the capital city of Austria, Vienna. The ecosystem faced drastic changes mainly by losing its natural connectivity from the main river during river regulation from 1868 onward, and further eutrophication from 1987 to 1994 due to the degradation of the riverine landscape into urban areas (Dokulil et al. 2018a) and global warming in recent decades (Teubner et al. 2018a). Early Secchi disc readings for Alte Donau go back to the late 80ies and were measuered under mesotrophic nutrient state conditions, when nutrients were mainly utilzied by dense meadows of bottom-dwelling Chara. The time series of Secchi depths (Donabaum and Riedler 2018) related to algal turbidity and other limnological measures covers up to 32-year study for this urban oxbow lake and is well documented for the whole management measuere period (Dokulil et al. 2018a; Teubner et al. 2020) or for specific short-term observations (e.g. Dokulil and Mayer 1996; Teubner et al. 2003). Water quality shits over time include man-made nutrient enrichment in the late 80ies to early 90ies due to the inclusion of the riverine landscape in the urban area, followed by lake restoration with an ecosystem shift from a nutrient-rich, algal-turbid water body to a nutrient-poor, clear-water macrophyte controlled system. In addition to the ecosystem response due to wax and wane of nutrients, global warming triggered lake penology by an earlier warming in spring, a prolonged warm season promoting thermophilic zooplankton species (Teubner et al. 2018a) but also hampered restoration efforts by decreasing water transparency during the extreme hot season with water temperatures above 21°C (Teubner et al. 2020). The aim of this Alte Donau study is to illustrate new emphasis on water transparency as socio-ecological indicator.

2. Material and methods

Alte Donau is a shallow groundwater seepage lake of 2.5m mean depth (7m maximum lake depth), 1.6km² lake area and 3.8×10^6 m^3 lake water volume (Fig. 1). Monthly sampling was the regular scheme throughout the more than two decades of lake observations. Lake morphometry, long-term restauration measures including long-term development of various biota from planktonic ciliates and other microbes to fish, macrophytes and water birds as well as a synthesis about lake restoration are described in detail in Dokulil et al. (2018a). Data treatment concerning nutrients, Secchi depth, phytoplankton (Teubner et al., 2018b), primary production (Dokulil and Kabas, 2018) and impact of climate (Teubner et al. 2018a; Teubner et al. 2020) are documented also in earlier publications. The interpretation of Secchi depth readings by light attenuation profiles is described in Teubner et al. (2020). Among others, it aimed at identifying the depth layers of specific ambient light requirements for photosynthetic domains (phytoplankton and submerged macrophytes), including the depth at 1% (minimum light requirements for phytoplankton growth as euphotic depth), 3% (minimum light requirements for macrophytes as maximum macrophyte colonization depth), and 12% (preferred light requirements for phytoplankton development) of surface ambient light.

3. Results and discussion

Measuring water transparency by disk visibility in the water body goes back to observations in the ocean (and not lakes) in 1815 to estimate the bottom distance in marine and coastal environments for safe navigation (time-line in Fig. 2). Lowering items such as a disk to measure visibility under water was introduced by Von

Kotzebue, while about 50 years later, Secchi (1866) established this method by profound marine experiments, now well known as Secchi depth measurement (Aarup 2002; Vincent and Bertola 2012; Täuscher 2015). According to the time-line in Fig. 2, this first epoch of Secchi depth measurements focused on the optical property of water. Forel (1892, 1893), the founder of the new science branch limnology, introduced Secchi depth reading to lake science (Fig. 2) and also started to understand lakes as ecosystems, meaning that lakes are more than geological shaped holes filled with water.

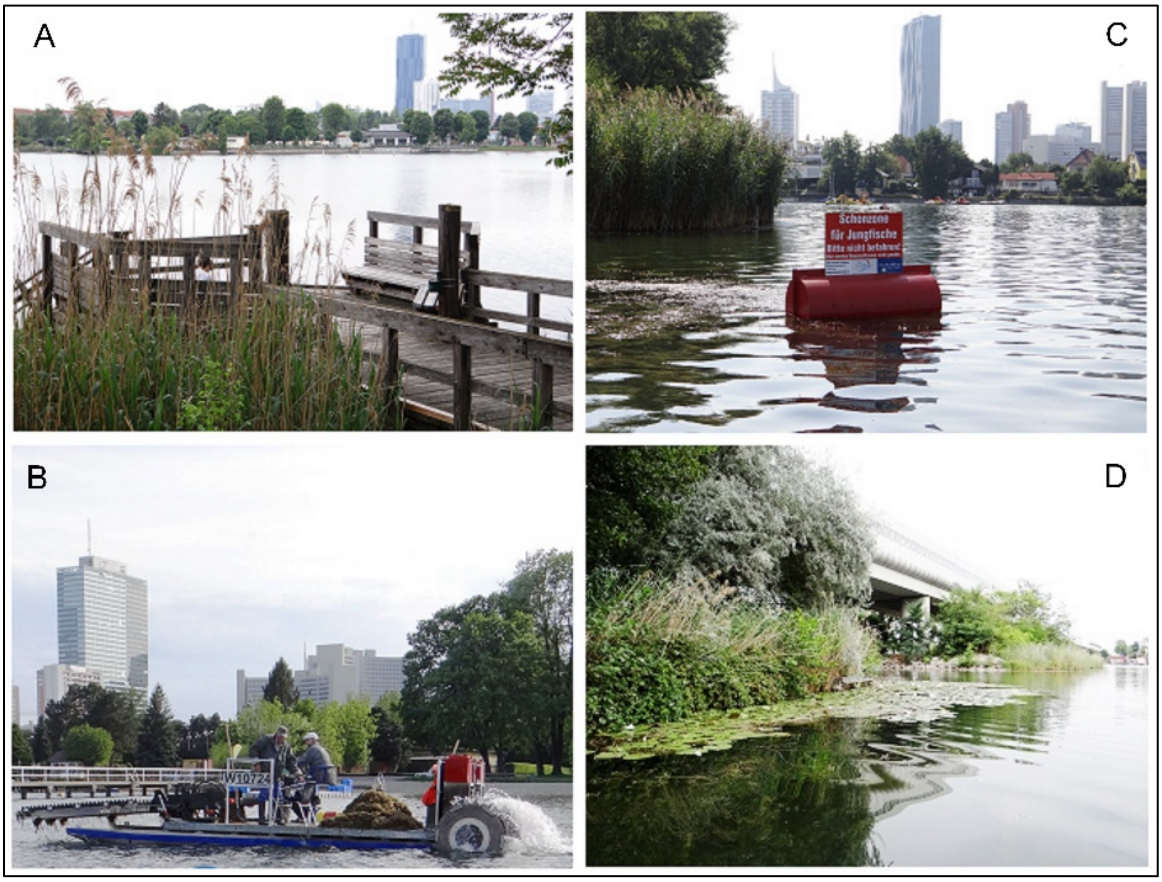

Fig.1: Alte Donau – an urban oxbow lake in the capital city of Austria, Vienna. (A) Reed belt mainly consisting of Phragmites australis and Typha were re-planted on banks. Public wooden bathing platforms give access to the open water for free, providing cultural ecosystem services in this urban recreation area. (B) Boat for managing underwater-macrophyte cutting with harvested "weed", mainly of tall-growing Myriophyllum spicatum. (c) Littoral zone with signs on buoys to stay away respecting nature: "Schonzone für Jungfische. Bitte nicht befahren. Hier werden Wasserpflanzen nicht gemäht." (translation: Protected area for young fish. Please stay away. Aquatic plants are not mowed here." (D) Viaduct of Vienna subway crossing the oxbow lake, (A-D) Photos taken in 2015, source: www.lakeriver.at.

With the eutrophication of lakes, water-clarity went beyond being an optical parameter of lake physics but was also applied in lake biology. Trophic classifications schemes in the late 60ies to 80ies were expanded to link an increasing algal biomass yield by eutrophication (Vollenweider 1968; Carlson 1977; Forsberg and Ryding 1980; Nürnberg 1996) with gradual deterioration of water-clarity. In turn, increasing water-transparency became the key target of lake restoration (e.g. Meijer et al. 1999; Hilt et al. 2006; Søndergaard et al. 2007; Gulati et al. 2008; Dokulil et al. 2018a) - it offered indicating an overall success of lake restoration. In addition, research about photosyntetic yield in lakes became of utmost interest at that time, including measurements of underwater light attenuation and light utilization by photosynthetic plankton (e.g. Harris 1978; compare with photosynthetic measurements for Alte Donau in Dokulil and Kabas 2018). Thus, the second epoch of water transparency measurements focussed on phytoplankton growth, photosynthetic light utilisation building up biomass (Fig. 2).

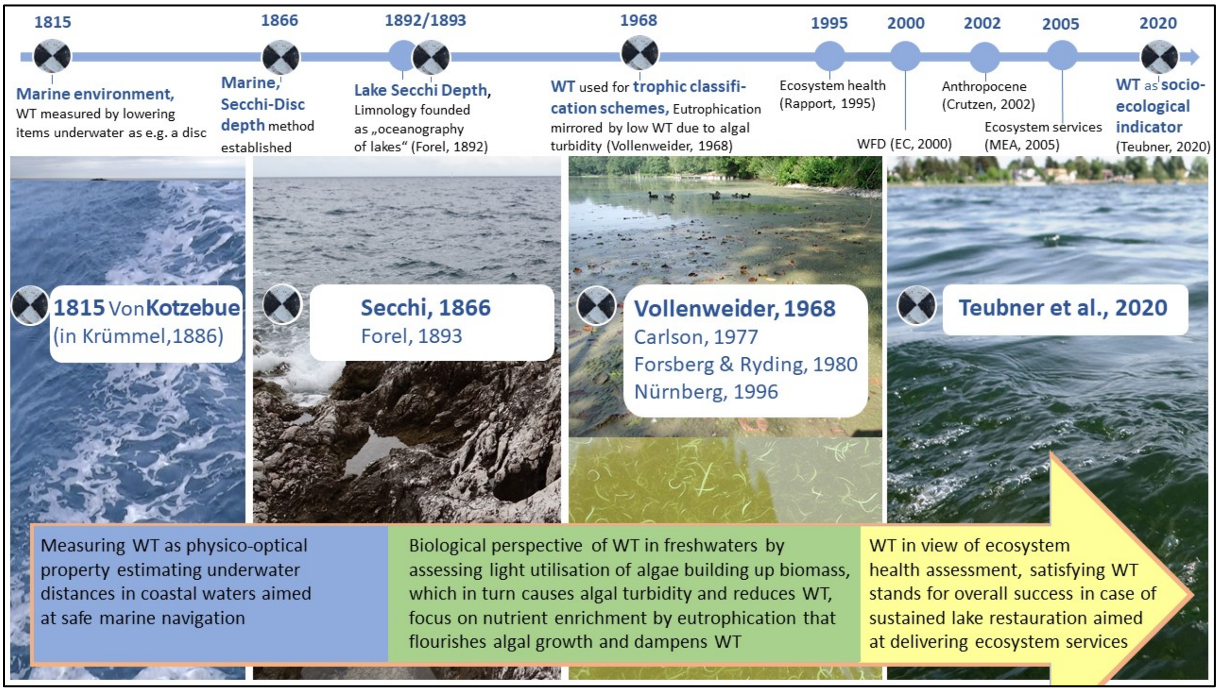

Fig. 2: Time line of identifying water transparency (WT) as physico-optical measure in marine environments in the beginning (WT epoch 1), as key parameter for assessing man-made nutrient enrichment in lakes during eutrophication periods (WT epoch 2), and as socio-ecological indicator in urban waters in recent time (WT epoch 3). Further abbreviations: Water Framework Directive (WFD), European Council (EC), Millennium Ecosystem Assessment (MEA).

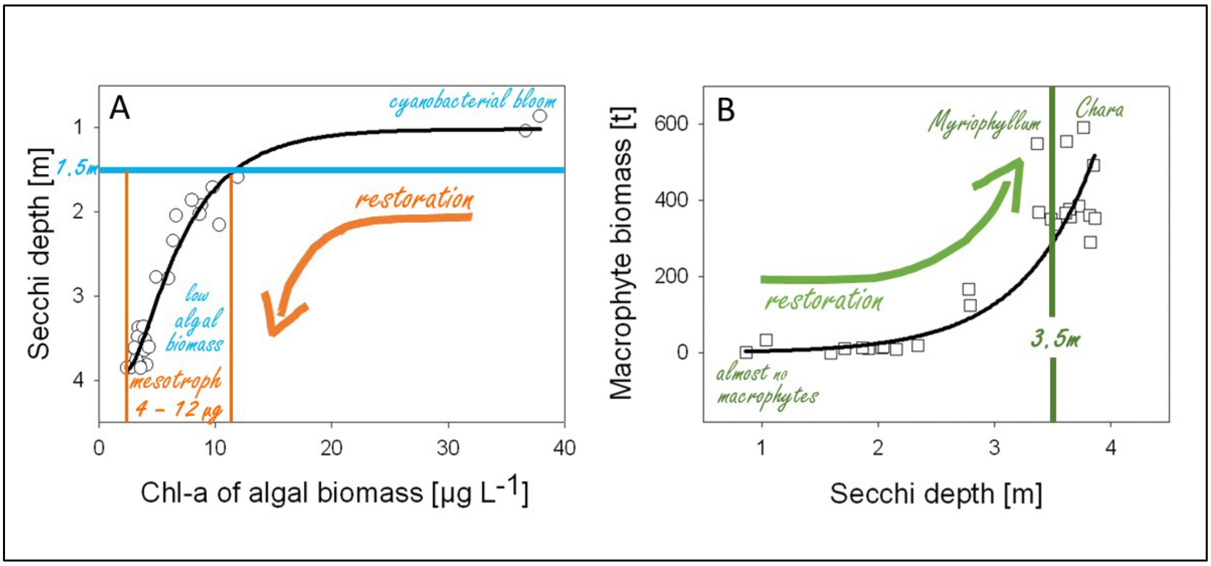

Fig. 3: The different ecological perspectives of water transparency during sustained restoration measures of oxbow lake Alte Donau: Water transparency indicated by Secchi depth (A) as response function of phytoplankton biomass (cyanobacteria and algae), where water turbidity increases with decreasing algal biomass (measured as Chlorophyll-a in µg L^{-1}) and (B) as light utilization factor increasingly stimulating the growth of underwater macrophytes (biomass as dry weight in t for the whole lake). A: High values of phytoplankton biomass during the period of nutrient enrichment, here expressed by the chlorophyll-a (Chl-a) concentration, were mainly built up by Cyanobacteria. Secchi depth below 1.5m coincides with the shift from eutrophic to mesotrophic status (range from 12 to 4µg Chl-a according to ÖNORM M6231 2001, which corresponds to the phytoplankton biovolume ranging from 2.4 to 0.8mm³ L^{-1}, see Fig. 9.10 in Teubner et al. 2018b). A Secchi disk water transparency of 1.5m ("lake bottom view") is judged as good water quality by human perception for bathing aesthetics (Smith et al., 1991). B: The critical threshold of 3.5m Secchi depth stimulating the growth of bottom-dwelling Chara species at the expense of tall-growing Myriophyllum spicatum, exceeds by far the threshold of good water quality by human perception but is most important for sustained restoration (dense stands of M. spicatum with canopy formations near the water surface are nuisance for recreational purposes such as boating or swimming). Water transparency is indicated by annual data of Secchi depth from 1993 to 2019 for A and 1993 to 2018 for B.

The peak of man-made phosphorus enrichment in Alte Donau was 1992-1994 (Donabaum and Riedler 2018; Dokulil et al. 2018b; Teubner et al. 2018b), and thus about 20 years later than the Vollenweider eutrophication study (Vollenweider 1968). The beginning of restoration measures in Alte Donau (initialized by phosphate precipitation in the water column; Donabaum and Dokulil 2018) coincides with the new era of ecosystem approach which went far beyond the algal blooms, namely developing ecosystem assessment strategies to understand ecosystem health (Rapport 1995), defining environmental reference conditions (Water Framework Directive in EC 2000) and in turn to understand the benefit of healthy ecosystems to human well-being by defining ecosystem services (MEA 2005). This new emphasis in applied lake science describes water transparency as socio-ecological indicator (Teubner et al. 2020) and refers to the third epoch interpreting Secchi depth readings (Fig. 2). Here, Secchi depths were not necessarily linked to bottom-up development of phytoplankton biomass or turbidity caused by phytoplankton only (phytoplankton often causes mainly turbidity in lakes as on average the abundance of phytoplankton cells, filaments or colonies is with about 10^6 L^{-1} much higher than those of other planktonic life forms, such as meta-zooplankton reaching on average abundances which are about 4 to 5 orders of magnitude lower, unpublished data; further, B: due to phytoplankton pigments, phytoplankton cells are pre-dominant filters of visible light with only one exception, the green light). The ecological perspective of Secchi depth interpretation can be also linked to the outcome of food web structure (e.g., Qu et al. 2021) (top-down control, identifies the “clearance” in the water column), related to ecosystem functioning in a broader sense. Judgment of water clarity by public perception is further of great importance for communicating the success of restoration or urban planning in modern city life mentioned before and thus underpins the relevance of water clarity also in view of sociological issues.

The two sides of one coin of water clarity, i.e., the two main ecological perspectives of water transparency during sustained restoration measures of oxbow lake Alte Donau are shown in Fig. 3. The graphs are underlying the assumption that lowered phytoplankton biomass (estimated by Chlorophyll-a, which is the ubiquitous pigment in all photosynthetic plankton organisms) in course of eutrophication, reduces light attenuation caused by decreasing algal turbidity and is thus responded by increasing water transparency (Fig. 3A). At the same time, with increasing Secchi depth the macrophyte biomass increases too. Thus, the growth of macrophytes at the expense of phytoplankton is mediated by the increasing light availability into deeper water layers, i.e., higher water transparency (Fig. 3B). A Secchi depth of 1.5m, which refers to minimum requirement of water clarity according to bathing aesthetics, coincides with the transition from a eutrophic state with mainly cyanobacterial blooms (Dokulil and Teubner 2000; Ibelings et al. 2021) to mesotrophic conditions of macrophyte dominated clear-water state. Further control mechanisms of water transparency alongside restoration are not explicitly shown here, but can be expected on the ecosystem level (see chapters 8-16 about biology, ecology and production for Alte Donau in Dokulil at al., 2018a). The control of algal growth is expected to become accomplished not only by shifting the nutrient allocation from algae towards macrophytes, but also e.g. by allopathic substances which are built by macrophytes supressing algal development. Further, macrophyte canopies can provide shelter for zooplankton and thus enhance the grazing effect. The latter both examples might illustrate that an increase of water clarity can also be accomplished on various levels within the ecosystem than just displayed in Fig. 3, but it would be challanging to detangle the different contributions to algal supression quantitatively.

Water transparency is understood as socio-ecological indicator for Alte Donau and thus points in two directions, namely to further ecosystem health (1) and ecosystem services (2) as summarized in Fig. 4. Concerning the ecological perspective, naturally high water clarity can be expected in pristine floodplain ecosystems of high habitat structure and high biodiversity. In turn, high biodiversity contributes to strengthening ecosystem functioning (Meyer et al., 2016), which can be most beneficial for urban floodplains that are threatened under various pressure (Funk et al. 2009; Sanon et al. 2012;

Haidvogl et al. 2013; Borgwardt et al. 2020; Preiner et al. 2020; Reitsema et al. 2020; Weigelhofer et al. 2020; Perosa et al. 2021). Concerning the sociological perspective, enhanced water transparency in Alte Donau attracted human perception to take advantage of ecosystem services enhancing quality-of-life in the city, which in turn increased public awareness of protecting nature in this urban blue-green spaces (see Hozang 2017, 2018; Teubner et al. 2020). Provisioning, regulating and cultural ecosystem services can be delivered as illustrated in Fig. 4 and benefit in many ways from a healthy state of the lake ecosystem indicated by high water clarity.

Fig. 4: Water transparency as socio-ecological indicator with implications for ecosystem health and ecosystem services. Urban waters with naturally high water clarity are close to the high habitat structure and biodiversity of pristine floodplain ecosystem (reference conditions), which in turn strengthens the ecosystem functioning. In addition, a high water clarity attracts human perception about a healthy environment to take advantage of ecosystem services enhancing quality-of-life in the city and in turn increases public awareness of protecting nature in urban blue-green spaces. Provisioning (e.g. harvesting fish), regulating (e.g. improving urban microclimate by evapotranspiration of floodplain ecosystems) and cultural (e.g. manifold recreational use of the oxbow lake) ecosystem services benefit from a healthy state of the ecosystem in many ways. Critical values of Secchi depth (> 1.5m and >3.5m) were derived from fig. 3. Photos from: www.lakeriver.at.

4. Conclusion

In conclusion, water transparency is identified as a key parameter which is important far beyond how we see it in limnology. It is the only parameter that the public can use by human perception for assessing the water quality or the progress of a lake restoration. In turn, a good status of water transparency close to ecosystem reference conditions attracts public awareness to take advantage of various ecosystem services enhancing well-being in urban life. In this view "green-blue" spaces are ranked higher for a better quality-of-life in cities than "green" spaces.

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43rd IAD Conference

Rivers and Floodplains in the Anthropocene – Upcoming Challenges in the Danube River Basin

June 9-11, 2021

- Proceedings -

edited by:

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Preface

Dear Readers,

These conference proceedings have resulted from the 43rd Conference of the International Association of Danube Research (IAD). This conference series has always been a meeting point for research teams from the Eastern and the Western Danube River Basin, facilitating knowledge exchange as well as joint projects and publications in the region. In 2021, the IAD celebrated a special event. For 65 years, it has continuously been present in limnological, river and floodplain research in the Danube River Basin. The Covid-19 pandemic forced the organization of an online event. Nevertheless, there was an awesome engagement of more than 100 participants with many fruitful discussions.

The 43rd IAD Conference was dedicated to the manifold challenges the Anthropocene poses to the rivers and floodplains in the Danube River Basin. The topics of the conference were as diverse and interdisciplinary as river science itself, ranging from hydrobiology to flood protection to policy related issues. The articles in this conference volume reflect this diversity of topics. In addition, they also represent the international character of the Danube River Basin being the most international river basin of the world. Researchers and practitioners from Germany, Austria, Hungary, Croatia, Serbia, Romania and Bulgaria are among the contributing authors.

Bringing together all these experiences from various scientific backgrounds and different countries highlights the relevance of the IAD for cooperation in the Danube River Basin and gives hope for jointly meeting the challenges of the Anthropocene.

The Editorial Team

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