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Sustainable Groundwater Management
Concepts & Tools

Briefing Note Series Note 14

Natural Groundwater Quality Hazards

avoiding problems and formulating mitigation strategies

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How can potable groundwater be affected by natural quality hazards?

- Trace elements make up only 1% of naturally-occurring dissolved constituents in groundwater, but can sometimes make it unfit or unacceptable for consumption (Figure 1). At the same time many trace elements are essential for human and/or animal health in small quantities (for example F and I—*see Figure-1 for explanation of chemical symbols*), and may be ingested from drinking water or solid food. However, the desirable concentration range may be small, and some trace elements are harmful at higher levels (for example, F). Others are always harmful for health, even at very low concentrations (for example, As and U).

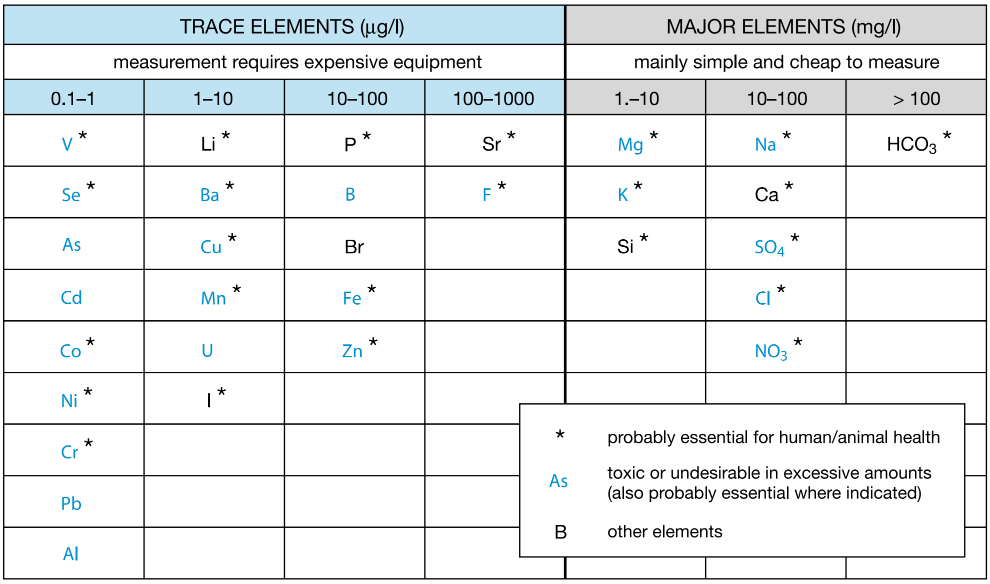
- Certain elements (As, F, Mn) are discussed in considerable detail below (Table 1), in view of the fact that they present known problems in groundwater. Other elements (notably Ni, U and Al) are of increasing concern and may merit investigation under some conditions. The concentration of some of these constituents can also be increased from polluting activities at the land surface, and it is important for management purposes to differentiate anthropogenic impacts from naturally-occurring problems; this will require investment in detailed groundwater investigation and monitoring.

- The philosophy of the 'UN Water Supply & Sanitation Decade' (1980s) was that hygiene-related diseases (associated with inadequate water washing) were of equal or greater importance than water-borne diseases, and thus the priorities were:
  - ready access to a reliable water source in quantity terms
  - improved microbiological quality of supply, but not necessarily to the zero 'fecal coliform standard'.

  In contrast inorganic quality was not given much consideration, unless taste or color (as a result of excessive $MgSO_4$, NaCl or soluble Fe) would lead to social rejection of the improved source.

- It remains true at the beginning of the 21st century that by far the greatest water quality problem in the developing world is the prevalence of pathogenic waterborne diseases, in large measure due to fecal pollution of drinking water as a result of inadequate sanitary protection. But the 'decade philosophy' has been found insufficient, because of the natural occurrence of elevated concentrations of certain trace elements in some groundwater supplies at levels above WHO drinking water guidelines and with longer-term health implications for water consumers. These occur in certain aquifers as a result of their mineralogical character, sluggish groundwater flow and only partial flushing.

Figure 1: Dissolved constituents in groundwater and their effect on human health



TRACE ELEMENTS (µg/l)				MAJOR ELEMENTS (mg/l)		
measurement requires expensive equipment				mainly simple and cheap to measure		
0.1–1	1–10	10–100	100–1000	1.–10	10–100	> 100
V *	Li *	P *	Sr *	Mg *	Na *	HCO_3 *
Se *	Ba *	B	F *	K *	Ca *	
As	Cu *	Br		Si *	SO_4 *	
Cd	Mn *	Fe *			Cl *	
Co *	U	Zn *			NO_3 *	
Ni *	I *					
Cr *						
Pb						
Al						

*	probably essential for human/animal health
As	toxic or undesirable in excessive amounts (also probably essential where indicated)
B	other elements

Al	aluminium	Mg	magnesium
As	arsenic	Mn	manganese
B	boron	Na	sodium
Ba	barium	Ni	nickel
Br	bromide	NO_3	nitrate
Ca	calcium	P	phosphorus
Cd	cadmium	Pb	lead
Cl	chloride	Se	selenium
Co	cobalt	Si	silica
Cr	chromium	SO_4	sulfate
Cu	copper	Sr	strontium
F	fluoride	U	uranium
Fe	iron	V	vanadium
HCO_3	bicarbonate	Zn	zinc
I	iodide		
K	potassium		
Li	lithium		

- Three other developments in recent decades have raised public health concerns over the inorganic quality of groundwater supplies:
    - the capacity to analyze ever smaller amounts of dissolved constituents in water, moving from the mg/l (ppm) to µg/l (ppb) level (Figure 1), even in many developing nations
    - epidemiological research has advanced, with better understanding of the longer-term health effects of prolonged ingestion of trace contaminants
    - health status and life expectancy have risen substantially across many countries (with the notable exception of Africa associated with the AIDS epidemic).

- The issues arising as a result of the discovery of a widespread naturally-occurring groundwater quality problem are such as to concern a wide range of stakeholders (community leaders, local government, international NGOs active in water supply and/or public health, local research and education centers, waterwell drilling contractors, etc.). Thus the remainder of this Briefing Note is directed towards national and provincial governments who need to define an appropriate mitigation strategy, but they in turn would be expected to involve stakeholders in strategy development and implementation.

How much is known about the origin and occurrence of these natural quality hazards?

- Reactions of rainwater in the soil/rock profile during infiltration and percolation provide groundwater with its essential mineral composition. It takes up carbon dioxide, and the resultant weak acid dissolves soluble minerals. In humid climates with regular recharge, groundwater moves continuously and contact times can be relatively short with only the most readily soluble minerals being dissolved.

- Nine major chemical constituents (Na, Ca, Mg, K, HCO_3, Cl, SO_4, NO_3, Si) make up 99% of the solute content of natural groundwaters (Figure 1). The proportion of each of these constituents, and

Table 1: Summary of main characteristics of principal trace elements sometimes causing a health hazard in groundwater

TRACE ELEMENT	WHO DW GUIDELINE	HEALTH SIGNIFICANCE & USE RESTRICTION	HYDROCHEMICAL CONTROLS ON OCCURRENCE	WATER TREATMENT STATUS*
Arsenic (As)	10 µg/l (p)	toxic/carcinogenic hazard, especially since inorganic form (arsenite or arsenate) usually present; WHO guideline value thus recently reduced from 50-µg/l	complex—release from bonding on iron oxides under unusual (highly anoxic) hydrogeochemical conditions or during oxidation of sulfide minerals under acidic hydrochemical conditions	oxidation and sedimentation (not requiring chemical additives) tend to suffer from unreliability, but those which include coagulation or co-precipitation or adsorption are more promising
Flouride (F)	1500 µg/l (1.5 mg/l)	essential element but desirable range narrow—at below 500 µg/l dental caries can result while above 2000 and 5000 µg/l severe dental and skeletal fluorosis can occur	dissolution of fluoride-bearing minerals from granitic or volcanic formations under some hydro-chemical/hydrothermal conditions, facilitated by slow circulation	precipitation with gypsum or lime/alum mix and filtration or use of ion-exchange resin (activated carbon, alumina)
Manganese (Mn)	(100) µg/l 500 µg/l (p)	essential element but excessive levels can affect neurological functions; also causes staining of laundry/utensils and imparts metallic taste at lower levels hence dual WHO guideline	abundant solid element in soils/rocks; under aerobic conditions the highly-insoluble form is stable but becomes soluble in increasingly acidic and/or anaerobic conditions	precipitation by aeration and filtration usually with prior settlement, but less operational difficulty than that normally encountered for soluble iron

(p) provisional value
(100) limit defined on acceptability, not health grounds

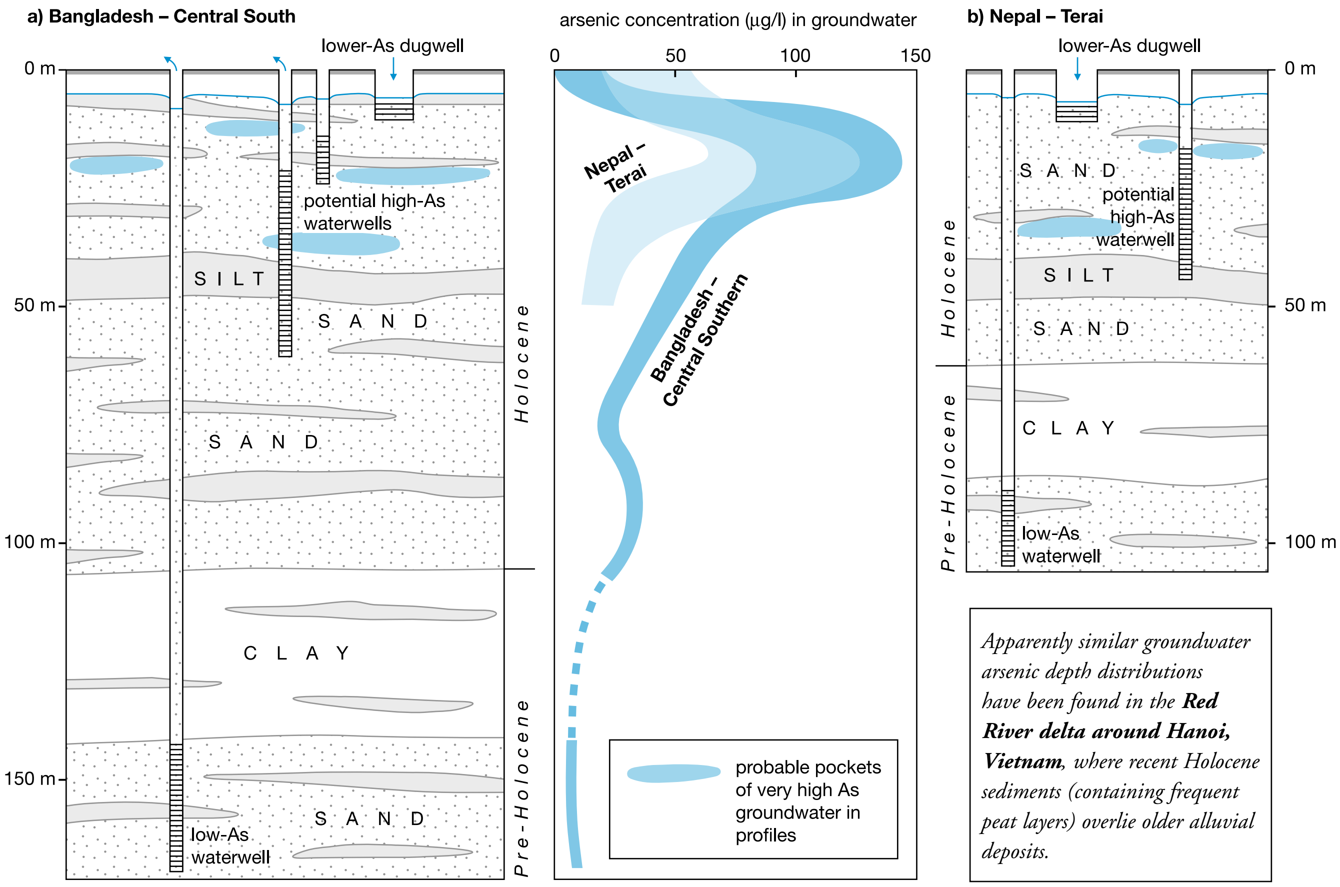
* although small-scale (lower-cost) methods may be available for use at household and/or village level, they generally tend to be costly per unit volume and problematic in terms of effectiveness and reliability

of the associated trace elements, reflects subsurface groundwater flow path and hydrogeochemical evolution of the groundwater concerned. Aquifer rock-type is also important, since, for example, groundwater movement in crystalline rocks occurs relatively rapidly via joints and fractures, and the rocks themselves are generally not very soluble.

- Groundwater in the recharge areas of humid regions is likely to be low in overall mineralization, compared to that in arid or semi-arid regions where the combination of evaporative concentration and slower groundwater movement can produce much higher concentrations. Elevated concentrations of specific solutes can occur in certain hydrogeological settings, such as high sulfate concentrations associated with the weathering of some basement rocks or dissolution of gypsum in sedimentary sequences, hardness associated with carbonate rocks or from association with some types of geothermal activity.

- ***Arsenic (As)*** is the trace element currently giving greatest concern in groundwater, being both toxic and carcinogenic at low concentrations (Table 1). The range of hydrogeological conditions which facilitate its solubility in groundwater is only just being appreciated—but its mobility at shallow depth under strongly-reducing conditions in geologically-recent (Holocene) aquifers is a special concern which greatly complicates low-cost water supply provision in alluvial and deltaic areas of southeastern Asia. The precise mechanism generating the highly anoxic groundwater, mobilizing the arsenic and the

Figure 2: Vertical variations of arsenic in specific aquifer systems



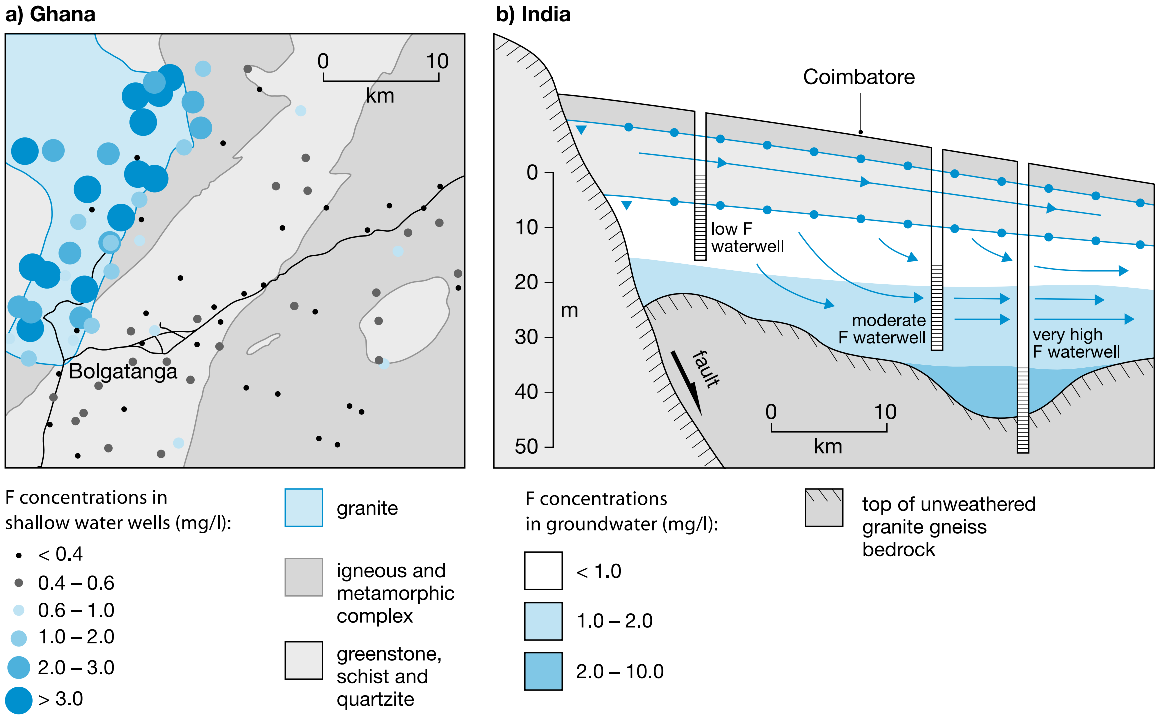
Apparently similar groundwater arsenic depth distributions have been found in the ***Red River delta around Hanoi, Vietnam****, where recent Holocene sediments (containing frequent peat layers) overlie older alluvial deposits.*

extent of induced downward migration due to pumping tubewells for irrigation, are still debatable. In many cases low-As groundwater is currently found at greater depth in older (pre-Holocene) aquifers, and also sometimes in very shallow wells just intersecting the water table (Figure 2), but considerable care will be required to avoid 'cross-contamination' when tapping this groundwater.

- ***Fluoride (F)*** is an element that is sometimes deficient, but in rural water supply provision from groundwater excessive concentrations can be a problem (Table 1). Elevated concentrations occur on a relatively widespread basis in volcanic, granitic and some other terrains (Figure 3) of Africa and Asia, and especially in more arid climates or during extended dry periods.

- ***Manganese (Mn)*** soluble Mn occurs widely where reducing groundwater conditions arise, because of the consumption of dissolved oxygen by naturally-occurring or anthropogenically-induced geochemical processes, and reaches higher concentrations under acidic conditions when solubility is greatest. Like elevated soluble iron, this can lead to rejection of water supply sources because it imparts unacceptable taste and causes laundry staining (Table 1), but there is growing concern that elevated soluble Mn may also represent a health hazard through ingestion in the long term.

Figure 3: Spatial and vertical variations of fluoride in specific aquifer systems



- Various other trace elements (including notably Ni, U and Al) are listed by WHO as potentially hazardous in drinking water (Figure 1), and caution is still needed to check for their occurrence, especially when commencing groundwater exploitation from aquifers characterized by sluggish circulation and/or significant geothermalism.

What should be the immediate strategy to minimize negative impacts?

- If excessive trace element concentrations in groundwater from an aquifer in use for domestic water-supply are discovered, an immediate emergency plan to cope with the potential problem must be defined and the outline of a longer-term strategy identified (Table 2). The emergency plan is likely to comprise the following elements:
  - hydrogeochemical evaluation at an appropriate scale and level of detail to enable identification of water wells affected and reasonable diagnosis of the overall problem
  - community guidance on use restrictions and safe locations of water wells
  - community health program to look for symptoms of any health conditions relating to drinking water and immediate patient management.

- A number of critical (and by no means straightforward) issues are likely to arise during the implementation of the immediate strategy:
  - definition of the 'scale of screening' will be a key decision, which needs to be taken on rational grounds both with regard to water wells (based on the hydrogeological framework, the health hazard of the trace element levels initially encountered, the number of existing wells and the size of

Table 2: Key issues in the definition of an integrated strategy for mitigation of a naturally-occurring trace element problem in groundwater

ACTION	ISSUES TO BE RESOLVED
SHORT TERM	
Evaluation of Problem	• appropriate scale (local/provincial/national) for groundwater quality survey • selection of appropriate analytical technique(s) (field kit/lab method) • government initiative versus private responsibility • availability of specialist advice for hydrogeochemical interpretation • assessment of other potential groundwater quality problems
Water Supply Management	• advice on well use (community information/well closure or labelling) • practical and social considerations on well switching • prioritization of field analytical screening (to confirm safe wells) • appropriate screening policy (universal or selective/temporal frequency)
Public Health Programme	• patient identification (active program or via medical consultation) • establishing relationship between health problem and water source(s) • diagnosing incipient symptoms • immediate patient treatment (organization of bottled water provision)
LONG TERM	
Water Treatment Option	• cost at scale of application (town/village/household) and effectiveness/ sustainability at scale of operation
Alternative Groundwater Supply	• usually involving (a) water wells with modified (often deeper) intakes or (b)-reticulation from local high-yielding, acceptable quality sources, both of which must be based upon systematic hydrogeological investigation and implemented with appropriate well construction standards
Alternative Surface Water Supply	• sustainability in terms of drought reliability and quality variability • evaluation of risks associated with treatment plant failure

ongoing investments in well construction) and to public health (based on the population involved, their probable period of exposure and the protocol for diagnosis of incipient symptoms)

- the expenditure on chemical analyses for any investigation and monitoring program will be high, especially by the standards of rural water-supply schemes, and although field kits are not very accurate they can be successfully deployed to reduce cost and increase coverage, provided that systematic cross-checking with laboratory analysis is included
- a public awareness campaign on the groundwater quality hazard (once reasonably characterized) needs to be implemented—in this context it may be better to conduct a field campaign to identify and positively label all waterwells which have tolerable levels of the trace element concerned (and no other quality hazards) rather than to label wells as 'unsuitable for human consumption', since the latter leaves some doubt over whether all unlabelled wells have actually been investigated
- short-term mitigation involving well closure will imply either (a) much more community time spent on water fetching or (b) provision of quality-assured bottled or tankered water supplies, and the cost of both can be highly sensitive to 'action trigger level' adopted, thus priorities will need to be established given the often uncertain epidemiology over a considerable range above WHO guideline values

- as regards newly-commissioned water wells in areas of little-known or questionable natural groundwater quality, provision for an initial comprehensive inorganic analysis is a prudent precaution, with possibility of later water well replacement should the source be found to have unacceptable quality.

How should these groundwater quality problems be mitigated in the longer term?

- The long-term mitigation of naturally-occurring groundwater quality problems raises important issues as regards institutional arrangements and organizational structure, and has an important cultural dimension. The following questions will need to be addressed before an effective operational response can be defined and implemented:
  - the agency responsible for defining strategy, mobilizing investment, setting priorities, coordinating actions and capacity building
  - the membership of the stakeholder group to be consulted throughout the above processes
  - the role of government in the investigation of potential problems, the dissemination of knowledge of groundwater quality and the site inspection and quality monitoring of existing potable groundwater sources, especially those of small scale.

- The approach to finding a long-term solution to potable water supply provision in areas affected by natural groundwater quality problems will depend considerably on the scale of the water supply required, the gravity of the quality problem encountered, the availability of local groundwater or surface water with acceptable quality and the pressure from the local community for water quality improvement—and will involve elements of strategic water supply planning, health risk and epidemiological studies, and technical and economic assessment of mitigation options.

- A number of different options are potentially available (Table 2), but their technical and economic feasibility needs to be carefully considered—the particularly pertinent question being ‘how and where to invest for most unit benefit in terms of overall health improvement’. Additionally, effective institutional arrangements and policy agreements will also be critical to the effective identification and efficient implementation of long-term mitigation strategies (Table 2).

- In the longer term it is essential that an integrated approach to achieving a safe and secure water supply in a cost-effective manner is taken—evaluating carefully the relative costs and hazards of the available options in terms of drought reliability, normal microbiological and chemical quality, and pollution risks.

- Great caution is needed with solutions involving surface water supply and/or water treatment, especially at the small scale, as a result of two considerations:
  - inexpensive but robust treatment methods to remove trace groundwater contaminants at small town, village and household levels are not yet available in developing countries (even if such treatment is now routine in large centralized water-treatment plants of the industrialized world) and thus bottled water for drinking and food preparation (while using lower quality water for other uses) may be the only feasible solution.
  - water supply contamination by microbiological pathogens (bacteria, viruses and protozoans) remains the major cause of morbidity and mortality in the developing world, and thus despite

natural aversion to chemically-induced poisoning due to long-term, low-level exposure to hazardous trace elements, it is more critical to make a realistic assessment of operational risk for any proposed solutions because of the possibility of creating a new and equally hazardous problem whilst attempting to mitigate an existing one.

- There will be many situations in which the most cost-effective solution will be to identify and develop alternative groundwater sources. Thus a high priority will be the reliable delineation of aquifers (both spatially and in depth) currently containing groundwater low in troublesome trace elements. Special attention to water well design (construction standards and siting regulations) and to aquifer monitoring will be needed where the preferred solution is to drill deeper to exploit better quality groundwater.

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