Guide for Monitoring Flux Dynamics at Catchment Scale

Deliverable 2.3

Work Package 2: Predicting Catchment Scale Nutrient and Contaminant Fluxes Between Environmental Compartments

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1 Introduction

Monitoring of environmental waters is an important task in order to protect environmental quality and ensure adequate fresh water resources for human activity. Over the last fifty years, surface water and groundwater monitoring have become routine on the state level in many countries, and the move towards standardized practices has greatly increased the credibility of modern data. For example, the European Water Framework Directive (WFD), first passed in 2000, ensured that large-scale monitoring of groundwater and surface water bodies throughout the European Union would be an environmental priority (The European Parlament and the Council of the European Union, 2000). In addition, the WFD changed the way that water bodies are managed, with primary focus on hydrological catchments as opposed to management within administrative borders (Hering et al., 2010).

The purpose of water monitoring is to survey the status of water quality and to identify temporal trends. Observation of temporal trends helps to determine specific factors or processes which control flux dynamics and event dynamics, gives insight into the performance of remediation efforts, and to forecast changes in water availability (e.g. Blaen et al. 2016). These questions of water quantity and quality are generally what come to mind when monitoring programs are discussed. In tandem with these concerns, water monitoring is also an essential aspect for water reuse programs. For example, surveillance of the fate of inorganic and organic solutes in soils and water bodies is a common practice in areas which implement wastewater irrigation (e.g. Lesser et al., 2018).

River catchments and their corresponding groundwater bodies are diverse in nature. Catchment size can range from tens of square kilometers to millions of square kilometers. The average catchment size of major rivers is generally on the order of hundreds to thousands of square kilometers. Apart from size, flow rates, presence and size of groundwater bodies, climate, and land use characteristics are also important factors that differentiate between catchments. Anthropogenic land use is often a top factor when dimensioning water monitoring campaigns, as we usually want to characterize human impact on water quality and estimate how much water may be sustainably exploited, among other things. Anthropogenic-influenced water cycles present a unique challenge in terms of hydrogeological characterization, as differences from a natural water cycle can be significant. The water balance as a whole is often artificialized, and human activity tends to introduce an innumerable amount of chemical compounds into the water cycle.

There exist many methods and technologies for monitoring of catchment waters. In the past few decades, technological increase has made more robust monitoring more affordable. In addition, there are some tried-and-true traditional methods which are still heavily used today, and offer the benefit that more traditional methods tend to be more standardized on even a global scale. The appropriate choice of method for implementation will depend heavily on the nature of the catchment and the flux under question.

The current deliverable offers a guide for the monitoring of water and solute flux dynamics on a catchment scale, with a special emphasis on agricultural environments in the European setting. Select site investigation and monitoring techniques, including those which are well-developed as well as some emerging techniques, are discussed. The principal aspect of this discussion is on surface water and groundwater and the major factors that are relevant in controlling water fluxes, such as climate, soil, and anthropogenic activity. The monitoring of flux dynamics is dependent on catchment and flux characteristics. Thus, these aspects are introduced first. Then, monitoring setups are discussed. The intention is that this information can be useful for those in research, industry, and public works alike.

This project is carried out in the framework of the European-wide Marie Curie Innovative Training Network (ITN) known as INSPIRATION. The objective of those involved in this ITN is to find solutions for the sustainable intensification of agriculture so that soil and groundwater impacts are kept under control while food production meets the needs of a growing human population.

2 Factors Influencing the Monitoring Protocol

To carry out a successful monitoring program, some a priori information on the objectives and characteristics of the catchment should be gathered. The objectives will clarify what a monitoring network needs to contain, and characteristics of the catchment and fluxes under question will provide for a proper conceptual model of the area. This conceptual model should include descriptive factors of the catchment including its physical characteristics, as well as any known properties of physical or chemical fluxes. A solid conceptual model provides the understanding that is necessary to set up a successful monitoring regime.

2.1 Monitoring Objectives

A monitoring protocol depends first and foremost on the objectives of the campaign. For the purpose of consistency, monitoring types as distinguished in the Water Framework Directive are used in the current text. The WFD differentiates between three major monitoring types: surveillance, operational, or investigative monitoring. Within these types, the type of dynamic to be monitored is also important to clarify. For example, is the interest in water quality or quantity?

As per the WFD, surveillance monitoring programs can provide information towards an assessment of long-term changes in a catchment, including natural variations as well as anthropogenic-influenced variations. Operational monitoring should provide information on the present status of water bodies, and should assess impacts of remediation or other measures on the water body. Investigative monitoring is carried out when sources or magnitude of pollution or other processes are unknown. Surveillance and operational monitoring are often carried out in systems that are reasonably well understood, while investigative monitoring is often carried out in systems where there are important gaps in understanding. However, there is some overlap in application.

In practical terms, these differences generally signify that surveillance monitoring will demand the most regular monitoring. Investigative monitoring can be demanding of higher-frequency measurements, although often over a relatively short period of time (weeks to months). Investigative monitoring may also demand that more parameters be collected than would be in a surveillance monitoring program, where the problem is clear and the necessary parameters are identified. Operational monitoring may require a measurement only once a year or less. However, any type of monitoring program will contain a certain amount of fluidity to its regime, whether this be a change in frequency, addition or subtraction of parameters, or change in monitoring locations. For example, operational monitoring of wastewater irrigated sites often sample several times a year, and may add or remove parameters from year to year.

The objectives of monitoring will thus determine the parameters to be measured, the ideal geographical location of focus, and the monitoring frequency. These objectives should be clearly defined before committing to a campaign in order to ensure success.

2.2 Catchment Characteristics

Relevant descriptors for catchment characteristics include climate, geology, hydrology and hydrogeology, topography, and land use (Fig. 1). All of these factors influence catchment flux dynamics, and will play a role in determining the configuration of a monitoring network as well as the parameters to be measured.

***Figure 1**: Example conceptual model of a river catchment, including the presence of groundwater bodies and various anthropogenic influences*

Major climactic factors to include in a conceptual model are temperature, rainfall, and estimated evapotranspiration. Evapotranspiration estimations in turn require detailed information on humidity and wind characteristics as well as information about soils and plant cover. Such information will allow the user to properly estimate how much water is entering and leaving the system, as well as being stored and for how long.

Data on catchment geology, topography, hydrology, and hydrogeology will provide insight into the presence and extent of permeable layers, aquitard or aquiclude layers, and potential locations for increased or decreased surface water – groundwater interactions. For example, in shallow sediment aquifers, it might be assumed that groundwater – surface water exchange is diffuse, occurring along most or all of the length of a riverbed. The presence of fractured rock or karstic aquifers can signify that these exchanges are point-like in nature. Then, topographic maps in tandem with soil maps will help to determine which areas are likely to have naturally increased surface runoff levels. For hydrological parameters, a seasonally average flow rate and catchment discharge rates for surface waters should be known. In the case of aquifers, classic parameters such as hydraulic conductivities, water table, recharge sources, and direction of flow should be known. If possible, a recharge rate should be estimated. In the case of anthropogenically influenced areas, this estimation should account for extraction rates and potential artificial sources of recharge (irrigation, pipe leakages).

In addition to physical characteristics arising from the above mentioned factors, chemical characteristics resulting from these factors are equally important. When referring to chemical fluxes, the redox conditions, for example, within a catchment will be a huge determining factor for chemical retention, release, or degradation, and the rate of reaction. Redox conditions are largely controlled by soil and geology, land use, and saturation levels. Similar can be said for pH, as well as temperature (although temperature is a physical characteristic, strictly speaking!). Often, particularly in the human environment, these chemical conditions will be altered by human alteration of the landscape (discussed below). If the 'background' chemical conditions can be known, it is perhaps easier to detangle what has been changed due to human influence.

Land use within a catchment is often the most complex factor to include in a hydrological conceptual model, due to relative lack of process understanding as well as difficulty in obtaining detailed information. However, as previous studies have shown, anthropogenic land use factors have an intimate impact on environmental water quality and quantity (Eckhardt and Stackelberg, 1995; Wittmer et al., 2010), and thus cannot be disregarded. Important factors include the type of land use, presence of impervious surfaces, and local technologies including irrigation and drainage systems, storm drains, river canalization, and wastewater networks and treatment, for example. Land use types can be bulk-classed into agricultural, urban, and industrial land use, and further refined if necessary (i.e. cultivated crops vs pasture land within agriculture). Information on population density and water exploitation should also be included. Detailed information on anthropogenic land use will make it possible to identify artificial inputs, like irrigation waters or leaky pipes, and modified pathways, like decreased evapotranspiration and increased storm runoff over roads, or clogged riverbeds and decreased exchange with groundwater bodies. Local anthropogenic patterns will also determine which types of pollutants could be found in a catchment, where they may be entering the environment, will determine high- and low-risk zones for pollution, and high protection zones which may be in the vicinity of a protected ecosystem or a pumping well for municipal water supply.

2.3 Flux Characteristics

The characteristics of specific fluxes depend in part on the characteristics of a catchment under question. As briefly mentioned in the previous section, the dynamics of solvents and solutes moving through a catchment are dependent on the physico-chemical properties of that catchment. Understanding how the flux parameter(s) under study respond to the temperatures, or redox potentials, or recharge rates, or groundwater exchanges, found to dominate a catchment, is the first step in dimensioning a monitoring campaign.

There are multiple types of fluxes that can be monitored in a catchment study, and deciding on which ones are important for a given project will determine which parameters need to be included in monitoring and how often. The two major fluxes that are addressed in the current text are water fluxes (surface water and groundwater) and solute fluxes. Sediment or biological fluxes are not included in this discussion. Proper methods to use will also depend on the type of flux being studied. Methods for characterizing flux dynamics are covered in **section 3**.

2.3.1 Water Fluxes

The movement of water within a catchment is, in and of itself, an extremely important factor in making decisions on water resourcing, defining sustainable exploitation, or further to determine vulnerability to contamination. For example, determining catchment water fluxes can help with estimates of local and regional groundwater recharge, which is the most important variable in determining levels of exploitation which are sustainable. According to the European Commission, more than half of drinking water throughout Europe comes from groundwater, and more than half of European cities are currently in a situation of groundwater over-exploitation.

Water fluxes in catchments are dominated by climactic and physical landscape drivers, and can be extremely altered in an anthropogenic environment. A conceptual model should hopefully offer broad answers as to the source and quantity of surface and groundwater in a catchment and in what direction it is flowing. If more detailed information are available, precise flow pathways as well as storage or infiltration in the unsaturated zone might also be determined.

2.3.2 Solute Fluxes

Solute fluxes in water bodies are concerned with dissolved solutes that pose a threat of contamination to fresh water bodies. While water fluxes are of extreme importance for ensuring adequate freshwater reserves into the future, monitoring solute fluxes (herein referred to as contaminant fluxes) are of importance for ensuring that such reserves remain usable. Water fluxes will give insight into the flux dynamics of solutes, but they can only tell part of the story. Water fluxes represent the physical driver of solute movement in catchment waters, but chemical (and biological) characteristics of the environment will also have considerable influence on contaminant fluxes. Landscape health, such as riparian zones and wetlands, has been proven to be an important factor in determining solute fluxes across interfaces.

Some contaminants are naturally occurring in nature, while many of concern are anthropogenic in origin. Notable examples of naturally-occurring contamination relevant in many regions of the world would be geogenic arsenic or fluoride contamination in groundwater (Bretzler and Johnson, 2015). However, in the European context, much of the contamination found in catchment water is a direct result of human activity. Human-induced chemical contamination of water resources can be via inorganic or organic constituents, while organic synthetic products are of ever-increasing concern. Nitrates and phosphates are among the biggest culprits of inorganic contamination, while pesticides (including herbicides and biocides) are widely-known contaminants in the organic category. Nitrates, phosphates, and pesticides are all found in abundance in both agricultural and urban impacted catchments.

3 Monitoring Protocol

In the context of surface and groundwater, monitoring of flux dynamics on the ground generally includes a network of measurement points and lines (in the case of river sections). Measurement points are often equipped with a variety of sensors which take measurements of basic parameters at fixed or adaptive frequencies. Samples should be collected at these points either manually or with an automatic sampler for more detailed information on water sources and contaminant fluxes. Sensors and samples collect data over a predetermined period of monitoring time, ranging from days to decades, in order to gain information on short-term or long-term temporal trends. In-field measurements may be supplemented with remote sensing data. In rare cases, remote sensing will be the main data source, with few to no in-field measurement points when none are available.

The first steps in implementing a monitoring program will be to select sites and measurement methods to use. When sampling is involved, the frequency and type of analysis needs to be determined. A successful campaign depends on representative data, which is in turn dependent on site selection and sampling frequency.

Methods for monitoring surface and groundwater bodies has seen great improvement in the last decades due to increases in understanding about flow and solute transport, particularly helped by increases in available technologies such as automatic sensors, sensor types and samplers, wireless networking, adaptive measurement frequencies, and remote sensing. These technologies have been an integral part in gaining understanding of flux dynamics on specific time scales, from short-term event dynamics (e.g. Schwientek et al., 2016) to long-term inter-annual changes.

Although monitoring networks are most often designed to assess anthropogenically impacted areas, there is a need to focus also on the surveillance of so-called reference sites, which are characterized by little to no presence of anthropogenic pressure with good quality conditions (Hering et al., 2010). Reference areas will reinforce assumptions of catchment dynamics in the absence of human influence. These types of sites are of interest for creating a reference to which impacted sites may be compared, as well as for the analysis of long-term trends due to large-scale phenomena such as climate change.

3.1 Selection of Monitoring Sites

As previously mentioned, selection of sites to include in a monitoring campaign will depend on catchment characteristics which have been organized into the conceptual model. Selection of sites will also depend on more logistical issues such as ease of access, availability of existing data and monitoring sites, and availability of means to install new monitoring wells, if necessary. When existing wells are being used in a monitoring network, well configuration should be known (i.e. total depth, screen depth, screen length), and it is ideal when the details of well installation (Fig. 2, drilling method, packer material, well log, level of development, …) are known as well.

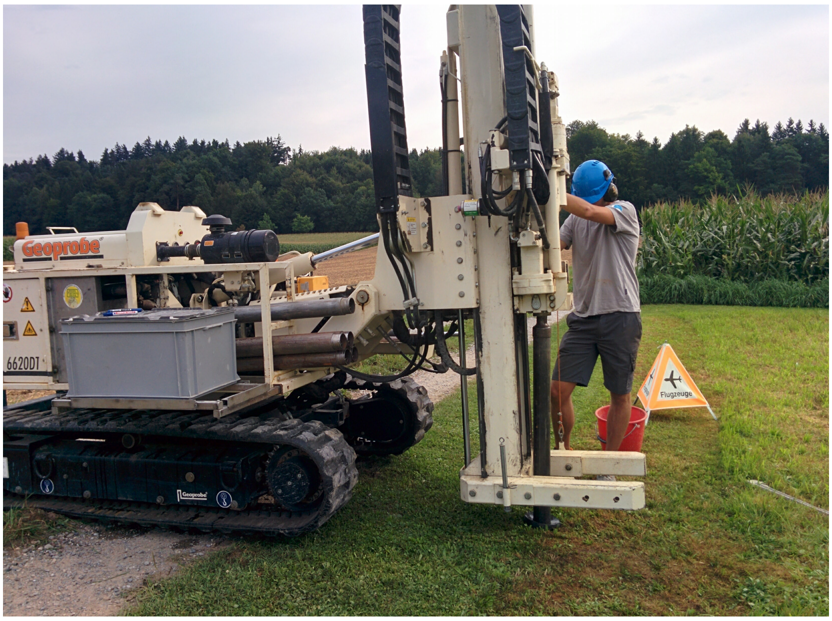

***Figure 2**: Typical illustration of monitoring well installation*

Surface water sampling along rivers should include, in the very least, one gauging station at or near the discharge point, and when possible, several locations along the length of the river, including headwaters, more-or-less evenly distributed. Care must be taken around tributaries and distributaries, and when possible, gauging stations and sampling points should always be located upstream of these branches in order to properly capture the dynamics of the main river. When tributary influence is desired, measurement points should be placed directly upstream and directly downstream of the discharge point along the main river. When assessing tributaries, gauging points should also be located at the discharge point and at several points along the tributary length.

Groundwater monitoring is carried out by using a network of monitoring wells or piezometers. The number of wells needed to make up a monitoring network is dependent on the size of the catchment, the changes in groundwater levels, and the nature of any present solutes of concern. In general, in larger catchments a smaller number of monitoring wells will be used per square kilometer, to ensure that the entire area of concern may be covered. Smaller catchments may allow for a higher well density per square kilometer, simply due to their size. However, even in larger catchments, a higher density of wells or special configuration over a smaller, specific area will be ideal. Such a configuration should be set up at active interfaces, in areas where groundwater is heavily pumped, in areas where contamination is known to occur, or in other areas where flux dynamics are thought to be most relevant. Well-designed, special configurations can be made possible when a detailed conceptual model is available.

A few examples of the selection process for specific catchment areas is now given. Where present, groundwater – surface water interfaces are among the most common areas which need to be characterized in order to properly determine catchment-level dynamics. Depending on the assumed nature of this interface, surface water and groundwater monitoring points should be planned to capture riparian dynamics, direction of flow across the interface, or evolution of chemical characteristics from surface to ground. When a surface water body is large, multiple measurements along the cross-section of the riverbed should be taken, including at the riverside and in the center of the river. For flow measurements, this can be achieved by carrying out a velocity profile. One to three groundwater wells should be located in proximity of the measured surface water site. These will be important to understand the transition of physical and chemical properties from surface water into groundwater, and can offer insight on long-term as well as event-based responses. Another example that demands a higher density of measurement points is near a contamination source. A contamination source might be part of a wastewater network, an irrigated crop field, a cattle farm, or a legacy industrial site. A higher density of monitoring wells is again ideal to assess changes within and at increasing distances from the source. This will give information on the expanse of a contamination issue, as well as any chemical processes that may be acting on the contaminant flux in the subsurface. When contaminant sources are near to rivers, a measurement point should be placed along the river just downstream of the source, and potentially at multiple points of increasing distance downstream of the source.

One of the most delicate balances when organizing a monitoring regime is balancing between large-scale representative monitoring locations, as evenly spaced as possible, and small-scale concentrated monitoring of areas of specific concern (near-source, riverside, known contaminated areas, etc.). When evaluating monitoring data, significant bias can arise depending on the spacing and timing of sampling. The timing issue is partially resolved by the use of automated sensors (see **section 3.5**). However, the spatial issue is constrained by the needs of particular monitoring type as well as access to sites. Often when carrying out an operational monitoring plan at a local site, the overall catchment dynamics are poorly represented and thus increases in bias are created. When carrying out surveillance or even sometimes investigative monitoring at the catchment scale, smaller-scale dynamics of solute or sediment fluxes, which are important factors in overall catchment dynamics, can be missed. The user must take care to balance between scales.

3.2 Data Collection Methods

There exist many methods to collect data in a catchment monitoring program. These can be largely grouped into in-field methods and remote sensing methods. Within the context of the INSPIRATION network, Bujak (2017) has reviewed common in-field monitoring methods used on the catchment scale, with case studies to illustrate how and why such monitoring technologies are utilized.

Briefly, in-field methods include sensors deployed in the field, manual measurements, and sample collection from point or line sources. Remote sensing uses either passive or active sensing technologies mounted to an aircraft or satellite in order to collect data often over larger surface areas rather than point or line measurements. Remote sensing data may be collected by individual users with proper material, or may be bought from institutions collecting such data (examples include ASTER from NASA and Japan Space Systems, or the LANDSAT project from the USGS and NASA). Remote sensing is particularly attractive for monitoring in ungauged basins (Sivapalan et al., 2003), however should be supplemented with field observations whenever possible.

Examples of measurements in the field for surface water fluxes are the use of flow meters, temperature profiling, or velocity profiling. Flow meters deployed at river gauging stations are particularly appropriate for measurements at a catchment discharge point, and may also be deployed along the length of a river. Temperature and velocity profiling along river sections are particularly well suited to determine discrete groundwater exfiltration points (for example in karstic or fractured rock environments), or surface infiltration points when used in tandem with a flow meter. These needs are often encountered in projects of operational or investigative monitoring, although not exclusively. Finally, remote sensing is particularly useful for determining changes in water flux over large scales, and so is well suited for large catchments. Information on the use of remote sensing in hydrology is given by (Schmugge et al., 2002).

Groundwater flow characteristics are somewhat more difficult to quantify, although methods do exist to this end. The end interest of gaining information on groundwater fluxes is generally to characterize groundwater recharge or discharge, changes in recharge over time, sources of recharge, and specific groundwater flow pathways. Some examples of field measurements that can be used to estimate groundwater flux include tracer tests or slug tests. Temperature and EC profiling have been used to detangle groundwater flow patterns in heterogeneous environments (Michalski, 1989), and temperature profiles are known to have a variety of applications in quantifying groundwater fluxes (Bense et al., 2016; Keery et al., 2007). In addition, stable water isotopes have been used in many studies to track the source of groundwater (e.g. Moeck et al., 2017). A multitude of geophysical methods, including wellbore, surface, or airborne, can also be used to collect data relevant for groundwater flux estimates, flux dynamics over time, and recharge estimates (Rubin, Y., Hubbard, 2005; Singha et al., 2015). Remote sensing data, including satellite imagery, temperature, or radiometry, can be particularly powerful for monitoring water flux dynamics, and there are many examples in the literature on using this data to estimate spatial changes in groundwater recharge or discharge over time (e.g. Jackson, 2002; Tweed et al., 2007). Often, this is carried out by identifying correlations between physical catchment characteristics and water movement, such as vegetation cover or temperature.

Solute flux dynamics can often be monitored in-situ with basic physico-chemical parameters including temperature, electrical conductivity (EC), pH, oxidative-reductive potential (ORP), oxygen content, or turbidity. For a low-cost or simple, exploratory approach, measurement of some or all of these basic parameters can be used as an indicator for water quality. For example, it is well known that EC can be a good proxy for inorganic contaminant concentration. All of these values can also give the investigator an idea of how likely a certain reaction affecting contaminant flux dynamics is to occur. pH and redox conditions (e.g. Burke et al., 2014) are particularly powerful determiners for this purpose. Monitoring of physico-chemical parameters can also offer insight into contaminant attenuation during such practices as artificial recharge (e.g. Massmann et al., 2006). In addition, efforts are underway to develop cost-effective and accurate 'lab on a chip' sensors which can measure more specific parameters such as contaminant concentrations (Jang et al., 2011), but for the most part, such globally-applicable sensors are not yet reliably available on the market.

For monitoring of specific compounds, therefore, laboratory analyses remain indispensable. Measurement of inorganics in the lab environment is a well-established and standardized practice, and a great number of synthetic organic compounds are also quantifiable with in-lab technology. This makes laboratory analysis an integral part of contaminant flux monitoring campaigns.

Finally, it is always good practice to use multiple data types to analyze in tandem, which can increase accuracy and reinforce hypotheses formed about specific processes. For example, river velocity profile data used with temperature data (from a distributed temperature sensor, for example), can help to validate specific points of groundwater exfiltration points along rivers. As another example, when samples are collected to analyze inorganic chemistry, field physico-chemical parameters should also be collected (with a sensor or a handheld device) in order to understand what drivers might be present and having an impact on the water signature.

3.3 Sampling

As laboratory analyses remain indispensable for most monitoring campaigns, regular sampling campaigns are necessary in most monitoring regimes. Samples are collected to analyze inorganic chemistry (nitrogen, phosphorus, heavy metals, among others), organic micropollutants (including pesticides, pharmaceuticals, lifestyle products, and transformation products, among others), industrial contaminants (flame retardants, VOCs, SVOCs, among others), and isotopic species. Except for isotopes, laboratory analysis is principally concerned with solute fluxes. Isotopic analysis may be used to detangle either water or solute fluxes.

Logistically, for all sampling campaigns, a standardized sampling protocol should be followed. Standardization allows for higher accuracy and lower risk of sample contamination, and makes comparisons with other datasets and other institutions easier in the long term. When conducting a sampling campaign, it is ideal for one user to carry out all sampling of one type across the entire network. This avoids errors which can arise from varied handling and sampling techniques from different users. However, there are small differences which arise even within the confines of standardized sampling. From time to time, duplicates or triplicates of samples at one monitoring site should be measured for quality control and error analysis.

Generally, separate samples need to be collected for each different type of analysis. For example, inorganic chemistry samples can be collected in plastic or glass bottles, and headspace is not an issue. Samples should be measured within 48 hours, however. Samples for isotopes generally need to be collected in shaded glass bottles, and headspace needs to be eliminated. Isotopic samples can theoretically be stored for months before measurement, however sooner is always better. Finally, sampling of organic contaminants is a particularly delicate task. It is advised to work with muffled (heat decontaminated) glass jars, to wear gloves, and to avoid sample contact with plastic lids by using aluminum covers, for example (Fig. 3).

***Figure 3**: Sampling for organic micropollutants in surface water: always use glass bottles and wear gloves!*

3.4 Sampling Frequency

The frequency of sampling is an important factor to properly characterize flux dynamics. Samples should be collected with a frequency that clearly represents the dynamics which are occurring, and both natural and anthropogenic variations should be targeted. To characterize seasonal changes, for example, at least one sample per season should be collected. Samples should be collected just before and after the start of crop seasons when relevant. Event samples should also be targeted in order to understand catchment dynamics as a response to storm events. This generally translates to higher frequency sampling during a rain event, which is made easier by using an automated sampler.

3.5 Wireless Networks

Natural systems display dynamics on various time-scales. Since manual measurement campaigns can be biased with regard to the time of day, weather conditions, or duration, much effort has been devoted to the development of autonomous, in-situ measurement technologies. Nowadays, most basic sensor types are available for long-term monitoring, and are increasingly outfitted with communication modules to complement real-time telemetric data supplied by remote-sensing.

The advantages of long-term in-situ measurement devices are manifold: dynamics can be observed in arbitrary time scales and in remote locations. For some of the most relevant physical water properties (temperature, atmospheric pressure, hydraulic head, electric conductivity) many such sensors already exist and are thus relatively more affordable, but for many others (pH, nutrients, trace contaminants) development of true long-term solutions is still a work in progress. Drawbacks of such field sensors include higher acquisition costs, a limited range of parameters, and the risk of sensor failure going unnoticed for long periods of time.

In situations where the latter risk is unacceptable, or a real-time data feed is required – for example to supply a real-time model with data – the establishment of a wireless sensor network is an option (Römer and Mattern, 2004). Approaches like LoRaWaN employ a local node which communicates through low-range transmission with its sensors (Fig. 4-1). The node collects the data, and relays it in packets to a server (Fig. 4-3). Advantages of such systems are a comparably high data transmission rate, at the cost of a limited reception radius. Especially in remote regions, or at sites whose measurement points are distant from each other, this technique may perform inadequately.

For such location, GSM-based techniques may be a better choice (Fig. 4-2). Typically, these are sensors which communicate and transmit their data through mobile phone networks. These systems can be applied anywhere with mobile phone reception, but come with a cost for every bit of transmitted data, which may render them unsuitable for sensors which transmit large quantities of data.

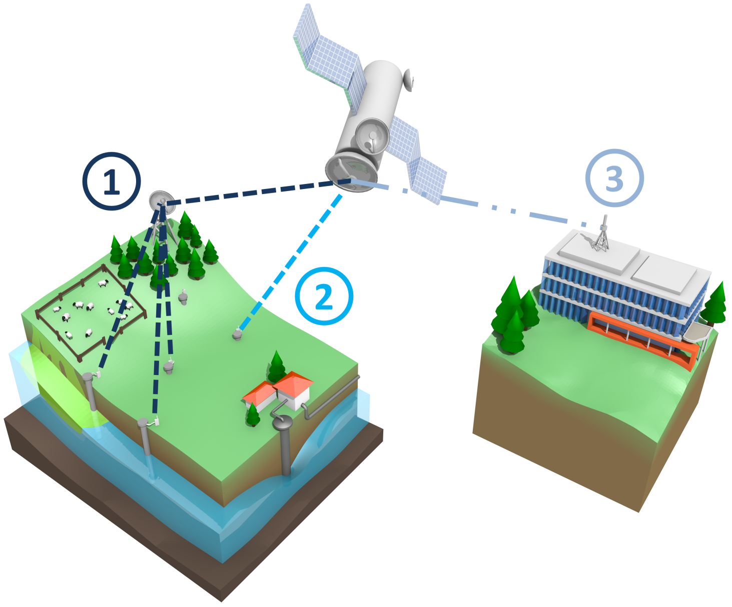

***Figure 4**. Conceptual overview of wireless sensor networks, featuring a low-range, node-based (1) and GSM-based (2) setup transmitting data to an off-site server (3).*

4 Discussion

This document has offered a brief guide to monitoring chemical and water flux dynamics on a catchment scale, including discussion on important factors to consider when dimensioning a monitoring campaign, monitoring methods available, and factors to account for when deciding on monitoring locations and sampling. Modeling as a tool to organize and interpret data is also an important step in monitoring campaigns, however, we kept our focus on field methods and data collection, leaving interpretation to future texts. The hope is that this guide will help stakeholders to collect data on groundwater and surface water flux dynamics in the most accurate way possible.

The focus of the current text was on rivers and groundwater systems in particular. Similar guides and methods could also be applied to characterize lakes and other surface water reservoirs, as well as soils. Soils in particular can be an important driver of flux dynamics in catchments, but were deemed beyond the scope of this text. Additionally, the emphasis of the current text has been on physico-chemical properties of fluxes. Of equal relevance in surface waters would be biological or other ecological parameters, which are included in many water monitoring programs and are heavily highlighted in the Water Framework Directive in particular. And, aside from water fluxes and solute fluxes, sediment fluxes are another item that can pose a major risk to fresh water quality and should be considered in monitoring programs where relevant.

Despite a great deal of progress that has been made on system understanding and technological availability, gaps in capability and understanding persist. It is imperative to close these gaps, particularly as our environments become more complex because of our human alteration on the environment. Determining water quantity and quality for all purposes – drinking, irrigation, industry, ecosystem functioning – will be a decisive factor for sustainable use, especially into a future where water cycles are changing and demand for resources is projected to grow. We firmly believe that if we are accurately able to characterize water bodies,

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