Environmental Engineering and Management Journal October 2018, Vol.17, No. 10, 2497-2505
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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INTEGRATED APPROACH FOR INNOVATIVE MONITORING STRATEGIES OF RESERVOIRS AND LAKES

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Abstract

An innovative strategy significantly increasing data density by introducing a flexible, problem-orientated, and cost-effective water quality monitoring approach is presented. Most current monitoring strategies produce water quality data based on fixed stations conducted on fixed dates throughout a defined period of time and, thus, often give a biased and insufficient picture of the water quality. Establishing a refined picture of water quality while not increasing monitoring costs clearly needs a change in monitoring strategy. The complexity of social-economic needs, environmental aspects and evolving legislative guideline values makes the design of a suitable innovative strategy challenging. The combination of investigative and risk-based monitoring with real-time monitoring of proxies (e. g., electrical conductivity (EC)) is a vital asset within this here proposed innovative strategy. For the former, organic micropollutants (e. g., pesticides, pharmaceuticals) are suggested in this article to be a powerful tool for source apportionment as they allow to determine and quantify the cause and impact of water quality impairments. This strategy was tested in a field campaign in which an area of elevated EC was investigated at Lake Garda, Italy. A radio-controlled boat was used for EC mapping and sampling. As no chemical indicators for significant anthropogenic sources could be detected, the elevated EC could be assigned to natural sources.

Key words: water quality monitoring, innovative monitoring strategy, micropollutants, proxy mapping, indicator concept

Received: March, 2018; Revised final: June, 2018; Accepted: September, 2018; Published in final edited form: October 2018

1. Introduction

According to the Water Framework Directive (WFD) (EC Directive 60, 2000) all member states of the European Union (EU) have to ensure a good chemical and ecological status of all surface water bodies by the year of 2027. Furthermore, within the precautionary principle article 7 (3) of the WFD states that "Member States shall ensure the necessary protection for the bodies of water identified with the aim of avoiding deterioration in their quality in order to reduce the level of purification treatment required in the production of drinking water.". Besides the EU framework directive, the water safety plans derived by the World Health Organisation (WHO, 2005) give new directions towards water quality monitoring by compromising the management of drinking water "from catchment to consumer". As a novelty compared to previous and established monitoring strategies this includes a preventive risk elimination and recurrent quality control. State-of-the-art monitoring to date stands for a water quality assessment based on data derived from *fixed* station on *fixed* dates with regular *frequencies* for *fixed* parameters. On account of modern analytical techniques, however, the number of detected anthropogenic micropollutants in the water cycle steadily increases (Amare, 2017; Brumovský et al., 2017; Petrie et al., 2014; Reemtsma et al., 2016; Scheurer et al., 2017; Yang et al., 2018).This bears

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substantial drawbacks to the current monitoring strategies as no information on system's dynamics nor compound diversity is given and, hence, this insufficiently reflects the real status of the water quality on catchment scale. This strategy is highly susceptible to discontinuous and/or unpredictable hazardous events, such as direct discharge of sewage, combined sewer overflows or surface run-off from agricultural areas into drinking water resources or water bodies used for recreational purposes. Such events occur occasionally and are usually not reflected by *fixed* date measurements and the results of those investigations are often rather poor in terms of data density, predictive power, and, thus, for deriving effective countermeasures. This points out the great importance of an improved monitoring strategy leading to more reliable datasets and, hence, allowing the prediction of water quality on catchment scale as well as paving the way to water quality improvements (Voulvoulis et al., 2017). In the view of the current water quality monitoring strategy at many sites the demand for more reliable data would require a larger number of sampling points with significantly higher sampling frequencies in order to gain temporally and spatially better resolved data. This is remarkably time and cost intensive, not feasible and often leads to the so called "data-rich but information-poor" syndrome (Ward et al., 1986). Thus, an innovative monitoring strategy will be a shift from mainly static sampling to dynamic real-time monitoring, which leads to an *optimum* water quality monitoring frequency for individual water bodies and, hence, an increase in information density without increasing costs, especially caused by non-focused sampling. Nearly three decades ago, scientist and stakeholders already called for more reliable and meaningful data by a strategic change in water quality monitoring and a more holistic approach by including the catchment information into monitoring strategies (Ward, 1997; Ward et al., 1986). Especially with the implementation of the WFD and recent developments of new monitoring tools such as remote sensing, automated sampling devices and effect-based tools, new strategies for water quality monitoring are needed (Behmel et al., 2016). But most tools are either too general or too site-specific and there is unfortunately no "one-size-fits-all" solution serving every catchment (Behmel et al., 2016). Newly developed mathematical models are more generic and enable to predict meaningful sampling points within a catchment: Thus, the implementation of decision support systems (DSS) can help decision makers to establish a monitoring network with optimum information density (Alilou et al., 2018; Behmel et al., 2016). Additionally to surveillance (long-term changes) and operational monitoring (asses success measures), especially investigative water quality monitoring is needed, because accidental pollution or areas with unknown problems in water quality are often overseen and can significantly harm water safety (Milano et al., 2018; Premazzi et al., 2003; Radu et al., 2016).

This publication aims to present a highly promising and target-oriented approach into investigative water quality monitoring leading into long-term real-time water quality monitoring using proxies. The first application of the investigative aspect of this innovative strategy from an exemplarily short field campaign on Lake Garda in autumn 2017 using a platypus boat equipped with an electrical conductivity (EC) probe for real-time mapping and an automatic sampling device is presented.

2. Aspects of an innovative monitoring strategy

The variety of climatic, topographical, geomorphological, hydrological, physical and cultural factors influencing water quality (Hu, 1999) creates numerous factors influencing water quality and makes finding a suitable strategy for water quality monitoring on catchment scale highly complex. Improving data quality and density without increasing the monetary effort in these complex systems therefore needs a shift into innovative information driven monitoring strategies. Considering the whole catchment in water quality management concepts allows identifying substantial sources for water quality deterioration as well as detecting hot spots and areas of higher risks than others. At these locations, highly spatially and/or temporally resolved or even real-time data can significantly better describe a potential risk, while at points of low potential risk monitoring efforts and, thus, costs can be minimised. Another important key element is investigative monitoring and, thus, assigning the appropriate best fit and problem oriented long-term monitoring strategy based on the area's vulnerability. This can be best achieved by using source and process specific indicator compounds (e. g., organic micropollutants) to identify the cause of water quality deterioration, differentiate between multiple sources or even quantify their impact accordingly. The idea of considering the whole catchment in water quality management strategies was developed in the early 1990s but to the authors' knowledge there is only one successful case study in Australia published (Bennett and Lawrence, 2002; Mitchell and Hollick, 1993) and a further publication on the transfer of the Australian study to China (Hu, 1999). All these publications mainly focus on the sociological and organisational aspects between stakeholders and citizens but not on a strategic technical approach as this publication aims to deliver.

An innovative monitoring strategy must include the reliable identification of the water quality status and must allow the detection of pollution sources and their impact. It should further allow the monitoring of the effect of management measures taken in the catchment in order to improve water quality selectively (e. g., elimination of misconnections, improvement of combined sewer overflows (CSO)). At the same time, it needs to be capable to capture single pollution events such as accidents or spillages, the release of combined sewage overflows (CSO) or wash off during rain events.

Furthermore, it must allow the prioritization of catchment measures based on their efficiencies in improving water quality on catchment scale. Finally, it is important that the strategy is flexible and applicable to a large variety of different water bodies and catchments across Europe and the entire world. Recently, a shift from the static state-of-the-art water quality monitoring into a dynamic risk-based strategy found application in a draft for a novel drinking water act in Germany, based on changes in the annexes of the European drinking water guideline 98/83/EG (EU: 31998L0083), which emphasizes the need for novel strategies also for surface water bodies.

First step: *Composing existing data and defining problems and needs for water quality*

A crucial point in setting up an innovative monitoring strategy for a catchment is to re-analyse existing data and to re-evaluate the current monitoring program. This includes the evaluation of the number and locations of existing observation points and monitoring parameters, the frequency of data collection and the water quality development on the basis of historic datasets. This will give a first impression on water quality issues and allows to judge on the meaningfulness and significance of the existing strategy. Initially, a catchment assessment which includes morphological information (e. g., estimation of run-off flow direction), land uses to identify possible pollution sources and especially locations which are very vulnerable to hazardous events (e. g., areas used for drinking water production) needs to be carried out. Additional information can be gathered from historical data, local stakeholders (e. g., farmers), and from citizens. Within this context existing numerical models can be used and, if required, extended. If the existing data base is not sufficient in its resolution, more information needs to be gathered and individual initial monitoring campaigns with focus on investigative monitoring might be useful to close these gaps. A further crucial factor is that the requirements on the water quality together with standards are clearly defined. Initially, legislative guideline values (in agreement with WFD, national guidelines or bathing water guidelines) should be identified. Then, socio-economic needs, such as the apparent water quality (e. g., odour, colour or turbidity), the requirements for fishing, bathing and tourism must be considered. These water quality demands can be diverse and strongly dependent on the individual requirements of the end users.

Second step: *Investigative real-time water quality mapping, sampling and identification of an appropriate set of source and process specific indicators*

A key element of the presented strategy is the investigative real-time mapping of areas with either real or suspected water quality issues by using universal sensors prior to collecting samples for laboratory analysis. As EC is a general parameter which comprises the simultaneous detection of numerous ionic substances it can be used to identify water quality changes or issues easily. Using such a probe in tracking contamination from, e. g., wastewater is well established. Bonvin et al. 2011 demonstrated the linear correlation of elevated EC with elevated source specific micropollutants, especially benzotriazoles (corrosion inhibitors) and paracetamol (analgesic). They could assign this water quality impairment to the effluent of a wastewater treatment plant discharging 30 m below the water table of Lake Geneva. Besides natural sources (e. g., caused by geological processes) EC can also be correlated to nitrate contaminations (Hu et al., 2005), pesticides (Castilho et al., 2000) and even to mining activities (Olías et al., 2004). Covering the most common pollution sources known for aquatic systems EC is a powerful parameter to detect any hot spots within the system. In combination with temperature (T) it may even be a more powerful tool within investigative monitoring strategies for water quality impairment detection. Mapping can be conducted manually (if accessible) by simple field measurements with handheld probes or via automated robotic systems, such as boats or drones equipped with a sensor and a positioning system. Manual samples should only be taken wherever anomalies in form of a deviation from the mean background (baseline) value of the system are detected. At these locations water quality impairments are very likely.

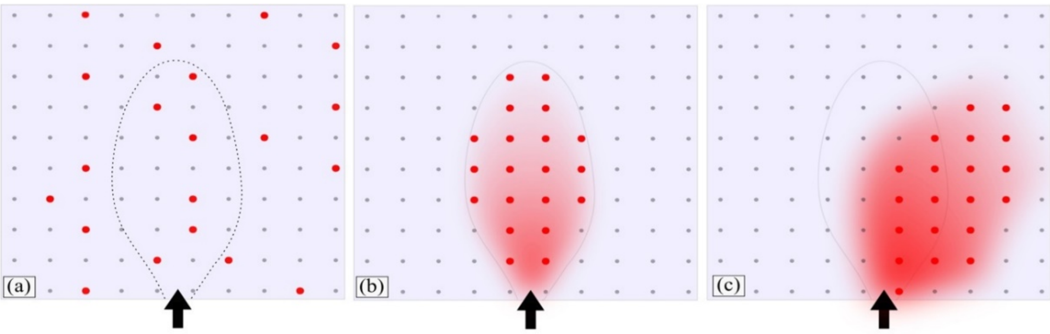

Fig. 1. All three figures show a potential plume (dotted line) originating from a hypothetic point source. The fixed number of twenty samples are marked as red dots. The proxy map (e. g., EC) is marked in red. By allocating all samples according to the mapped plume the information density increases remarkably and becomes independent from plume dynamics. In (a) all are samples distributed equally over the water body, in (b) they are distributed within the plume and (c) they are distributed accordingly to the drifted plume

As shown in Fig. 1, mapping can increase data density significantly: In Fig. 1a all hypothetic samples are distributed equally over the water body and randomly six out of twenty samples were collected within the actual plume (dotted line). After mapping (red coloured) all sampling points were located in the area of the plume and information density increases from 30 % to 100 % without increasing the total number of samples (Fig. 1b) and thus, cost. If the plume drifts (Fig. 1c), for example due to changing weather conditions, real-time mapping is able to visualise this change and sampling locations can be reallocated accordingly without any information loss and avoids non-focused sampling. Water bodies are highly dynamic systems. Contamination plumes, flow directions or the impact of water quality impairing sources are highly variable. Initial mapping reduces cost for sampling and laboratory analysis because only meaningful samples are taken. In order to assign the observed anomaly (e. g., increased EC) to the induced causes in an investigative monitoring strategy samples are then screened for a variety of chemical source and process indicators with a cost-effective multi-residue analytical method. Here, micropollutants such as life-style products, pharmaceuticals, personal care products or pesticides and their respective transformation products are well established (Barbosa et al., 2016; Glassmeyer and Meyer, 2005; Jekel et al., 2013; Lapworth et al., 2012; Lim et al., 2017). According to their negligible natural background and often unique transformation products, they are highly selective compared to classical inorganic tracers, which allows them to be very source specific (Khazaei and Milne-Home, 2017). Their wide range of physicochemical properties let them interact in numerous ways with the environment (e. g., during transport processes) and thus can help to estimate residence times or flow paths (Clara et al., 2004; Gasser et al., 2010; Warner et al., 2016).

Some prominent and established examples are briefly given in Table 1. For most catchments, a standard set of indicators is already established and can be easily adapted to specific catchment requirements (Jekel et al., 2015; Lim et al., 2017; Seitz and Winzenbacher, 2017; Zirlewagen et al., 2016). Chemical analysis for these indicators is often conducted using modern techniques such as liquid-chromatography coupled with tandem mass spectrometry (LC-MS/MS). A strategy for method development can, for example, be found in Nödler et al. 2010; Wode et al. 2015; Reemtsma et al. 2016; or Gago-Ferrero et al. 2015. Recent analytical developments allow simplified methods with small sample volumes, direct injections of water samples, and short analysis and processing times, which significantly decreases costs (Oliveira et al., 2015). The high sensitivity of modern analytical instruments also simplified the sampling procedure and logistics, as sample volumes <50 mL are rather the rule than the exception. Once contamination sources, their impact, location and point of discharge are identified by the aforementioned indicators, the overall number of analytes can be limited to a few meaningful and problem-orientated key indicators to even further reduce laboratory costs in future investigative monitoring strategies.

Table 1. Examples of typical indicators used in the last decades

Source	*Indicator*	*Reference*
Untreated effluent	Caffeine and its human metabolites	Seiler et al. (1999) Hillebrand et al. (2012)
	Cyclamate (artificial sweetener)	Zirlewagen et al. (2016)
Treated effluent	Valsartan Acid	Nödler et al. (2016)
Agriculture	Selected pesticides	(e.g., Nödler et al. 2013)
	Selected veterinary antibiotics (livestock)	e.g., Kay et al. (2005)
Tourism	Selected UV blocker	e.g., Gago-Ferrero et al. (2013)

Building a correlation function between a real-time parameter collected by a sensor such as temperature or EC and the source of deterioration, e.g., wastewater, using the chemical indicators will now allow the continuous and cost-efficient quantification of the individual amount of discharge and to reflect the dynamics of the impact. For mainly site-specific problems individual specific problem oriented tools, e.g., nitrate sensors or even biosensors (Proll et al., 2005) are possible options. Some established proxies are potassium as a proxy to quantify the impact of effluents from wastewater treatment plants (Nödler et al., 2011) and turbidity as a proxy for *E. coli* and for CSO overflow (Nnane et al., 2011; Viviano et al., 2017). Another well-established proxy for eutrophication is chlorophyll-α, which can be easily detected by remote sensing techniques (Barrett and Frazier, 2016; Duan et al., 2007).

Third step: *Real-time monitoring by using proxies*

Once the proxy-source-relationship is established and a suitable proxy sensor type or sensor array is selected, the amount and source(s) of the water quality impairment become quantifiable by the proxy(ies) in real-time. The proxies can serve in long-term, cost-efficient monitoring programs generating real-time monitoring data and contribute to the understanding of water quality on catchment scale. Thus, they are important within a risk-based monitoring strategy. Within this context threshold values need to be defined for indicating a potential risk for water quality deterioration. These should not be mistaken with legislative guideline values. When just a single source for water quality impairment was detected during the investigative strategy it may be sufficient to solely monitor one proxy parameter and directly associate it to that specific source. If there are multiple sources such as leakage from waste-water pipes and run-off from agriculture causing water quality deterioration in the same catchment, more proxies are needed. Possible powerful ways are building ratios of proxies to differentiate between sources, e.g., temperature and EC or using combination of them as sampling or monitoring criterion. If only one proxy is available because of limited probe availability, this general proxy is still useful in investigative and long-term monitoring to give a warning signal and for triggering meaningful manual sampling. These samples must later be screened for the specific key indicators as defined in step two. After screening, all sources and their impact can be differentiated with greater confidence and the appropriate and most efficient catchment management measures even preventative ones can be implemented. A crucial point is to regularly verify the proxy-source-relationship as catchments are dynamic systems in space and time. When demands, water/land uses within the catchment or sources and their impact change new proxies or indicators might need to be included or need to be changed to reflect the sources and their impact and, thus, to ensure a safe monitoring strategy.

By using this innovative monitoring concept samples are limited to source identification and apportionment or within the validation of the proxy-water-quality-impairment relationship. This significantly saves resources and costs. A graphical summary can be found in form of a flowchart in Fig. 2. In order to demonstrate the applicability of the investigative aspect of the presented monitoring strategy under field conditions data from a test site at Lake Garda, Italy, is presented in the following.

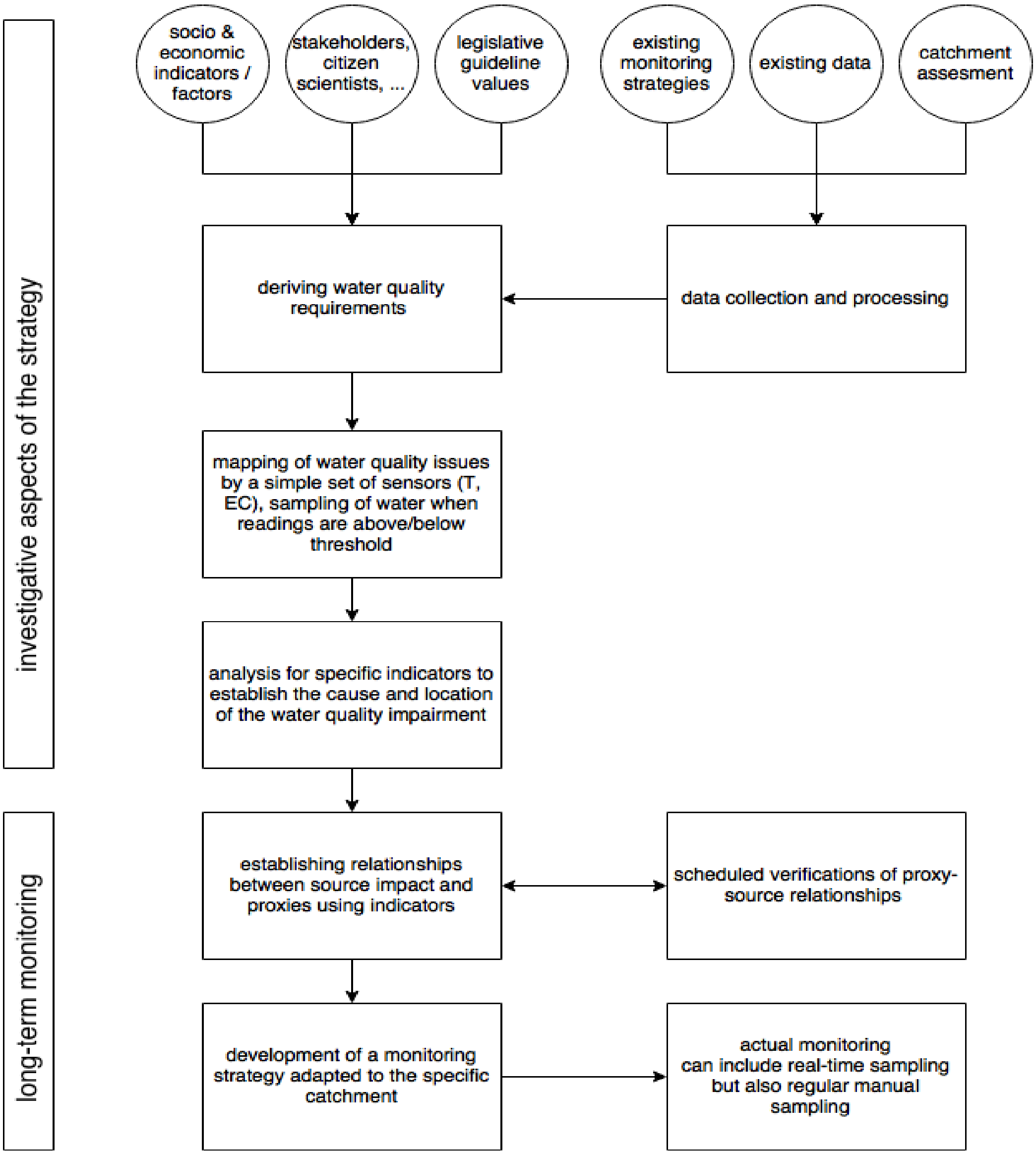

Fig. 2. Graphical overview over the different steps of the described innovative monitoring strategy

3. Application of the investigative monitoring aspects within the innovative monitoring strategy

3.1 Field site

With a total surface area of 368 km^2 and a catchment area of 2,350 km^2 Lake Garda is the largest lake in Italy. The main tributary of Lake Garda is the River Sarca (North) but it is also served by smaller streams. The northern part of the lake catchment is dominated by woodlands, mountains and agriculture, while the southern part functions as popular touristic area with amusement parks, campsites, hotels and marinas. As Lake Garda is dominated by tourisms it has a summer population estimated to be more than 400,000 and in contrast less than 80,000 people during winter months. A circular pipeline collects wastewater from all municipalities around the lake and serves a centralised WWTP (330,000 PE) in Peschiera del Garda, which discharges into the River Mincio.

Routine water quality monitoring at Lake Garda is accordingly to the WFD and comprises four samples per year to define the ecological status and twelve samples to evaluate the chemical status of the water body. For bathing water quality 65 sampling points on the Eastern shore are tested monthly from May to September for the detection of two microbiological parameters (*E. coli* and intestinal Enterococci). Further, the lake water serves as raw water resource for 6 % of the population. Therefore, four locations around the lake are tested according to national guideline values. Key challenges for the catchment of Lake Garda include ensuring a good bathing water quality and evaluating the impact of combined sewage overflows (CSO).

During a short field campaign in autumn 2016 at Lake Garda near the village Ronchi (20 km West of Verona, Italy) significantly elevated EC values of up to 1,348 µS/cm were observed in a small tributary of Lake Garda. This elevated EC (five times higher than the background value of lake Garda, 250 µS/cm) can be caused by either natural or anthropogenic sources. Possible causes for elevated EC include misconnections in the sewage system of the amusement park nearby or the stream might be connected to saline hot springs in Colà, a small town a few kilometers upstream. Additionally, nearby sampling points for bathing water quality occasionally show impairments in the microbiological parameter. As this area is used for recreational activities and is a natural reserve for birds a contamination by wastewater would be a significant impairment despite the low flow rate of the tributary.

3.2. Materials and methods

Initial EC-mapping was conducted by a robotic in-water propeller boat produced by Platypus engineered for the INTCATCH project (EU, Horizon 2020). This boat is equipped with an automated sampling system for four water samples and an EC/T-probe. Automated sampling was triggered by an exceeded EC value three times higher (800 µS/cm) than the background EC value of Lake Garda (250 µS/cm). Samples were carefully transferred into glass storage vials for transport and stored under cool and dark conditions until analysis via LC-MS/MS (Sciex Qtrap 6500+ equipped with a Shimadzu Nexera X2 liquid chromatography system) by direct injection. In total 76 organic contaminants as indicators were analysed.

Additionally to analytes in Nödler et al., 2010 samples were screened for 4-nitro-sulfamethoxazole, acesulfame, atenolol acid, bentazone, benzenesulfonic acid, benzimidazole, benzocaine, fluorescent brightener 28, chloridazon, desphenyl-chloridazon, desphenyl-methyl-chloridazon, ethyl sulfate, famotidine, furosemide, gabapentin, haloperidol, irbesartan, losartan, melamine, metaldehyd, primidone, propranolol, ritalinic acid, sulfamic acid, valsartan and valsartan acid. Method quantitation limits varied between 0.3 ng L^{-1} (isoproturon) and 34.5 ng L^{-1} (fluorescent brightener 28).

3.3. Results

An additional field campaign in October 2017 with the aim of testing the proposed monitoring strategy was conducted. On both days, a distinct plume of elevated EC around the area where the tributary meets the lake was observed. As can be seen in Fig. 3 the location and extend of the plume significantly changed between both days. This clearly points out how dynamic surface water bodies may be and, hence, the importance of real-time-mapping supported sampling.

No micropollutants which would indicate a possible anthropogenic influence of, e.g., domestic wastewater was detected. Besides, constantly increasing EC values of up to 1,410 µS/cm and temperatures of up to 25.9°C near Colà (hot springs) were observed by manual measurements upstream using a handheld probe. Beyond the area of hot springs, decreasing EC values and lower temperatures were observed. As a result, it can be concluded that the elevated EC values are predominately caused by a natural source most likely from hot springs upstream. Based on this, no immediate catchment measures need to be taken, because the risk that pathogens are connected to natural hot springs is assumed to be low. Further investigative monitoring can rule out anthropogenic influences completely. Moreover, in this area of Lake Garda EC can serve as a proxy for compounds introduced by tributaries. This information can be implemented within emergency plans: In case of substantial contamination within a tributary (e.g., accidents, spillages etc.) the application of the here proposed monitoring strategy will allow for straightforward and focused determination of the distribution of associated pollutants.

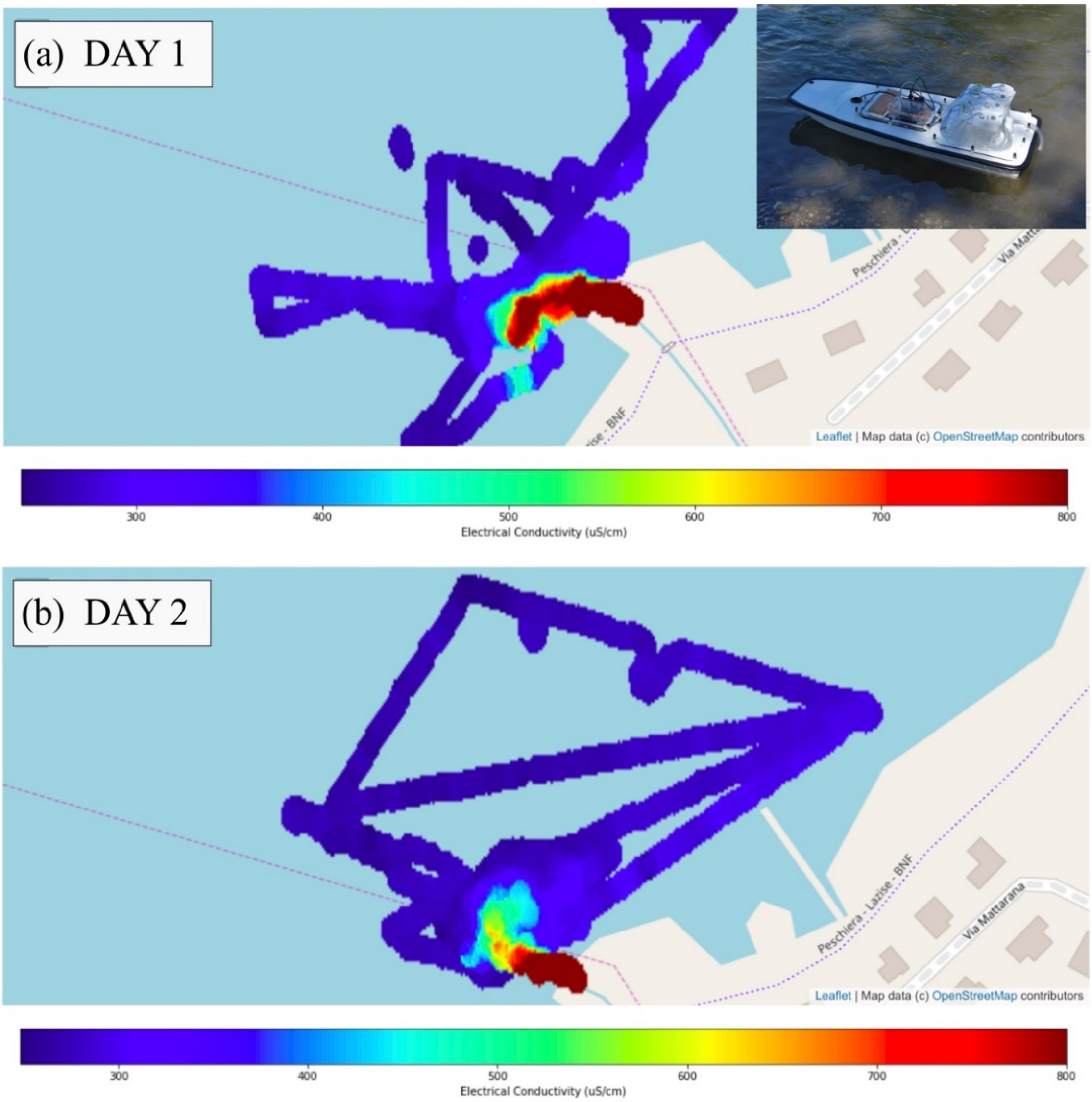

Fig. 3. Picture of a proxy mapping campaign by using an automated boat during a mapping and sampling campaign in October 2017 in Italy / Lake Garda near Ronchi. As can be seen in: (a) on the first day the plume drifts southwards, while (b) one day later the plume changed directions

4. Conclusions

The field campaign at Lake Garda clearly demonstrated the superiority of the suggested water monitoring strategy over state-of-the-art approaches. Mapping by using general parameters, such as EC and T, before actual sampling increases information density significantly and greatly reduces costs. Especially for highly dynamic systems, such as plumes, this approach is highly effective. Source and process specific chemical indicators allow to differentiate between different sources, such as anthropogenic and natural sources and enable to derive most efficient catchment management measures.

A promising micropollutant-based indicator set for the described test site is caffeine to detect untreated wastewater, valsartan acid for treated wastewater, a dermal UV blocker for tourism and a corrosion inhibitor, e.g. tolyltriazol, for industry or facilities from the amusement park nearby. As a proxy for long-term monitoring at Lake Garda we suggest EC to cover all possible sources of water quality impairments even though this is supportive rather than directive.

Finding a suitable relationship between a proxy and the source makes even real-time monitoring affordable and informative, which can significantly reduce potential risks in highly vulnerable areas. This demonstrated the effectiveness of the investigative aspects of the here suggested innovative monitoring strategy. Even with a small budget and little time it was possible to differentiate between the two potential sources with completely different risk potentials. How transferable this monitoring strategy is to river systems may depend on flow velocity, river size and morphology.

Acknowledgments
This study was funded by the European Commission

(contract number 689341), INTCATCH, “Development and application of Novel, Integrated Tools for monitoring and managing Catchments”. The catchment information for Lake Garda has been kindly provided by Instituto Di Santia (ISS) and Azienda Gardesana Servizi Spa (AGS).

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