Groundwater Information Sheet:

The Impact of Industrial Activity

This is one of a series of information sheets prepared in relation to specific human activities which are of significant concern for the management of groundwater resources and protection of groundwater quality. The sheets aim to summarise the characteristics of each activity, describe the risk of each one impacting on groundwater, the possible approaches to their investigation and potential methods of control, mitigation or restoration. The purpose of the sheets is to raise the awareness of these issues amongst WaterAid Country Office staff, to provide guidance on taking the potential impacts of these activities into account in programme planning and implementation and on targeting monitoring and assessment efforts accordingly, and to encourage further thinking in the organisation on water quality and water management issues. The three sheets in this series (agriculture, industry and urbanisation) complement previous briefing sheets on specific groundwater quality parameters and for target WaterAid countries, and should be read in conjunction with these.

Water use by industry

Water is used by industry in many ways – for cleaning, heating and cooling and generating steam, as a solvent and for transporting dissolved substances, and as a constituent part of the industrial product itself. Withdrawal of water for industry is usually much greater than the amount actually consumed (WWAP, 2006). Following major growth between 1960 and the 1980s, water withdrawal for industry worldwide has more or less stabilised; falling in Europe and rising steadily, but not as rapidly as previously, in Asia. In areas where surface water resources are scarce groundwater is used to meet industrial demand. While it is often difficult to obtain specific data concerning groundwater withdrawal for industry, it clearly remains a fraction of that used for agriculture.

Industry as an environmental pressure

Of greater concern than the actual volume of groundwater withdrawn by industry is the potential for negative impact of industry on the quality of the subsurface environment (WWAP, 2006). This is because the balance between the volume of water withdrawn and the much smaller volume actually consumed becomes wastewater or effluent to be disposed of. This is usually by means of one of the following (WWAP, 2006):

- direct disposal untreated into the ground, or via streams, rivers and canals to aquifers;
- disposal to municipal sewer systems, which may or may not include sewage treatment;
- treatment of wastewater on-site before disposal by either of the above.

While there is sometimes scope for reclamation of industrial wastewater to make it reusable within the industry itself or by other users, nevertheless most effluent is returned directly to the water cycle, often without adequate treatment. It is the volumes of these effluents and the concentrations of hazardous substances they contain, combined with the mode of disposal and the vulnerability of the underlying groundwater which determine the risk of pollution.

In assessing industrial impacts, therefore, groundwater quality issues are likely to be much more dominant than quantity. The latter, which include groundwater level recovery in response to declining industrial or mining abstraction, are considered to be adequately dealt with by the discussions of the impacts of groundwater abstraction in the companion briefing notes on agriculture and urbanisation. This note focuses on the impacts of industrial and mining activities on groundwater quality.

For highly-developed countries, often the greatest concern is dealing with the residual impacts of the industrial and mining legacy of the past two centuries. In contrast, for newly-industrialised and developing countries, the main concern may be for rapidly-growing, often unplanned and poorly regulated industrial activities, which may be widely dispersed in urban and peri-urban areas. Their potential environmental impact may not yet be observed, and the risk they pose to groundwater not appreciated.

Table 1. Common sources of groundwater pollution from industry (modified from Morris et al, 2003)

Source	Mechanism or main contributory factors
Underground and surface storage tanks, processes and effluent pipe work or other transfer system	Undetected leakage or inadequate bunding to retain major failures
Industrial sewers/collectors	Leakage because of poor maintenance
Soakaways, waste injection wells	Pollution because of inappropriate disposal practice
Bulk chemical storage areas	Poor handling and storage procedures, leaks
Liquid effluent and process lagoons	Leakage because of poor construction/maintenance
Solid process-waste disposal sites	Leakage of leachate through poor construction or failure of design
Accidental/catastrophic discharge	Plant fire, explosion, impact and loss of material to ground

Industrial facilities and practices

Industry and mining cover a vast spectrum of activities and processes, and an equally large range of scales. By no means all will generate significant pollutant loads and, just because an industry employs hazardous chemicals in its production processes it does not follow that it will necessarily be a groundwater polluter. Industry-specific, process-specific or even site-specific factors such as the method of effluent disposal and storage practices (Table 1), the integrated pollution control procedures used and the vulnerability of the underlying groundwater will all influence whether an industry will have a negative impact (Morris et al, 2003). The pollution sources and pathways to groundwater mentioned in Table 1 are largely the same as those identified for general urban impacts, but are probably derived more often from point than diffuse sources.

Characterising industrial pollutants

Given this vast array of industries, there are equally large numbers of heavy metals, organic solvents and hydrocarbons associated with them. Fortunately these associations are well known and documented. The leather industry, for example, produces solid and liquid waste which could contain high concentrations of chromium, organic carbon, nitrogen, sodium chloride and chlorinated solvents, depending on the production processes used and methods of waste disposal (Armienta and Quéré, 1995; Chilton et al, 1998). This is one of the industries that often occurs as dispersed, small premises, as described for Tamil Nadu by Muthu (1992) and for Léon, Mexico (Armienta et al, 1997). where more than 500 separate small tanneries were identified in the city.

Information designed specifically to help identify industries and substances most likely to become groundwater pollutants is summarised by Foster et al (1988; 2002), Morris et al (2003) and Schmoll et al (2006). Chapter 4 of Schmoll et al (2006) also provides useful references to the more detailed literature on industrial chemicals (Mercer and Cohen, 1990; Montgomery, 1996 and Pankow and Cherry, 1996). The US EPA website is also a valuable source of substance-specific information.

The potential pollutants identified as arising from industrial activities can be conveniently grouped together to indicate their relative importance in different industrial sectors (Morris et al, 2003). The physical and chemical properties of the substances influence their behaviour in the subsurface and their likely impact on groundwater quality (Montgomery, 1996). Industrial chemicals can be discharged from the sources listed in Table 1 both as 'neat' compound (from pipes and storage tanks) or contained in wastewater. Both immiscible phase and dissolved-phase constituents can thus occur in the subsurface. Solubility in water is an important factor in their transport, with phenolic compounds being soluble and hydrocarbons much less so. Their density with respect to water also determines behaviour and transport. Fuel compounds and oils are usually less dense than water and tend to float at the water table (scenario A in Figure 1). Some are also of low viscosity at typical subsurface temperatures (Mercer and Cohen, 1990), making them significantly less mobile.

In contrast, the chlorinated hydrocarbons widely used as industrial solvents are both denser than water and have low viscosity, and can instead descend rapidly through the aquifer (Pankow and Cherry, 1996). As the chemical sinks through the aquifer to its base (scenario B in Figure 1), some of the immiscible phase will be left behind in pore spaces and fractures. This residual forms a slowly-dissolving pollutant source which can generate and maintain a plume extending throughout the full thickness of the aquifer and moving slowly down the hydraulic gradient (Figure 1).

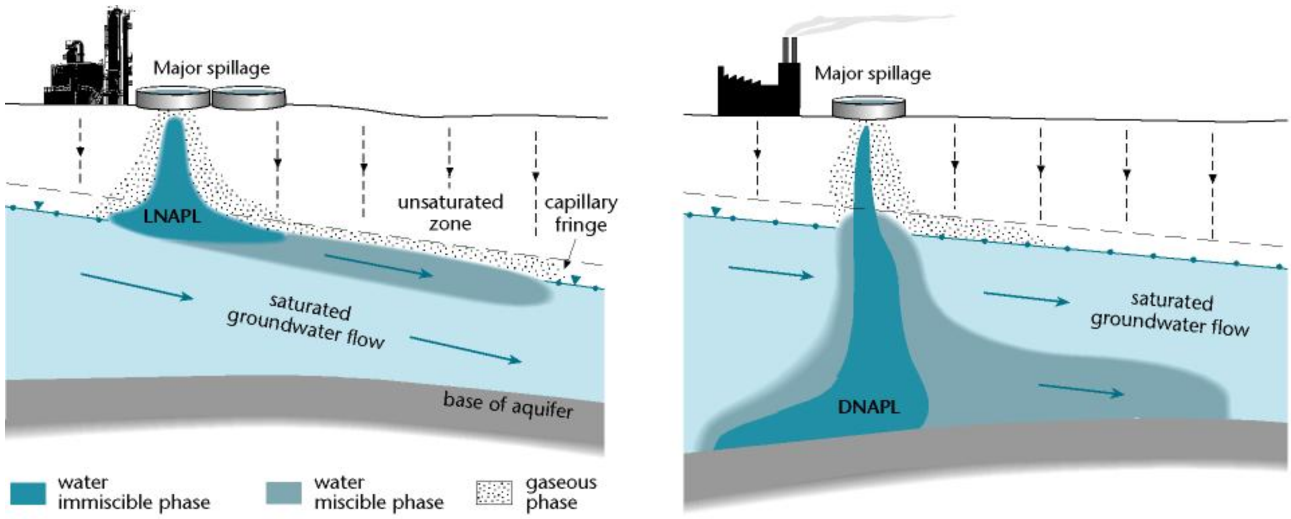

Figure 1. Behaviour of A) aromatic low-density and B) halogenated high-density hydrocarbons following an industrial spillage (modified from Lawrence and Foster, 1987)

Once an industrial chemical is in the subsurface, the effectiveness of various processes of attenuation determines the potential for pollutant plumes to develop and expand. These processes of dilution, retardation and elimination are likely to be varyingly effective in soil, unsaturated zone and saturated zone (Morris et al, 2003). Biodegradation, sorption, filtration, volatilisation, precipitation and hydrolysis are likely to be most effective in the soil layer, with its active microbial populations and high content of clay and organic matter. These processes are less well known in the unsaturated zone but almost invariably slower and, while they may still occur below the water table, dispersion and dilution in the regional groundwater flow system become more important. Attenuation processes are also of varying importance for different groups of pollutants (Morris et al, 2003).

The severity of impact at the point of groundwater discharge in a well, borehole or spring depends on the toxicity of the chemical. Information on toxicity can be obtained from the WHO Drinking Water guidelines (WHO, 2004) and associated supporting technical documents.

Mining activities and processes

Activities associated with mining and mineral processing operations have significant potential to pollute groundwater either directly or indirectly. Mining areas are quite often located in the mountainous upper parts of catchments and, via the surface water system, impacts can be felt far downstream, as in the case of the Baia Mare cyanide spill (UNEP/WWF, 2000).

The broad term mining includes both open pits and underground workings for minerals and quarrying for building materials. The sources, pollution pathways and potential impacts on receptors are summarised in Table 2. Both open pit and underground mines often require substantial withdrawals of groundwater to create an

Table 2. Groundwater problems arising from mining activities (modified from Morris et al, 2003)

Mining activity or process	Potential impact on subsurface if inadequate design and implementation	Resulting environmental problem
Mine drainage	Mine water rebound	Groundwater or surface water pollution from acid mine drainage
Mine gas generation	Migration through strata	Mine gas emission at the surface
Shallow mining	Ground instability	Subsidence
Deep mining	Enhanced transmissivity above workings due to collapse fractures	Localised dewatering of overlying aquifer on intrusion of lower quality water on rebound
Extractive operations	Pollutants used for mine operations used and left in situ	Residual, fuels, hydrocarbons, solvents, explosives leached to groundwater
Tailings lagoons	Effluent seepage, tailing dam failure	Pollution of groundwater and surface water
Solid waste dumps/spoil heaps	Acidic and metal-rich leachate	Pollution plumes below tailings

artificial cone of depression within which the mining operations can take place. Many metalliferous mines are in remote, often mountainous, crystalline rock areas. These rocks may be relatively impermeable, and probably do not usually constitute usable aquifers, local populations may be small and the impacts of withdrawing groundwater not great. For open pits (for example coal mines) and quarries in more productive sedimentary sequences, the groundwater volumes are likely to be larger and the resource implications greater. However, the abstracted water has to be disposed of and, quality considerations allowing, may be returned elsewhere within an overall water management scheme.

Apart from the groundwater quantity impacts of the abstraction and eventual recovery, large volumes of rock may become temporarily aerated and sulphides and other minerals subjected to oxidation. The resulting acid mine drainage is one of the most widespread and severe quality problems associated with mining and discharge into surface waters as at the well known Wheal Jane site in South West England (Bowen et al, 1998; Morris et al, 2003;) and into groundwaters can have major environmental impacts. These impacts are often the most severe but difficult to predict when recovery of water levels into previously dewatered ground on cessation of pumping re-mobilises both the oxidation products and other pollutants left by the mining operations.

Liquid and solid mining waste in the form of tailings lagoons and spoil heaps respectively can be important pollution sources (Table 2). The spectacular tailings dam failures at Baia Mare in Romania (UNEP/WWF, 2000) and Aznalcóllar in Spain (Grimalt et al, 1999) caused extensive and widely publicised environmental damage.

Investigating industrial and mining impacts on groundwater

An assessment of the risk to groundwater from industrial and mining activities needs to take account of interaction between discharge pressures and pollutant loading on the one hand, and the nature the subsurface environment on the other (Schmoll et al, 2006). As for agriculture and urbanisation, the potential for these activities to have a quantity impact on the underlying groundwater is a function of the aquifer's susceptibility to the consequences of excessive abstraction (shown in Table 1 of the Agriculture theme sheet). The risk of impacts on groundwater quality is a function of pollutant loading and aquifer vulnerability.

To investigate and understand the impacts of industrial and mining activities, it is essential to develop a conceptual model of the groundwater system (Schmoll et al, 2006). Even if such a model is initially merely a sketch cross-section of the aquifers, it should embrace the source-pathway-receptor concept, using Tables 1 and 2 to identify sources and possible pathways. This forms the basis for deciding which activities occur and need to be investigated. The conceptual model can be refined as work progresses, and more knowledge of the ability of the subsurface to transmit or attenuate pollutants and of the scale and scope of the various industrial or mining activities is obtained.

The general information requirements for an assessment of pollutant loading are set out in Figure 2. Answers to the questions are usually obtained by conducting a survey to identify industries within the catchment or area of interest. This should be followed by more detailed inventory of those likely to produce polluting effluents (Foster et al, 2002; UNESCO, 2002 and Morris et al, 2003), including an assessment of their effluent volumes and mode, duration and intensity of disposal (Figure 2). Further guidance for each of these components is provided by these references, together with Schmoll et al, (2006), which includes useful check-lists to help in data collection. The general scheme set out in Figure 2 can be applied also to agricultural activities and the impacts of urbanisation.

In practice, it is often the reporting of health effects in water users or the detection of high concentrations in discharging groundwater that initiates concern about industrial pollution. The follow-up action takes on the nature of a detective investigation, looking back up the groundwater pathway from the discharge to identify the culprit pollution source or sources. In the Ron Thibun area of southern Thailand, chronic arsenic poisoning was caused by drinking groundwater from shallow wells that had been contaminated by tin mining waste and alluvial tin mining (Williams et al, 1996). Arsenopyrite associated with the tin had been oxidised by the dewatering and then re-mobilised when groundwater levels recovered after mining ceased (Morris et al, 2003). High arsenic and fluoride concentrations in groundwater at Kalalanwala in the Kasur District of Pakistan were investigated by Farooqi et al (2007) and found to be linked to local brick factories. In this case, samples of local rain contained such high concentrations of fluoride and arsenic that part of the pollution loading must have been transported by air.

Implications of industrialisation for water resource management

Components of a water management strategy which relate specifically to industry and mining are likely to concentrate on protecting groundwater (and surface water) to minimise the likelihood and magnitude of

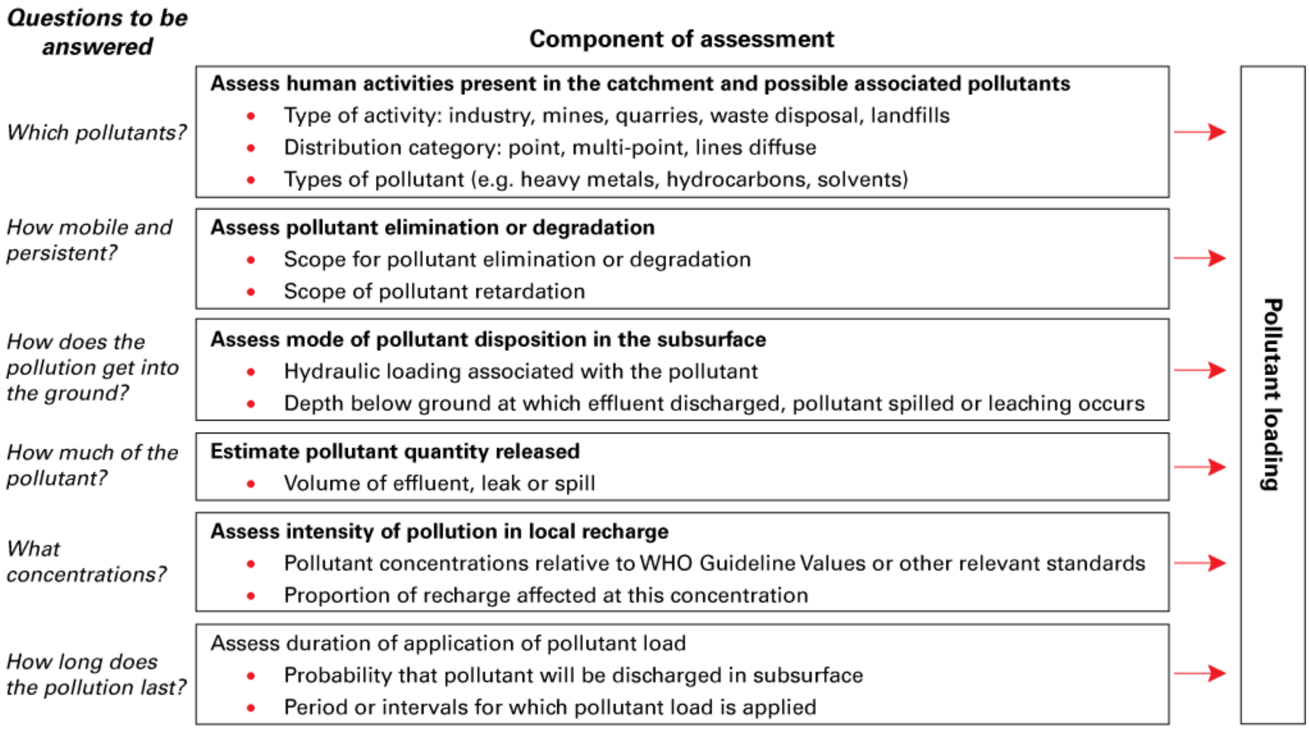

Figure 2. Components of assessment of pollutant loading (modified from Schmoll et al, 2006)

pollution. Management measures fall broadly into three categories (Schmoll et al, 2006):

- planning and site selection in relation to the vulnerability of groundwater;
- engineering measures in the design and construction of facilities, processes, storage and waste disposal;
- operational procedures and controls on maintenance, handling and waste disposal.

In practice, long-established industries may provide significant risks that cannot realistically be modified, certainly from the first of these and probably for many aspects of the second. Designation of protection zones around municipal boreholes or wellfields may be impractical, especially if both industrial sites and supply boreholes are many and interspersed with each other. The emphasis then needs to be placed on operational measures, including maintenance and rehabilitation programmes, training to help prevent spillages during delivery and proper functioning of waste treatment and disposal to help reduce the pollution loading (Schmoll et al, 2006).

Protecting groundwater may present great practical difficulties in towns and cities in developing countries where small-scale industries are widely dispersed throughout entire districts, suburbs or peri-urban areas and completely intermingled with poorer communities depending on shallow aquifers for private or community water supplies, often using handpumps. Effective groundwater protection may only be achieved at great expense by relocating the industries close together so that their effluents can be collected and treated, as proposed in the Léon case (Chilton et al, 1998).

Monitoring industrial impacts on groundwater

Monitoring the management measures outlined above is essential to ensure that they are in place and effective. Options for monitoring and verification of the three broad categories of measures outlined above are given by Schmoll et al (2006). These options include regular monitoring in soil and groundwater for parameters selected from the inventory to indicate leaks, spills or effluent releases. Such monitoring in the subsurface becomes particularly important for abandoned, decommissioned or remediated industrial or mining sites and may need to be maintained for many years. Effective monitoring of groundwater quality in these situations is likely to require purpose-built observation boreholes within the pollution pathway but close to the source (Foster et al, 2002). Water supply boreholes further down the pathway are likely to provide belated information for groundwater quality management. By the time pollution reaches these or other receptors, considerable quantities of pollutant may already be moving through the subsurface and may be difficult or impossible to deal with.

Metalliferous mining areas are often characterised by high natural chemical concentrations, and this should be taken account of in parameter selection for regional drinking water quality monitoring and assessment. Gold mining in particular is associated with arsenic (Smedley and Kinniburgh, 2002) which should then automatically be included for sampling of new wells and boreholes before they are put into potable supply and in routine monitoring programmes.

Detailed guidance and further reading

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