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Optimizing the water quality monitoring network by maximizing the economic value of information

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Acting on water quality requires, above all, knowing about it. Water quality monitoring networks (WQMN) first appeared in the Netherlands in 1950 and expanded to other developed countries since the 1960s¹ to provide this knowledge. However, perfect knowledge based on continuous measurement in time and space is not feasible. A central question for network managers is: what is the optimal network design?

There are two types of literature in the field of WQMN. The first takes into consideration hydrological and physical aspects to optimize the WQMN design (physical optimization). The second type estimates the Economic Value of Information (EVOI) for a predefined WQMN. Our research combines the two types of literature by proposing economic optimization to determine the WQMN design that maximizes the EVOI. Here we overview WQMN economic optimization, our new model, and what this contributes to water quality decision-making.

Physical optimization: spatial and temporal factors

The literature on physical optimization has focused on taking hydrological considerations into account when designing WQMN, with the aim of minimizing imprecisions regarding water quality monitoring. The optimization can be spatial and/or temporal.

Spatial issues comprise the optimization of the location and the number of monitoring stations. For example, some authors² determined the location of the monitoring stations that minimized the deviation of the observed pollution from the average water pollution, others³ focused on determining the location of the monitoring stations that minimized detection time for accidental pollution.

Sampling is costly, and so temporal issues deal with the optimization of the sampling frequency, with the aim to eliminate redundant information and unnecessary sampling. For example, if the WQMN objective is only to determine the pollution trend: upward, downward, or no trend, the frequency of the measurement should be the smallest that gives this information⁴.

Economic Value of Information (EVOI)

The second type of literature has focused on estimating the benefit provided by a WQMN with a predefined design. These efforts are valuable because measuring pollution has a cost. Thus, the knowledge of the "benefit" generated by the WQMN would allow the network manager to carry out a cost-benefit analysis based on the number of stations and the temporal intensity of the measurement. The benefit generated by WQMN can be estimated by the EVOI. The EVOI is calculated as the difference between the benefit derived from a decision based on additional information and the benefit derived from the decision without additional information.

EVOI estimation techniques are based on Bayesian decision theory. Bayes' theorem is used in the field of decision-making under uncertainty. When a decision-maker updates his or her prior beliefs by acquiring new information, this leads to better informed decisions. Thus, the relative benefit of the new information can be estimated using a Bayesian model.

Economic optimization

In our studies^{7, 8}, we combine, for the first time, both types of literature in order to determine the design of the WQMN that maximizes the EVOI. This is what we call the economic optimization.

Our model couples a network design optimization problem with a Bayesian model to determine the value of information in a decision context.

In our model, the information collected must be used for a short- to medium-term decisions. For example, the authorization/banning of swimming in a lake, or actions to stop the spread of pollution. Our method cannot be used to calculate the EVOI for a monitoring network aimed at observing the evolution of water quality over the long term just for "information" purposes.

The benefits of physical versus economic optimizations in different scenarios

To further develop our methodology, we take the example of a WQMN where the sole objective is to detect any accidental pollution that may occur with a uniform probability over a stretch of river (or another freshwater system).

As a first step⁷, we compare the EVOI of a physically optimized WQMN and of an economically optimized WQMN. In a physically optimized WQMN, the monitoring stations location minimizes the detection time of an accidental pollution. In an economically optimized WQMN, the monitoring stations location minimizes the economic damage generated by the accidental pollution.

The objective of the comparison is to measure the advantage of our method. For this purpose, we assume three different vulnerability scenarios along the river:

- uniform vulnerability,
- decreasing vulnerability (pollution generates more economic damage upstream), and
- increasing vulnerability (pollution generates more economic damage downstream).

Vulnerability to pollution can vary due to many factors. Broadly speaking, these factors can be physical (e.g. water flow rates) or economic (e.g. water uses). Thus, the same pollution may not generate the same economic damage in a swimming area, a catchment area for producing drinking water, a fishing area, etc.

In this study, we consider the spatial question that is optimizing the number and location of stations for each of the three vulnerability scenarios. In general, stations must be located where the stakes are highest: further upstream in the decreasing vulnerability scenario, and further downstream for the increasing vulnerability scenario. Moreover, on certain parts of the river, if the cost of action to stop the damage generated by the pollution is greater than the damage potentially avoided, it is not economically rational to locate stations there. Thus, depending on all these elements, economic optimization may appear more or less useful.

Our results show that the advantage of maximizing the EVOI compared with physical network optimization is relative to the context, i.e., the number of stations and the vulnerability scenario.

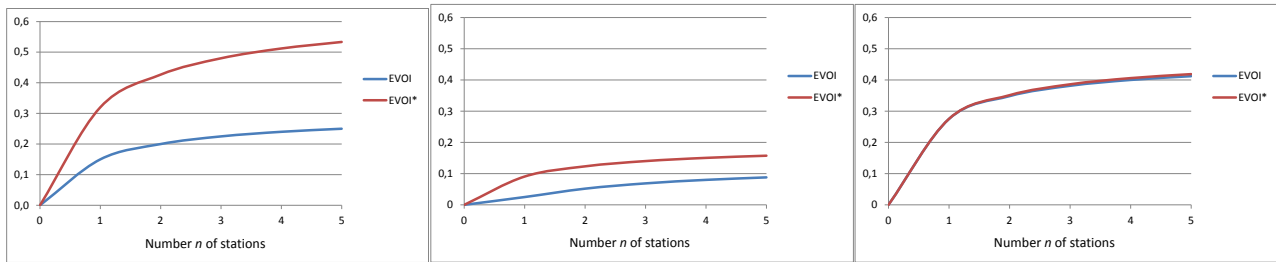


Figure 1. EVOI by number of stations for uniform (left), decreasing (middle) and increasing (right) vulnerability scenarios (Source ⁷¹)

The advantage of economic optimization is higher for the uniform vulnerability scenario. The advantage is almost nil for the increasing vulnerability scenario (Fig. 1).

The relative benefit of economically optimizing the design is independent of the number of stations in the uniform vulnerability scenario. By contrast, this benefit is dependent on the number of stations in the other two scenarios of increasing and decreasing vulnerability.

Spatio-temporal economic optimization design in integrating monitoring costs

As a second step⁸, we optimize the spatio-temporal design of the WQMN by maximizing the EVOI and integrating costs of monitoring. This methodology provides network managers with tools to answer key questions such as: Are the costs of monitoring justified by generating benefits in excess of costs? What network design (spatial and temporal intensity of measurement) should be adopted to maximize the net benefit generated? What is the optimal network design when working with a fixed budget?

We observe that as the temporal or spatial intensity of the measurement increases, the EVOI increases, but at a decreasing rate (Fig. 2). In relative terms, we observe that we earn less from each additional unit of spatial or temporal measurement, which suggests that in the presence of monitoring costs, continuous measurement is a waste of money.

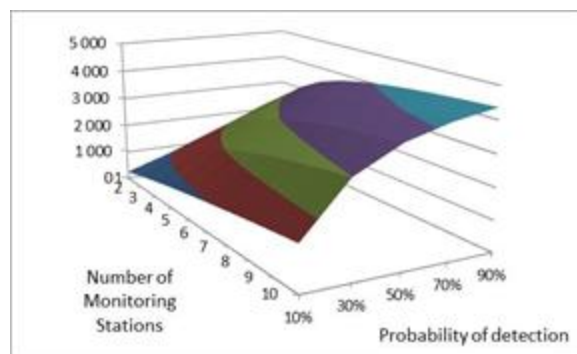


Figure 2. Variation of EVOI according to the spatial and temporal intensity of the measurement (Source ⁸²)

¹ These figures show the evolution of EVOI according to the number of monitoring stations for economic (EVOI* in red) and physical (EVOI in blue) optimization. For more details, please refer to article ⁷.

² In the article from which this figure is taken, the temporal intensity of the measurement is not estimated by an annual frequency of measurement but by a probability of detection of accidental pollution at each station. For more details, please refer to article ⁸.

Moreover, in maximizing the net benefit, we note that the more the number of monitoring stations increases, the more the maximum of the net benefit (EVOI minus costs of monitoring depending on the number of stations and the frequency of measurement) is obtained with a lower measurement frequency.

When we maximize the EVOI with a fixed budget, it is interesting to note results that may appear to be counter-intuitive, such as reducing the frequency of the measurement when the budget increases. Indeed, depending on the context, adding an optimally located monitoring station may be more advantageous, even if the frequency of the measurement is reduced over the entire network.

Both results above show the trade-off between increasing the intensity of the measurement spatially and temporally. Increasing the number of stations or the frequency of the measurement in our context of accidental pollution detection means choosing between increasing the probability of detecting the pollution earlier (with a station closer to the pollution emission), or increasing the probability of detection at fixed stations (by increasing the frequency of the measurement). The trade-off between these two options will depend on the evolution of costs and the EVOI generated by each.

Increasing the probability of detection by increasing the frequency requires an increasing cost at an increasing rate, whereas the increase in cost is linear when the number of stations is increased. Furthermore, the increase in EVOI stagnates more quickly when it is generated by a temporal increase in the measurement. Thus, increasing the frequency of monitoring becomes less advantageous than increasing the number of stations.

Providing better responses to environmental challenges requires, first of all, better informing the relevant decision-makers. In the case of pollution in freshwater environments, information on quality is provided by monitoring networks whose design involves choices related to the number & location of monitoring stations as well as temporal frequency of the measurement. These choices made by network designers/managers can thus have a significant impact on the environmental outcomes that result from them. Research work on WQMN design optimization therefore deserves special attention.

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