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Inspiring Aquatic Monitoring

A review of innovative approaches to monitoring the aquatic environment

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Research summary

Key Findings

- Regulatory objectives are driving innovation within aquatic monitoring, resulting in diverse methodologies delivering to national and regional strategies.
- The specific monitoring objective – such as informing short-term interventions, or determining cause of failure – often determines the method employed.
- Broad areas of innovation are identified. Notably increased use of satellite and radar data with methodologies capable of increasing spatial and temporal data density, such as that seen in Estonia and Norway.
- The use of tiered assessment methods and involvement of citizens in gathering low cost data is becoming commonplace, as are eDNA methods.
- More attention is being paid to risk assessment of emerging contaminants (or substances of high concern) through effect based monitoring and innovative screening methods such as the non-target analytical method used in Norway.
- These approaches should be considered in the specific context of the Scottish and UK requirement.
- Alongside 'added value' of the new methods, added value of current methods must also be considered.
- Interdisciplinary, interdepartmental collaboration and co-construction of monitoring programmes is evident from data, literature and conversations with actors.
- Changing data collection methods for data used in trend monitoring may impact data continuity.

Background

Regulatory and management decisions made by the Scottish Environment Protection Agency (SEPA) are based on evidence from a variety of sources, including environmental monitoring data. SEPA's aquatic monitoring has evolved in response to changes in the environment, policy priorities and financial constraints. Previous strategic reviews have considered aquatic monitoring; however existing networks had a strong influence on the outputs of these. With the start of monitoring for the second cycle of the River Basin Management Plan in 2016, there is an opportunity thoroughly reflect on why and how SEPA monitors. To inform this, CREW commissioned an international review of monitoring networks, to identify and summarise innovative and radical approaches. The focus was on nation-wide monitoring networks, ideally those with similar objectives to the WFD monitoring carried out in Scotland, the UK and across Europe.

The need for innovation appears greatest for investigative monitoring because traditional monitoring methods cannot always reveal why water bodies fail to reach quality standards.

Research undertaken

In parallel to a literature review, we sought information from networks of contacts across the EU, supplemented by interviews with those leading monitoring strategy development and implementation. The approach was that of an invitation for interviewees to share experiences. It is recognised that the number of interviews is limited meaning that the list of monitoring activities identified is not exhaustive. The qualification of 'innovative' was largely left with the respondents. Certain areas, such as biological scoring systems, were mentioned by a few respondents but have not been covered in detail; this may be a topic area for further investigation. The focus of the project is on surface waters and to a lesser extent coastal and transitional waters; only one response about groundwater was received.

The information gathered from the interviews informed the design of a workshop, held at Glasgow Caledonian University's offices in London. Here, representatives from eight countries including the USA came together to discuss innovative monitoring and exchange expertise. The outputs from the research activities (literature review, interviews and workshop) informed the detailed project report.

The future of monitoring

Interviewees and workshop attendees were asked their vision for the future of aquatic monitoring:

- More attention for mixture toxicities, effect-based sampling tools and ecosystem functioning.
- Incorporating biomarker technology in biological quality elements.
- Integrated monitoring of chemical, biological and hydro-morphological data to enable measures towards improved ecological quality.
- Further application of remote sensing technologies, including (aerial) drone technologies and higher resolution satellite data.
- Use of combined datasets from image data, automated measurements and classic sampling; combining radar systems with ground based data.
- A network of fixed automated analysers, satellite and drone systems, delivering data (almost) in real time.
- Data mining of existing datasets, advances in mapping, increased data sharing, including cross-disciplinary.
- Accurate and cost-efficient monitoring using eDNA techniques; further research to deal with issues of transport, quantification and intellectual property issues associated with the method.
- Increased engagement of citizens in water policy.

Contents

1.0 Introduction

1.1 Purpose

SEPA's investment and development decisions affected are based on evidence from a variety of sources; a key source is from monitoring the aquatic environment. SEPA's monitoring has evolved in response to changes in the environment and policy priorities, as well as revisions due to financial constraints. There have been previous reviews of aquatic monitoring (major changes were made in 2006 and 2010), however the legacy networks had a strong influence on the outputs of these. Although thoroughly considered, changes to monitoring have been made at a tactical level. With the start of the second cycle of the River Basin Management Plan in 2015, there is an opportunity to take a more strategic approach, and thoroughly consider how SEPA monitors. This report was commissioned by CREW to inform SEPA's thinking around the potential revisions to their monitoring strategy.

1.2 Background

Monitoring has multiple purposes under the WFD. It provides evidence for the status assessment for water and allows for the assessment of long term natural changes in the status of our waters. It informs appropriate management actions and can reduce unnecessary spend on ineffective measures. The method of monitoring is of strategic importance as it impacts on spatial and temporal data density, on data quality, on the speed with which data are available (and can then be used for decision making and intervention); and on the efficiency and capacity of the monitoring network, but also on the development of understanding of a causal relationship between pressures and ecosystem functioning, which is critical to developing an effective water management.

In this review, innovative approaches in monitoring and modelling were considered. The project had a duration of three months and did not aim to be exhaustive; instead, the report will inform the SEPA strategic review of aquatic monitoring by give examples of how, where and why innovative methods are being successfully and strategically implemented.

1.3 Approach

The project consisted of an exploratory phase and an evaluation phase. In the exploratory phase, three research activities were applied simultaneously.

I. Call for expertise in innovative approaches and methods in water monitoring

A number of known expert networks were approached with a request for experience or expertise of innovative approaches. In total, 190 recipients in 22 countries were contacted by email, resulting in around 40 responses. In addition, a similar request for information was placed on a number of water-related 'LinkedIn' forums, resulting in a further 19 responses.

II. Literature review

SEPA expressed particular interest in remote sensing technologies, citizen science, modelling, use of 'Big Data' and environmental DNA (eDNA). A literature search was carried out for the use of these methods in a water monitoring context via the Thomson Reuters Web of Science (www.webofknowledge.com) using Boolean search terms. A substantial amount of documentary information was also received in response to the call for expertise.

III. Collection and analysis of 'grey' literature, using EU information systems as a starting point.

Annex 2 of the 2nd WFD implementation report reviews the monitoring strategies as submitted by EU countries. The Annex does not go into enough detail to gauge the extent to which innovative approaches are used, but hints at design principles of monitoring strategies and also contains a number of useful references.

In the evaluation phase, positive responses from the 'Call for expertise' were followed up by telephone interviews (16 in total). A workshop was held in London, which brought together water monitoring professionals from 8 countries to exchange experiences and innovative/novel approaches to monitoring and modelling.

1.4 Report structure

Our data shows that decisions on monitoring objectives, network design principles, spatial and temporal sampling regimes, as well as what to monitor, informed or were integral to the choice of monitoring method or technology. The results of the data collection exercise are collated under the following headings, each starting with a brief general introduction before reviewing specific implementations.

WHY, WHEN and WHERE: Objectives, network design and sampling regimes

WHAT: Emerging pollutants

HOW: Citizen Science, Remote Sensing, eDNA, Automated Macro-Invertebrate Identification, 'Big Data', Effect-based monitoring and determining impact, and Modelling.

In the main report, only a brief outline of our findings is included; further detail on methods, approaches and applications, including further examples, is provided in a set of Appendices (2-16) referenced in the section headings. A table with an overview of summary information is provided in a Matrix in Appendix 1.

2.0 WHY, WHERE, WHO, WHEN: Principles and objectives of monitoring, site selection, organisational innovation and sampling regimes

2.1 Objectives of monitoring

During the interviews, it became clear that there is some divergence between member states both with regards to the objectives of monitoring and the interpretation of in particular operational and investigative monitoring, which has implications for both the network and the methods selected for monitoring. Key objectives encountered are summarised in Table 1.

2.2 Network design and site (de)selection (Annex 2)

To illustrate how new monitoring networks were developed or adapted to better deliver the WFD requirements, this report highlight approaches implemented or proposed in selected countries.

Denmark: the NOVANA programme

Denmark's WFD monitoring network comprises of an intensive and an extensive programme. The network is representative of geological and geographical variation and stream types are defined in part by the type and intensity of anthropogenic impact. The programme is fully described by Friberg *et al.* (2005).

The Netherlands: a clustering approach

The Dutch approach is described by Van Splunder *et al.* (2006, in Dutch). Sites for the surveillance network were chosen at representative locations in state-owned waters, at or near regional catchments into larger water bodies, and at border locations. Surveillance monitoring is infrequent and in-depth. A clustering approach is used in operational monitoring. Investigative monitoring is carried when breaches in regulatory parameters action limits are noted and/or a water body is 'at risk' but the cause is not known, requiring case-by-case action.

Norway: streamlining the network

The Norwegian spatial monitoring network was recently streamlined to free up resources for other aspects of monitoring, such as the inclusion of new compounds. A recent review considered quality trends up to 2012; sites with stable or upward trends were deprioritised. Acidification of rivers was deprioritised as an issue as there has been a general improvement, although some monitoring in this area remains.

Finland: towards an adaptive network

Dr. Kristian Meissner, Research Programme Manager at the Finnish Environment Institute (SYKE) explained that Finland is interested in moving from the current fixed nationwide WFD monitoring programme to a more adaptive monitoring approach, whereby a flexible part of the programme would respond to data generated by low resolution methods.

Scotland's coastal waters: a nested approach

A respondent at Marine Scotland proposed a 'nested approach',

Table 1	
Defining and prioritising environmental policy issues	Monitoring and modelling, particularly around longer term trending projects is strategically important for informing policy. Monitoring can deliver the evidence needed to build a case for environmental protection.
Determination of reference conditions	Where reference conditions no longer exist, specific monitoring approaches can be used to obtain historic information.
Establishing the effectiveness of medium to long term interventions	Medium term monitoring programmes are specifically designed to evaluate (elements in) a Programme of Measures designed to improve water quality or prevent deterioration.
Identification of cause of failure	Where objectives for ecological status are not reached, an investigative programme of sampling is undertaken to establish why the failure occurred, requiring a specific approach.
Informing short-term management interventions	In many cases, information is sought to inform short-term water management: 'early warning systems' may be in place to allow fast intervention when blue algae threaten the quality of lakes used for swimming, hosepipe bans can be enforced, monitoring for mud-dwelling fish species informs dredging practices, and planning decisions are influenced by Environmental Impact Assessments.
Investigation of pollution accidents and incidents	Reliable investigative monitoring is important in national and trans-boundary water management incidents, events and enforcement, where there may be disputes. Investigative monitoring includes both source tracking and impact assessment.
Long term trend assessments	Required in relation to 'natural' changes and anthropogenic influence. Existing time series restrict network changes and method changes.
Status assessments	Specific sampling programmes deliver data for status assessments to fulfil to the minimum sampling frequencies as specified by the WFD.
Science-driven	Specific pollutant groups are monitored as 'compounds of emerging concerns', not directly as a result of an identified risk of failure but rather driven by emerging scientific evidence.
Source tracking	Known problematic compounds or microbiological organisms are traced back to their point of emission/release.

whereby monitoring data is gathered to fulfil a range of commitments (WFD, Marine Strategy Framework Directive, Habitats Directive, Birds Directive, Joint Nature Conservation Committee (JNCC)) on various scales of monitoring, by determining the spatial validity of data and grouping data from small scales into larger scales.

Spatial statistics

A spatial statistics approach was adopted by Jackson *et al.* (2014) in a project with Marine Scotland to develop a Scotland River Temperature Monitoring Network. Temperature logger locations were chosen to be representative in terms of landscape characteristics of influence on water temperature, rather than just being spatially representative. The resulting dataset is to form the basis of a model, enabling accurate prediction of water temperatures anywhere in Scotland.

2.3 Towards interdepartmental integration (Annex 3)

In both Germany and Finland, departmental integration is in progress, whereby formerly independent organisations under ministries of e.g. Agriculture, Water, Forestry or Environment are merged or enter into collaborative arrangements, leading to strategic innovation in monitoring.

2.4 Sampling regimes (Annex 4)

This section discusses sampling regimes that provide an alternative to traditional spot sampling. Spot sampling is usually carried out with low temporal density and can miss event based pollutants, misrepresent dynamic pollution loads and be unsuitable for the detection of trace pollutants. Especially in operational and investigative monitoring, novel sampling regimes are tailored to flow and pollution dynamics.

Event-triggered sampling

In the German Erftverband, an autosampler is activated by rising water levels to monitor the effectiveness of a soil filter used to mitigate impact from a Combined Sewer Overflow (CSO). Stadler et al (2010) used a spectral absorption coefficient at a specific wavelength as a real-time warning proxy for (in this case diffuse) faecal pollution, whereas Jaskulke and Himmel (2005) describe a system triggered by salinity, which increase after salt-bearing influxes of deep water from the North Sea into the Baltic Sea and affect the balance of the brackish ecosystem.

Continuous sensors

In water board Brabantse Delta in the Netherlands, strategically located (typically in sensitive waters) continuous sensors (conductivity, pH, Oxygen, temperature and blue algae) on a measuring buoy are used for surveillance both monitoring and to inform management interventions. Another respondent indicated the intention to start continuous monitoring of nitrate with UV sensors.

Automated analysers

Dermot Diamond at the Irish National Centre for Sensor Research leads the development of microfluidic autonomous analysers, which can rapidly analyse samples for phosphates, nitrates, nitrites and ammonia and other parameters measured by colorimetry measurements, minimising amounts of reagents, waste storage and power required.

Passive diffuse sampler

The German water service provider Erftverband uses a specially designed unit consisting of a rectangular box embedded into the soil along the river course. The system catches surface and subsurface run-off water with the side facing away from the water course containing perforations on its entire surface (hole size 3mm). Sensors in the collection pan allow tracking of the filling process; data is transmitted daily via SMS to staff, who periodically collect the sample.

3 WHAT: Emerging pollutants (Annex 5)

In addition to the requirement to monitor the centrally defined Priority and Priority Hazardous Substances, Member States are required to identify Specific Pollutants, defined as substances that can have a harmful effect on biological quality and are identified as being discharged to water in significant quantities. Monitoring programmes are in place or encouraged for GMO material (Germany), microplastics (Scotland), pharmaceuticals (Rhine basin), and diffuse agricultural micropollutants (Switzerland). A large innovative screening programme for micropollutants is implemented in France, whilst in Norway a 'Non-target analytical method' is used to identify compounds of interest.

4 HOW: Innovative monitoring methods (Annex 6)

This section covers innovative ways to generate, analyse and interpret data on the aquatic environment. The methods are loosely grouped into (in no particular order) citizen science, remote sensing, data management and 'Big Data', environmental DNA, automatic macro-invertebrate ID, the benthotorch, passive samplers, using dogs for aquatic monitoring, effect based monitoring, and modelling.

4.1 Citizen Science

The term 'Citizen Science' covers a broad range of initiatives where non-specialists are involved in scientific research. Public participation is a key principle of the Water Framework Directive; involving citizens in scientific aspects such as monitoring can have the potential to engage and inform and thereby engender stewardship, increase compliance with and acceptance of specific requirements

The following examples in the water context were encountered

Lil' Miss Atrazine

A research project at the University of Nebraska, in which citizens deploy commercially available detection strips (costing10 US dollars each) to screen for atrazine, the most commonly used herbicide in the area, in a nearly 1400 mile long stretch of land in the Mississippi basin.

Kentucky Watershed Watch

In operation since 1998, its vision is to empower citizens to monitor streams using proven technologies. The programme has a collaborative relationship with the Kentucky state EPA, which uses the volunteer data for screening but generate their own data for regulatory purposes. Volunteers are encouraged to engage with local government and water managers.

Mobile phone apps and web based information systems for crowd sourced data

Volunteer citizen monitoring data, collected and/or transferred via mobile phones or the internet, can extend observation networks spatially and temporally. Examples are crowd sourced algal bloom monitoring in Finland (Kotovirta *et al.* 2014), and a 'crowd hydrology' project described by Fienen (2012).

4.2 Remote sensing

The term 'remote sensing' is used with different meanings; below we focus on systems where the sensor is distant from the water body.

Radar gauges to measure the water level and the state of the sea

Water-level and sea-state parameters, measured via a low-cost and low-maintenance radar sensor, are computed in real time and transmitted to the coastal communication network which distributes the data instantaneously (Wilhelmi and Barjenbruch, 2009).

HydroNET / rain radar

The Dutch water boards purchase rainfall data and rain forecasting data (two datasets, one for 48 hour forecasts and one for 10 day forecasts) from HydroNET (http://www.hydronet.com/).

Use of Satellite data in a three-tiered remote sensing approach

The Estonian environment ministry uses free low resolution satellite data as a first screening tool in a three-tiered approach to monitoring for a range of water quality issues. Problems spotted are investigated by a specially equipped plane, which has higher spatial and spectral resolution than the satellite, and if necessary subsequently by boat.

'Ships of Opportunity': Ferrybox and Alg@line.

These two initiatives both use ferries on existing routes, fitted with various sensors and automated samplers. NIVA, the Norwegian Environmental Protection Agency, processes and presents data from the ships together with data from the environmental satellite ENVISAT.

4.3 Data Management and 'Big Data'

Increased availability of data can lead to more effective management and cost savings .

'Control Room technology'

Brabantse delta use 'control room' technology for quantitative and qualitative water management, where various datasets can be viewed simultaneously. The system enables easier interpretation and analysis of the combined data.

Data and meta data portal development

The EMECO data tool (http://www.emecodata.net/) is currently being developed by a consortium involving Marine Scotland and other agencies with responsibilities for marine monitoring to improve data and metadata sharing.

4.4 Environmental DNA

This strategy is based on the premise that organisms shed tissues, organs, faeces, epithelia etc. into the environment and the DNA therein persists for a time and can be isolated from water or sediment. The approach was introduced to monitor diving whales (Amos *et al.*, 1992) and later bullfrogs (Ficetola *et al.*, 2008) and has subsequently been widely extended in the aquatic environment. Several Dutch water boards use the method. eDNA methods can be significantly cheaper, faster, more reliable and less invasive than traditional methods, but quantifying abundancies and the issue of transport of DNA are still somewhat problematic.

4.5 Automatic Invertebrate ID

Dr. Kristian Meissner from the Finnish Environment Institute has been involved in the development of a method using automated optical recognition. Macro-invertebrates can be identified, at least to taxa but often to species level, with accuracies around 80-90%. Difficulties in securing funding are hampering further development, as the method is not likely to be commercially viable. It may however be suitable to application in conjunction with eDNA methods and can contribute morphological and biomass data.

4.6 Benthotorch

The Benthotorch tool, also used in Finland, uses different spectra of light to analyse the composition of diatoms in the sample. Initial results suggest that in the WFD context the tool is highly applicable to identification of riverine diatoms, though less so in lakes.

4.7 Passive samplers

Traditional sampling methods rely on the collection of discreet volumes of water at set intervals, either manually or via automated samplers. For pollutants only present at trace level, large volumes of water are required in order to detect these compounds (Vrana *et al.*, 2005) and pollutant spikes can be missed. Passive sampling involves either the deployment in situ of devices or organisms, or the use of native organisms, to collect pollutants over time via the natural flow of pollutant through the device or organism.

Sclerochronologic Assessment

Sclerochronology of calcium-based biogenic growth increments, e.g. mussel shells, provides a timeline of pollutants and other parameters on a site-specific basis over the life of the organism. Marine Scotland routinely analyse fish ear bones with this technique.

Aquatic mosses as passive samplers

In this method, transplanted mosses are used as bio-accumulators. The method was used during a 2-year preliminary project in collaboration with Water Authorities in the North of Italy, where both permitted and illegal wastes caused sporadic, intermittent and chronic pollution events (Cesa, 2013).

Use of substrate strips to collect native biofilm

One respondent used substrate strips, suspended from buoys, in coastal and estuarine situations. The native biofilm which naturally forms on the strips acts as a passive sampler for trace chemicals.

Chemical Sorbent Passive Samplers

Vrana et al (2005) give a comprehensive overview of different types of passive samplers using a chemical sorbent, usually fixed on a disk or strips. The French micropollutant screening programme and the M3 project make use of chemical passive samplers.

4.8 Use of dogs in aquatic monitoring

'Working Dogs for Conservation' is a USA-based organisation using dog skills for a range of conservation purposes. Dogs were used in projects include using detection of micropollutants in river otter and mink scats, sewage detection and for combating aquatic invasive species. Dogs show a high level of accuracy to species, resulting in less erroneously analysed samples, which offsets higher survey costs.

4.9 Effect-based monitoring and determining impact

Triad approach

Respondent Thijs de Kort (Grontmij Consultancy, the Netherlands) uses the 'triad approach', more established in the fields of soils and sediments than in aquatic monitoring, where chemistry, ecotoxicity, and ecosystem functioning are considered together. Bioassays are used as a first step and a screening tool, so that those sites where a toxic situation exists can prioritised for management intervention.

Biomarker approach

Biomarkers are defined as measurements of body fluids, cells, or tissues, that indicate in biochemical or cellular terms, the presence of contaminants or the magnitude of the host response (Borja *et al.*, 2012). A battery of suitable biomarkers for exposures and effects is proposed by Cajaraville, *et al.* (2000), who suggests the biomarker approach could be incorporated into the definition of biological quality.

4.10 Modelling

Germany: the DWA model

Developed in 1998, the DWA model is now the standard tool for water quality modelling in Germany. Case studies include modelling of the influence of CSO, assessment of the influence on water quality of measures to minimise soil erosion, examination of ecological potential of a river section, impact of modified hydro-morphological conditions on oxygen balance and plankton growth.

Belgium: the WEISS model

In Flanders, the Vlaamse Milieumaatschappij (Flanders Environment Agency) uses the 'Water Emissions Inventory Support System` (WEISS), mapping significant sources and their contribution to water pollution. Emissions are calculated from a bottom-up approach from the detailed location of the source, followed by calculations of transport.

Participatory modelling and water resource management

In participatory modelling, stakeholders are involved in developing water quality and quantity models and water resource management decision support systems. Several examples were encountered during literature study, including Lupo Stanghellini (2008), Castelletti (2007) and Molina (2011).

5 The future of monitoring

This report represents current and emerging monitoring strategies. Many other innovative approaches are likely to be developed but not yet implemented. The respondents were asked about their vision for the future of aquatic monitoring. These were their answers:

- More attention for mixture toxicities, effect-based sampling tools and ecosystem functioning[1].
- Incorporating biomarker technology will be incorporated in biological quality elements.
- More integrated monitoring of chemical, biological and hydro-morphological data to enable measures towards improved ecological quality.
- Further application of remote sensing technologies, including (aerial) drone technologies and higher resolution satellite data.
- More use of the combined datasets from image data, automated measurements and classic sampling; combining radar systems with ground based data,
- A network of fixed automated analysers, satellite and drone systems, delivering data (almost) in real time.
- Data mining of existing datasets, advances in mapping, increased data sharing, including cross-disciplinary.
- Accurate and cost-efficient monitoring using eDNA techniques; further research to deal with issues of transport, quantification and intellectual property issues associated with the method.
- Increased engagement of citizens in water policy; engagement with schools

Barriers to the implementation of innovative methods included perceptions about quality (in particular for Citizen Science), limited - and reducing - monitoring budgets which can prohibit 'additional' monitoring, institutional resistance to changing roles (e.g. from generating data to analysing automatically generated data), cultural barriers between disciplines (e.g. biologists and GIS technicians), difficulty with out-of-hours and remote staffing requirements (in particular for biological monitoring), and difficult to generalise monitoring outputs due to the size of the catchment.

[1] Toxicity tests can be carried out for single substances or whole effluents. They test toxicity to a single test organism; separate tests are carried out for normally three trophic tiers. Ecosystem functioning can consider species diversity, pools of materials such as carbon and organic matter, fluxes of matter and energy between trophic levels, and process rates.

6 Discussion and recommendations

This presentation of innovative methods in aquatic monitoring hopes to inform and inspire the 2015 review of SEPA's monitoring strategy. Innovation is pervasive within aquatic monitoring internationally, resulting in a diverse array of monitoring solutions delivering to national and regional strategies.

Clear 'themes' of innovation emerged from our review. Increased use of satellite and radar data, various methods capable of increasing spatial and temporal data density, eDNA methods, effect based monitoring, new approaches to modelling, effective data management, the use of tiered assessment methods, and increased involvement of citizens in not just water policy but also water science, and more attention for 'unknowns' through effect based monitoring and innovative screening methods were mentioned repeatedly. Increased interdisciplinary and interdepartmental collaboration was

Workshop participants agreed that various methods of monitoring across different project in Europe had complex functions and utility, depending on the objectives. It is recommended that these approaches should be considered in the specific context of the Scottish requirement, and that, therefore, the merits and bottlenecks of the current monitoring system are duly considered.

Alongside 'added value' aspects of the new methods, added value of current methods must also be considered – we refer to the comment by an interviewee who stated that sampling officers are 'the eyes and ears of the water board'. Furthermore, there may be organisational implications of strategic changes, such as human resource requirements associated with particular methods.

The 'call for expertise' was successful and many actors in a range of water related positions generously contributed, sharing their knowledge and experience with us. It is hoped this project will have contributed to strengthened networks and ongoing knowledge transfer between monitoring professionals, and are exploring ways to further facilitate such networks. Due to time constraints, we have not been able to include all methods we were alerted to and for this we would like to apologise. Omission does in no way indicate that the method is not deemed relevant.

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Annex 1

Table 1 Overview of methods and approaches (for respondent codes, see overleaf)

	Parameters	Method	Environment	Screening	Routine	Project	Research
Biology	Divergence from reference	Diatom record in sediments	Lakes				FI1
Biology	Algae / chlorophyll	Aeroplane with RS cameras	Lakes & Coastal	EST1			
Biology	Algae / chlorophyll	Citizen Science (observations)	Lakes			FI1	
Biology	Algae / chlorophyll	Satellite data 300m-1km	Lakes, Coastal & Marine	FI1, EST1			
Biology	Diatoms, macroinvertebrates	Benthotorch	Rivers				FI1
Biology	Diatoms	eDNA	Rivers & Lakes				NL3
Biology	Macrofauna and fish	eDNA	Rivers, Wetlands, Lakes				NO1, NL3, US5, US7
Biology	Marine mammals	eDNA	Marine				UK1
Biology	Sea Birds	Remote Sensing (aircraft)	Marine				SC1
Biology	Invasive species	eDNA	Rivers & Lakes				US6
Biology	Fish	eDNA	Marine				DK1
Biology	Invasive species	Citizen Science (photographs)	Rivers & Lakes		NL1		
Biology	Invasive species	Using dogs	Rivers			US1	
Biology	Macrofauna and fish	QuickScan	Rivers & Lakes	NL4			
Biology	Macroinvertebrates	Automated macroinvertebrate ID	Rivers & Lakes				FI1
Biology	Macroinvertebrates	Electrofishing	Rivers & Lakes				FI1
Biology	Macroinvertebrates, E. coli	Citizen Science	Rivers		US3		
Biology	Red/Green/Brown algae	Satellite data 2m	Lakes & Coastal		EST1		FI1
Biology	Sewage detection	Working dogs	Rivers			US1	
Biology	Invasive species	Working dogs	Rivers			US1	
Biology	Sewage	Event triggered sampling	Rivers		GE1		CH1
Data	Data sharing portals	Inter-institutional data sharing					EMECO, CWMI
Data	Realtime data management	HydroNET modelling			NL1		
Data	Modelling	Bayesian approaches					FI1
Hydro	Flow	Citizen Science	Rivers		US3		
Hydro	Water level	Citizen Science	Rivers		US4		
Hydro	Water level	Mobile app	Rivers		NL1		
Hydro	Wave height	Radar	Marine				GE1
	Substrate	Citizen Science	Rivers		US3		
Integrated	Effects	TRIAD approach	Rivers	NL2		NL2	
Integrated	Effects	Genomic biomarkers	Coastal	SP1			SP1
Integrated	Biol. / chem. record in time	Sclerochronology	Coastal		SC1		
Integrated	Toxicity identification	TIE evaluation	Rivers			NL2	
Integrated	Effects	Genomics in sentinel fish spp.					SC1
Physico-Chem.	Wet chemistry, nutrients	Continuous sampler	Rivers		NL1,GE1		
Physico-Chem.	Wet chemistry, nutrients	Citizen Science (standard tests)	Rivers		US3		
Physico-Chem.	Nitrates	UV sensor	Rivers				
Physico-Chem.	Wet chemistry, nutrients	Automated Analysers	Rivers & Lakes			IR1	IR1
Physico-Chem.	Wet chem., nutrients, chlorophyll A	Ferrybox	Coastal & Marine		NO, SC, GE		
Physico-Chem.	Salinity	Event triggered sampling	Marine				GE2
PS/CEC	Pesticides	Peristaltic continuous sampler	Rivers				CH1
PS/CEC	Pesticides	Passive diffuse pollution sampler	Rivers		GE1		
PS/CEC	Atrazine	Citizen Science	Rivers			US2	
PS/CEC	Micropollutants	Mossbags	Rivers			IT1	
PS/CEC	Micropollutants	Non-Target Analytical Method	Coastal	NO1			
PS/CEC	Micropollutants	Working dogs	Rivers			US1	
PS/CEC	Micropollutants	Chemical Passive Samplers	Rivers, Coastal, Ground Water	FR1	SC1	LU1	FI1
Strategy	Network Design	Adaptive approach					FI1
Strategy	Network Design	Nested approach	Marine & Coastal				SC1
Strategy	Network Design	Risk based approach			NO1		
Strategy	Network Design	Spatial statistics	Rivers				SC1
Strategy	Various	Interdepartmental integration					FI1, GE, SC

Code	Respondent / Reference
CH1	EAWAG, Switzerland
EST1	Estonian Marine Institute
DK1	Thomsen, 2012a
FI1	Finnish Environment Institute (SYKE), Finland
FR1	INERIS, France
GE1	Erftverband, Germany
IR1	National Centre for Sensor Research,Ireland
IT1	Cesa, 2013
LU1	Henri Tudor, Luxembourg
NL1	Brabantse Delta,Netherlands
NL2	Grontmij, Netherlands
NL3	STOWA, Foundation for Applied Water Research, Netherlands
NL4	Waterschap Rivierenland, Netherlands
NO1	Norwegian Environment Agency
SC1	Marine Scotland
SC2	Scottish Environmental Protection Agency,Scotland
SP1	University of the Basque Country
UK1	Amos, 1992
US1	Working Dogs for Conservation, USA
US2	Nebraska Watershed Network, USA
US3	Kentucky Watershed Watch,USA
US4	Fienen, 2012
US5	Goldberg, 2011
US6	Jerde, 2011
US7	Ficetola, 2008

Annex 2

Network design

Denmark: The NOVANA programme (based on Friberg et al., 2005)

A new monitoring network was designed for the purpose of WFD monitoring. Site selection was constrained by the fact that the number of monitoring stations in each county was fixed, based on a combination of size and existing monitoring commitments. Geographical representation was sought because of geological and geographical differences across the counties within Denmark.

The monitoring network is divided into an intensive and an extensive programme. The intensive network stations provide in-depth knowledge of elements, including methodological issues, year-to-year variability etc. The extensive programme aims to provide knowledge on the overall status of Danish streams and rivers.

New sites were selected for the programme; 800 extensive (1 per 53km^2) and 50 intensive, which was determined by the economical scope of the programme. A subset is used to monitor year-to-year variations in macro-invertebrates. The distribution of sampling points across the country (i.e. the number in each county) was established from economic and geographical metrics.

Seven different stream types were defined, which should in principle be equally represented in the network, based on type of impact - agricultural (AG), Point Source (mainly sewage; PS) and habitat degradation (HAB), in subcategories of level of risk of being impacted, as well as reference sites. The selected impact types were the ones most likely to cause failure of quality objectives.

Each county submitted potential monitoring sites. Some were preselected, because of other monitoring commitments, the presence of continuous sampler or other factors. The remaining sampling points were selected using stratified sampling, taking into account, stream size, impact type and regional distribution. For the intensive network, all stations were selected from either the least intensive category of agricultural impact or as reference sites. Three of the intensive sites are along a restored river, allowing annual post-restoration monitoring of quality elements.

Suitability of application:	Strategic, surveillance, will inform operational and investigative
Specific application:	n/a
Stage of development:	Implemented
Broad category:	All
Parameters:	All
Barriers:	• None mentioned
Key advantages:	• Representative network

Netherlands: national guidance on a clustering approach (based on Van Splunder et al, 2006).

Surveillance monitoring is carried out once every 6 years and is interpreted as very detailed monitoring at a limited number of locations. Sites were chosen at representative locations in state-owned waters, at or near regional catchments into larger water bodies, and at border locations. 'Measuring Points' can refer to aggregated reports of several 'measuring locations'. Measuring locations are spread evenly over an area, in such a way that all water types that exist in that area are monitored in at least one location. Locations are chosen by the accountable local water authorities. Nearly all water bodies are at risk or potentially at risk. For operational monitoring, a clustering of water bodies, based on type, status, impacts etc., has been carried out to ensure monitoring is practicable. Within each cluster, one water body is measured; where possible surveillance locations and operational locations are the same.

Operational monitoring focuses on parameters that can be indicators of change in the 'poor' or 'bad' status. National guidance indicates which biological quality elements should be monitored, depending on water type and pressures. Only one biological element is required, but many water authorities choose to monitor two.

Investigative monitoring is carried out in case of calamities and when a water body is 'at risk' but the cause is not known. This requires case-by-case action and will be further developed following results of surveillance and operational monitoring. Already, some water boards are carrying out project based monitoring, such as the 'broad screening herbicides/pesticides'. General guidelines of how to investigate cause and effects are available, to facilitate a structured approached to investigative monitoring.

Suitability of application:	Strategic
Specific application:	n/a
Stage of development:	Implemented
Broad category:	All
Parameters:	All
Barriers:	• None mentioned
Key advantages:	• Representative network and efficiency gains

Norway: streamlining the monitoring network

The Norwegian (spatial) monitoring network was streamlined to free up resources for other aspects of monitoring, such as the inclusion of new compounds. A recent review considered quality trends up to 2012; sites with stable or upward trends were deprioritised. Acidification of rivers was deprioritised as an issue as there has been a general improvement, although some monitoring in this area remains.

Suitability of application:	Strategic, surveillance
Specific application:	n/a
Stage of development:	Implemented
Broad category:	All
Parameters:	All
Barriers:	• Trend disruption, reduction of spatial density
Key advantages:	• Cost reduction

Finland: an adaptive network

Dr. Kristian Meissner, Research Programme Manager at the Finnish Environment Institute (SYKE) explained that Finland is interested in moving from the current fixed nationwide WFD monitoring programme to a more adaptive monitoring approach. The envisaged monitoring programme would include a principle part, which would be defined and not open to amendment, and a second, flexible part. This flexible part would respond to data generated by low resolution methods such as satellite data, which are comparatively cheap and accessible, and allow for targeted surveillance of parameters that were at risk of breaching regulatory limits.

Suitability of application:	Strategic
Specific application:	n/a
Stage of development:	Not implemented yet but interest in adopting the approach
Broad category:	All
Parameters:	All
Barriers:	• Current overall organisation of WFD monitoring, e.g. involvement of multiple authorities
Key advantages:	• Efficiency and a more targeted programme

Scotland's coastal waters: a nested approach

A respondent at Marine Scotland proposed a 'nested approach'. Monitoring happens at a range of scales under various commitments, for example, WFD has a very small scale but for Marine Strategy Framework Directive (MFSD), the scale is much larger. In the proposed 'nested approach', the starting point is assigning a geographical area to a water body by determining the spatial validity of data. Data from coastal water bodies monitored under WFD can then be grouped into a larger water body. Additional monitoring outwith WFD can be combined to give an even larger water body, etc. The 'size of the nest' must be appropriate to the parameter measured, e.g. the scale appropriate for phytoplankton is not appropriate for other biology such as cetaceans. Apart from WFD and MSFD, this approach could be tied in with the Habitats Directive, the Birds Directive and the Joint Nature Conservation Committee (JNCC).

Suitability of application:	Strategic, surveillance
Specific application:	n/a
Stage of development:	Not widely implemented but a general move in this direction
Broad category:	All
Parameters:	n/a
Barriers:	• Requires agreement on precision and to what extent the methodology should be prescribed • Trend disruption possible • By reducing sampling frequency, uncertainties increase, which could result in changes in status assessments
Key advantages:	• Efficiency gains • Strengthened institutional links

Decentralised monitoring

The degree of decentralised decision making in aquatic monitoring appears to vary considerably between countries. In Germany and the Netherlands, respondents involved in decision making within the water service providers raised this issue. The local water service providers carry out a significant amount of monitoring, delivering information for operational, surveillance and investigative purposes. Local decision making results in a goal-driven approach tailored to maintaining or improving water quality in the specific catchment, but can be a barrier to innovations requiring larger investments. Within the Erft catchment, a 'typical' stream is monitored intensively; data drive understanding of pollution dynamics and are also used for the validation of models.

Suitability of application:	All
Specific application:	All
Stage of development:	Implemented
Broad category:	All
Parameters:	All
Barriers:	• Strategic innovation and large investments harder to achieve
Key advantages:	• Optimised monitoring for operational and investigative needs • Manageable scale • Local knowledge • In-depth study of 'typical' water bodies

Annex 3

Towards interdepartmental integration

At Federal level in Germany, water monitoring is undertaken by two administrative departments (Environment / Water and Agriculture). Traditionally, these departments have worked independently and separately, but currently the Federal Agencies are funding work on a more integrated monitoring approach, including making use of data gathered for Environmental Impact Assessments. Departmental integration of monitoring efforts is also in progress in Finland, where formerly independent organizations under the ministry of agriculture and forestry were recently merged into one institute (LUKE). In addition, there is a virtual alliance of environmental organizations (LYNET). This is leading to rethinking the entire national monitoring network, with for example a possibility that LYNET may be with monitoring coordination. In Scotland, the Coordinated Agenda for Marine, Environment and Rural Affairs Science (CAMERAS) aims to align and coordinate scientific activity of partner organisations to make best use of resources and support policy delivery (Scottish Government, 2015).

Suitability of application:	Strategic
Specific application:	n/a
Stage of development:	Working towards an integrated approach
Broad category:	n/a
Parameters:	n/a
Barriers:	• Sectoral budgeting • Competition between administrative department • Some institutional resistance
Key advantages:	• Efficiency • Larger pool of expertise • Larger datasets

Annex 4

Sampling regimes

This section discusses sampling regimes that provide an alternative to traditional spot sampling. Spot sampling is usually carried out with low temporal density and can miss event based pollutants, misrepresent dynamic pollution loads and be unsuitable for the detection of trace pollutants. Especially in operational and investigative monitoring, novel sampling regimes are tailored to flow and pollution dynamics.

Event-triggered sampling

Event triggered sampling can be used to investigate pollution dynamics, often following heavy rain. Typical applications are monitoring of agrochemical run-off and of CSO related parameters; the 'first flush' effect can give rise to a sharp rise in concentrations that would otherwise be hard to capture. Event triggered sampling can also save power, enabling the system to operate autonomously for longer. Parameter concentrations measured by continuous monitoring systems (using sensors) can also be used as a trigger.

The method used in the German Erftverband in the context of the M^3 project (Gallé *et al.*, no date); it is useful in operational and investigative sampling. An autosampler is activated by rising water levels in a CSO filter. Another application is described in Sinclair et al (2014), monitoring a uranium mine, who used a combination of continuous monitoring of electrical conductivity and an automated event-triggered samplers, which were activated when EC reached a certain limit. Stadler et al (2010) used a spectral absorption coefficient at a specific wavelength as a real-time warning proxy for (in this case diffuse) faecal pollution, whereas Jaskulke and Himmel (2005) describe system triggered by salinity, which increase after salt-bearing influxes of deep water from the North Sea into the Baltic Sea and affect the balance of the brackish ecosystem.

Suitability of application:	Surveillance, operational, investigative
Specific application:	Surveillance, operational
Stage of development:	Implemented
Broad category:	Chemical, biological
Parameters:	Various
Barriers:	• None mentioned
Key advantages:	• Can save power / battery life • Better insight in pollution dynamics • Can yield cost savings compared to continuous or routine sampling

Peristaltic continuous sampling

One Swiss canton used a 'liquid passive sampler'. This is a continuous sampler using capillary action to draw up water (Wittmer *et al.*, 2014).

Suitability of application:	Operational
Specific application:	Operational
Stage of development:	Implemented
Broad category:	Chemical
Parameters:	Micropollutants
Barriers:	• Relationship between flow and sampling rate unclear
Key advantages:	• No power required • Continuous sampling means short pollution spikes are still captured

Continuous sensors and samplers

Manual sample collection and laboratory analysis requires manpower and is costly, often leading to spatially and temporally sparse sampling regime, in which short-lived / event-based incidents are easily missed. Various continuous monitoring methods exist for a range of parameters. Some methods listed under 'Remote Sensing' also generate continuous or high resolution data.

Most sensors that are permanently in the water suffer from fouling and require regular cleaning, although some have automated cleaning mechanisms. Ion sensitive electrode sensors have been used for some time but there are issues with accuracy, precision, and drift; a number of more recently developed applications using colorimetric or spectrometry measurements for some parameters.

In water board Brabantse Delta in the Netherlands, strategically located (typically in sensitive waters) continuous sensors (Fig.1) are used for surveillance both monitoring and to inform management interventions, such as regulating flows. Conductivity, pH, Oxygen, temperature and blue algae are monitored continuously via a measurement buoy. Although expensive to buy and maintain, they can act as an early warning system, allowing management intervention and thus prevention of bathing water quality failures, use of water containing blue algae for irrigation, and fish death .

In the Erftverband in Germany, the monitoring programme includes use of a fixed continuous sampler measuring pH, nutrients, oxygen, temperature, conductivity, and routine spot sample checks. Heavy metals and micro-pollutants are monitored periodically via spot sampling. Some of the analyses are made in directly in the water, whilst for others water is pumped up and analysed on site. The water service provider distinguishes monitors, not only the water body itself, but also pathways such as CSOs and surface and subsurface run-off, the latter via a specialist device described below.

Suitability of application:	Surveillance, operational
Specific application:	Surveillance, operational
Stage of development:	Implemented
Broad category:	Chemical, biological
Parameters:	Conductivity, pH, Oxygen, temperature and blue algae
Barriers:	• Cost
Key advantages:	• Early warning • Model development and validation • Increased temporal data density leads to improved understanding of pollution dynamics

Figure 1 Continuous sensing in the Netherlands (photo: J. Oosthoek, 2012)

Continuous sensors – UV nitrate sensors

One respondent indicated the intention to start continuous monitoring of nitrate, as it was felt that the current regime of monthly samples does not give sufficient detail on 'spikes', which are particularly important to fish and invertebrate populations. Simultaneous to nitrate monitoring, Hydrometric measurements in ground and surface water simultaneous to nitrate monitoring will allow flux to be calculated. Current lab based analyses would be ongoing and used for validation and calibration. Our respondent alerted us to a UV absorption method for Nitrate; nitrate absorbs in the UV region at a rate proportional to the concentration of nitrate ions in the water and can thus be measured using spectrometry measured using spectrometry. Some sensors also include part of the visible spectrum (UV–Vis), permitting correction for humic matter in water. Still others also monitor in the NIR spectrum (>700 nm) so permitting correction for light scattering (turbidity).

Suitability of application:	Surveillance, operational, investigative
Specific application:	Not specified
Stage of development:	Proposed
Broad category:	Chemical
Parameters:	Nitrates
Barriers:	• Initially expensive • Require more power than some other sensors
Key advantages:	• High resolution, accuracy and precision (repeatability) • Long term stability • Low operating cost • Mostly maintenance-free (with auto compressed air or mechanical wiper cleaning) • Can measure over a wide range (though different path lengths needed) • No chemicals needed • Robust and durable • Fast response time • Spectra may also detect Turbidity, NO3-N, COD, BOD, CDOM (humic matter) • Easy to deploy… 'plug and measure' • Factory pre-calibrated; some can be multi-point calibrated locally water' • Not temperature dependent

Automated analysers

The Irish National Centre for Sensor Research leads the development of autonomous analysers, which can be applied in a range of environments and have been successfully tested in several research projects. Microfluidic analysis systems can rapidly analyse samples whilst minimising amounts of reagents, waste storage and power required. The integrated sampler is designed to be deployed in remote locations and needs to be able to function with little maintenance. In combination with low power wireless communications systems, reliable information on the state of natural waters can be delivered over a long period of time (Cogan et al, 2013). The sampler is capable of analysing for most parameters for which a colorimetric method exists, including phosphates, nitrates, nitrite and ammonia, and can be used in a semi-continuous or high frequency sampling regime.

Suitability of application:	Surveillance, operational, investigative
Specific application:	n/a
Stage of development:	Research
Broad category:	Chemical
Parameters:	All for which colorimetric method exists
Barriers:	• Public procurement regulations inhibit use of innovative methods by SMEs such as university spin-off companies • For a period, a remote sensor network would need to operate alongside existing methods so it can be validated; in this phase, there would be an additional cost • Further development required in collaboration with material science to bring down unit cost • Creates toxic waste • Complex technology
Key advantages:	• Near-real time data availability • Potential for increased spatial and temporal data density • Sampling in remote locations could become much cheaper • Better data may result in new observations of patterns and more effective programme of measures • Mobile devices suitable for flexible application

Passive Diffuse Sampler

To monitor diffuse pollution, the German water service provider Erftverband uses a specially designed unit consisting of a rectangular box (Fig. 1), which is embedded into the soil along the river course. The system catches surface and subsurface run-off water with the side facing away from the water course containing perforations on its entire surface (hole size 3mm). The water enters the device and is collected in two separate reservoirs, each with a capacity of 50L. Sensors in the collection pan allow tracking of the filling process; data is transmitted daily via SMS to staff, who periodically collect the sample. It has not yet been possible to correlate data from this device with water quality in the river.

Suitability of application:	Operational, investigative
Specific application:	Investigative
Stage of development:	Implemented
Broad category:	Chemical
Parameters:	Diffuse pollutants
Barriers:	• None mentioned but requires regular attendance
Key advantages:	• Improved insights into diffuse pollution dynamics) • Data used for modelling and validation purposes

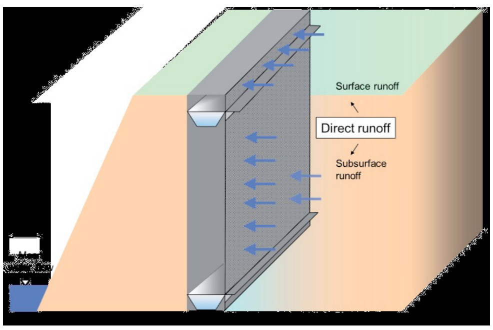

Figure 2 Schematic diagram of Passive Diffuse Sampler. Adapted from Galle *et al.* (2012)

Annex 5

Emerging pollutants

It is increasingly difficult for regulators to keep up with the expanding list of emerging pollutants (Gunningham, 2002). Within the WFD Annex X there is a list of existing priority substances (33 No) which is revised on a regular basis to include emerging pollutants (or substances of high concern). Annex VIII informs the risk assessment processes that are used for the basis of developing regional and national monitoring programmes within the EU.

Different drivers are identified for monitoring projects of four groups of emerging contaminants, described below: GMO material, micro-plastics, emerging pesticides and pharmaceuticals, as well as a novel screening method.

Effects of GMO crops

Monitoring the effect of GMO crops on the aquatic environment in Germany was driven by scientific evidence: in a key publication, Dr. Emma Rosi-Marshall established that exposure of Bt-maize toxin is abundantly detected in almost all headwater streams in an Iowa test region and that caddisfly feeding on genetically engineered maize did not grow as fast and showed lower survival than caddisfly fed on conventional maize (Rosi-Marshall, 2007).Environmental consultant Frieder Hoffman, who is involved in monitoring potential adverse effects of GMO on the aquatic environment in Germany, a project funded by Federal Agencies. Hofmann explained that following the Rosi-Marshall paper "the evidence [of effects on the aquatic environment] could no longer be ignored". Monitoring of effects of GMO had already being carried out in Germany by the department of Agriculture, but not in aquatic environments. It is now integrated in WFD monitoring and this interdepartmental integration is a strategic innovation. The programme has focused on areas close to GMO crops, but our respondent suggested that the most sensitive organisms may no longer reside in these areas and that the monitoring programme should shift to locations with lower concentrations.

Suitability of application:	Surveillance, operational, investigative
Specific application:	Surveillance, operational, investigative
Stage of development:	Implemented
Broad category:	Chemical, biological
Parameters:	GMO
Barriers:	• None mentioned
Key advantages:	• General contribution to scientific body of knowledge on effects of GMO • Interdepartmental integration

Micro-plastics

Microplastics are monitored by SEPA in the coastal environment, following their unintentional detection whilst looking at zooplankton. The reason given by the respondent for continued monitoring of these substances is again not driven directly by monitoring requirements or by Annex VIII: "We need to do this because no one else is".

Suitability of application:	Surveillance, investigative
Specific application:	Surveillance, investigative
Stage of development:	Completed project
Broad category:	Chemical
Parameters:	Micro-plastics
Barriers:	• None mentioned
Key advantages:	• General contribution to scientific body of knowledge on bioaccumulation

Pharmaceuticals

The Rhine commission instigated research into pharmaceutical compounds in the Rhine primarily because of concerns over drinking water sources (RIWA, 2010). National initiatives also exist: for example, the French 'Action Plan on Drug Residues in Water (2011)', co-led by the Ministries of Ecology and Public Health, supports prioritisation of pharmaceuticals for which screening studies are needed in view of the implementation of emission reduction measures.

Suitability of application:	Surveillance, operational, investigative
Specific application:	Operational, investigative
Stage of development:	Completed project
Broad category:	Chemical
Parameters:	Pharmaceutical compounds
Barriers:	• None mentioned
Key advantages:	• Enabling risk assessment for drinking water and general contribution to scientific body of knowledge

Pesticides and other micropollutants

In a conference communication in 2013, Fabrizio Botta of the French national environmental institute INERIS states that, "it is widely recognised by the scientific community that several substances of emerging concern are currently overlooked by legislative requirements" (Botta, 2013). As part of the implementation of the National Action Plan on Micro-pollutants in the Aquatic Environment (2010), the French Ministry of Ecology decided on a comprehensive and innovative approach, involving surface water testing, coastal passive sampling and sediment analysis. France set up a national 'watch list' of substances to be investigated in order to acquire missing information about the level of exposure of emerging contaminants and to allow regular updating on the list of River Basin-specific pollutants, and carried out a large national screening programme in 2012. The programme used the NORMAN methodology for prioritisation of emerging substances and assessed circa 11 million data-points from existing monitoring programmes for adequacy (in terms of the matrix and compatibility).

Suitability of application:	Screening, surveillance, operational, investigative
Specific application:	Screening
Stage of development:	Should be complete but report not found
Broad category:	Chemical
Parameters:	Identification of Specific Pollutants
Barriers:	• None mentioned
Key advantages:	• Comprehensive screening

Diffuse micro-pollutants

A national strategy for monitoring diffuse micro-pollutants was developed by the Swiss research institute EAWAG, with Federal funding, in acknowledgement of the fact that peaks in pollution regularly occur and can exceed regulatory limits in most rivers (Wittmer et al, 2014). Cantons are free to decide whether or not to implement the regime. Compound selection was based on consumption data and toxicological risk. A list of 48 substances is recommended for monitoring; the main groups are pesticides, biocides and heavy metals. The recommended sampling regime is fortnightly of time proportionate composite samples during the summer months. Monitoring locations are selected based primarily on land use maps.

Suitability of application:	Operational, investigative
Specific application:	Operational
Stage of development:	Suggested for adoption by Cantons
Broad category:	Chemical
Parameters:	Diffuse pollutants
Barriers:	• Cantons may choose not to implement the strategy
Key advantages:	• Up-to-date selection of compounds • Careful consideration of optimized regime and spatial distribution • Improved insights in pollution dynamics

Emerging contaminants

Norway has started using a new technique for screening for emerging contaminants, the 'Non-Target Analytical Method' (Miljødirektoratet, 2013). Within the methodology, environmental pollutants can be identified without preceding selection of the compounds of interest, as is the case in approaches using traditional trace chemical analytical methods. The concentration of unknowns and unidentified compounds can far exceed the concentration of identified compounds, whilst effect studies have shown that toxicity cannot always be explained by the concentrations of known contaminants. The final selection of substance(s) is made with input from an in-house group of experts, industry, and the scientific community in collaboration with other institutes. Each year a new contaminant is selected for monitoring, starting in urban fjords, and if of concern, added to routine monitoring programmes.

Suitability of application:	Initially screening and investigative but delivering input into surveillance and operational regimes
Specific application:	Screening
Stage of development:	Implemented once for water, will be repeated. Implemented in other media.
Broad category:	Chemical
Parameters:	Full range of chemical pollutants
Barriers:	• Cost • Some analytical difficulties • Quantification not currently possible for all compounds, only those analysed by GC-MS, but could be developed for LC-MS
Key advantages:	• No preselection of chemicals necessary so more likely to identify chemicals of concern

Annex 6

Citizen Science

The term 'Citizen Science' covers a broad range of initiatives where non-specialists are involved in scientific research. Public participation is a key principle of the Water Framework Directive; involving citizens in scientific aspects such as monitoring can have the potential to engage and inform and thereby engender stewardship, increase compliance with and acceptance of specific requirements placed on the public or costs relating to water management. The US Environmental Protection Agency (US EPA) uses trained volunteer water quality monitors, who "build community awareness of pollution problems, help identify and restore problem sites, become advocates for their watersheds and increase the amount of needed water quality information available on our waters" (US EPA, 2013). Other initiatives, covering monitoring and management of water resources, exist around the globe. The nature, depth, and frequency of involvement varies enormously, as does the target citizen group, which can be the broad public but also specific stakeholder groups such as anglers, farmers or landowners. The project identified a range of examples as described below.

Lil' Miss Atrazine

The University of Nebraska runs and sponsors a student-driven research project entitled 'Lil' Miss Atrazine', in which citizens deploy commercially available detection strips (costing10 US dollars each) to screen for atrazine, the most commonly used herbicide in the area, in a nearly 1400 mile long stretch of land in the Mississippi basin. The strip gives a yes/no result at a level relevant to the Clean Water Act reporting requirements. A training video is disseminated via YouTube, whilst participants use social media applications such as Twitter and Instagram, as well as email or traditional mail, to report data and their coordinates. As many people test the river on the same day, the data output is a 'raster' of points in the catchment, which can be used to identify hotspots and aid insights in spatial distribution; the use of social media results in near-real time information. Social media are also used to communicate the results back to participants. Although atrazine levels have been examined before, this was the first time testing was coordinated at such a scale. Professor Alan Kolok, who coordinates the project, notes added value in terms of awareness and stewardship. In an article in 'Environmental Science and Technology', he promotes the use of what is called 'small scale scientists' (Kolok, 2011), meaning for example citizens, water board operatives, or students, in screening. However, he notes that for the moment, the project is 'riding under the radar of the regulating agencies' and remarks that citizen science projects such as his should be seen primarily as a screening tool and as such as complementary to, rather than competitive with, traditional monitoring methods.

Suitability of application:	Screening, surveillance, investigative
Specific application:	Screening
Stage of development:	Implemented once
Broad category:	Chemical
Parameters:	Atrazine and other parameters of interest (strips exist or can be developed for the detection of parameters of interest)
Barriers:	• Not yet accepted by regulator • Ad hoc recruiting strategy resulting in uneven spatial spread
Key advantages:	• Citizen empowerment • Raster data on large spatial scale

Kentucky Watershed Watch

A respondent from the Kentucky Watershed Watch (KWW) program, which has been in operation since 1998, highlighted that the vision of the programme is to empower citizens to monitor streams, including educating the volunteers to understand how to assess the quality of a stream. Volunteers are provided with equipment and laboratory access. The technology is proven and commercially available, but does not require excessive calibration (volunteers only sample periodically, not daily). Scientific advisors work directly with volunteers to plan and implement sampling programs. Training programs are in place, with refresher and advanced training, such as data analysis, for long-term volunteers (some have been sampling 10+ years). Volunteers are asked to participate in statewide systemic monitoring 4 days a year to sample for chemical (dissolved oxygen, conductivity, pH, temperature, e coli, phosphorus, total nitrogen), biological assessment (macroinvertebrate), and stream characteristics (flow rate, substrate, exact location). In addition, volunteers propose studies based on their sampling, which are organised and supported by the KWW. The respondent notes it is important to be genuinely flexible and responsive to the local situation. The programme has a collaborative relationship with the Kentucky state EPA; the state uses the volunteer data for screening but generate their own data for regulatory purposes. Volunteers are further empowered by being encouraged to speak to local government or water managers, with back up from the University, have access to Public Speaker Training, and have been involved in local planning decisions.

Suitability of application:	Screening, surveillance, investigative
Specific application:	All
Stage of development:	10+ years of implementation
Broad category:	Biological , chemical, hydromorphological
Parameters:	• Macro-invertebrates • Dissolved oxygen, conductivity, pH, temperature, e coli, phosphorus, total nitrogen • Flow rate, substrate, exact location
Barriers:	• Monitoring activity has to be relevant for the volunteer and feedback and support is essential. • Strong organization and strong leadership is important, with volunteer involvement at steering committee • Recruitment is helped by good relations with local media
Key advantages:	• Citizen empowerment • Increased spatial and temporal data density

Mobile phone apps and web based information systems for crowd sourced data

The now ubiquitous access to mobile phones and the Internet is useful for facilitating collection and, in part, analysis of crowd sourced data. The level of involvement for the citizen is generally fairly low, but in some cases the mobile phone apps do provide an opportunity to engage the public. Volunteer citizen monitoring can extend observation networks spatially and temporally.

A 'crowd hydrology' project (Fienen, 2012) entitled "Social Water" used crowd-recorded data on water levels. Members of the public took a reading of an in-situ gauge and used a text message to convey the data, which was then displayed in real time on the Internet. A second hydrology app, used by Brabantse Delta in the Netherlands, utilises the phone's camera and uploads the data automatically; at the moment this is used only by Water Board staff it has potential for use in Citizen Science. Brabantse Delta also use a mobile app whereby the public gathers data: members of the public are asked to photograph invasive water plants in drains and ditches. The photograph and location data are uploaded and passed to an ecologist, who identifies the invasive species; the crowd-sourced photographs are thus used to create a spatial record.

In Finland, due to the large number of lakes, algal bloom monitoring poses a challenge for resources, as trained observers are restricted to a limited number of lakes. Variability in space and time means occurrences are missed where monitoring is infrequent or lacking. Remote sensing can be useful (see below) but has limitations, especially in smaller water bodies. A recent paper by Kotovirta *et al.* (2014) describes how members of the public are invited to report algal blooms via two applications, one web based and one mobile phone application. Observations were made at ad hoc locations and from stationary sites defined by citizens. The web based service, Järviwiki – which translates as 'Lake wiki' - provides the opportunity to share information on the web, raising awareness of and promoting protection of waters. GPS based mobile devices provide a second platform for collecting data through 'participatory sensing': devices are enabled to collect data automatically as 'opportunistic sensing' and to allow users to analyse and discuss data through software and social media. Citizen observers were recruited through local and national media and at water related events, at the start of the algal bloom season; motivation was simply to take part and participants were sent notifications about the algal situation and reminders to take part. Experts also make observations from fixed shore observation sites. Cyanobacterial bloom intensity is evaluated in four classes (0=not detected to 3=very high amount) by both experts and citizens. On average, citizen evaluations were higher than expert ones; this could be explained by the fact that citizens probably made observations more often when algae are visible and tend to omit 'no algae' reports. Direct comparison between citizen and expert data was not possible due to the ad-hoc nature of citizen observations.

Although most people have mobile phones, the number of people with smart phones is lower, so that a system using text messaging has a lower barrier of participation. Measurements can be taken as part of a pre-established programme or in an opportunistic manner; the former requires more commitment from the volunteer.

Suitability of application:	Surveillance, operational
Specific application:	Surveillance (algal bloom and invasive species), operational (hydrological)
Stage of development:	Implemented
Broad category:	Biological, hydromorphological
Parameters:	• Algae, invasive species, water level
Barriers:	• Trade-off sometimes needs to be made between level of access (need for a smart phone) or more restricted engagement opportunities; instructions need to be kept simple when using text messages • Potential for misuse, especially when users do not have to register and cannot be tracked • Real or perceived issues of reliability; variability between users • Data quality is an important issue especially when using data for the validation and evaluation of models
Key advantages:	• Low-cost field data acquisition, enabling engagement • Increased spatial and temporal density of observations • Citizen engagement and awareness • No misuse recorded (algal bloom study) • Systematic positive correlation between expert and citizen observations suggests that citizen observers can provide useful additional information (algal bloom study)

Open source technologies

Hardware and software developed by citizen scientists in the open-source movement could become increasingly useful as inexpensive sensors and other measurement technologies. Some developers are coordinated in "The Public Laboratory for Open Technology and Science (Public Lab; publiclab.org)", a community that develops and applies open-source tools to environmental exploration and investigation. Public Lab's aim is to create a collaborative network of practitioners who actively re-imagine the human relationship with the environment by democratizing inexpensive and accessible Do-It-Yourself techniques. A case in point, brought to our attention by a respondent in the USA, is an Arduino based underwater sensor project, involving a well-researched and well-designed water flow sensor using open-source hardware. Such devices can easily be integrated into local monitoring stations or as a front-end sensor connected to centralised cloud-based storage and analytics systems.

This development is citizen-driven and not an approach that can be adopted; neither is it suggested that routine water monitoring should use open-source sensors. Rather, it is included because of its relevance for Citizen Science projects, in particular where these are designed and funded by community initiatives.

Remote Sensing

The term 'remote sensing' is used with different meaning: the 'remoteness' can refer to the distance between the water body and the nearest population centre, infrastructure or water manager (e.g. a very rural or mountain location), to the distance between the water body and the sensor (e.g. when the sensor is a satellite) or to the distance between the sensor and the water manager (i.e where the sensor it in the water body but data is accessed remotely). As in-situ (continuous) sensors and analysers with remote data tend to be applied because of the continuous nature of the data they generate, they have already been covered under sampling regimes; below we focus on systems where the sensor is distant from the water body.

Application of Radar gauges to measure the water level and the state of the sea (Wilhelmi and Barjenbruch, 2009)

The sea state in coastal waters and on the open sea used to be measured with pressure sensors, acoustic (ADCP) systems, or wave buoys. These measuring techniques are both costly and labour intensive and require regular maintenance. A novel device for operative wave height measurements, using a low-cost and low-maintenance radar sensor, was developed and tested by the German Federal Institute of Hydrology (BfG), Department of "Hydrometry and Hydrological Survey".

Radar (microwave) sensors are appropriate when vapor, dust, or a foaming surface prevents ultrasonic-wave measurements (http://www.omega.co.uk/pptst/LVRD500.html) Water-level and sea-state parameters are computed in real time and transmitted to the coastal communication network which distributes the data instantaneously. The total costs of the radar-based measuring system amount to about Euro 5000. The main advantage of the radar system compared to a Waverider® buoy is its low maintenance requirement. In a three month study of wave height and period (radar compared to Waverider buoy) the measurements of the radar system and the Waverider buoy were shown to deviate from each other only slightly.

Suitability of application:	Surveillance
Specific application:	Surveillance
Stage of development:	Proven technology
Broad category:	Hydrometry
Parameters:	Hydrometry in coastal areas and open seas
Barriers:	• None mentioned
Key advantages:	• Low maintenance

HydroNET / rain radar

The Dutch water boards purchase rainfall data and rain forecasting data (two datasets, one for 48 hour forecasts and one for 10 day forecasts) from HydroNET (http://www.hydronet.com/), a commercial company providing live access to data from innovative water quantity monitoring sources such as radar and satellite. The main challenge for the water board, in terms of water quantity, is to deal with new climate scenarios and to ensure ditches and canals can cope with the extra water. Combining monitoring and modelling data allows accurate predictions of when and where problems can be expected. The data can also be used to refute legal claims from farmers when these hold the water board responsible for flooding issues. Similar data is accessible in the UK from the Met Office.

Suitability of application:	Surveillance, operational
Specific application:	Surveillance, operational
Stage of development:	Implemented
Broad category:	Hydrometry
Parameters:	Hydrometry in rivers
Barriers:	• None mentioned
Key advantages:	• Accurate predictions • Prevention of flooding • Contest liability

Use of Satellite data in a three-tiered remote sensing approach

The Estonian environment ministry used MERIS satellite data as a first screening tool in a three-tiered approach to monitoring for a range of water quality issues. The Medium Resolution Imaging Spectrometer (MERIS) was one of the main instruments on board the European Space Agency's Envisat platform. MERIS is now no longer operational and its function will be taken over by the new satellite Sentinel II, which is expected to be operational in September 2015.

Radar data has a typical resolution of 2km or so, satellite data 300m – 1km. This low resolution satellite imagery is available free of charge. More detailed (2m) imagery is also available but needs to be purchased. Two years ago, the department fitted a plane equipped for mapping purposes with remote sensing instrumentation, which has a spatial resolution of <2m and also a better spectral resolution than the satellite. From the plane, transparency, Suspended Solids, Chlorophyll A, DOC and carbon related issues can be measured, as well as benthic algal cover. Problems (pollution, algal blooms) spotted on the satellite are now investigated further by plane and, if necessary, subsequently by boat.

For open oceans it would be possible to use standard algorithms (which can be downloaded from the space agency and used with confidence) for temperature, transparency, chlorophyll A, the Baltic Sea is optically complex and most of Estonia's remote sensing budget is spent on developing and testing algorithms for the Estonian seas and lakes. The respondent mentioned the Global Lakes Project - in which Stirling University is involved – which is developing remote sensing of lakes.

Using multiple images at the same location, longer term processes can be followed which aids understanding. The department is in the process of analysing 10 years' worth of MERIS data to look at spatial and temporal variability of cyanobacterial blooms and suspended solids. This is used to streamline the monitoring network by reducing redundancies. Satellite data are also used to assess the impact of improvements, such as recent upgraded wastewater treatment facilities in a number of large cities, or pollution events from oil spills or illegal discharges of dirty water from ships. Although the method has not been used to prosecute anyone, it could identify which ship was responsible even on a busy shipping route. Finally, a high correlation was found between the spatial heterogeneity of the image and biodiversity.

Thus, in Estonia, satellite and airborne remote sensing data improves temporal and spatial data density, helps streamline the monitoring network, informs a risk-based three tiered approach, enables monitoring change, is used in validating and informing environmental modelling and could be used for source identification of pollution incidents.

In Finland, satellite data is also used as a first-tier assessment for algal blooms, and methods are being developed to use it for macrophyte cover. The planned second tier in Finland is the use of drones, but for now limited battery life and legal restrictions prevent implementation.

Suitability of application:	Surveillance, operational, investigative
Specific application:	Surveillance, operational, investigative
Stage of development:	Implemented
Broad category:	Biological, physicochemical
Parameters:	Chlorophyll A, benthic algae, biodiversity, DOC, suspended solids, temperature
Barriers:	• Not currently a certified method
Key advantages:	• Increased spatial and temporal density • Increased coverage • Daily images allows immediate response • Model validation

'Ships of Opportunity': Ferrybox and Alg@line

The Alg@line -project was generated in 1993 to improve the coverage of existing pelagic monitoring in the Baltic Sea. The temporal and spatial frequency of the collected data in the old monitoring programmes were far too sparse to reveal the possible changes in this highly fluctuating, patchy ecosystem. However, it was not possible to increase the sampling frequency by using traditional sampling techniques i.e. the expensive use of research vessels. The SOOP approach i.e the 'ship-of-opportunity platforms' facilitate the adequate monitoring of highly fluctuating pelagic ecosystem; It offered an extensive and inexpensive automated sampling method on board merchant ships. This meant a fundamental change in phytoplankton monitoring as the 'few-station' sampling on board research vessels was extended to SOOP sampling. (from: http://www.syke.fi/en-US/Research__Development/Research_and_development_projects/Projects/Real_time_algal_monitoring_in_the_Baltic_Sea_Algline)

Norway's NIVA uses the Ferrybox system for the collection, analysis and presentation of water quality data. The system combines information from sensors installed on board ships sailing along fixed routes with data from environmental satellites and collected water samples. This automatic monitoring system has been developed and partly financed by NIVA, with support from national and international research projects. Once every minute, the Ferrybox system measures temperature, salinity, oxygen, chlorophyll and particle content at a depth of four metres along the fixed route of a vessel. This amounts to about one measurement every 500 metres. Some of the ships with Ferrybox equipment also carry advanced instruments for measuring solar radiation and reflection from the ocean surface. The data is transmitted to NIVA in real time. Other countries, including Scotland and Germany, also operate the FerryBox system.

The system can activate sampling of water from predetermined sites. Sampling can also be triggered by NIVA during a voyage as necessary.

NIVA downloads data from the environmental satellite ENVISAT. This data is processed and presented together with data from the ships. from: http://www.niva.no/en/miljoedata-paa-nett/ferrybox-og-satellittdata)

Suitability of application:	Surveillance
Specific application:	Surveillance
Stage of development:	Implemented
Broad category:	Chemical
Parameters:	Sensors: salinity, oxygen, chlorophyll, particle content, solar radiation, reflection. Also sampling capacity
Barriers:	• None mentioned
Key advantages:	• Real time data • Cost effective

Data management and 'Big Data'

HydroWatch and HydroView: 'Control room' technology

Brabantse delta use 'control room' technology for quantitative and qualitative water management, where various datasets can be viewed simultaneously. The system enables easier interpretation and analysis of the combined data. Aside from the HydroNET 'rain radar' data, predicted drainage and water level data from the water board's Decision Support System, which uses SOBEK flood forecasting models, are also integrated, as are data from the measuring buoy described above. The software packages, HydroWatch and HydroView, were developed in collaboration with, and purchased from, the company HydroLogic, who also supplies the HydroNet 'rain radar' data mentioned above. The HydroNET website also mentions the possibility to collect citizen observations in real time via smartphone or browser.

Suitability of application:	Surveillance, operational
Specific application:	Surveillance, operational
Stage of development:	Implemented
Broad category:	Chemical, hydrological, biological
Parameters:	Any real-time available data
Barriers:	None mentioned
Key advantages:	Better insights into relationships between different parameters

KISTERS water management

A respondent mentioned KISTERS, a company delivering a wide range of techniques and services to support (amongst other domains) natural and urban water management. KISTERS deliver modern multi-tiered computing architectures within a cloud infrastructure. The infrastructure allows the company to provide end-to-end solutions from sensing, data-transmission, storage, analysis and visualisation (via web technologies - providing flexibility of client devices to access system information - from desktop computers to mobile devices). The uses of complex IT architectural approaches are becoming standard across many industries for data analytics. The techniques used support integration with other computer-based systems, enabling detailed trending of macro-data sets.

'Big Data'

'Big data' is somewhat of a buzzword and refers to the analysis of large data sets. Large data sets exist and have previously been used in a water context. For example, social media data were analysed to analyse the public discourse in relation to an oil spill (Starbird, 2015) and environmental concerns in general (e.g. Martinello, 2012). 'Big data' analysis was mentioned by two respondents as 'thoughts on the future of water monitoring'.

Data and meta-data portal development

Two initiatives aiming to improve data access were given as examples. The EMECO data tool (http://www.emecodata.net/) is currently being developed by a consortium involving Marine Scotland and other agencies with responsibilities for marine monitoring. It has been available for circa five years and it is hoped that all biological, physical and chemical data will be able to be reported via this tool. The possibility of linking EMECO with the Hazardous Substances reporting tool is also being explored.

The second example is a long-term 'Cross –border Water Management Initiative', started by twelve partners from the Netherlands and Germany in order to contribute to the development of an international hydro-geo information structure (Lipke and Kukuric, 2007). Its objective was to create an easy and customized web-bases access to water information that resides on various servers in the two countries, by providing a catalogue of meta-data. A metadata catalogue is an online search tool, like Google, that allows the user to find geodata. Geodata can only be found when the data provider has described the data with meta-data, i.e. the type of data (shape, raster, table), category (e.g. surface water, groundwater), key words, data owner, or area. Several countries have data portals that include meta data functioning, although neither of the two mentioned by Lipke and Kukuric (2007) appeared to be working at the time of writing.

Environmental DNA

Monitoring of the health of aquatic environments depends on a range of determinations including those of ecological and chemical status. Ecological status is measured by occurrence of phytoplankton, macrophytes, phytobenthos, benthic invertebrates and fish fauna (EU Dir, 2000/60). However, ecology programmes are dependent on sampling strategies that may be reasonable for moderately abundant species but are less than satisfactory for rarer examples. Sometimes it is concluded that species are absent, because they evade capture, when in reality they are present. In any event it may be better not to capture those rarer species for fear of further compromising a small population. One possibility of overcoming problems associated with traditional ecological approaches is by the use of environmental DNA (eDNA). This strategy is based on the premise that organisms shed tissues, organs, faeces, epithelia etc. into the environment and the DNA therein persists for a time and can be isolated from water or sediment. The approach was introduced to monitor diving whales (Amos *et al.*, 1992) and later bullfrogs (Ficetola *et al.*, 2008) and has subsequently been widely extended in the aquatic environment. However, the method is not limited to water and can also be used for terrestrial environments and the atmosphere (Lodge *et al.*, 2012).

The species-of-origin of the recovered eDNA can be identified by a "bar-code" technology. This requires the amplification of a piece of 'species-specific' DNA within the eDNA followed by a diagnostic step that requires sequencing at development stage but once established detection by gel electrophoresis. Typically the targets for PCR are features of mitochondrial DNA such as the D-loop (Jerde *et al.*, 2011, Takahara *et al.*, 2012, Turner *et al.*, 2015), cytochrome b (Goldberg *et al.*, 2011, Takahara *et al.*, 2012, Thomsen *et al.*, 2012) or cytochrome oxidase (Kress *et al.*, 2015, Thomsen *et al.*, 2012b). Two strategies can be adopted and depend on bioinformatic examination of an ever-increasing number of reference sequences available on the databases (EMBL, GenBank etc). When species-specific assays are required, sequences unique to the species are located and used for primer design for subsequent PCR. Such primers must allow amplification from DNA of the target species only. Alternatively, when larger groups of organisms are being monitored, portions of the sequences that are conserved within a genus or higher taxonomical level are identified allowing the amplification of DNA from all related organisms. Subsequent sequence determination of intervening, hypervariable sequences allow species identification. Targeting larger assemblies is a metagenomic approach to estimates of biodiversity (Creer *et al.*, 2010, Bohmann *et al.*, 2014) that may use alternative sequences such as 28S rDNA or 16S rDNA as in the case of bacteria (Ram *et al.*, 2011, Sangwan *et al.*, 2012).

The advent of applications of eDNA for monitoring purposes has emerged very rapidly from research phases investigating the stability and detectability of DNA in sloughed tissues obtained in a laboratory or managed pond environment. In an early demonstration of the power of the method, invasive carp in tributaries of the Mississippi where shown to be far further north than traditional methods had detected and nearer to feared progression into Lake Michigan (Jerde *et al.*, 2011). Demonstrating that the approach is not limited to freshwater systems, researchers in Denmark have shown they could detect the presence of many fish species in sea water samples (Thomsen *et al.*, 2012a). Goldberg et al (Goldberg *et al.*, 2011) have used the method to demonstrate the presence in a fast-flowing stream of rare frogs and salamanders. That group have also defined some of the conditions that affect the detection of salamanders in running streams (Pilliod *et al.*, 2014). The method also has the potential of estimating the mass of a species that might be present. Takahara et al (Takahara *et al.*, 2012) showed that the quantity of eDNA shed by carp was proportional to the mass of the fish present and used that relationship to determine carp mass in a natural setting. Similar conclusions were reached by Thomsen et al (Thomsen *et al.*, 2012b) who developed models for the computation of mass based on animal number, size and time since shedding. The strategy has also been important in archaeological investigations and used to trace back plants over 50000 in an Arctic region (Pedersen *et al.*, 2014).

The technology behind the use of eDNA is very simple. Water is filtered to collect material of cellular origin prior to isolation of DNA with proprietary kits such as used for the isolation of DNA from blood, stool or soil. Suitable DNA isolation methods have to ensure the removal of compounds that may inhibit subsequent PCR. These requirements have been investigated for many years by those working with microbiota from the environment. Turner et al (Turner *et al.*, 2015) have exploited this knowledge by introducing the use of CTAB for eDNA isolation reducing cost and increasing the efficiency of removal of PCR inhibitors. They have also introduced a qPCR application for the detection of big headed carp with much higher sensitivity than previously used assays. Perhaps the biggest challenge is the design of suitable primers for eDNA amplification but that can be achieved with very moderate bioinformatics skills.

In principle the eDNA approach has a number of advantages over traditional ecological monitoring. It takes far less time and needs less trained personnel for field sampling and species identification. Complications associated with physical sampling of organisms such as requirements for permits and licences are largely eliminated. The survival of DNA in the environment, indeed for thousands of years allows determinations to be made over time and over wide areas. Various technologies allow quantitative methods to be applied such as qPCR (Thomsen *et al.*, 2012, Takahara *et al.*, 2012, Turner *et al.*, 2015). The application of Next Generation Sequencing (NGS) will allow ever wider assemblages to be measured and in a quantitative manner (Thomsen *et al.*, 2012a, Thomsen *et al.*, 2012b).

In the Netherlands, several water boards now used eDNA techniques; we present three examples:

eDNA detection of the Water Shrew (*Neomys fodiens*), Eurasian Weather Loach (*Misgurnus fossilis*) and blue algae.

The water shrew is a protected species in the Netherlands and whenever works to the water column or the river bank are being planned, an impact study on this species is often required. The traditional method is live trapping. Disadvantages of trapping are that it is very labour intensive, that traps cannot always be placed optimally due to steep banks or fluctuating water levels, and that deaths can never be avoided. eDNA can offer a cheaper alternative (saving 75% of monitoring costs) and be more reliable, which is attractive for developers as it minimises the risk that the shrew was not detected during surveys but is detected during the implementation of a project. eDNA techniques were also successfully piloted in the Netherlands to detect *Misgurnus fossilis*, or Eurasian Weather Loach. This rare and protected mud-dwelling species is notoriously difficult to detect with traditional methods. Its presence has consequences for dredging practices. During the pilot, eDNA techniques resulted in detection of the species at a number of locations where it was not previously recorded.

A 'Hydrochip' was developed by a partnership of organisations in the Netherlands and is used for the indentification of diatoms. These microscopic algae respond sensitively and rapidly to quality changes such as changes in nutrient concentrations. The traditional method of detection is by microscope, whereby the species detected can be 'translated' into a water quality assessment. This method is very specialist, time consuming and expensive. Following a filtration and amplification step the isolated DNA is applied to the Hydrochip and binds to target-DNA contained in the Hydrochip. A chip reader is used to obtain data on which diatom species are present in the surface water sample (Van Der Weeren, 2012). Currently, reliability of eDNA testing is around 65%; the reliability of trapping methods is not known.

Suitability of application:	Baseline, surveillance , operational, investigative
Specific application:	Operational
Stage of development:	Implemented alongside traditional methods
Broad category:	Biological
Parameters:	Diatoms, fish, water shrew
Barriers:	• Results take 3 weeks (mammal trapping 1 week) • Suitability for determining abundance still disputed and quantitative estimates of biomass not yet approved under WFD • Some elements (e.g. High Throughput Sequencing) still very expensive • No morphological information such as length, development and vitality of the individuals • Questions over DNA mobility in the environment, especially in flowing waters

Key advantages:	• Cost saving of 75% • Only 1 field visit required • For some species, increased accuracy and reliability • Less animal deaths • Can be applied year round when water is not frozen (mammal trapping only in summer and autumn) • Simple training is sufficient • Little or no habitat destruction

Automatic invertebrate ID

A method using automated optical recognition is in development in Finland. Macro-invertebrates can be identified, at least to taxa but often to species level, with accuracies around 80-90%. Difficulties in securing funding are hampering further development, as the method is not likely to be commercially viable. It may however be suitable to application in conjunction with eDNA methods. A collaborative project with German researchers is ongoing, in which DNA techniques are used as a prior to identify a range of taxa; the identification algorithm has less taxa to consider and becomes faster and more accurate, providing abundances for the DNA approach. The imaging is not expensive as it is an extension of normal sampling procedures. Aside from morphological information, it can also provide accurate biomass data. An advantage of these methods is that the error is quantifiable, unlike in human identification. For accurate status assessments, a knowable error is highly preferable. The method is described by Joutsijoki *et al.* (2014).

Suitability of application:	Surveillance, operational, investigative
Specific application:	Surveillance
Stage of development:	Method in development
Broad category:	Biological
Parameters:	Macroinvertebrates, diatoms
Barriers:	Automatic ID: Accuracy still needs improvement; cost
Key advantages:	• Accurate identification • Knowable error

Benthotorch

The Benthotorch tool uses different spectra of light to analyse the composition of green algae, cyanobacteria and diatoms in the sample. Initial results in Finland suggest that in the WFD context the tool is highly applicable to identification of riverine diatoms, though less so in lakes. This instrument was mentioned by one respondent, who had not used the instrument themselves. We we therefore refer to http://www.bbe-moldaenke.de/chlorophyll/benthotorch/ and http://ppsystems.com/Literature/BenthoTorch.pdf for further information.

Passive Samplers

Traditional sampling methods rely on the collection of discreet volumes of water at set intervals, either manually or via automated samplers. For pollutants only present at trace level, large volumes of water are required in order to detect these compounds (Vrana *et al.*, 2005). A grab sample provides only a snapshot of the concentration of the determinand, which may be problematic as pollutant concentrations may vary both due to input factors and hydrological factors and particularly where they are likely to be released during short-term events (Cesa, 2013). Passive sampling involves either the deployment in situ of devices or organisms, or the use of native organisms, to collect pollutants over time via the natural flow of pollutant through the device or organism. This usually results either in a time-averaged result over the sampling period or an equilibrium concentration, although the sclerochronologic assessment method below creates a record in time. One respondent suggested that passive sampling may be especially suitable to groundwater situations, where variability tends to be less and a time-averaged result is therefore sufficient; the rationale for passive sampling in this situation would be that lower concentrations can be detected than by spot sampling.

Due to the build-up over time of trace pollutants, a wider range of pollutants may be found than when analysing discrete water column samples, making passive samplers eminently suitable for screening purposes.

Respondents from DG Environment deemed that passive samplers are not suitable for compliance monitoring but Cesa *et al.*(2013) believes that this is possible, quoting Guidance Document 27. Various types of passive samplers are suitable for monitoring trends and for investigative sampling, both source tracking and when exploring reasons for failure of biological quality elements.

Sclerochronologic Assessment

Sclerochronology of calcium-based biogenic growth increments, e.g. mussel shells, and included contaminants, provides a timeline of the presence or absence and bioavailabilities of many on a site-specific basis over the life of the organism, analogous to tree rings in dendrochronology. Temperature and pH records can be obtained from annual growth and micrgrowth patterns, whilst chemical analysis of the shell is performed by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA ICP-MS), proton microprobe and ion microprobe, combining high multi elemental capacity and low detection limits with high spatial resolution. Fish earbones are also used for analysis by the same method. Sclerochronology is used routinely by Marine Scotland Science.

Suitability of application:	Surveillance
Specific application:	Surveillance
Stage of development:	Implemented
Broad category:	Chemical, physical, biological
Parameters:	• Chemical: e.g. metal loadings • Physical: Temperature, pH, salinity: • Biological: productivity, seasonality
Barriers:	None mentioned
Key advantages:	• Long term, historical trends, inter-annual records • Exposure data

Aquatic mosses for trace element assessment and temporal trend monitoring

In this method, transplanted mosses are used as bio-accumulators. The method was used in collaboration with local Water Authorities during a 2-year preliminary study in an industrial district in Northern Italy, where both permitted and illegal wastes caused sporadic, intermittent and chronic pollution events (Cesa, 2013). It was used for continuous monitoring of Priority Substances Cd, Hg, Ni and Pb and other trace elements (Co, Cr, Cu, Fe, Mn and Zn) in existing monitoring sites previously selected on the basis of environmental risk. 190 out of 300 'monitoring actions' happened under acceptable conditions and provided results suitable for comparisons. Cesa (2013) concludes the method provides a flexible approach suitable for used for trend (surveillance) and investigative (source tracking) monitoring.

Suitability of application:	Surveillance, investigative
Specific application:	Trend monitoring and investigative (source tracking)
Stage of development:	Implemented
Broad category:	Chemical
Parameters:	Priority Substances Cd, Hg, Ni and Pb and other trace elements (Co, Cr, Cu, Fe, Mn and Zn)
Barriers:	None mentioned
Key advantages:	• Uptake does not significantly depend on biotic factors • Mosses do not metabolise pollutants in the short term • Suitable for transportation from an unpolluted site to the survey area, • Resistant to pollution and adverse conditions • Can be inactivated in advance to prevent colonisation • Can be introduced for a specific period of time (unlike native bryophytes)

Use of substrate strips to collect native biofilm

One respondent used substrate strips, suspended from buoys, in coastal and estuarine situations. The native biofilm which naturally forms on the strips acts as a passive sampler for trace chemicals.

Suitability of application:	Surveillance, operational
Specific application:	Trend monitoring
Stage of development:	Implemented
Broad category:	Chemical
Parameters:	Trace chemicals
Barriers:	Need fortnightly maintenance
Key advantages:	• Cheap • Coninuous sampler • Detects trace

Chemical Sorbent Passive Samplers

Vrana et al (2005) give an overview of different types of passive samplers using a chemical sorbent, usually fixed on a disk or strips. Examples are the Semipermeable Membrane Device (SPMD), Polar Organis Chemical Integrative Sampler (POCIS), which have been used in pesticide and pharmaceutical monitoring. POCIS was used in the M3 project. SPMD is generally used for sampling neutral organic chemicals with a Kow >3; POCIS for Kow<3 (Alvarez, 2010), as used by the USGS. Many other types are available; for the overview see the very useful Tables 1 and 3 in Vrana et al (2005), which also give specific advantages, drawbacks and development phase of each type. The deployment period can be from hours to a year, depending on the type. The sampling purpose can be integrative, flux proportional, equilibrium or screening/qualitative and sampling locations have included all types of water bodies including sea, lakes, rivers, and groundwater, as well as wastewater effluents, irrigation canals, industrial effluents, and harbours.

Suitability of application:	Screening, surveillance, operational, investigative
Specific application:	• Screening for contaminants • Speciation of contaminants • Monitoring of temporal pollution trends • Monitoring of spatial distribution and source tracking • Assessment of contaminant fate and distribution between environmental compartments, measurement of time weighted average concentrations • Estimate of organism exposure • Biometric extraction for toxicity assessment of aqueous contaminants.
Stage of development:	Implemented (e.g. France, M3) but also further research
Broad category:	Chemical
Parameters:	PAHs, BTEX, Chlorinated Hydrocarbons, Polar and non-polar organics, Atrazine, Metals, Anions, MTBE, VOCs, SVOCs, PCBs, Organochlorine pesticides, petroleum hydrocarbons, aniline, phenols, chlorobenzenes, nitrobenzenes nitrotoluenes, trace elements, triazines, polar phytotoxins
Barriers:	See introductory section
Key advantages:	See introductory section

Use of dogs in aquatic monitoring

'Working Dogs for Conservation' (http://workingdogsforconservation.org/) is a USA-based organisation using dog skills for a range of conservation purposes. One of their projects sought to investigate whether flame retardants, pharmaceuticals and heavy metals could be detected in river otter and mink scats. The pilot project was initiated due to a staff member's experience in contaminants monitoring, and the organisation sought funding to cover our costs. Detection dogs are far more efficient at finding scat samples than human surveyors, so despite the fact it costs more for dog-handler teams to survey an area, far more samples are retrieved, which significantly reduces search effort, and dogs also show very high accuracy to species, e.g. even experienced surveyors can often be visually confused by whether or not a scat is of the correct species. Therefore, the trade-off to higher survey costs are more samples and less erroneously analysed samples (wrong species) in the lab.

Dog surveys could be used strategically either for long- or short-term monitoring efforts. For example, they could be used to initially and quickly scour a delineated area to locate latrine sites that human surveyors could then return to periodically to collect scat samples for contaminants analysis. Given the efficacy of dogs to find scat samples dog-handler teams could also be deployed over the long-term to monitor the same river stretches and assess changes over time. The respondent suggested that this was the first study in the State of Montana to show presence of pharmaceuticals in rivers (vs groundwater). It is thought nothing had previously been done to assess presence or absence of flame retardants, so another goal of the pilot was to show the need for this type of monitoring. The organisation is now engaged with one government agency for further ecological monitoring and hopes to create and seek funding for several additional student projects based on additional dog surveys and scat retrieval.

In other projects, monitoring with dogs has also been used for sewage detection (http://www.savannahriverkeeper.org/canine-sewage-detection-program.html) and for combating aquatic invasive species (http://workingdogsforconservation.org/projects/combatting-aquatic-invasives)

Suitability of application:	Surveillance , operational, investigative
Specific application:	Surveillance
Stage of development:	Project scale. Further implementation being discussed
Broad category:	Chemical , biological
Parameters:	Micropollutants, aquatic invasive species, sewage
Barriers:	• None mentioned
Key advantages:	• Potential cost savings • Increased accuracy • Social benefits

Effect based monitoring and determining impact

Triad approach

Dutch consultancy firm Grontmij, contracted by dutch water board Delfland, has started using effect-based monitoring, a fundamentally different approach to the separate assessment of biological and chemical quality elements. Respondent Thijs de Kort explains the 'triad approach', more established in the fields of soils and sediments than in aquatic monitoring. Three elements are considered. Firstly, the chemistry – both total and bioavailable; secondly, whole sample ecotoxicity, and thirdly, the ecosystem – does the ecology look as expected, or are abundancies higher or lower? The relationship between the outcome of these three assessments is not obvious; sometimes all chemicals look to be within acceptable limits but the sample is nevertheless toxic, sometimes chemical norms are exceeded but the ecosystem looks nevertheless healthy, etc.

Bioassays are used as a first step and a screening tool, so that those sites where a toxic situation exists can prioritised for management intervention. If targets for biological quality elements are not met, but bioassays indicate that toxicity is not the problem, there is no point in investing heavily in measures to reduce chemical inputs. A water board can then be bold and justify not addressing chemical status. If, on the other hand, a toxic situation is identified, the site can be prioritised. As a next step, a Toxicity Identification Evaluation (TIE) is carried out, involving fractioning the sample to identify which compounds are problematic. This stage falls in the realms of investigative monitoring. False positives and false negatives are possible, but as a screening method effect-based monitoring is seen as preferable to analysis of a limited number of chemicals, where the main issue can be missed.

Suitability of application:	Screening, prioritising locations and investigative
Specific application:	Prioritisation and investigative
Stage of development:	Early stage of implementation
Broad category:	Integrated biological and chemical
Parameters:	Bioassays and TIE
Barriers:	• Not yet accepted by regulator • No direct driver in current legislation
Key advantages:	• Better signposting to effective interventions

Biomarker approach

Biomarkers are defined as measurements of body fluids, cells, or tissues, that indicate in biochemical or cellular terms, the presence of contaminants (exposure biomarkers) or the magnitude of the host response (effect biomarkers) (Borja *et al.*, 2012).

The method is particularly suitable in exploratory or investigative monitoring for emerging contaminants, when effects are not yet known or understood. The respondents are researchers are currently involved in studies tying biomarkers to established metrics for benthic organisms and suggest the biomarker approach could be incorporated into the definition of biological quality. The same suggestion has been made by Sanchez, *et al.* (2008 and 2009). There are many different types of biomarker, from biochemical and histological markers, to proteonic and transcriptomic markers. Vitellogenin, for example, is a marker for endocrine disruption whereas metallothioneine is a marker of exposure to metals. A battery of suitable biomarkers for exposures and effects is proposed by Cajaraville, *et al.* (2000). The biomarker approach can be used as a warning system and is suitable for a tiered approach, where simple biomarkers are used in first instance with more diagnostic work to follow when appropriate, followed in turn by pathological studies. Although biomarker technology is labour intensive and thus expensive, it is not as expensive as chemical testing. The respondents stressed that it is not possible to monitor all chemicals and their interactions and that a biomarker approach offers much better protection of our ecosystems, especially given that the range of chemicals used is changing and expanding and cannot be adequately covered by an expanded list of priority substances. Biomarker approaches are not yet used in WFD monitoring in Spain, but rather undertaken by academic institutions. The respondents indicate that the main role for this technology in the short term is likely to be in investigative monitoring.

Suitability of application:	Screening, surveillance, investigative
Specific application:	Screening
Stage of development:	Research
Broad category:	Integrated biological and chemical
Parameters:	Biomarker effects
Barriers:	• Not yet accepted by regulator • No direct driver in current legislation • Labour intensive
Key advantages:	• Early warning system of unknown or unexpected effects • Better protection for ecosystems

Modelling

Germany: the DWA model

DWA models quantitative and qualitative conditions and processes in rivers and streams. Developed in 1998, it is now the standard tool for water quality modelling in Germany. It is applicable in both larger and smaller streams, and in particular its applicability in small streams is of interest, as these are usually highly sensitive to morphological and physico-chemical changes. The model is applied in a wide range of contexts, including monitoring network design, monitoring data analysis, analysis of sources and sinks, scenario planning and simulations, environmental impact assessment, impact prediction of accidental pollution. The model has 17 modules (see table below).

Case studies include modelling of the influence of CSO, assessment of the influence on water quality of measures to minimise soil erosion, examination of ecological potential of a river section, impact of modified hydro-morphological conditions on oxygen balance and plankton growth. In the river Swist, the model revealed significant fluctuation of nitrate nitrogen concentrations at different times of day downstream from WWTW; these dynamic effects would be hard to capture by monitoring. Training and support is available for users and the model is updated constantly.

Suitability of application:	n/a
Specific application:	n/a
Stage of development:	Implemented
Broad category:	Chemical, physico-chemical, biological, hydrological
Parameters:	Flow, Solar Radiation, BOD/COD, Phosphorous, Nitrogen compounds, Silicate, Diatoms, Green Algae, Zooplankton I and II, Benthic flora and fauna (exchange with the sediment), SS, Oxygen balance, pH, heavy metals, organic substances.
Barriers:	None mentioned
Key advantages:	• Monitoring network design • Monitoring data analysis • Analysis of sources and sinks • Scenario planning and simulations • Environmental impact assessment • Impact prediction of accidental pollution

Flanders: the WEISS Model

In Flanders, the Vlaamse Milieumaatschappij (Flanders Environment Agency) uses the 'Water Emissions Inventory Support System` (WEISS) in their integrated water management approach. The WEISS model maps significant sources and their contribution to water pollution. Emissions are calculated from a bottom-up approach from the detailed location of the source, followed by calculations of transport. 'Gross emissions' are defined as emissions from the source, net emissions are those that reach the environment following wastewater treatment and transport. Using data from measurements at point sources, WEISS is capable of calculating total gross and net emissions by compound and by sector. Losses to soils, air, groundwater, and across national borders are taken into account, as are sewer leakage and CSO emissions. The gross and net 'emissions maps', which give emissions per hectare on a raster map of Flanders, are publicly available online (http://weiss.vmm.be/geoloket/), allowing the user to select the source (population, soils erosion, atmospheric deposition, energy, trade and services, industry, agriculture and transport), the substance group (organic compounds, anorganic compounds, metals, PAH), the substance (total P, total N, As, Cd, Cr, Cu, Pb, Hg, BOD, COD, and 5 PAH substances), the year of interest and the catchment.

https://www.vmm.be/data/weiss/weiss

Suitability of application:	n/a
Specific application:	n/a
Stage of development:	Implemented
Broad category:	Chemical
Parameters:	Total P, total N, As, Cd, Cr, Cu, Pb, Hg, BOD, COD, and 5 PAH substances
Barriers:	None mentioned
Key advantages:	• Publicly available pollution maps • Data by sector or by parameter

Participatory modelling and water resource management

In participatory modelling, stakeholders are involved in developing water quality and quantity models and water resource management decision support systems. Several examples were encountered during literature study, including Lupo Stanghellini (2008), Castelletti (2007) and Molina (2011). Molina (2011) describes how probabilistic models (Bayesian networks) are used to construct a Decision Support System to assess the impacts of different groundwater management scenarios on environmental, economic and social aspects in the region. Castelletti (2007) described how, for example, stakeholder satisfaction is affected by management scenarios via water quality. The focus of the literature appeared to be primarily on participatory decision making and less on the relation between modelling and monitoring for WFD reporting; as such, an in-depth literature review was not carried out for this topic.

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