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Rationale for groundwater monitoring in the context of the Lowland Permeable Catchment Research Programme (LOCAR)

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1. CONTEXT

The purpose of this short report is to discuss the rationale behind the design of hydrogeological monitoring networks. More specifically, to provide the background necessary for an assessment of the options for establishing hydrogeological baseline monitoring networks in three lowland permeable catchments that are being developed by the NERC Lowland Catchment Research (LOCAR) Thematic Programme.

The aim of LOCAR is to undertake detailed, interdisciplinary programmes of integrated hydro-environmental research relating to the storage-discharge cycle and groundwater-dominated aquatic habitats in three lowland catchments, the Pang-Lambourn, the Tern, and the Dorset Frome. In addition to the hydrogeological monitoring networks, instrumentation will also be established to monitor surface and atmospheric water and the ecology of each of the catchments. The LOCAR Programme will address five central questions, these are: -

(i) What are the key hydrogeological processes controlling surface water-groundwater interactions and the movement of groundwater in lowland catchments?

(ii) What are the key physical, chemical and biological processes operating within the valley floor corridor that affect surface water and groundwater?

(iii) How do varying flow regimes control in-stream, riparian and wetland habitats?

(iv) How does land use management impact on lowland catchment hydrology, including both water quantity and quality?

(v) How can the hydrological, hydrogeological, geomorphalogical and ecological interactions resulting from natural or anthropogenic changes be predicted using integrated mathematical models?

Data and observations from the hydrogeological monitoring networks and instrumentation will be principally used to address questions (a), (b) and (e), but will also be used along with data from the other monitoring networks in investigations and studies related to questions (c) and (d).

The LOCAR Programme has identified a number of specific tasks or topics that may influence the design of the hydrogeological monitoring network and instrumentation. These may be summarized as follows: -

- Flow and transport in the Chalk and Triassic Sandstone aquifers are poorly understood and the relationships between flow and transport properties at different scales, i.e. pore scale, borehole scale and catchment scale needs elucidating.

- Aquifer heterogeneity is a dominant influence on contaminant dispersion and is not yet adequately characterized. The role of fracture flow in the Chalk and sandstones need particular attention.

- The role of drift deposits in influencing recharge and pollution pathways needs investigation.

- Chemical interactions need an understanding of pore and fracture scale processes (including heterogeneiety and scaling properties), and the role of, and constraints on, microbial degradation, and hence the scope for natural attenuation of pollutants, require investigation.

- The spatial functioning of the surface water system must be mapped onto an understanding of surface water-groundwater interactions.

- Interannual variability in groundwater input into streams is likely to have major ecological impacts and may be strongly influenced by groundwater management. These relationships need investigation.

- Integrated modeling should include improved representation of the interaction between surface and groundwater in terms of both flow and quality, transfer of pollutants, impact of land use management change, linkage of ecological responses to changes in the hydrological regime, catchment management strategies and climate variability.

2. AIMS OF GROUNDWATER MONITORING NETWORKS AND DESIGN CONSIDERATIONS

Significant effort has been invested in the development of techniques to design groundwater monitoring networks, particularly groundwater quality monitoring networks, in the last few years. Loaiciga et al. (1992) have provided a detailed review of groundwater quality monitoring network design. The principals behind monitoring water quality and water resources are identical; consequently, the following section draws on many of the observations in review by Loaiciga et al.

The design of modern groundwater monitoring networks requires consideration of a range of factors that include the following: -

- Adequate spatial and temporal coverage of sampling sites
- Balancing potentially competing objectives within a monitoring programme
- The complex nature of geologic, hydrologic, and other environmental factors
- The significant uncertainty about many parameters used in the design process
- The range of applicability of the various methods in network design including their relative strengths and weaknesses.

2.1 The Need for Specific Objectives

Good design of groundwater monitoring networks requires clearly stated objects. The objective of a groundwater monitoring programme is the main factor determening cost, level of detail and appropriate methodology. Loaiciga et al. (1992) suggest that monitoring objectives may typically fit one or more of the following categories: -

- Ambient monitoring
  To establish an understanding of characteristic regional groundwater trends with time.

- Detection monitoring
  To identify the presence of targeted parameters, such as contaminants, as soon as they exceed background or established levels.

- Compliance monitoring
  A set of specified groundwater-monitoring requirements, usually for chemical constituents, for example near waste disposal facilities.

- Research monitoring
  Characteristically detailed spatial and temporal groundwater sampling designed to meet specific research goals.

For a given objective or set of objectives it is then necessary to choose an appropriate methodology to design the monitoring network. If the monitoring network is designed on the basis of mathematical models it will be necessary to choose objective functions that represent the monitoring objective (Loaiciga et al. 1992). These objective functions may be 'ultimate objectives' or 'surrogate objectives'. Ultimate objectives consider the value of groundwater information in monitoring goals such as environmental protection, resource availability, reduction in remediation costs or minimizing exposure risks or health hazards. Surrogate objectives would be the minimization of statistical parameters (such as the variance of groundwater levels or contaminant concentrations) or of the maximum difference between actual and predicted values.

2.2 Static or Dynamic Monitoring Networks

In many groundwater-monitoring programmes the dynamic nature of the programme is an important factor in network design. Network design may be an iterative process, where initial sampling programmes are often revised or updated as a result of previously collected data. In addition, the objectives of the monitoring network may also change with time. Dynamic monitoring networks also offer the potential for significant cost savings due to optimization of data collection and analysis, however, they may be difficult to plan when institutional constraints require budgets and programmes of work to be set in advance.

2.3 Monitoring Scale

The monitoring scale is determined by the objectives of the monitoring programme, i.e. data used in analysis should be collected at the same scale as the problem under investigation (Domenico and Schwartz 1990). For example, ambient monitoring is commonly undertaken at the regional scale with an annual or semi-annual sampling frequency, research monitoring may be undertaken at the site scale with much higher sampling frequencies.

2.4 System Heterogeneity

Aquifers are highly heterogeneous and as data is rarely available at sufficient density to characterize them deterministically. Consequently, design of monitoring networks involves the use of sparse data to estimate an unknown spatial and or temporal pattern in aquifer properties. An understanding of geological processes and the resulting structures can add significantly to models of aquifer properties (e.g. Fogg 1986). Regional geological structure, topography, and surface drainage patterns can all provide information, which affect the hydrogeology.

To map hydraulic gradients it is necessary to obtain water level or head data over a regional scale over time. In strongly anisotropic aquifer systems the potentiometric head map will not indicate true groundwater flow directions unless the hydraulic gradient is coincident with one of the principal axes of hydraulic conductivity. When the aquifer is anisotropic the degree of anisotropy needs to be characterized.

2.5 Conceptual Model of the Aquifer/Catchment

Before a monitoring network programme is planned a conceptual model of the aquifer system should be developed. This should encompass the following aspects: -

- Geological and hydrogeological boundaries
- Physical structure of the aquifer
- Recharge
- Discharge

- Groundwater flow pattern and mechanisms
- Rock-groundwater interactions
- Effects of unsaturated zone processes

2.6 Constraints

There many constraints on setting up a groundwater monitoring programme, most of them are institutional. It is useful to have a clear appreciation of these constraints at the start of a programme as they will affect decisions at each stage of the design and implementation, and they are likely to dictate the overall philosophical approach (described in the Section 3 below). Some of the main constraints are listed below

- Money. What are the financial resources available and over what time scale. What is the balance between capital and recurrent expenditure?
- Time. Is the monitoring programme to be iterative? Will results from initial phases be used to re-assess the monitoring needs or even aims of subsequent phases?
- Access to appropriate sites within each catchment. Access may be limited by the degree of cooperation from local landowners. Some installations in or near rivers and some activities such as groundwater tracing may have undesirable environmental impacts. Approval may be required from the appropriate regulatory agencies.
- Availability of staff with appropriate skills during installation and monitoring.
- Technical limitations. There may be technical limitations to data acquisition. For example, limits on the capability to remotely monitor hydrogeological variables and / or limitations to measurement resolution and accuracy.

2.7 Auxiliary Data

Central to any extensive groundwater monitoring exercise is the collection, collation and integration of appropriate geological data. Geophysical logs including, wireline logs, borehole imaging, and flow logs when used with core analysis provide the best constraints on the local or site geology. This data enables quantitative geological controls on the hydrogeology to be established and also allows the borehole data to be put in the context of the geology and hydrogeology of the catchment.

3. PHILOSOPHICAL APPROACHES

Loaiciga et al. (1992) identified two general types of approach to groundwater monitoring network design namely hydrogeologic and statistical approaches.

Hydrogeologic approach

- Monitoring networks and instrumentation based on assumptions regarding or investigation of specific hydrogeological processes
- Generally requires much more prior information on the hydrogeology and hydrogeological processes in the catchment or similar systems than the statistical approach.

Statistical approach

- Monitoring networks based on analysis and quantification of the phenomenological characteristics of the catchment, e.g. distribution of heads, or contaminant concentrations throughout a catchment

- This approach generally requires limited or sometimes no prior knowledge of the hydrogeology and no knowledge of hydrogeological processes in the catchment.

The statistical approach may be limited in value in heterogeneous aquifers.

To compare relative strengths and weaknesses of the two approaches it is necessary to consider the following factors: -

- Objectives of the monitoring programme (ambient, detection, compliance, research)

- Scale of monitoring programme

- Type of available data (geological, hydrogeological, water quality)

- Nature of investigated process (unsaturated or saturated zone flow, transport, reactive transport, groundwater – surface water interaction)

- Steady-state or transient processes

- Resources available for monitoring programme

- Single installation or iterative process

The next two sub-sections provide an overview of the different approaches to groundwater network design. The strengths and weaknesses of different approaches and their applicability to different problems are summarized in the Appendix in Tables 1 and 2 respectively. Table 3 is a summary of a selection of papers, including those cited in Table 2, related to the design of groundwater monitoring networks.

3.1 The Hydrogeologic Approach

This approach uses qualitative and quantitative hydrogeological information to establish a monitoring network based on calculations (including statistical and numerical models) and the judgement of hydrogeologists without recourse to advanced geostatistical analysis. Prior knowledge, based on similar or related problems, may form a significant component of the approach through explicit and implicit assumptions regarding the hydrogeological behavior of the system. The hydrogeological approach relies heavily on descriptive information and does not always fully use quantitative hydrogeological information.

Loaiciga et al. (1992) provide examples of how the number and location of sampling points and sampling frequency in a groundwater quality monitoring network are determined by the hydrogeological conditions near a contaminant source. For example, boreholes are sited up gradient of a source to define background levels of a contaminant and boreholes are sited down gradient to define the contaminant distribution. The analogy for a catchment study of groundwater resources would be the location of boreholes on or near interfluves to define groundwater divides and characterize recharge processes, and near rivers to characterize discharge and processes related to groundwater surface water interaction. Although it is not within the scope of this review, it should be noted that the choice of appropriate borehole construction details is strongly dependent on local hydrogeological conditions (e.g. Rushton 1994) and any relevant information gathered as part of planning a groundwater monitoring network will also be used in the design and construction of individual monitoring boreholes and piezometers.

The nature of hydrogeological monitoring networks will vary significantly depending on the aims of the programme or depending on the processes being investigated. Data may be needed for inclusion in simple numerical models or for stochastic analysis (distributed functions). Brouwer (1986) suggested some basic rules for network development using the hydrogeological approach, as follows: -

- the development of line wells near rivers or near the coast
- the development of radial structures near sites of groundwater abstraction
- well density should generally be greatest in regions with a high variability in piezometric head.

Heath (1976) discussed hydrogeological monitoring strategies that addressed three problems as follows, the effects of abstraction on recharge and natural discharge characteristics, the hydraulic characteristics of groundwater systems, and the extent and degree of confinement of an aquifer. In such circumstances he identified three types of networks. A network needed to define the extent of the aquifer and changes in storage, a water-management network to determine the effects of withdrawals and hydraulic characteristics, and a baseline network to determine the response of groundwater systems to natural changes such as those related to climate.

Czako (1994) describe the rationale behind the establishment of an ambient-monitoring programme, based on a hydrogeologic approach, for groundwater quality monitoring in Denmark. If the objective is research monitoring, data may be collected to investigate specific postulates or to establish correlations between dependent variables. Monitoring networks based on the hydrogeologic approach may be small scale, i.e. limited to borehole or piezometric clusters (e.g. Lloyd et al. 1996), and may provide the opportunity to obtain novel and potentially useful data, i.e. cross-borehole tomography, large-scale tracer tests, long-term pumping tests etc. A limitation to this type of monitoring programme is the difficulty in integrating disparate and diverse data sets across a catchment to produce a coherent view of catchment scale processes.

WMO (1989) provided a detailed and systematic methodology for managing groundwater monitoring programmes, including recommendations for the selection of observation boreholes and siting of new monitoring boreholes. They suggested the following sequence of decisions: -

- Define purpose of the network
- Geographical scope of the network
- List observed variables
- Select spatial layout of the network
- Decide on the temporal distribution of observations

They recommended the following products should be derived from the observations: -

- Maps showing contour lines of the state variables (e.g. water levels, solute concentration, temperature)
- Graphs showing variation in state variables with time at any location in the catchment

- Provide input data for models to enable, i.) water balance to be obtained and ii.) hydrogeological forecasting

To enable the above products to be produced WMO recommended that the following elements should be covered in the basic ambient monitoring network: -

- Groundwater level observation wells
- Groundwater quality observation wells
- Seawater intrusion observation wells (in coastal aquifers)
- Groundwater discharge measurement (pumping) wells
- Groundwater recharge measurement (injection) wells
- Spring discharge and quality observation stations
- Precipitation gauging stations
- Stage observation posts in major surface water bodies hydraulically connected to the groundwater

They suggested that site selection should be based on the following considerations: -

- Geostratigraphic zoning
  If several aquifers are present within a catchment with differing heads and/or chemical compositions, different wells or monitoring networks should be used to sample the system

- Coverage of spatial heterogeneity
  Each aquifer should be subdivided into zones of relatively common major characteristics that influence the hydrodynamic and hydrochemical balance (e.g. topography, vegetation, soils, lithology, unsaturated zone thickness, hydraulic conductivity, porosity, intensity of recharge or discharge, chemical composition of the groundwater). At least one observation well should be present in each zone, where zoning may be horizontal or vertical.

- Hydrogeological continuity
  The distance between neighboring boreholes should be much smaller than the distance over which the hydrogeological characteristics of the aquifer can be extrapolated.

- Coverage of boundary conditions
  Lateral groundwater boundaries should be defined with one well either side of the groundwater divide. At a surface water boundary at least two wells should be located on the same side of the boundary. The configuration should be such that it enables the vertical component of flow to be characterized and hydraulic diffusivity to be calculated (on the basis of groundwater and surface water fluctuations). Observation wells near surface water boundaries may be configured so that transition zones or interfaces in groundwater chemistry may be characterized. Where two aquifers are separated by a semi-pervious layer, pairs of observation wells should be placed either side of the layer to characterize leakage.

- Meet prescribed error levels
  Network should be designed subject to a constraint on the accuracy and reliability level of estimation errors and/or errors of prediction of water levels, solute concentration etc.

- If possible incorporate existing wells

3.2 The Statistical Approach

There are a number of weaknesses associated with the hydrogeologic approach to groundwater monitoring design. These are principally due to uncertainties in the results of models of groundwater flow and transport. These errors stem from two sources, the simplifications and errors at the conceptual and numerical modeling stage and the inherent heterogeneity of natural systems. The first set of errors (the 'information uncertainty' of Detinger and Wilson 1981) may be reduced by additional sampling. The second set of errors are due to the spatial and temporal variations of many parameters, e.g. hydraulic conductivity and dispersion coefficients. These parameters could be modeled as classical random variables with no spatial structure, but this is inappropriate for most groundwater variables that clearly show spatial trends. Consequently, a range of geostatistical techniques has been developed to characterize spatially distributed random hydrogeological variables.

Geostatistics is a systematic approach to making inferences about quantities in space. It enables calculation of the most accurate predictions of the spatial and or temporal distribution of parameters based on previous measurements and according to specified criteria. It provides a quantification of the accuracy of these predictions, and enables simulation by generating spatial functions or sets of properties that are consistent with the available information.

Three general types of geostatistical technique have been developed for groundwater monitoring network design. These are simulation, variance-based and probability- or risk-base approaches. Each of these approaches has specific characteristics and strengths and weaknesses. The following sections briefly describe the techniques. The strengths and weaknesses of the different statistical approaches and the hydrogeological approach are summarized in Table 1.

3.2.1 Simulation approach

This approach uses the simulation capabilities of geostatistics. The simulation approach generates multiple synthetic fields of a regionalized variable (such as hydraulic conductivity or a fracture parameter related to groundwater flow) to determine the statistical properties of flow or mass transport in an aquifer. These simulations are then used as the basis for an assessment of the reliability of a given monitoring network. For example, Meyer and Brill (1988) used the simulation approach to demonstrate how wells can be located in a monitoring network given no prior hydrogeological data. They used Monte Carlo techniques to translate uncertainty in simulation model parameters into uncertainty in a contaminant concentration distribution. The simulation model determines which well locations would detect a given realization of a contaminant plume with a concentration above a specified limit. A facility location model is then used to select a fixed number of well locations so that the maximum number of such plume realizations are detected. The simulation approach is computationally intensive.

3.2.2 Variance-based approach

Variance-based approaches use the estimated values that can be obtained from geostatistical analysis, specifically their estimation of variance of a regionalized variable. The estimation of variance produced by kriging is a measure of the dispersion of the collection of plausible values at the estimated point and so can be regarded as a measure of accuracy of the estimated value. The aim of variation-based approaches is to minimize the estimation variance or some function by additional measurements. Three methods fall under the collective heading of the variance-based approach these are the global method, variance reduction-analysis and the optimization approach.

3.2.3 Variance-based approach: The Global method

The aim of this approach is to identify the best regular pattern (e.g. othogonal, triangular or other geometrical arrangement) and sampling density for obtaining some index of performance of a monitoring network (Olea 1984). The index chosen is usually an average or maximum variance of estimation of the parameter of interest.

3.2.4 Variance-based approach: Variance reduction-analysis

This method uses a systematic search for the number and location of sampling sites that will minimize the variance of estimation error for the parameter of interest. Starting with data from exiting sampling points, additional sampling points are chosen from a 'pool' of potential new sampling sites. New sampling sites are added until the estimation variance can no longer be reduced or when the marginal gain in statistical accuracy is outweighed by other factors (e.g. budget considerations). In the absence of no initial sampling points this method can be used based on hydrogeologic considerations.

3.2.5 Variance-based approach: Optimization approach

The optimization approach also aims at minimizing the variance of estimation error for the parameter of interest, but does this subject to a range of different constraints. For example, governing equations of physical processes, resource constraints, or statistical constraints (i.e. accuracy of groundwater parameter measurements or estimates). The optimization approach identifies the location of the best site from a 'pool' of sites (Loaiciga et al. 1992).

3.2.6 Probability-based approach

A final statistical approach has been developed. This is the probability-based approach. The variance-based approaches all aim to maximize the information gain by locating sampling points at locations that will minimize the estimation variance of the parameter of interest. As such they give most weight to points with high estimates of variance, regardless of the magnitudes of the estimated variable. This approach may be suitable for meeting monitoring objectives, particularly groundwater quality monitoring programmes where there is a need to obtain both information but also to monitor areas where the variable under investigation may be at a critical level. Probability-based methods use a combined criterion of variance of estimation and magnitude of the variable in question for site selection. Loaiciga et al. (1992) note that where the aim of the network design methodology is to undertake hazard or dose-response assessments this approach may be termed 'risk-based'.

3.3 Stochastic Well Capture Zones

A topic that has been the subject of a number of recent papers is the definition of well capture zones (Varljen and Shafer 1991, van Leeuwen et al. 1998, in press) conditioned by transmissivity measurements. The location and density of these transmissivity measurements may significantly effect the errors associated with definition of the capture zone and stochastic, Monte Carlo (MC), analysis techniques have been used to visualize and quantify the uncertainties associated with heterogeneous properties of porous media surrounding boreholes.

3.4 Summary and Comments on Previous Related Studies

Table 3, in the appendix, is a summary of some of the more significant studies related to the design of groundwater monitoring networks. There are few precedents in the published literature for the design of regional scale groundwater monitoring networks for water resources. Most of the previous studies have been related to water quality monitoring problems. These include baseline groundwater quality monitoring, regional monitoring of diffuse agricultural contaminants (nitrate and pesticides), and a range of site specific monitoring programmes designed to investigate the distribution of contaminants, for example from landfill sites. Many of the studies summarized in Table 3 describe investigations of unconsolidated aquifers in North America. These are usually relatively homogeneous sand and gravel aquifers. The hydrogeology of these systems may be seen as relatively simple compared to the structure of consolidated aquifers and particularly fractured consolidated aquifers.

Non-hydrogeological factors often dictate final network configuration. Quite often the final implementable sampling programme is strongly influenced by institutional factors. Factors such as quality assurance and quality control (QA/QC) and practical considerations regarding data acquisition, analysis and storage may influence the sampling programme. For example, Johnson et al. (1995) note that statistical techniques designed to evaluate sampling frequencies based on empirical analysis have a number of drawbacks. They employ concepts not easily implemented without training in statistical methods, they do not exploit the often substantive knowledge from the relevant hydrology and environmental science domains, and they typically result in recommended frequencies greater than regulatory customers require which does little to increase their (the techniques) popularity. Although statistical techniques may make more effective use of the available empirical hydrogeological data, hydrogeological techniques may be easier to implement and may be more acceptable institutionally.

4. PREVIOUS STUDIES IN ENGLAND AND WALES

In 1994 the British Geological Survey undertook two reviews for the NRA one of groundwater level monitoring strategy (McKenzie et al. 1994) and one of groundwater quality assessment (Chilton and Milne 1994). Up until that date the regional groundwater monitoring networks had developed in response to demands in the regions, often in very different ways. They developed in response to varied geology, groundwater abstraction regimes, changing institutional perspectives, and different perceptions of the most effective methods to monitor and store data. The aim of the review was to standardize the classification and use of existing monitoring boreholes, rather that develop new boreholes for monitoring.

4.1 Recommendations Following the Review of Groundwater Level Monitoring Strategy

The key recommendations regarding groundwater level monitoring strategy (McKenzie et al. 1994) were that there was a need for a classification of groundwater monitoring boreholes common to all NRA (now EA) regions. The aim of the suggested classification is to enable an accurate assessment of the relative effectiveness, in both scientific and financial terms, of regional monitoring programmes, and to ensure the same criteria were used nationally. The following classification was proposed : -

- Reference monitoring sites
  These sites are a subset of the National network and are used to provide the detailed, long-term perspective that is vital for resource management. The sites are located, as far as possible, in areas not subject to short-term fluctuations caused by abstractions. They would form the basis of routine monitoring of natural groundwater level fluctuations.

- National monitoring sites
  A network that provides data needed to monitor resource variations and to effectively manage groundwater resources at the regional scale.

- Local monitoring sites
  Sites for monitoring for specific purposes, e.g. monitoring point source contamination, river augmentation schemes.

A scheme was proposed to classify existing boreholes into one of these categories. This ranking scheme included the following criteria relating to the nature of existing water level data: -

- the hydrogeological context of the borehole

- site characteristics

- 'location features', i.e. relationship with neighboring boreholes.

In terms of the Loaicga et al (1992) classification scheme for groundwater monitoring objectives the proposed Reference Monitoring Sites and the National Monitoring Sites should be considered as ambient monitoring, while the Local Monitoring Sites should be considered as detection, compliance or research monitoring sites. The approach to borehole classification was essentially hydrogeological in nature. It was envisaged that there would be periodic reviews during which sites might be reclassified.

4.2 Recommendations of the Groundwater Quality Review.

Chilton and Milne (1994) identified five primary objectives for national groundwater quality monitoring: -

- Trends in groundwater quality changes due to natural or anthropogenic causes
- Establishment of 'baseline' water quality for future issues
- Spatial distribution of water quality
- Early warning in recharge areas, particularly of the impacts of diffuse pollution
- Monitoring of nitrate

And they identified a range of secondary objectives that included the monitoring of industrial and urban impacts, evaluation for groundwater protection, contaminated land and landfill impact, the affect of groundwater – surface water interaction (including saline intrusion), monitoring the impact of specific incidents, e.g. mine drainage, and model validation. Chilton and Milne (1994) identified a range of factors that would determine the nature of the monitoring network. These are summarized in Table 4 in the appendix. Chilton and Milne noted the development of a suite of statistical tools to help in the development of groundwater quality monitoring networks and noted the following problems with their application: -

- Most statistical methods make important simplifying assumptions about the hydrogeology
- Most methods target the assessment of potential or actual contamination from point sources often on a relatively local scale
- It may be difficult to identify a statistical objective or set of objectives that adequately represent the complex objectives of a monitoring programme

Chilton and Milne (1994) proposed a hydrogeologic approach to the monitoring of groundwater quality consistent with the approach envisaged by (McKenzie et al. 1994), i.e. the use of three types of network, the Reference, national and Research Networks.

5. AIMS FOR LOCAR MONITORING NETWORKS AND FACTORS AFFECTING THE DESIGN OF THE LOCAR MONITORING NETWORKS

What are the specific objectives of the LOCAR monitoring network, and what is the most appropriate approach to meeting those objectives? There are four principal aims for the hydrogeological component of the LOCAR monitoring networks. These are: -

(i) Provide information on appropriate groundwater parameters to enable a consistent (balanced) model of groundwater flow in each catchment to be constructed. This includes location of groundwater divides.

(ii) Provide instrumentation to enable investigation of groundwater processes such as:-

- 3-D flow and transport processes as a function of time and place within each catchment
- Scale dependence of flow and transport processes
- Aquifer heterogeneity and role in contaminant dispersion
- Flow and transport in fractured aquifers
- Reactive transport from the scale of pores and fractures to the catchment scale
- Surface water-groundwater interactions
- Ecological impacts of groundwater processes and groundwater management

The list is not exhaustive.

(iii) Ensure that the hydrogeological monitoring network is fully integrated with other catchment monitoring networks.

(iv) Establish hydrogeological monitoring networks and instrumentation within budget and within timeframe of the LOCAR Programme

Given the above aims the LOCAR programme is likely to have the following characteristics: -

- The network(s) will be based on research monitoring objectives (Loaicga et al 1992).
- The network(s) need to be amenable to quick design and implementation so that they may be used in the main LOCAR research programme.
- There will be limited scope for iterative development of the monitoring network(s) given the time constraints of the LOCAR programme.
- Maximum use should be made of the significant background information, both qualitative and quantitative and hydrogeological and non-hydrogeological.

6. OPTIONS FOR LOCAR MONITORING STRATEGIES

The aims of the LOCAR programme, summarized in Section 1, and of the hydrogeological component of the LOCAR monitoring network, summarized in Section 5, place restrictions on the options available for the groundwater monitoring network. The aims of LOCAR are principally to investigate processes and, therefore, the network will be based on research monitoring objectives. If there is a need for ambient monitoring this can potentially be met through the use of the existing arrays of boreholes present in each catchment, as described by McKenzie et al. 1994, and Chilton and Milne 1994). In this context, where additional boreholes are needed to provide data for water balance models their development may be seen as a response to a research-monitoring objective. Similarly, boreholes located to define recharge characteristics of the aquifers, catchment boundaries, or additional information in areas of steep head gradients may also be considered as meeting research monitoring objectives.

If the establishment of the hydrogeological component of the LOCAR monitoring network is to meet research monitoring objectives, what are the problems or benefits associated with each of the basic approaches to groundwater monitoring as applied to LOCAR? The following section briefly describes some of the most important strengths and weaknesses of the approaches that were described in section 3.

- Hydrogeologic approach
  The hydrogeological approach is a good, practical, option that can use prior hydrogeological knowledge. It is flexible in response to research monitoring needs, is appropriate to complex hydrogeological systems, and can be developed more quickly than the statistical approaches. A weak point is that it does not necessarily provide the best information to enable a water balance model to be developed, and that it lacks the rigor of a statistical approach. It is probably the most broadly acceptable approach given the institutional constraints.

- Statistical approach – Simulation
  This approach is computationally demanding and is difficult to apply to a relatively complex hydrogeological system. It is likely to be inappropriate for most of the research monitoring needs.

- Statistical - Variance based (Global)
  This technique is relatively simple, but is inappropriate for research monitoring needs and is not practical given the constraints on land access and the need to co-ordinate groundwater, surface water and ecological monitoring networks.

- Statistical -Variance based (Variance reduction)
  Along with the optimization approach the most appropriate of the statistical techniques. A multi-variate approach would have to be developed if more than one parameter was to be investigated (e.g. piezometric head, hydraulic conductivity, water quality). This approach would be relatively time consuming as it would require full digital data for each catchment. The use of the approach may be inappropriate for research monitoring needs (i.e. where borehole location is not necessarily determined by the need to reduce uncertainty in measurements, but rather to investigate site specific processes).

- Statistical - Variance based (Optimization)
  This approach is similar to the previous approach and the comments are the same as those applied to the variance reduction approach (see above).

- Statistical - Probability based
  The use of the approach is inappropriate for most of the LOCAR research monitoring needs, and it is not practical given the need to co-ordinate groundwater, surface water and ecological monitoring networks.

In summary, the hydrogeologic approach and the statistical variance reduction and optimization approaches appear to be the best approaches for designing the LOCAR groundwater monitoring arrays. However, on balance, the hydrogeologic approach is the most appropriate, particularly given the need to co-ordinate the groundwater monitoring with surface water and ecological monitoring activities. It is also likely to be the most acceptable approach given the complex institutional framework

If the establishment of hydrogeological instrumentation is to be based on research monitoring objectives using the hydrogeologic approach, it is important to ensure that the monitoring infrastructure is suitable and addresses the research aims of LOCAR. The following section gives an example of how LOCAR research aims may be linked with the type of groundwater monitoring instrumentation that may be needed to investigate groundwater processes (see section 5). The implications for instrumentation in six different areas are considered. They are as follows:

- Definition of groundwater catchment boundaries

- Recharge processes in the interfluve areas
- 3-D definition of flow across the catchment
- Characterisation of fracture flow
- Aquifer heterogeneity and scaling effects
- Groundwater – surface water interaction near discharge areas

6.1 Implications for Instrumentation

6.1.1 Definition of groundwater catchment boundaries

Possible instrumentation needs and monitoring requirements

- Piezometers, and possible boreholes, either side of groundwater divides, at various locations around the margins of the groundwater catchments sufficient to define the groundwater divides.
- Nested piezometers used to characterize sub-vertical head gradients throughout the full thickness of the zone of 'active' groundwater circulation either side of the divide.
- Boreholes to characterize the geological controls on interfluve hydrogeology (e.g. geophysical logs, including borehole imaging, flow logs and core analysis)
- Monitoring frequency consistent with other data sets used to establish the groundwater balance, e.g. rainfall and surface water data. It should also be adequate to provide information on recharge events as well as seasonal variations in the groundwater divides (see section below on recharge processes in the interfluve areas).
- Information on existing boreholes used where possible, however, purpose built piezometer arrays preferable.
- Piezometer arrays positioned to investigate the effects of cover on the position of the groundwater divides?

Linkages to LOCAR research aims

- Integrated modeling of the interaction between groundwater and surface water to produce water balance at catchment scale.
- Investigation of key hydrogeological processes controlling movement of groundwater in lowland catchments.
- The role of drift deposits in influencing recharge pathways.

6.1.2 Recharge processes in the interfluve areas

Possible instrumentation needs and monitoring requirements

- Piezometer arrays at representative (principally interfluve areas) locations within the catchments, sufficient to characterize the recharge processes.
- The piezometer arrays located i. at sites that have also been instrumented to study unsaturated

zone (matric potential and flow in fractures), and ii. could use piezometer arrays and/or boreholes that have been developed to define groundwater catchment boundaries (see above).

- The piezometer arrays to provide good vertical head definition through the 'active' zone of the aquifer.
- Ideally the piezometer array should be associated with a well-characterized borehole to enable geological controls on recharge to be investigated.
- Sites chosen specifically to target recharge through drift deposits or associated with perched aquifers.

Linkages to LOCAR research aims

- Investigation of the key hydrogeological processes controlling the movement of groundwater in lowland catchments.
- Investigation of the role of drift deposits in influencing recharge and pollution pathways.
- Investigation of the role of fracture flow.
- Contributing to a better understanding of surface water-groundwater interactions.

6.1.3 3-D definition of flow across the catchment

Possible instrumentation needs and monitoring requirements

- Piezometer arrays penetrating the full thickness of the 'active' aquifer, aligned down the hydraulic gradient to characterize the 3-D head distribution. Ideally these arrays located across a relatively steep section of the hydraulic gradient.
- Cored boreholes associated with each piezometric array for geological control on hydrogeology. Multiple cored boreholes (vertical and possibly inclined boreholes in fractured sections) could be developed to enable hydraulic and geophysical tests to sample the 2-D and 3-D structure of the aquifer using techniques that cross-borehole tomography, tracer tests.
- The cored boreholes analyzed to characterize the matrix and fracture properties of the aquifer to enhance interpretation of the borehole tests.
- The borehole sites may not be co-ordinated with other components of the catchment monitoring network, however, it would be helpful if the piezometer arrays were located at sites that were also being used for surface water and particularly unsaturated zone monitoring.

Linkages to LOCAR research aims

- Investigation of key hydrogeological processes controlling the movement of groundwater in lowland catchments.
- Enhance hydrogeological mathematical models of catchments.
- Enables investigation of flow and transport, particularly transport properties at different scales, i.e. pore scale, borehole scale and catchment scale.
- Investigation of aquifer heterogeneity and the role of fracture flow.

- Investigation of chemical interactions and the role of microbial degradation during 3-D flow.
- Investigation of interannual variability in groundwater input into streams.

6.1.4 Characterization of fracture flow

Possible instrumentation needs and monitoring requirements

- Development of boreholes on interfluve, within the catchment, and at groundwater discharge points that enables study of the variation in fracturing with depth and across the catchment. The interfluve boreholes should ideally be associated with unsaturated zone monitoring sites to enable the study of recharge through fractures.
- Detailed fracture logging (borehole imaging and core logging), flow logging and hydraulic testing.

Linkages to LOCAR research aims

- Investigation of key hydrogeological processes controlling the movement of groundwater in lowland catchments.
- Investigation of the role of fracture flow.
- Enables investigation of flow and transport, particularly transport properties at different scales, i.e. pore scale, borehole scale and catchment scale.
- Investigation of the role of fractures in recharge pathways.
- Enhance hydrogeological mathematical models of catchments.

6.1.5 Aquifer heterogeneity and scaling effects

Possible instrumentation needs and monitoring requirements

- Fully cored boreholes that intersect the maximum possible thickness of the aquifer that enable the full core characterization of the matrix.
- Geophysical (borehole imaging) logs, flow logs, and packer tests should be undertaken to characterize the distribution of hydraulically significant fractures.
- Boreholes developed for the characterization of fracture flow could also be used for the study of aquifer heterogeneity and scaling effects.

Linkages to LOCAR research aims

- Investigation of key hydrogeological processes controlling the movement of groundwater in lowland catchments.
- Investigation of the role of fracture flow.
- Enables investigation of flow and transport, particularly transport properties at different scales, i.e. pore scale, borehole scale and catchment scale.
- Enhance hydrogeological mathematical models of catchments.

6.1.6 Groundwater – surface water interaction near discharge points

Possible instrumentation needs and monitoring requirements

- Piezometer arrays adjacent to groundwater discharge sites through the full depth of the 'active' zone of the aquifer and inclined boreholes beneath rivers should be developed to investigate groundwater - surface water interactions.

- The selected groundwater monitoring sites consistent with surface water, unsaturated zone and ecological monitoring sites.

- The piezometer arrays and boreholes capable of monitoring seasonal and variations in head distributions, flow characteristics, storage, water chemistry, and microbiology as well as being amenable to use in monitoring very short term events.

- Boreholes provide direct and indirect information on geological controls on the hydrogeology (borehole logging, including borehole imaging, and core analysis)

- Instrumentation should have minimum impact on the natural hydrogeological regime.

- Piezometer arrays developed to study groundwater – surface water processes to also study 3-D definition of flow across the catchment and fracture flow.

Linkages to LOCAR research aims

- Study of the key physical, chemical and biological processes operating within the valley floor corridor that affect surface water and groundwater.

- Investigation of how varying flow regimes control in-stream, riparian and wetland habitats.

- Study of how land use management impact on lowland catchment hydrology, including both water quantity and quality.

- Investigation of how the hydrological, hydrogeological, geomorphological and ecological interactions resulting from natural or anthropogenic changes can be predicted using integrated mathematical models.

- Investigation of the spatial functioning of the surface water system.

- Investigation of interannual variability in groundwater input into streams and their likely ecological impacts.

- Integrated modeling of the interaction between surface and groundwater in terms of both flow and quality, linkage of ecological responses to changes in the hydrological regime, catchment management strategies and climate variability.

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APPENDICES

Table 1 Strengths and weaknesses of various approaches to the design groundwater monitoring programmes

Approach	Strengths	Weaknesses	Summary
Hydrogeological	• Applicable in complex hydrogeological settings • Can easily take into account qualitative and quantitative non-hydrogeological information and ideas. • Can provide information on sampling frequency, usually based on previous data and appreciation of groundwater processes.	• The hydrogeological approach relies heavily on descriptive information and does not always fully use quantitative hydrogeological information. • The approach is data intensive and requires a good appreciation of hydrogeological processes in the catchment. • Need to develop conceptual and numerical models of the area of investigation. These should ideally include the unsaturated zone and unsaturated zone processes for which there is often limited and/or poorly constrained data.	• Approach is best suited for site specific studies where there is a lot of existing high quality information on geology, hydrogeology and hydrology. • Applicable in complex hydrogeological settings (regional and site scales) • Appropriate technique to use where the objective is research monitoring.
Statistical : Simulation	• Flexibility to examine efficiency of alternative network configurations and sampling frequencies under relatively simple hydrogeological settings • Allows of consideration of constraints such as budgetary limitations	• Requires numerical hydrogeological models to be developed. These models are the weakest link in the simulation approach (particularly if they involve mass transport models that neglect key chemical or biological processes) • Computationally very intensive. This may make the approach too cumbersome or impractical for all but a limited number of network configurations	• Approach best suited for solving problems at the field/site scale. • Increases in cheap computational power will make this approach increasingly attractive
Statistical : Global	• Quick and relatively easy analysis	• Global standards (pattern of sampling points e.g. orthogonal or density) are inconsistent with many groundwater monitoring goals, particularly where observations at various densities are needed	• Approach best suited for groundwater monitoring network design of preliminary or exploratory layouts in regional-scale programmes.
Statistical : Variance-reduction	• The value of alternative sampling strategies can be assessed before new measurements are made, because the uncertainty-reducing effectiveness of any sampling scheme depends only on the number and location of measurement sites and not on the magnitude of the values • Can be used with a step-by-step development of groundwater monitoring networks	• Limited capability to incorporate complex hydrogeological settings	• Most useful when the environmental variable of interest has a homogeneous and isotropic spatial behavior • Technique best suited to problems related to the determination of additional sampling sites when the primary objective is to gain as much information as possible.
Statistical : Optimization	• It provides optimal sampling locations and sampling frequencies while considering restrictions on the sampling plan.	• Can only be used to select optimal sampling sites from a pool of potential sites, cannot be used consider the entire continuum of points in an area to be monitored. • Needs simplification of the hydrogeology to make network design problem feasible and requires numerical hydrogeological models to be developed (see 'Simulation' weaknesses for additional comments) • Static development of groundwater monitoring network, does not enable iterative development of network.	• Promising analytical tool for regional groundwater monitoring network design, where the hydrogeological resolution is relatively coarse and easy to model.
Statistical : Probability based	• Unlike previous three statistical models the selection criteria includes a consideration of both accuracy and magnitude of the estimated variable. • Can include risk-based considerations	• Monte Carlo simulations and other realization methods may be used that can be computationally intensive	• Method has only had limited application to date • May find principal application in water quality issues where the magnitude of critical parameters is of principal interest.

Table 2 Summary of applicability of various approaches to the design groundwater monitoring programmes (based on Table 2, Loaiciga et al. 1992)

Features	Approach					
	Hydrogeological	Statistical				
		Simulation	Variance-balanced			Probability-based
			Global	Variance-reduction	Optimization	
Scale : Field / Site	X	X		X?	X?	X
Scale : Regional	X?		X	X	X	X
Constraints: Resource	X	X	X	X	X	X
Constraints: Statistical		X	X	X	X	X
Constraints: Hydrogeological	X	X				
Data intensive	X	X				
Complex hydrogeology	X	X?				
Temporal effects: Sampling frequency	X	X			X?	
Representative references	WMO (1989) Czako (1994)	Massman & Freeze (1987a, 1987b), Meyer & Brill (1988)	Sophocleous (1983), Olea (1984)	Rouhani (1985)	Hsueh & Rajagopal (1988), Loaiciqa (1989), Andricevic (1990), Ben-Jemaa et al. (1994)	Rouhani & Hall (1988), Scheibe & Lettenmaier (1989), Hudak & Loaiciga (1992)

Table 3 Resume of some selected papers on designing groundwater monitoring programmes (in chronological order).

Authors & data	Type of study	Approach	Field case study
Hsu S-K Hydrogeology Journal, 3, 405-415 1998	Hydrogeological	Review of the planned implementation of a national groundwater monitoring network in Taiwan. Plan calls for 517 hydrogeological survey stations and 990 monitoring wells to be established in the next 17 years. Water levels will be continuously monitored and water quality samples will be taken only at the initial stage of drilling. The paper outlines the activities that are planned.	Na.
Johnson V M et al. Environmental Science and Technology, 30, 355-358 1996	Statistical Trend analysis to optimize sampling frequency	Study of sampling frequency of groundwater monitoring wells. Use descriptive rather than inferential statistics in the development of sampling programmes. The rate of change of data and the degree of uncertanty attached to data are important. A least squares regression is fitted to yearly water quality data and used to inform descisions regarding modification of sampling frequency depending on goodness of fit to data. Good review of technical literature on monitoring frequency.	Examples given for some VOC data from selected wells at the Lawrence Livermore National laboratory research site in California.
Zhou Y J. Hydrology 180, 301-318 1996	*Statistical* Trend analysis to optimize sampling frequency	Determination of sampling frequency can be based on 1. analysis of trends, 2. the accuracy of estimation of periodic fluctuations, and 3. The accuracy of estimation of the mean values of the stationary component of the state variable (eg. gw head or temperature). Good description of the theory and methodology behind sampling frequency.	The criteria are applied to the determination of sampling frequency of gw level data infour boreholes near the Spannenburg pumping station northeast Holland. Analysis of the data indicated that the most appropriate sampling frequency was once a month.
Ben-Jema et al. 1994	Statistical *Variance-based optimization approach* Uses multi-variate statistics	Multivariate geostatistical approach to design of groundwater monitoring network augmentation programmes, based on cokriging. The design problem is posed as an optimization model in which the variance of estimation is minimized. Network design is based on several variables that are jointly monitored. 'Branch and bound' technique is used to select the optimal sites for monitoring. Useful literature review.	The methodology is applied to the design of a monitoring network to observe transmissivity and specific capacity in the Yolo County sain, California. No data given regarding the geology or hydrogeology of the site. The study area is about 400 km^2, and correlation lengths in T and SC were found to be of the order of 20km.
Czako T Hydrogeological Sciences Journal des Sciences Hydrologiques, 39, 1-17 1994	*Hydrogeological*	Review of the national Danish groundwater monitoring network established to monitor nitrate in groundwater. 67 groundwater monitoring catchments each associated with a large public supply borehole. Each 'catchment' typically a few km square. Boreholes and piezometers located on the basis of a priori knowledge of the geology and hydrogeology of each catchment (see synopsis of Danish monitoring programme).	Na.
Hudak PF & Loaiciga HA Water Res. Res., 28, 643-649 1992	*Statistical* *Probability-based approach* Uses a heuristic method based on facility location theory	Heuristic approach (dependent on assumptions based on past experience or data) using facility location theory to locate additional wells in an existing groundwater quality monitoring network. This approach is an alternative to the variance-based schemes that have previously been used (eg. Andricevic 1990 and Carrera, 1984). The method uses five steps, 1. Define grid containing possible sites, 2. Locate existing wells on grid, 3. Use a gw flow and mass transport model calibrated to existing data, 4. Use calibrated output as nodal weightings, 5. Apply maximal covering location model to weighted data to find maximum coverage. NB. Good literature review.	Approach applied to case study of a landfill-contaminated buried valley aquifer in southwest Ohio. The aquifer consists of unconsolidated sands and gravel up to 12 m thick. Chloride was used as a tracer in modeling the contaminant migration. Data from eight boreholes was used. An additional 10 wells were sited.
Andricevic R	*Statistical*	Groundwater flow monitoring network augmentation	7.7 km^2 field site in Pomona Basin,

1990	*Variance-based optimization approach*	designed to maximize statistical monitoring power for specified budget constraint while minimizing monitoring costs for statistical power requirements. Methodology is in three parts, 1. Stochastic groundwater flow simulation, 2. Simulation algorithm for obtaining variances in piezometric level estimates, and 3. 'Branch and bound' algorithm used to solve for optimal monitoring network design.	central California. Aquifer is a 45 m thick unit of sands and gravel at a depth of about 100 m bGL. Monthly piezometric data from three abstraction wells and five observation wells is used to calculate contours of the s.d. of errors in hydraulic heads. Optimal monitoring network was found to be 11 observation wells sampled 24 times a year.
Mayer P D & Brill E D Water Res. Res. 24, 1277-1282 1988	*Statistical* *Simulation approach*	A method is developed to locate wells in a monitoring network given no previous hydrogeological data. The model couples a simulation model of contaminant transport and a facility location model. Monte Carlo techniques are used in the simulation model to translate uncertainty in the simulation model parameters into uncertainty in the contaminant concentration distribution. The simulation model determines which well locations would detect a given realization of a contaminant plume with a concentration above a specified limit. The facility location model is then used to select a fixed number of well locations so that the maximum number of such plume realizations are detected. Approach is computationally intensive.	Na.
Carrera J et al J. Hydrology, 73, 147-163 1984	*Statistical* *Variance-based approach*	Kriging method to locate optimal location of measurement points in a groundwater monitoring network augmentation programme. Method is based on nonlinear programming and a 'branch and bound' technique. Methodology is simple and data requirements are small. Good review of relevant theory.	Method applied to San Pedro River basin (Arizona) to estimate fluoride concentration of the groundwater. Study area was about 7 km^2 (?) and used fluoride data from 14 wells to select an addition six wells from ten existing wells without fluoride data.
Sophocleous M J. Hydrology, 61, 371-389 1983	*Statistical* *Variance-based global approach*	The theory of regionalized variables is used to estimate the amount of regional variability in a water table measurements and so design optimum uniform spacing of gw monitoring wells. Semivariogram analysis of groundwater level data is used.	Study involves four of the five Kansas Groundwater Management Districts. These are very large >2,000 km^2 areas of predominantly unconsolidated Tertiary sands and gravels. Optimal borehole spacing in these systems was estimated to be on a regular 6.4 km grid.

Table 4 Factors that determine network design for groundwater quality monitoring schemes (from Chilton and Milne 1994).

Sampling point		Sampling frequency	Choice of determinands
Type	**Density**		
Primary assessment objectives	Primary assessment objectives	Primary assessment objectives	Primary assessment objectives
Hydrogeology (complexity)	Hydrogeology (complexity)	Hydrogeology (residence times)	Water uses
	Geology (aquifer distribution)	Hydrology (seasonal influences)	Water quality issues
	Land use		Statutory requirements
	Statistical considerations	Statistical considerations	
Costs	Costs	Costs	Costs

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