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DESIGN, IMPLEMENTATION AND OPERATION OF A LARGE SCALE GROUNDWATER QUALITY MONITORING NETWORK

G. ZACHARIOUDAKIS[1], M. STREETLY[1] AND M. FERMOR[1]

ABSTRACT

The main elements of the development of a groundwater quality monitoring network include, setting of objectives, selection of design criteria, frequency and determinands for analysis, and a choice of an appropriate data management tool for data manipulation, interpretation and reporting. The objectives of the monitoring network should be initially defined. The hydrogeological setting, the land use, budgetary limitations and monitoring points density comprise the main design criteria. The sampling frequency depends mainly on the hydrogeological conditions and the suites chosen for analysis is a function of local issues, the natural geochemical conditions of the aquifer and also human activities which could introduce a potential contaminative threat. The selection of a robust data management system is essential to handle, migrate and adequately store the data to enable interpretation and reporting.

KEY WORDS: groundwater quality; monitoring network; Water Framework Directive; data management; sampling strategy

1. INTRODUCTION

During recent years the increasing need to manage water resources proactively and the growing awareness of the technical difficulty of remediating groundwater once it has become contaminated has led to an increased requirement for monitoring the background quality of groundwater. Groundwater quality varies naturally in space and time. This natural variability of groundwater quality is a complex function of the physicochemical processes occurring between the aquifer material and the groundwater and the residence time in the aquifers. It is neither technically feasible nor economically justifiable to monitor everywhere all of the time. Consequently, the design of a groundwater quality monitoring system involves a cost-effective approach that considers the objectives and any limitations. The monitoring points locations, the time, the sampling frequency, the results, analysis, storage, interpretation and reporting are also issues that need to be investigated and resolved.

To be truly effective monitoring programmes for groundwater quality therefore require that:

- the objectives of the monitoring are properly defined
- a transparent and achievable strategy is established
- there is sufficient conceptual understanding of the aquifer and pressures on it
- there is adequate planning of collection, handling storage and analysis of samples.
- data are properly archived and easily retrieved so that interpretation and reporting is simple.

This paper outlines the main issues involved in the design, implementation and operation of a groundwater quality monitoring network. This work presents an overview of the ongoing review of national groundwater quality monitoring in England and Wales(ESI 2000a).

2. NEEDS AND DRIVERS FOR THE DESIGN OF A GROUNDWATER QUALITY NETWORK.

The main legislative driver for national monitoring of groundwater quality in the European Union is currently the recently published the Water Framework Directive (2000/60/EC).

The purpose of this Directive is to establish a framework for the protection of inland surface water, transitional waters, coastal waters and groundwater. In regards to groundwater quality issues, this framework is intended to prevent further water quality deterioration, restore bodies of groundwater and ensure a balance between abstraction and recharge.

1. Environmental Simulations International (ESI) Priory Road, Priory House, Shrewsbury SY1 1RU, UK

The Water Framework Directive specifies that all Member States should monitor groundwater bodies both qualitatively and quantitatively. These groundwater bodies would meet certain criteria (such as supported yields, use of water). General guidelines for groundwater quality monitoring, network design, frequency of sampling, interpretation and reporting are presented in Annex V of the Directive.

The Groundwater Directive (80/68/EEC)mainly focuses on pollution prevention of the groundwater by substances that are grouped in two lists (List I and II)and are reported in detail in the Directive Annex. It requires a clear understanding of the hydrogeological systems, the natural defensive and attenuating properties which require the establishment of baseline (natural)groundwater quality conditions through surveillance groundwater quality monitoring.

Another relevant Directive that requires groundwater quality monitoring is the Nitrates Directive (91/676/EEC) where State Members are required to establish surveillance monitoring of all groundwater to provide the basis for designation of Nitrate Vulnerable Zones and effectiveness of action plans.

3. OBJECTIVES OF A GROUNDWATER QUALITY MONITORING ASSESSMENT.

The main objectives of a national groundwater monitoring strategy are principally driven by the legislative and institutional framework, the importance of groundwater as a resource and the strategy for the protection of groundwater. It is essential to identify the objectives of a groundwater monitoring strategy prior to the actual network design. The objectives of a groundwater monitoring strategy should(Chilton, Milne 1994)

- comply with statutory and non statutory National and European commitments
- provide objective comparable and reliable information that could be used, stored, combined and retrieved in a simple way.
- define baseline groundwater conditions, in both currently used aquifers and those as yet unused, so that suitability for future use and potential impact of permitted discharges is assessed.
- determine trends in groundwater quality and quantity, against the identified baseline resulting from natural causes, from the impact of diffuse pollution sources (particularly for nitrates).
- provide a three-dimensional picture of groundwater quality within aquifers, where suitable infrastructure exists.
- provide early warning of groundwater pollution, particularly in outcropping aquifer recharge areas and other sensitive areas, such as wetlands.
- identify links between groundwater systems, surface water systems and terrestrial systems (land use) to support a truly integrated approach to river basin management.

4. DESIGN CRITERIA

At a large scale, each groundwater body may be characterised and differentiated by its unique socio-economic regime. Local needs and pressures could influence the theoretical criteria that would apply to the design and choice of the appropriate monitoring points for groundwater quality monitoring.

The criteria selected should reflect and incorporate the guidelines set by legislative bodies, the land use and local issues. They also need to be structured on a robust scientific base reflecting the hydrogeological setting. Costs should be analysed and the criteria chosen should ensure a cost effective approach. Application of these criteria should result in a network that will also satisfy the specified objectives of the monitoring.

The design criteria are related and should satisfy the specific objectives of the groundwater monitoring.

An initial step is the aquifer characterisation in respect to supported yields, use and significance. In this stage the aquifers that would be required to be monitored should be selected.

A hydrogeological assessment should identify the main groundwater flow mechanisms, the residence time of the water in the aquifer, the interaction of groundwater with surface water bodies, and the recharge and discharge zones of each aquifer. A conceptual model should quantify the demand and the available resource. The permeability and hydraulic properties, the drift or superficial deposits cover and the soil leaching potential should be assessed to identify the natural protection of the system to potential contaminative risks. In other words, the overall aquifer complexity and vulnerability should be determined.

The different types of land use should be defined so that susceptibility to various types of potential contamination is assessed. Groundwater quality is affected by the land use overlying the groundwater system as well as up hydraulic gradient in the aquifer. The land uses could be grouped in simple categories to avoid complications in the methodology development.

One suggested approach to the selection of the appropriate points reflecting the different steps highlighted above, could be the structure of a prioritisation matrix that will assess the needs, pressures and priorities of use of a specific point within a designed network.

Table 1 presents an example of such a matrix considering the various components of the criteria design:

Table 1 Monitoring points selection matrix

Priority Level[i]	Principal Purpose/Criteria[ii]	Minimum Quantity[iii]	Aquifer A (example)
Optimum number of monitoring points required[iv] ⇒		12	
1a	Recharge (Unconfined)	1	BH1
	Discharge	1	BH9,6
1b	Confined Aquifer	1	BH3
2	Land Use[v] -Arable	1	BH1,8
	Land Use - Urban	1	
	Land Use -Grassland	1	BH4
	Land Use - Semi-natural vegetation	1	
	Land Use Forestry	1	
3	Land Use - Arable (deep/shallow)	1	
4	Land Use - Urban sub-division (industrial/residential)	1	
5	3-D monitoring	1	
3 - 5	Local/Other criteria	x	BH5,7

i ***Priority ranking for developing the monitoring network. Highest priority areas should be addressed first. Where local issues and conditions dictate, some re-prioritisation may be necessary for levels 3-5***

ii ***The monitoring point selected may satisfy more than one criteria, e.g. be suitable as the recharge and arable land use type sampling point. Hence, the borehole identifier inserted into the matrix may occur more than once.***

iii ***The minimum number of monitoring points required for each category in an optimised groundwater body network. Additional monitoring points are likely to be required for some categories on the basis of special density criteria and conceptual model.***

iv ***The optimum (target) number of monitoring points in each groundwater body should be determined depending on the hydrogeological regime of the aquifer and its importance as resource. The distribution of monitoring points should be based on the prioritisation matrix and the conceptual model. Statistical methods could also be used.***

v ***Land use within Groundwater bodies will be divided into one of five types and each will require a minimum of one monitoring point. Guidance will be developed to establish a protocol that considers how land use should be identified and appropriate areal thresholds***

The spatial density of the monitoring points should be derived after careful judgement of the parameters above. Statistical methods may also be considered for the calculation of spatial density requirements(Chilton, Milne 1994). These approaches focus mainly on network optimisation to ensure that the hydrogeological complexity and groundwater quality is properly represented. Statistical methods are difficult to apply due to uncertainties and the complex nature (heterogeneity) of aquifers. As an example Chilton and Milne (1994) suggested that for England and Wales the monitoring network should consist of:

- one sampling point per 25 km^2 for the outcrop areas of aquifers that have a high yield and are significant as a groundwater resource
- one sampling point per 35 km^2 for the confined areas of such aquifers
- one sampling points per 50 km^2 for outcrop and confined areas of other aquifers with smaller yields and which are less significant as a resource.

5. NETWORK IMPLEMENTATION

Implementation of the design criteria should have a primarily cost effective basis. A groundwater quality monitoring network should [illegible] boreholes.

Candidate monitoring points could include:

- a pumped borehole (public water supply, or municipal irrigation abstraction or industrial)
- a small abstraction (private borehole)
- a borehole that is not pumped but will be purged during sampling
- a spring

The differentiation of the above categories is the pumping yield and the time required for adequate sampling in each case. The ideal network should comprise mainly medium to small yield abstractions, purged boreholes or springs. In this way, the groundwater sampled represents relatively local to the sampling point quality conditions, which allow a clearer understanding of the quality issues and identification of potential deterioration origins in the monitored aquifer system. A hypothetical example should provide a better perception:

Let's suppose that the monitored aquifer system is an unconfined aquifer where large and smaller abstractions exploit the groundwater. The main land use in the area is arable. Selection of only the large abstractions in a monitoring network will show the effects of the farming activities in the groundwater (a rising trend to the nitrates) but no more information could be obtained. However, if smaller abstractions are incorporated in the network, more information about the source and the development of the contaminative threat could be extracted from a routine groundwater monitoring exercise.

However, such an approach is not always cost beneficial. Therefore, a maximum proportion of heavy abstractions over the total number of points within an aquifer should not be exceeded during the selection of the points that already satisfy the design criteria. This proportion is function of the size and the flow mechanisms within the aqnifer, the available points that satisfy the design criteria and the available budget for the selection and implementation of new monitoring points.

Adequate information about total depth, screen depth, aquifer monitored and construction specifications should be available for all the network monitoring points. Springs should also be targeted for implementation in the network subsequent to a hydrogeological conceptual model that will assess the spring flow mechanisms and groundwater origin. Furthermore, additional new boreholes should be drilled to satisfy density criteria and other network design factors. Abstraction points that exploit multi-aquifer systems should also be identified so that trends in the groundwater quality could be monitored in the vertical dimension.

Discharge wells and/or springs that are used as drinking supplies and are regularly sampled to comply with drinking water guidelines should also be identified and selected. In this case, specific agreements should be set with the companies/authorities responsible for the above category of wells so that the targeted sampling suites and frequencies for the monitoring purposes are agreed.

If more than one points are candidate for a specific site after this pass, then accessibility issues should be investigated. All the selected points should have a health and safety assessment done, which will guarantee the good condition and operation of the point, the safety and the good working conditions of the visiting sampling team.

6. SAMPLING FREQUENCY AND ANALYTICAL SUITES

The choice of analytical suite should represent a balance between obtaining sufficient information to characterise the baseline (natural) quality and identify presence of contaminants (as part of the surveillance monitoring for the protection of the resource) and cost of the analysis. It is suggested that determinand suites should be grouped into two categories: one standard suite and one selective suite.

The standard suite is the minimum for all samples collected. It should provide a basic analysis of all the major groundwater quality components. The selective suite is tailored to address specific monitoring requirements and the exact determinands should depend on site specific and local factors. Detection limits for each determinand should be appropriate for the major use of groundwater (drinking water)and in accordance with national and european requirements.

The selective suite will need to be determined based on the activity and take account of human activities that may occur and industrial processes. (ESI, 2000b). Table 2 presents a representative layout of the standard and selective suites.

Table 2. An example of Determinand suites for Groundwater Quality Assessment

Suite	Determinands	Notes
Standard	Field Parameters	
	Major Ions	
	Additional	Specified target determinands identified during initial characterisation which show concentrations above background (e. g. specific contaminants).
Selective	Heavy Metals	
	Organic Compounds	E.g. Aromatic hydrocarbons, halogenated hydrocarbons, phenols, chlorophenols, MTBE
	Pesticides	Land use, environment and property (e.g. mobility) dependent.
	Additional	Other target determinands and microbiological contaminants.

The sampling frequency of a monitoring network is considered as a function of the hydrogeological and hydrological conditions of each site, the objectives of the monitoring strategy, and the total budget allocated for the sampling and analysis operations.

The potential of groundwater quality alteration over a specific time period in a system, is related to the specific flow conditions, to the rate of flow and nature of the aquifer. Thus, these parameters affect the flow regime and the residence time of groundwater. Therefore, sampling should be more frequent in thin, highly permeable, fractured or karstic aquifers in contradiction to thick granular, confined systems.

Sampling frequency should be a function of the susceptibility to changes of the groundwater quality at a specific location. Groundwater residence time in the aquifer controls this susceptibility to changes. For example, in an aquifer where the flow domain is fast, the residence time is small and the groundwater flows with higher rates than within a slow flow domain. In such systems the potential of change in the groundwater quality is high. Therefore, sampling should be more frequent in thin, highly permeable, fractured or karstic aquifers compared to thick granular, confined systems.

The factors analysed above, are taken into account on Table 3 which presents a sampling frequency schedule. This approach has been also adopted by Chilton and Milne (1994).

Table 3. Proposed Sampling Frequencies

Aquifer		Determinand Suite Standard	Selective
Slow[1]	Outcrop	6 monthly	every 2 years
Slow	Confined	annually	every 5 years
Fast[2]	Outcrop	3 monthly	annually
Fast	Confined	6 monthly	every 2 years

[1] *'Slow' aquifers means those with low permeability and/or high effective porosity.*
[2] *'Fast' aquifers means those with high permeability and/or low effective porosity.*

7. OPERATION

Some of the issues that need to be addressed, considered and resolved during the operation stage include:

- sampling strategy
- sample analysis and method development
- data migration, results analysis and reporting

It is essential that a consistent and robust sampling methodology should be established prior to any sampling commencement. The groundwater sampling should be undertaken to fulfil field work health and safety requirements. The methodology should elaborate issues such as:

- recommended type and material of equipment for use
- purging volume and time to ensure aquifer rather than borehole water sampling
- secure sample storage and transport

Table 4 Main steps and levels within a groundwater monitoring programme[1]

Levels		Needs	Related Issues
Level 1	Legislative and environmental framework		
		Definition of objectives	EU guidelines and Directives National legislation Other initiatives
Level 2	Monitoring Strategy	Current situation assessment Prioritisation of needs	National guidance, establishment of protocols Human Resources, training Field and laboratory services Existing practice on data management, processing and reporting
Level 3	Operational programme	Development of the regional strategy - Design Criteria	Identification of groundwater bodies Collation and evaluation of existing data information on groundwater systems Local issues, pressures, water use, land use, water demands Development of conceptual model. Hydrogeological conditions Relevant point selection, prioritisation of selection (land use, hydrogeological considerations, abstraction rates), budgetary limitations Analytical suites, sampling frequency
		Network operation, sampling and analysis	Training, health and safety issues Equipment maintenance Data management, liaisons with labs, lab checking procedures, (blanks etc)
		Reporting	Analyses management, data processing, results, Feedback to the conceptual model, verification, reiteration of the process to achieve best representation of the system

[1]*In each level more than one issues could be identified/resolved simultaneously*

- equipment cleaning to avoid cross contamination when sampling more than one points with same equipment
- despatch of blanks and spiked samples to the labs for internal labs operations quality control.
- equipment storage and maintenance after the end of each sampling session.

It is apparent that operation of a large scale monitoring network will result in numerous samples with multiple results for each monitoring point during each sampling session. This data population requires a robust data management system which will provide sample tracing and validation but also results storage and retrieval for interpretation and reporting. Therefore, the data handling and management issues should not be overlooked or ignored.

The selected data management system should be used during the different phases of the process from the sampling stage to reporting. A unique identifier for each site should be established with a preferential encoding that should denote, location and aquifer monitored from which the groundwater is sampled. The sample codes should be created and input in the system prior to the sampling process. The sampling team should be supplied with the codes and assign the appropriate one to each sample after collection. The laboratories should use if not the same, a compatible similar system which could interact with the data management tool. In this way, data check and import should be facilitated. If for example the samples are bar-coded, then the identification process should be accelerated using a scanner. On the other hand, such a tool would be convenient for the labs, because they would be informed for the expected number of samples and the detailed suite for analysis. Thus, the results for a site would not be released for processing and interpretation, without all the sample records for this site or with the wrong determinands analysed. Compatibility of such a system between labs and interpretation team would also allow automatic notification of data availability and data upload from the laboratories to the agreed data storage location. This system should allow the user to query, report and generally manipulate the data to conclude to the demanded deliverables.

8. CONCLUSIONS

The development of a large scale groundwater quality monitoring strategy is essential to monitor the baseline quality of the aquifers and meet the wide ranging statutory and non-statutory requirements. This need is reinforced by the latest European legislation, the Water Framework Directive. Table 4 presents a summarised chart of the main steps of a groundwater quality monitoring programme.

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