Chapter 4.2
Assessing and aggregating trends in groundwater quality

Broers H.P.[1], Visser A.[2], Chilton P.J.[3] and Stuart M.E.[4]
[1] TNO Geological Survey of the Netherlands / Deltares, P.O. Box 80015, 3508 TA, Utrecht, The Netherlands, h.broers@tno.nl
[2] Universiteit Utrecht, Faculty of Geographical Sciences, Budapestlaan 4, 3584 CD Utrecht, The Netherlands.
[3] International Association of Hydrogeologists, P. O. Box 4130, Goring on Thames, Reading RG8 6BJ, UK.
[4] British Geological Survey, Wallingford, OX10 8BB, UK

4.2.1. Legislative reasons for performing trend analysis

"Groundwater is a valuable natural resource and as such should be protected from deterioration and chemical pollution. This is particularly important for groundwater dependent ecosystems and for the use of groundwater in water supply for human consumption" [after EU, 2006]. The EU Water Framework Directive [EU, 2000] aims for integrated management of surface water and groundwater. It is the most advanced regulatory framework for the protection of all natural waters in the European Union, seeking to achieve "good status" for all water bodies by the end of 2015. In relation to groundwater quality, the WFD requires Member States to:

- delineate groundwater bodies and characterise them according to the anthropogenic pressures in order to identify groundwater bodies at risk of failing to meet their environmental objectives and that may fail to meet the criteria for "good status";
- establish a groundwater monitoring network to provide a comprehensive overview of the chemical and quantitative status of the groundwater body. This was required to be operational by the end of 2006.

The recently adopted EU Groundwater Directive (GWD) [EU 2006] on the protection of groundwater against pollution in the EU Member States better defines the environmental objectives of the WFD for groundwater. Thus, the GWD is based on three pillars:

- specific criteria for defining "good chemical status" (Article 3);
- criteria for the detection of significant and sustained long term anthropogenic induced upward trends in the concentrations of pollutants (Article 5) as well as the definition of starting points for trend reversal and requirements on the implementation of measures necessary to reverse any significant and sustained upward trends;
- Preventing and limiting the inputs of pollutants to groundwater (Article 6).

So, the identification of sustained upward pollution trends and their reversal is the second "pillar" of the new directive, which stipulates that trends must be identified for any pollutant putting the groundwater "at risk". This links to the analysis of pressures and impacts carried out under the WFD (Article 5). The issue of "significance" is clarified in Annex IV of the GWD. Trends must be both statistically significant (mathematical) and environmentally significant. Environmental significance relates to potential future impact of the identified upward trends.

The trend reversal obligation requires that any significant and sustained upward trend will need to be reversed when reaching 75% of the values of EU-wide groundwater quality standards and/or threshold values (Figure 1). Trend reversal has to be achieved through establishing the programmes of measures defined by the WFD (Annex VI).

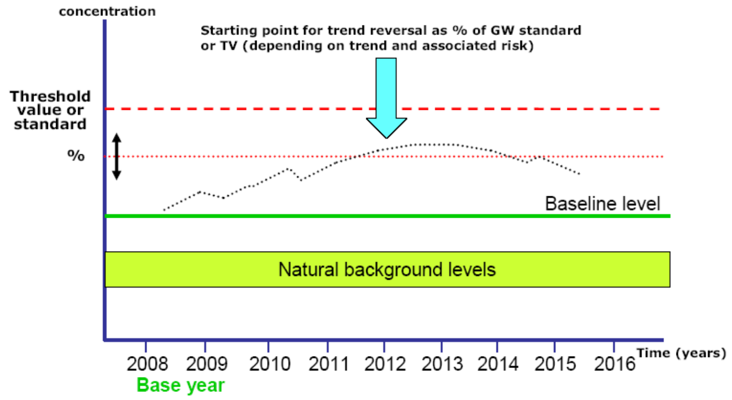

Figure 1: Principle of the identification and reversal of statistically and environmentally significant upward trends (after Quevauviller 2008)

The Water Framework Directive also requires monitoring and trend assessments at individual groundwater drinking water abstraction sites. Under Article 7.3 of the WFD, Member States shall ensure the necessary protection for groundwater bodies identified as Drinking Water Protected Areas "with the aim of avoiding deterioration in their quality in order to reduce the level of purification treatment required in the production of drinking water."

By implementing groundwater protection measures that are technically feasible and proportionate, Member States need to use their best endeavours to ensure that groundwater quality does not deteriorate at the point of abstraction for drinking water supply, and, so that there is no need to increase the level of purification treatment (EU 2007b). Member States should ensure that raw water quality monitoring is representative and sufficient to ensure that significant and sustained changes in groundwater quality due to anthropogenic influences can be detected and acted upon. Compliance points must be set at appropriate locations to detect such changes. This objective may be achieved by groundwater protection measures (which may be focused using safeguard zones) and the monitoring of raw groundwater quality to demonstrate significant and sustained improvements (trends).

4.2.2. Scope and trend definition

In this chapter we explore different methodological aspects of trend analysis in relation to the new WFD and GWD legislation. Part of the approach presented originates from the 6th EU Integrated Research and Technology Development Framework Programme (FP6) Project Aquaterra. Within this project, work package TREND 2 (Visser et al. 2008) was dedicated to the development of operational methods to assess, quantify and extrapolate trends in groundwater systems. Trend analysis techniques were tested on data from a wide range of European environmental settings including unconsolidated lowland deposits in the Netherlands and Germany, chalk aquifers in Belgium and a fractured aquifer with a thick unsaturated zone in France. In addition, this chapter presents recent developments in trend analysis on data from abstraction sites in the UK. This is particularly relevant for the Drinking Water Protected Area (Article 7.3) requirements of the WFD.

We define a trend as 'a change in groundwater quality over a specific period in time and over a given region, which is related to land use or water quality management'. Trend analysis for the Groundwater Directive is dedicated to distinguishing these anthropogenic changes from natural variation "with an adequate level of confidence and precision" (GWD, Annex IV, Article 2(a)(i)).

Temporal variations due to climatological and meteorological factors have the potential to complicate trend detection. Also, spatial variability is an additional complicating factor, especially when aggregating trends at the groundwater body scale. The requirement to aggregate trends is defined in

European Union WFD Common Implementation Strategy guidance (EU 2008). Relevant factors influencing spatial variation include:

- flow paths and travel times;
- pressures and contaminant inputs and;
- the chemical reactivity of groundwater bodies.

These variations result in variable and different trend behaviour across the scale of the groundwater body, because some monitoring points might be along flow paths which originate from areas with high contaminant inputs to groundwater and others along flow paths that originate from areas of low input.

Trend analysis techniques aim to reduce the variability which is not related to anthropogenic changes themselves. Therefore, trend detection becomes more efficient when the aforementioned spatial and temporal variability are reduced by taking into account the physical and chemical temporal characteristics of the body of groundwater, including flow conditions, recharge rates and percolation times (GWD, Annex IV, (2(a)(iii)). Several statistical techniques, modelling techniques and combinations of both are available for trend analysis and some of the promising techniques have been tested in the TREND2 work package and at UK abstraction sites, including age dating and transfer-function approaches (Visser et al. 2008, Stuart et al. 2007).

4.2.3. Trends in relation to pressures, monitoring strategies and properties of groundwater systems

The Aquaterra comparative approach showed that there is no unique approach which works under all hydrogeological conditions and for all monitoring systems across Europe. However, reducing variability by including information on pressures, hydrology and hydrochemistry did help to improve the detection of relevant trends in each of the hydrogeological settings studied. Specific conclusions included:

- grouping of wells is recommended to improve trend detection efficiency;
- grouping is preferably done according to pressures (often land use related), hydrologic vulnerability (travel time frequency distributions, unsaturated zone depth) and chemical characteristics such as rock type and organic matter contents (Figure 2);

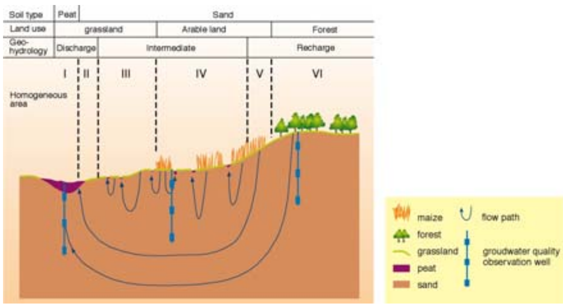

Figure 2: Grouping of wells according to pressures (land use), hydrologic vulnerability (hydrogeological situation) and chemical vulnerability (soil type). The resulting combinations were called homogeneous areas and used for determining trends and assessing chemical status (Broers and van der Grift, 2004)

- grouping should also consider the depth dimension because groundwater generally becomes older with depth (Figure 3) and trends at depth might be completely different from trends in the shallower parts of the aquifer.

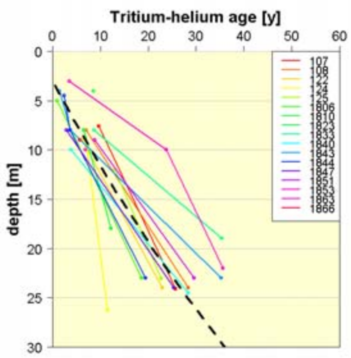

Figure 3: Increase of groundwater age with depth as determined by an analytical equation (dashed line) and tritium-helium age dating in 14 multi-level observation wells (separate colours for each well)

- it is essential to distinguish abstraction wells and springs from observation wells which are not pumped or naturally flowing;
  - *Pumping wells and springs* normally have water mixed from different layers and the resulting water quality reflects a broad range of travel times. As a further complicating factor, the contributions of young and old water in the mixture may change with time
  - Water quality measured in *observation wells* is normally related to a distinct groundwater age, and the time series can be related to a specific infiltration period once the age has been determined

  If different monitoring types occur in a groundwater body, trend detection is best done by grouping similar types of monitoring point together;

- Unsaturated zone thickness is one of the controlling variables when considering the choice of trend analysis technique. Thick unsaturated zones lead to long response times which can lead to difficulties in early detection of trends related to anthropogenic inputs from the land surface.

4.2.4. Aggregation of trends at the groundwater body scale

Although grouping of wells according to pressures and monitoring depths helps to identify trends (previous section), large spatial variability is also often observed in trend direction (up/down) and trend slope across a groundwater body (Figure 4). The implementation of the GWD requires a procedure where the trend assessment results at individual monitoring points are combined (or aggregated) to identify significant and sustained trends at the groundwater body scale body’ (EU 2008). Two possible ways of aggregating individual trends are illustrated below using data from the Dutch monitoring network in Noord-Brabant.

The monitoring network comprises standardized monitoring wells with fixed screens at specific depths. The wells consist of purpose built nested piezometers with a diameter of 50 mm and a screen length of 2 m at a depth of about 8 and 25 m below surface (Broers, 2002). The subsurface of Noord-Brabant consists of fluvial unconsolidated sand and gravel deposits from the Meuse River, overlain by a 2–5 m thick cover of Middle- and Upper-Pleistocene fluvio-periglacial and aeolian deposits consisting of fine sands and loam. Noord-Brabant is a relatively flat area with altitudes ranging from 0 m above Mean Sea Level (MSL) in the north and west to 30 m above MSL in the south-east. Groundwater tables are generally shallow, usually within 1-5 m below the surface.

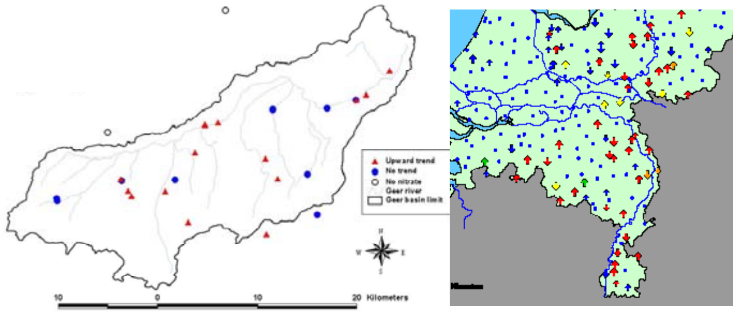

Figure 4: Spatial variability in trends in the Geer basin, Belgium (left) and southeast Netherlands (right)

As a first step in aggregating trends it was recommended to group monitoring wells on the basis of pressures/vulnerability and hydrological properties such as the probable travel time distribution in the groundwater body (previous section). Two methods for aggregating the trends are possible:

1. a statistical method, for example by defining the median trend slope and the corresponding confidence interval
2. a deterministic method, for example using age dating to aggregate time series along a standardized X-axis showing recharge time.

Both approaches are illustrated below using Aquaterra results.

Example 1: Aggregation using median trend slopes

First, all trend slopes of individual monitoring points were determined, through linear regression or a Kendall-Theil robust line (Helsel and Hirsch 1992). Aggregated trends were then determined by taking the median of all trend slopes to test whether this median differs significantly from zero (Broers and van der Grift 2004). A significant upward aggregated trend for the group of wells is established when the 95% confidence level of the median is completely above the zero slope line (Figure 5). A downward trend is identified if the complete confidence interval is below the zero slope line. Confidence intervals around the median slope were determined non-parametrically following the method of Helsel and Hirsch (1992) and using a table of the binomial distribution. In the example shown in Figure 5, significant upward trends (filled symbols) were detected for OXC and Sumcat in the lower graphs which represent the deeper screens, and downward trends for Sumcat and OXC in the upper graphs which represent the shallow screens. The results indicate reversal of trend direction with depth, with improving conditions in the shallow subsurface due to action programmes which effectively reduced the pollutant inputs, while the old pollution front still leads to deteriorating conditions in deeper groundwater.

It should be noted that trends can often have reversed directions at different depths in the aquifer, due to differences in groundwater age and the corresponding contaminant inputs during the period of infiltration (see for example Figure 5). One of the conclusions of aggregating trends in a statistical manner is that often a relatively large number of observation wells (20 to 40) is necessary to statistically demonstrate trends because of the observed large temporal and spatial variability which is inherent in groundwater quality datasets.

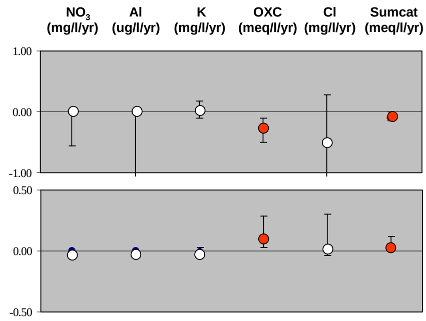

Figure 5: Aggregated median trend slopes for agricultural recharge areas in the province of Noord-Brabant for 6 chemical indicators for shallow screens (upper graph) and deeper screens (lower graph). Source: Visser et al. 2005. OXC= oxidation capacity, Sumcat = sum of cations)

Example 2: Aggregation based on recharge time using age dating

A new and promising aggregation technique is to use age dating to determine the recharge period of the groundwater and relate the measured concentration data to the derived recharge time. This technique proved to work well for monitoring systems based on multi-level observation wells in areas with porous aquifers. In this example, tritium-helium ages were used to determine the travel time to the monitoring screens. These travel times were used to relate the time-series of measured concentrations to the time of recharge, instead of the time of sampling (Figure 6). In this example, the aggregated time series shows a sustained upward trend with higher concentrations in recently infiltrated groundwater.

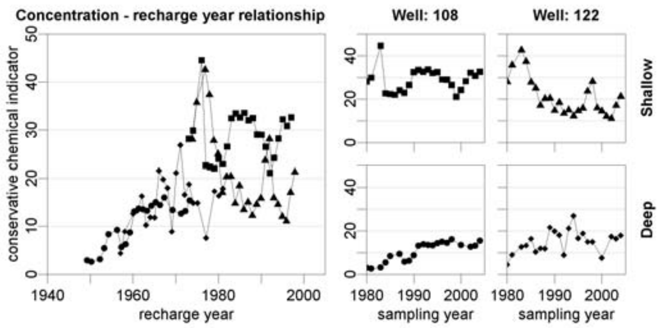

Figure 6: Translating time series measured in individual observation multi-level wells at shallow depth (10 m –sl) and deep (25 m –sl) into an aggregated time series plot using recharge year as X –axis after age dating using tritium-helium (Visser et al. 2007). The aggregated time series shows a sustained upward trend with higher concentrations with recharge time

Subsequently, the results of all 28 time series in the ‘intensive agricultural land use in recharge areas’ type were aggregated in one graph and analysed using LOWESS smoothing (Cleveland 1979) and ordinary linear regression approaches (Figure 7). The method successfully identified statistically significant ($P<0.005$) trend reversal of nitrate concentrations and oxidation capacity for this area type.

The observed trend compares well with the known input history of agricultural pollutants based on historical data series of the production and use of fertilizer and manure under various crop types. Trend reversal is generally most easily demonstrated for conservative solutes and indicators, such as ‘oxidation capacity’ (Visser et al. 2007). Downward trends in the most recent groundwater could also be demonstrated for reactive solutes such as nitrate, which is transformed to nitrogen when it encounters denitrification by reactive organic matter or sulfides at some depth in the subsurface.

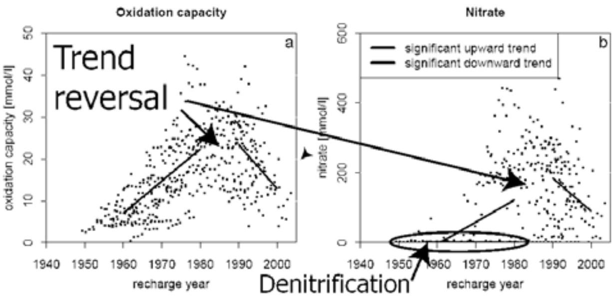

Figure 7: Aggregation by using age dating to determine recharge year corresponding to the measured concentrations.

4.2.5. Trend detection at drinking water abstraction sites

Trends and fluctuations

A trend is an underlying rate of change, and is often used to distinguish a long-term tendency from erratic short-term fluctuations. The latter are often referred to as 'noise', although they may have real and legitimate causes. Groundwater quality can vary over time scales ranging from tidal and daily cycles, seasonal or annual to longer periods, depending on the varying time scales governing the sources and input and output functions, and the properties of the aquifer. The underlying cause of these patterns of variation may reflect 'regional' changes in catchment land use, fertiliser applications, pollution history and the evolution and development of pollutant plumes and climatic factors. However, solute concentrations in samples of discharging groundwater from a single abstraction borehole or spring also depend on numerous 'local' or site factors such as borehole depths and open or screened interval, depths and lengths of groundwater flow paths, possible groundwater quality stratification in the aquifer and changes (at various timescales) in groundwater levels, directions of flow and pumping regime. These sources of variation are often superimposed on one another in a time series of an individual parameter, such as nitrate or chloride, at a drinking water abstraction site and their resolution can be a challenging task (Stuart et al, 2007).

Short-term peaks in solute concentration at abstraction sites are a particular problem for water supply utilities, and may compromise their ability to meet groundwater quality obligations under the Drinking Water Directive and the Water Framework Directive. Such variations may be qualitatively understood to be related to, for example, seasonal responses to groundwater recharge. However, the precise nature of the variations and the hydrogeological processes and pollutant transport mechanisms controlling them may be difficult to identify and quantify and the timing and scale of the peaks correspondingly difficult to predict. If observed groundwater quality time series are reasonably well described by a statistical model which accounts for both trends and seasonal variability, then there is a good prospect for determining trends and predicting groundwater quality within the timescales envisaged by the Water Framework Directive and Groundwater Directive.

In many cases, the monitoring itself can introduce its own characteristics which may make it difficult to assess and presence and significance of trends. These characteristics include the sampling frequency, the amount of missing data and its distribution within the time series, the length of the monitoring period and the presence of uncontrolled variables such intermittent abstraction, varying abstraction rates and unrecorded pumping regime.

Using abstraction site monitoring for trend detection

Many, perhaps most, national groundwater quality monitoring programmes, especially those that have developed gradually over time, depend to a large extend on sampling of groundwater at water supply sites (EU, 2007a). Of these, public supply boreholes have one major advantage of being operated and discharging more or less continuously. Purging is not normally required, the discharging groundwater represents water from within the aquifer, although sometimes from uncertain and varying locations within the aquifer, and sampling the discharge may be easy and relatively inexpensive. Private domestic, industrial and irrigation boreholes are also widely used, but may be operated less regularly.

It is, therefore, not surprising that such boreholes and, where suitable, springs form the backbone of many networks. There are, however, some pitfalls and limitations of abstraction sites which can affect the assessment of trends in water quality, and the regional and local factors referred to above must be understood in the interpretation of the monitoring results. At the simplest operational level, it is critical to obtain the sample from the supply pump or directly at the spring, and at the same point each time, before any treatment, storage or blending processes. Groundwater quality rarely changes extremely rapidly and if in examining closely-spaced time series data from abstraction boreholes there are sharp excursions of individual points (either upward or downward), these should be examined carefully. They are unlikely to be 'real' groundwater responses. Single individual outliers may be an analytical error; repeated individual outliers or very noisy plots are likely to represent local operational factors.

Particular problems can occur at multiple borehole sites, wellfields and multiple spring sources. It might be expected that variations in solute concentration with time for a cluster of boreholes within metres or tens of metres of each other at one site would be similar and related. However, individual abstraction points may have different concentrations and trends. This may be due to stratification of groundwater quality in the aquifer combined with differences in borehole depths, water levels, abstraction rates and inflow levels, or to differences in direction of groundwater flow, capture zone, soils and protective geological cover and land use (Stuart et al, 2007). In such situations, complex operating regimes, with rotating duty and standby boreholes mean that pumping from one may affect the quality of the others, and individual capture zones may be disturbed by the regular rotation of pumping. In some cases, abstraction from one borehole at such a site has been discontinued because of high nitrate concentrations, only for the adjacent low-nitrate borehole to experience a sharp step rise in nitrate as it captures more of the available high-nitrate water (Figure 8).

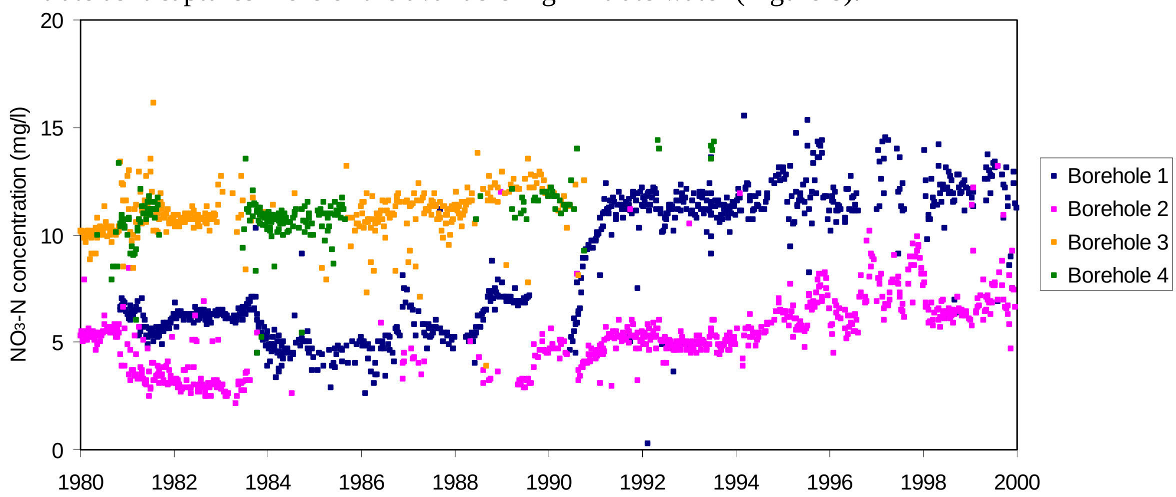

Figure 8: At this Triassic sandstone site, the shutdown of borehole 3 in 1990 due to high concentrations of nitrate leads to the transfer of high nitrate water to the next nearest borehole (1) within a few months (after UKWIR, 2004)

Approaches to trend detection

There is a long history of the application of statistical methods to water quality data, particularly to surface waters (Helsel and Hirsch, 1992; Peters, 1996), but also to groundwater (Frapporti, 1994; Beeson and Cook, 2004; Broers and van der Grift, 2004; Grath et al, 2001; Stuart et al, 2007). Many of the classical statistical procedures for analysing time series, such as autoregressive integrated moving average (ARIMA) methods, require regular sampling intervals. Although missing data can sometimes be accommodated by these methods, groundwater quality data from most water supply abstraction sites are so irregular as to preclude these types of analysis.

The trends of interest include monotonic, linear, cyclic (seasonal) and step changes. Grath et al (2001) proposed statistical tests for each of these, although their robustness against outliers, missing data and censoring vary. The Spearman rho and Mann-Kendall tau methods have been used to test for the presence of monotonic trends (Yue and Yang, 2002; Broers and van der Grift, 2004) and the Spearman rank correlation coefficient was also used by Yue and Wang (2002). Seasonal responses can be detected by methods such as periodograms, Students *t*-test (Helsel and Hirsch, 1992); Mann-Witney rank-sum test, analysis of variance, Kruskall-Wallis test, periodic functions, seasonal Mann-Kendall (Helsel and Hirsch, 1992) and spectral analysis (Fleming et al, 2002). However, seasonal patterns in groundwater quality are often complicated by the variation between years of the length, timing and scale of responses to climatic factors and the associated modifications to operational abstraction regimes related to increase or decreases in water demand and water availability.

Stuart et al (2007) summarise a simple semi-automated approach to trend estimation which incorporates a series of descriptive and statistical tests to determine the regularity and frequency of sampling, whether the data show a significant linear trend with time, whether there is any seasonality in the data, whether the data show any unusually large deviations from the assumptions made in the statistical tests used, and whether there is any evidence of a change in trend or a trend reversal. The 'R' statistical programming language (R Development Core Team, 2005) is used because of its powerful built-in graphical features, its ability to deal with large numbers of data sets in 'batch' mode and its facility for summarising the results of these tests. The approach has been extensively applied to groundwater nitrate time series data from public water supply sites in the major Chalk, limestone and sandstone aquifers of the UK (UKWIR, 2003; Stuart and Kinniburgh, 2005; Stuart et al, 2007).

The steps employed in this approach comprise descriptive, statistical and trend tests. The descriptive tests include graphical methods and summary statistics, and do not involve any estimation or testing of hypotheses. Five descriptive plots are automatically produced by this method:

Plot 1: a raw data scatterplot of concentration versus date;
Plot 2: a step plot showing the gap between successive samples in days, annotated with the mean and standard deviation of the gap, to illustrate the regularity of sampling;
Plot 3: a histogram of the gap to show sampling interval;
Plot 4: a box and whisker plot of concentrations each calendar month to show the range of monthly values. Cyclical behaviour on an annual timescale indicates seasonality (see for example Figure 9a)
Plot 5: a smoothed trend based on a LOESS smoother plotted with the raw data.

These plots provide a quick summary of the amount range and quality of the time series data at each abstraction point, with information about the regularity of sampling, the presence and importance of outliers, the degree of seasonality and the 'smoothness' of the data. Where the quality of the time series data is poor, this may be all that is possible or appropriate.

Following this, two standard plots are produced to show the results of statistical tests. Plot 6 shows the raw data overlain with linear trend lines determined by three regression-based methods (for example Figure 9b, Stuart et al, 2007). The plot is annotated with potential outliers, trend values, probability of significant seasonality, and the root mean square error (r.m.s.e). If detected, a 'broken stick' plot is included to show a change or reversal of trend. Where there is variation that cannot be accounted for by a linear model, a warning is included that 'additional' structure exists in the time series data. Plot 7 illustrates the results of standardised residuals tests in the form of a scatterplot of standardised residuals against date based on the seasonal or non-seasonal model and influential points and possible outliers are highlighted.

Figure 9 (Stuart et al, 2007) illustrates results obtained for nitrate in groundwater from an abstraction source in the UK Chalk aquifer which is subjected to strongly seasonal influence. As a consequence, while the overall upward trend is rather modest, the seasonal peaks have provided non-compliant groundwater nitrate concentrations since 1995, except in the dry years of 1996 and 1997. The very good correlation between nitrate concentrations and groundwater levels in a nearby observation borehole (Figure 9c) is clear, and was maintained in these dry years, suggesting a fundamental, process-based connection between the two.

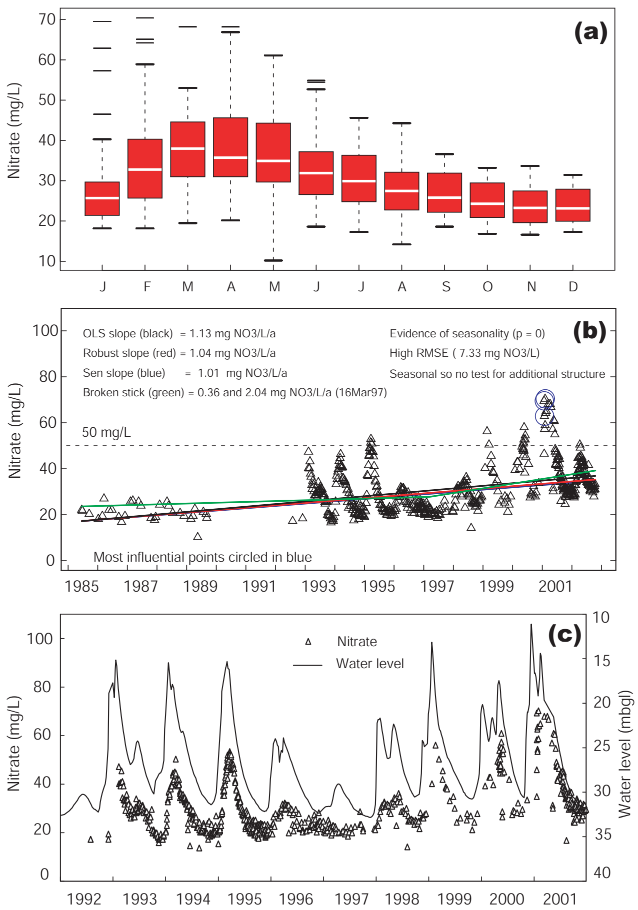

Figure 9: Seasonal data from a site in the Chalk aquifer: (a) range of monthly values (Plot 4), (b) trend fitting (Plot 6), (c) correspondence with water level for part of the data series (1993–2001).

Aggregation of data from abstraction sites

Time series and trends from single drinking water abstraction sites are essential for determining whether there is deterioration in groundwater quality in the safeguard zones and Drinking Water Protected Areas (DWPAs) established under the Water Framework Directive and Groundwater Directive (EU 2007b). As is the case for observation boreholes described in section 4.2.4 above, aggregation of data from abstraction sites is needed for assessing trends in groundwater bodies. Two approaches have been tested for a selection of groundwater bodies in the UK (Kinniburgh et al, 2004):

- an ‘average of averages’ approach in which an average of all data within the groundwater body for each time interval is taken, and the trend with time of these averages taken – spatial average and then time trend;

- a ‘median trend’ approach in which the data for each site are used to determine an individual trend, and then the median of these individual trends is used to provide a trend for the groundwater body – time trend and then spatial average. This is similar to the approach described in section 4.2.4.

The former method is that proposed by Grath et al, (2001). This works well if the sampling is indeed very regular and there a few missing data points. However, where there is both a large amount of systematic variation within the groundwater body and many missing data, the average of averages approach becomes less robust, as sites are counted in and counted out for different time intervals. The median trend approach is less susceptible to outliers and missing data. Moreover, as the trend at the individual site is in any case needed for DWPAs and, for nitrate, also for the Nitrates Directive, and probably for other purposes, it may make more sense to take this approach. In addition, trends for individual abstraction sites may respond to both the regional and local factors outlined above, about which there may be considerable knowledge and information. There is also likely to be detailed construction and operational detail about the site, and the trend information provided may greatly assist both the regulatory agency and the water supply operator in managing groundwater quality, before being incorporated into a broader assessment at groundwater body level.

Where groundwater bodies are of substantial size and there are considerable numbers of monitored abstraction boreholes and differing concentrations and trends may be observed. These may vary systematically across the body (Figure 10, Stuart et al, 2007), in a broadly similar way to the relationship with depth illustrated in Figure 5. This groundwater body in the north east of England comprises part of a productive Permian limestone aquifer, dipping from west to east beneath younger confining strata (Figure 11). The outcrop receives recent recharge from relatively nitrate-rich infiltration from agricultural land. As the groundwater move eastwards along flowpaths down the dip of the aquifer (Figure 11), nitrate concentrations decrease, either because the water is older recharge with less nitrate, or some of the nitrate is removed by denitrification in changing redox conditions beneath the confining strata. Evidence of chemical denitrification in the hydrogeological setting shown in Figure 11 has been widely detected in Chalk, sandstone and limestone aquifers in the UK.

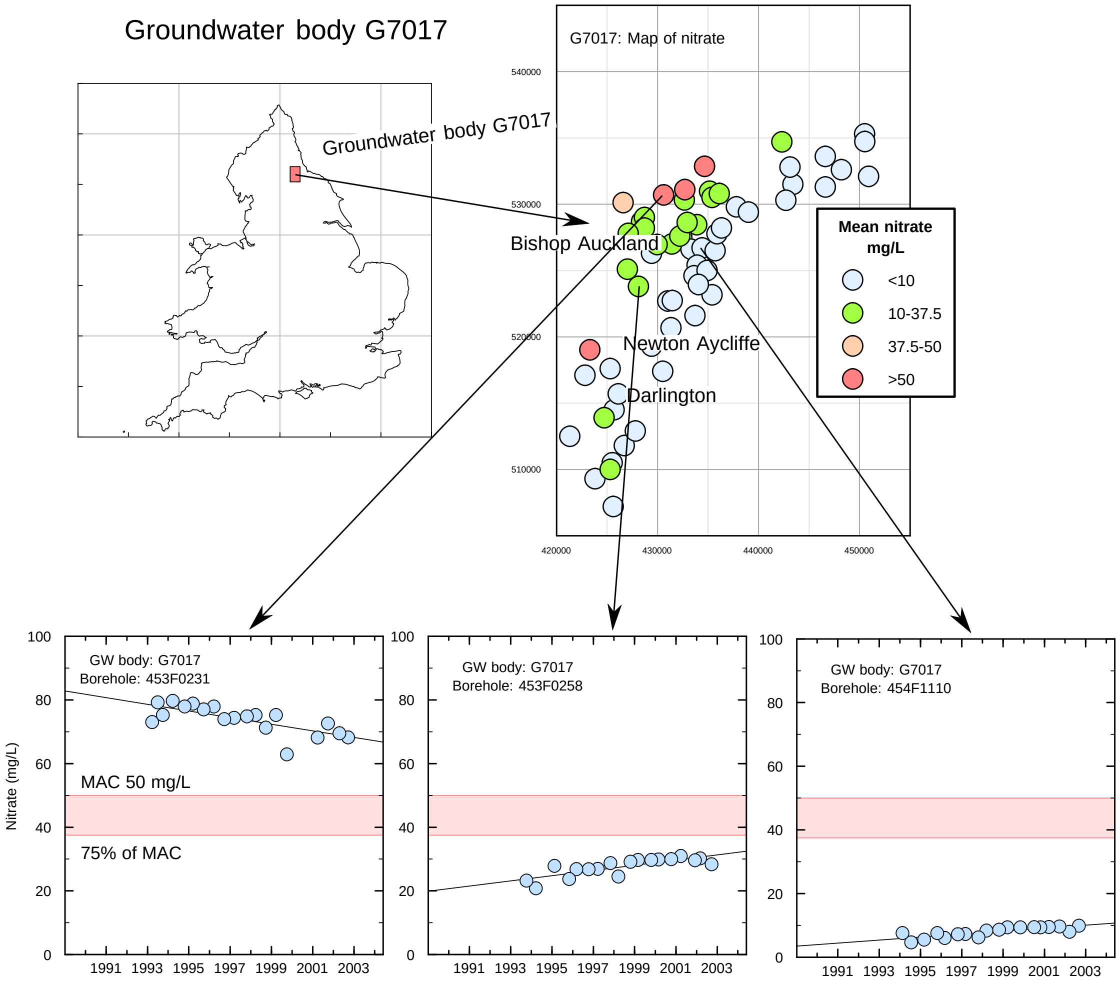

Figure 10: Variation in mean nitrate concentration in a groundwater body, and differing trends across the groundwater body.

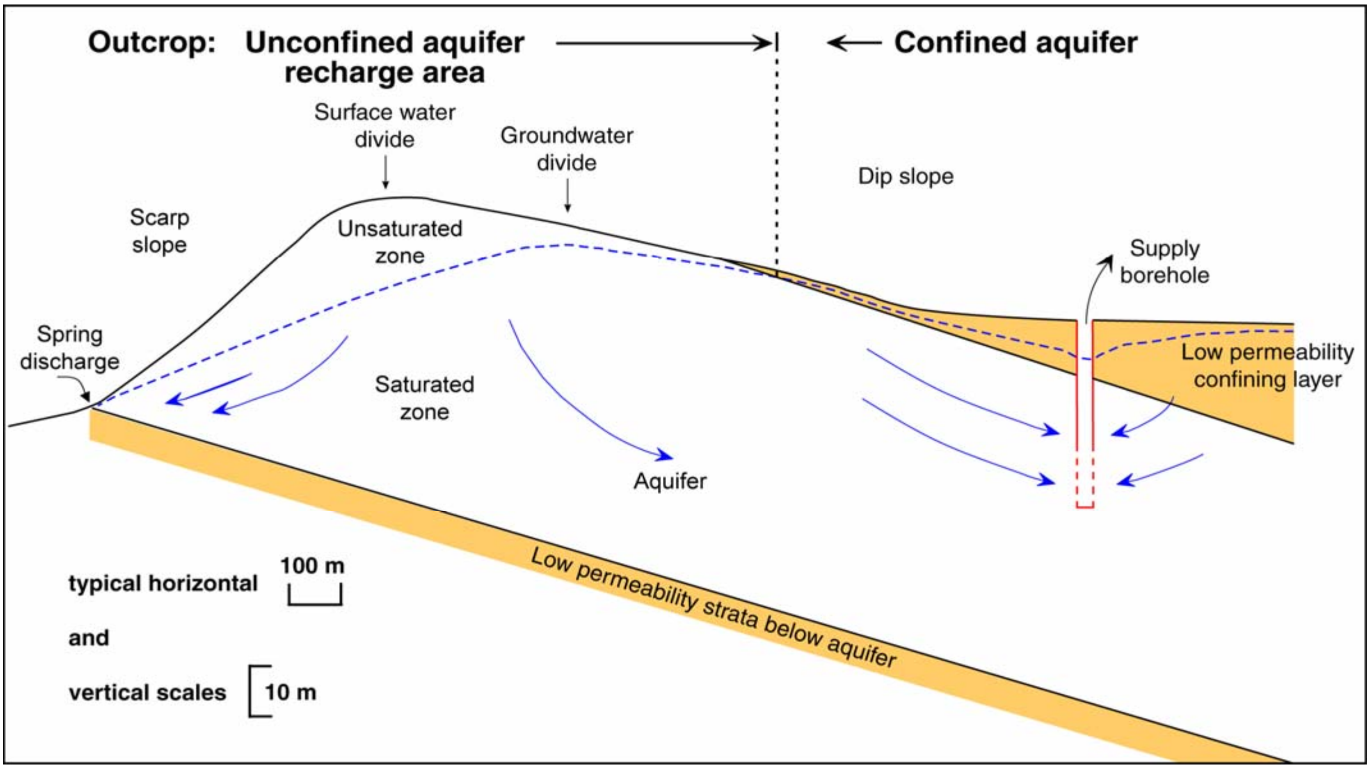

Figure 11: Simplified conceptual sketch of hydrogeological setting from which the data in Figure 10 are taken.

Trends in nitrate concentration also vary systematically across this groundwater body (Figure 10). Thus the highest nitrate concentrations at the outcrop tend to be decreasing, which is likely to reflect the beneficial impact of agricultural control measures, as was inferred in the example shown in Figure 5. Further down the groundwater flowpath, nitrate concentrations are still increasing towards 50 mg/l – a statistically and environmentally significant trend. The lowest concentrations are also increasing (Figure 10) but, although clearly statistically significant these trends are not yet really significant environmentally. It should be noted that the reversing directions of trends along a flow path are conceptually similar to the trend direction reversal shown in section 4.2.4, example 1, which deals with observation wells screened at multiple depths at the groundwater body scale.

Applying both of the aggregation approaches described above, the average of averages (Grath et al, 2001) suggests an almost imperceptible downward trend of 0.08 mg/l/a (Stuart et al, 2007) and the median trend approach an upward trend of 0.08 mg/l/a. Although these are different directions of change, the magnitude is small and both suggest there is very little overall trend within the groundwater body. Of the two, the median trend approach provides a better indication of how the situation varies across the groundwater body, and where groundwater quality management and pollution control measures should most effectively be targeted. These findings of course raise the question as to whether it would be more appropriate under the Water Framework Directive to take account of such major differences in chemical quality status by sub-dividing the groundwater body. The soundness of hydrogeological definition of the groundwater body and the integrity of the groundwater flowpath, however, suggest that, as a management unit, it should remain as it is.

CONCLUSIONS

The trend analysis results presented in this chapter show that it is feasible to detect trends and demonstrate trend reversal both at the individual abstraction site and groundwater body scale, and to assess the corresponding level of confidence. The results show that trend detection is preferably tuned to pressures to the groundwater system, to the monitoring set-up and to the hydrological and chemical properties of the system. It also illustrates how groundwater age dating can improve trend detection.

REFERENCES

Batlle Aguilar, J., Orban, P., Dassargues, A. and Brouyère, S., 2007. Identification of groundwater quality trends in a chalk aquifer threatened by intensive agriculture in Belgium. Hydrogeology Journal, 15(8): 1615.

Beeson, S and Cook, M. (2004). Nitrate in groundwater: a water company perspective. Quarterly Journal of Engineering Geology and Hydrogeology, 37, 261-270.

Broers, H.P. (2002). Strategies for regional groundwater quality monitoring. Netherlands Geographical Studies no. 306, Ph.D. Thesis University of Utrecht, the Netherlands.

Broers, H.P. and van der Grift, B., 2004. Regional monitoring of temporal changes in groundwater quality. Journal of Hydrology, 296(1-4): 192-220.

Broers H.P, Visser A.,(eds.), Gourcy L., Dubus I.G. Baran N., Mouvet C. & Gutierrez A.(2005). Report on concentration-depth, concentration-time and time-depth profiles in the Meuse basin and the Brévilles catchment. Aquaterra deliverable T2.3 (http://www.attempto-projects.de/aquaterra/21.0.html)

Cleveland, W. S. (1979) Robust locally weighted regression and smoothing scatterplots. J. Amer. Statist. Assoc. *74*, 829-836.

EU (2006), Directive 2006/118/EC on the Protection of Groundwater against Pollution and Deterioration.

EU (2007a) Common Implementation Strategy for the Water Framework Directive(2000/60/EC).Guidance Document No. 15. Guidance on Groundwater Monitoring.

EU (2007b) Common Implementation Strategy for the Water Framework Directive(2000/60/EC).Guidance Document No. 16. Guidance on Groundwater in Drinking Water Protected Areas. Technical Report - 2007 – 010.

EU (2008) Common Implementation Strategy for the Water Framework Directive(2000/60/EC).Guidance on Groundwater Status and Trend Assessment - Final Draft 2.0, 15 October 2008, Working Group C – Groundwater, Activity WGC-2, “Status Compliance & Trends”.

Fleming, S. W. Lavenue, A.M. Aly, A.H. and Adams, A. (2002). Practical applications of spectral analysis to hydrologic time series. Hydrological Processes, 16, 565-574.

Frapporti, G. (1994). Geochemical and statistical interpretation of the Dutch national groundwater quality monitoring network. University of Utrecht.

Grath, J., Scheidleder, A., Uhlig, S., Weber, K., Kralik, M., Keimal, T., & Gruber, D. 2001. The EU Water Framework Directive: Statistical aspects of the identification of groundwater pollution trends, and aggregation of monitoring results. Final Report. No.41.046/01-IV1/00 and GZ 16 2500/2-I/6/00, Austrian Federal Ministry of Agriculture and Forestry, Environment and Water Management and European Commission, Vienna

Helsel, D.R., Hirsch, R.M., 1992. Statistical methods in water resources, Studies in Environmental Science 49, Elsevier, Amsterdam.

Kinniburgh, D.G, Chilton, P. J. and Cooper, D. M. 2004. Identification and reversal of trends in groundwater pollution: Part 2 – possible approaches and their implications with some trial assessments using existing monitoring data. British Geological Survey Commissioned Report, CR/04/207C.

Loftis, J.C., 1996. Trends in groundwater quality. Hydrological Processes, 10: 335-355.

Peters, N. E. (ed) 1996. Trends in water quality. Special Issue. Hydrological Processes, 10. .

Pinault, J.L. and Dubus, I.G., 2008. Stationary and non-stationary autoregressive processes with external inputs for predicting trends in water quality. Journal of Contaminant Hydrology, In Press, Accepted Manuscript.

Quevauviller, Ph. (2008) European regulatory framework of integrated groundwater management. Theory versus realities. In Proceedings EU Groundwater Policy Developments Conference, 13-15 November 2008, Unesco, Paris France.

Stuart, M.E., Chilton, P. J., Kinniburgh, D.G. and Cooper, D.M. 2007. Screening for long-term trends in groundwater nitrate monitoring data. Quarterly Journal of Engineering Geology and Hydrogeology, 40, 361-376.

UKWIR. 2003. Implications of changing groundwater quality for water resources and the UK water industry. Phase 2: Trend detection methodology and improved monitoring and assessment programmes: Main report. UK Water Industry Research Report 03/WR/09/06.

UKWIR. 2004.Implications of changing groundwater quality for water resources and the UK water industry. Phase 3: Best practice guidelines for investigating processes controlling groundwater quality. UK Water Industry Research Report 04/WR/09/07.

Visser, A., Broers, H.P., Van der Grift, B. and Bierkens, M.F.P., 2007b. Demonstrating Trend Reversal of Groundwater Quality in Relation to Time of Recharge determined by 3H/3He. Environmental Pollution, 148 (3): 797-807.

Visser, A., Broers, H.P., , I.G. Dubus, J.L. Pinault, M. Korcz, Batlle Aguilar, J., Orban, P., and Brouyère, S and M.F.P. Bierkens (2008) Comparison of methods for the detection and extrapolation of trends in groundwater quality. Aquaterra deliverable T2.12, submitted to Journal of Hydrology.

Yue, S. & Wang, C.Y. 2002. The influence of serial correlation on the Mann-Whitney test for detecting a shift in median. Advances in Water Resources, 25, 325-333.

KEYWORDS

Groundwater Directive, trends, pressures, monitoring, travel times, age dating, aggregation procedure