Characterising and Prioritising Groundwater Pollution Threats –

POLLUTION RISK ASSESSMENTS

Lessons learnt from Bishkek and Narayanganj

Groundwater Vulnerability Assessments

- The overlay and index vulnerability mapping system was easy to devise in Bishkek because the geological setting was already well conceptualised, so existing maps could be adapted to draft the various overlays. There exist numerous versions of the overlay and index vulnerability mapping system (see Vrba & Zaporozec *op.cit,* Table 6, p39 where 24 vulnerability mapping methods are listed) but most, like the present study, use hydraulic inaccessibility as the key criterion in deciding which parameters are important in determining aquifer vulnerability. Cities with a good background understanding of geology, hydrogeology and soils understanding will need to use this criterion if limited to using available data to construct their vulnerability maps

- In Narayanganj the information base was much weaker, and it was only the fact that shallow drilling by hand is so inexpensive in Bangladesh that the project could afford the luxury of supplementing its available data with additional field surveys. This made it possible to collect enough information on depth to water table and presence/thickness of the low permeability surface layer to construct maps. There will be numerous cities in a similar data-deficient situation to Narayanganj, and many will require significant resources to conduct a supplemental field survey programme to enable construction of an index and overlay-based vulnerability map.

- There will also be cities where there is no merit in conducting the exercise because land use zoning based on the results would be ineffective in reducing pollution risk. In the Caribbean and some Gulf coastal areas of Central America for instance, unconfined limestones are productive and widely used aquifers, overlain by cities with significant populations like Mérida and Campêche in the Yucatan Peninsula of Mexico or Santo Domingo in the Dominican Republic. Vulnerability mapping is redundant in such cities because the entire outcrop is of equal, extremely high, vulnerability. Instead the effort needs to be concentrated on contaminant load estimation and on developing land use policies which can control contaminant loads.

- Although parametric rating/index-and-overlay systems are the most widely used method of classifying intrinsic aquifer vulnerability, they can be criticised as being subjective. This is because the indices ascribed are comparative, and although rational, cannot be quantitatively defined. Partly to test whether a different, less subjective approach can be employed and partly to extend vulnerability considerations to the assessment of the impact on lower members of a multi-aquifer, a new, analytical, method of assessing vulnerability was developed by R Litvak at the Kyrghyz Research Institute of Irrigation (Box 1).

- The need arises because intensive pumping from a dense array of private or public wells either distributed across a city, or in intensively exploited wellfields, can induce significant head differences between a shallow unconfined aquifer and a deeper semi-confined aquifer, causing the leakage of polluted water down from the shallow aquifer. This is a lesson learnt from a previous DFID R&D project. In one study of the groundwater-dependent city of Santa Cruz in Bolivia (BGS & Saguapac 1995, 1997) such vertical leakage had reached 90 m after about 30 years, or a vertical velocity of up to 3 m/a. In another study of the city of Hat Yai in Thailand (BGS *et al* 1997) polluted near-surface water in a highly stratified aquifer took typically 35-45 years to migrate from the shallow watertable to the semi-confined aquifer. Thus even apparently well-protected deep aquifers can eventually be prone to degradation by persistent and mobile contaminants.

- The analytical method was successfully applied to the Bishkek aquifer system, and as details of the method are to be published separately from this guide, only a summary is presented here in Box 1.

Box 1 A new quantitative approach to vulnerability assessment: outline of analytical approach

The method (R.Litvak, pers.comm.2000) seeks to quantify the vulnerability of a well in a leaky aquifer system to pollution by estimating leakage to that well from the overlying saturated layer. Steady state is reached when leakage from the upper and lower layers matches flow to the well. A vulnerability index could therefore be constructed based on the fraction of downward leakage in the total abstraction volume of the well. The higher the index is, the greater the proportion, at steady state, of leakage from the upper layer (presumed polluted) in the pumped water, and so the higher the vulnerability. The index is defined as:

$$\Psi(R) := \frac{\int_0^R \frac{2\cdot\pi\cdot r\cdot Kv\cdot(Hv - H(r))}{Mv}\,dr}{Q}$$

Where

Ψ - vulnerability index

R - the radius of influence of the well, where 99% of leakage occurs

Kv - vertical permeability of upper leaking layer

Hv - head in upper layer

H(r) - head in aquifer as function of distance from centre of the well

Mv - saturated thickness of upper leaking layer

Q - abstraction rate

T - transmissivity of the aquifer

Using simplifying assumptions this expression is transformed to

$$\Psi(R) := \frac{Kv}{T\cdot Mv\cdot P1}\cdot\left(1 - R\cdot\sqrt{P1}\cdot K1\left(\sqrt{P1}\cdot R\right)\right)$$

where K1(x) is the modified Bessel function of the second kind and first order and

$$P1 := \frac{1}{T}\cdot\left(\frac{Kv}{Mv} + \frac{Kn}{Mn}\right)$$

and Kn, Mn are the vertical permeability and saturated thickness of the lower (main) aquifer.

Thus an index can be constructed ranging from 0 (no leakage) to 1 (all abstraction derived from local leakage). This can then be scored comparatively in terms of high moderate or low vulnerability. An example scoring from Bishkek is shown in the Table below.

In practice, this method can only be used objectively in very well-understood settings because the aquifer property data needs are demanding. Not only is the vertical permeability of both the upper (leaking) and lower (leaked-to) aquifer required but also the thickness and piezometric contours for each aquifer (to derive average heads). Otherwise, these need to be assumed and the method becomes as subjective as the index and overlay systems.

Table: Example of vulnerability scoring using the analytical solution method

Index Ψ	Score	Comparative Vulnerability
0-0.1	0	Non-aquifer
0.1-0.2	1	
0.2-0.3	2	Low
0.3-0.4	3	
0.4-0.5	4	Moderate
0.5-0.6	5	
0.6-0.7	6	High
0.7-0.8	7	
0.8-0.9	8	
0.9-1	9	Extreme

Potentially hazardous activity surveys/maps (PHAMS)

Diffuse sources

- In both case-study cities wastewater disposal practices were too complex, compared to the project resources available, to disentangle, for other than first-pass contaminant load calculations. However, enough information was gathered to identify the likely role of subsurface wastewater disposal on the urban water balance.
- Links with the water supply/wastewater disposal utility make assessments of both diffuse and point source loads easier because they have information on the extent and type of wastewater arrangements in force. However it is easy to become mired in the detail of disposal arrangements to the detriment of the objective, which is to assess the overall impact on the urban subsurface. Thus for instance it is extremely useful to locate maps of which residential/industrial/commercial districts are sewered, and statistics on likely leakage rates, but the engineering details of pipe network and treatment facilities are typically only of minor relevance at this city-wide level of assessment.

Point sources

- In both cities it proved impossible to obtain a representative view of the distribution and nature of potentially contaminating point-source activities (mostly industry) from existing documented sources. Typically, governmental statistics were too broad, while national census data was either inadequate in this area or cited statistics not useful in deducing industry type. In both Kyrghyzstan and Bangladesh the environmental protection agency is poorly resourced, unable to provide even the most basic industrial activity survey data, while municipal records e.g. from environmental health departments were incomplete and sporadic. These sources might however be more useful elsewhere.
- Commercial directory sources have some potential as survey aids, at least to provide a core list of industry sites still operating. Trade directories (Yellow Pages or equivalent) exist for many cities and most use a well-defined occupational classification that can be very informative if directory use is widespread. Bishkek had a Yellow Pages, but lack of subscriber user base made it poorly representative. More useful was a small-to-medium business aid directory on CD produced commercially with KfW support under the German Technical Assistance programme. In Narayanganj, even the membership of the industry trade associations was not freely available.
- A field survey to supplement documentary sources was necessary in both cities and it is almost certain that it will be a required component of any potentially contaminating activity assessment. Such surveys help identify small-to-medium enterprises (SMEs), which are less likely to be members of trade associations or subscribe to commercial directories, locate closed-down plants which may have a contamination legacy, and identify change of use on large sites or industrial parks. This was very much for different reasons in both cities. In Bishkek, the vast former state-owned heavy industrial plants were often semi-moribund and instead were attracting small consortium-based industries united in requiring cheap premises but making quite unrelated products. In Narayanganj, the growth in the textile industry has been enormous, so in just a few years, the rate of factory construction has increased steeply.
- A reconnaissance-level contaminant load assessment typically involves deducing likely mode, magnitude and class of contaminant release from a potentially contaminating activities survey and then inferring load from the persistence, toxicity and mobility of the main contaminant types likely to be present. This was the type of assessment undertaken in both Bishkek and Narayanganj. Even at this first-pass level the resources required to

collate, analyse and interpret results to the point where they can be used in a risk assessment is not a trivial exercise.

- The next stage verifying whether potential contamination has resulted in actual contamination of the subsurface involves a step-change in resources and data. This is because identification of pollution problems requires monitoring to identify physical evidence, enabling legislation to permit on-site inspection and an agency empowered and willing to enforce both activities. A few cities would be able to make the transition to evidence-based contaminant load assessment quite easily, but for many others the contaminant load control aspects of an aquifer protection policy would have to be promulgated on inferred hazard while the monitoring and audit infrastructure is still developing.

Hot spot maps

- In both cities concerted efforts had been made during the production of the vulnerability map layer to avoid too many vulnerability classes and to make sure the resultant map did not become a fragmented mosaic. There is an inherent hazard in the overlay process of producing artefacts in the form of small areas which may be strictly correct but which could not subsequently be translated into workable land-use zones. An interim 'smoothing' stage is required and, with some care in the choice of symbol and polygon colour combinations, the resultant 'hot-spot' map can convey a lot of information in an easy-to-assimilate format.

- In both cities stakeholders had no trouble identifying what the 'hot-spot' map meant. Furthermore, it was considered by the two case-study teams that while technicians might be interested in the component vulnerability and contaminant load layers, for the policy-development process, in order to avoid an overload of technical detail, this was the first map that stakeholders should see and use. The technical steps involved in developing the 'hot-spot' map were best reserved for a limited circulation technical report which could contain the data, the method, their constraints and any qualifying points to consider when interpreting the results.

Groundwater resource protection/planning maps (GRPMs).

- The groundwater resource protection/planning map was the last of the maps produced and also came late in the stakeholder consultation exercise. This was not the sequence that had been planned; the GRPM was originally intended for issue before the stakeholder consultation commenced. However it became clear that this would have made the consultation in effect a sham exercise, because stakeholders would have viewed the presence of draft policy suggestions right from the start as an attempt to manipulate the direction that policies would take. In effect there would have been no incentive to take ownership of the policies because they had not been seen to be developed in discussion by all those interested. So this proposal was abandoned, and in the event, in both Bishkek and Narayanganj the GRPM did not evolve until policy formulation and stakeholder consultation had been almost completed, and that exercise in turn very much guided what each city's map would emphasise.
- Thus for the same city a map could be very simple, showing for instance just areas zoned for effluent-producing industry, commerce and residential use (the Bishkek GRPM shown in Figure 9 could for instance be easily adapted for such a zoning policy). Or it could be more complex, for example delineating areas of restricted development around important potable water supply wellfields or zones to prioritise replacement of on-site sanitation. Figure 10 shows how this was done in Narayanganj, where protection of the water utility's wellfields and control of abandoned brickpits were identified by stakeholders as the important local issues.

Points added to Pollution Risk Assessment Methodology from applying it to case-study cities

- It is important to identify at the outset settings where land zoning will be ineffective, such as vulnerable karst limestone, and risk assessments will have little value.
- In practice, diffuse sources may be difficult to disentangle but it should still be possible to gain information on their role in the urban water balance. Links with the water supply/wastewater disposal utility makes assessment of both diffuse and point source loads easier because they should have information of the extent and type of wastewater arrangement in force.
- Point source information is difficult to obtain but commercial/industrial directories may be a useful source.
- Hot spot maps are a very useful tool for presenting information to the non-specialist. Care needs to be taken to avoid dividing the information presented into too many different classes giving a mosaic effect and confusing interpretation.
- Scheduling of production of the Planning Maps can be usefully linked to stakeholder mobilisation, giving an incentive to take ownership of the policies because they have been seen to be developed in discussion by all those interested.