URBAN GROUNDWATER IN DRESDEN, GERMANY

by

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ABSTRACT: The results of groundwater studies in Dresden, Germany, during 1991-94 show that groundwater levels are more affected by natural fluctuations of the Elbe River and by precipitation than by urban impacts. But urbanization has caused significant groundwater pollution. The main quality problem is widespread groundwater contamination by tetrachloroethene and trichloroethene. The sum parameter Adsorbable Organic Halogens (AOX) was used to evaluate groundwater quality. Higher concentrations of nitrates, sulphates, and boron also indicate urban impacts on groundwater quality.

RÉSUMÉ: L'étude des eaux souterraines à Dresde (Allemagne) dans la période 1991-94 montre que les niveaux piézométriques sont plus affectés par les fluctuations naturelles de l'Elbe et par les précipitations que par les impacts dus à la ville. Cependant l'urbanisation a provoqué une nette pollution de l'eau souterraine. Le principal problème de qualité est la contamination générale de l'eau souterraine par le tétrachloréthane et par le trichloréthane. Le paramètre global " composés halogénés organiques adsorbables " (AOX) a été utilisé pour évaluer la qualité de l'eau souterraine. De plus fortes teneurs en nitrates, en sulfates et en bore sont aussi des indicateurs d'impacts urbains sur la qualité de l'eau souterraine.

RESUMEN: Los resultados de unos estudios en las aguas subterráneas en Dresden, Alemania, durante 1991-94, muestran que los niveles freáticos están más afectados por las fluctuaciones naturales del Río Elba y por la precipitación que por los impactos urbanos. Sin embargo, la urbanización ha producido una contaminación importante de estas aguas subterráneas. El problema de calidad más importante es la contaminación, extendida por todo el área, por tetracloroetano y tricloroetano. Para evaluar la calidad del agua se usó el parámetro Halógenos Orgánicos Adsorbibles (AOX). Las altas concentraciones de nitratos, sulfatos y boro son otra muestra indicativa de los impactos urbanos en la calidad de las aguas subterráneas.

INTRODUCTION

In urban areas, the density of population and industry often results in serious problems of groundwater quantity and quality. The wide variety of impacts from different sources demands an integrative approach for investigation and evaluation.

Urbanization creates radical, but not easily measured, changes in groundwater recharge, with modification to existing recharge mechanisms and the introduction of new ones (Foster et al., 1994). The serious pollution of groundwater under cities has been stated for many countries (Lerner and Tellam, 1992). In Europe, the main pollutants are volatile chlorinated hydrocarbons, aromatic organic compounds, sulphate, chloride, nitrate, oil products and heavy metals (EC Ministers, 1991; Lloyd et al., 1991). The number of cases is increasing, suggesting widespread urban pollution. Various techniques for local remediation of contaminated sites are available, but it would be too expensive to apply these techniques to deal with widespread pollution.

Within the last few years, additional treatment steps had to be established in some Dresden water works due to poor groundwater quality, in order to meet the high standard of drinking-water quality. Groundwater-quality investigations of the Dresden water company were concentrated on the areas near the well fields. The Environmental Authority of the city of Dresden initiated a study in 1991 to survey groundwater quality in the Quaternary aquifer (Amt für Umweltschutz, 1992). The project was continued in 1992/93 (Amt für Umweltschutz, 1993; Thomsch and Korndörfer, 1995). Other institutions, such as the Institute for Groundwater Management of the Dresden University of Technology and the environmental authorities of Saxony, carried out additional groundwater investigations at a smaller scale.

The objective of this paper is to summarize the urban impact on groundwater in the Quaternary and sandstone aquifer in Dresden, by incorporating basic hydrogeological information, geohydraulics, groundwater recharge, and groundwater-quality data.

LOCATION AND HYDROGEOLOGY

Dresden is the capital of the county of Saxony in the eastern part of Germany (fig. 1). The city area is 226 km^2, including a forest in the northern part. Nearly half a million people live in Dresden. The city is situated in a rift valley along the Elbe River. The valley is mainly filled with glacial deposits consisting of gravels and coarse sands (fig. 2; Huhle, 1972). Under normal conditions, these Quaternary deposits form an unconfined aquifer as much as 15 m thick. The aquifer is overlain partly by a layer of meadow loam, 2-4 m thick. The deeper deposits are marl (Turonian Formation), which have a maximum thickness of about 250 m beneath the city centre. A deep aquifer beneath the marl is formed by Cretaceous sandstones (Cenomanian) and is partly artesian. The sandstones crop out at the southwestern boundary of the city. The northern boundary is formed by the Lusatian overthrust (granitic massif).

The Quaternary aquifer is in direct hydraulic contact with the Elbe River. In Dresden, the mean flow of the Elbe River is about 300 m^3/s and ranges from 100-3,000 m^3/s. In general, groundwater flows from both sides of the valley to the river (fig. 3). During floods, the rising water level of the Elbe River results in a natural infiltration of river water into the aquifer. Near the river, water-table fluctuations correspond closely with the dynamic water level of the river. The water-table fluctuation in the centre of the city is more than 3 m. Hydraulic conductivity ranges from $0.6\text{-}2\times10^{-3}$ m/s. Groundwater flow velocity ranges from 0.5-2.5 m/d, except at locations of water abstraction. In general, in the city centre the water table is 5-10 m below ground, and in the outskirts, 20-60 m.

GROUNDWATER ABSTRACTION

As in many cities in Europe, groundwater resources in Dresden have been used for public water supply, to a large extent combined with river-bank infiltration schemes along the Elbe River (table 1). Wells were installed along the Elbe River to abstract groundwater derived from river-bank infiltration. Since 1874, artificial infiltration of river water has been induced by pumping. Figure 4 shows a cross section of water works A in 1990. The groundwater flow situation observed in 1991 (fig. 3) is different, due to a significant decrease of water demand resulting in the closure of water works (table 1).

Poor water quality in the Elbe River was the main hydrologic problem before 1990. Hydrochemical aspects of river-bank infiltration in Dresden were discussed in detail by Nestler et al. (1991). After reunification of Germany, a significant improvement of river-water quality occurred due to cessation of industry (e.g., paper mills) and improved sanitation measures (Grischek et al., 1994). Meanwhile, urban groundwater quality is now the major problem in water treatment.

The sandstone aquifer has been used for individual industrial water supplies (e.g., breweries) since the 19th century. Many wells were abandoned after destruction during the Second World War.

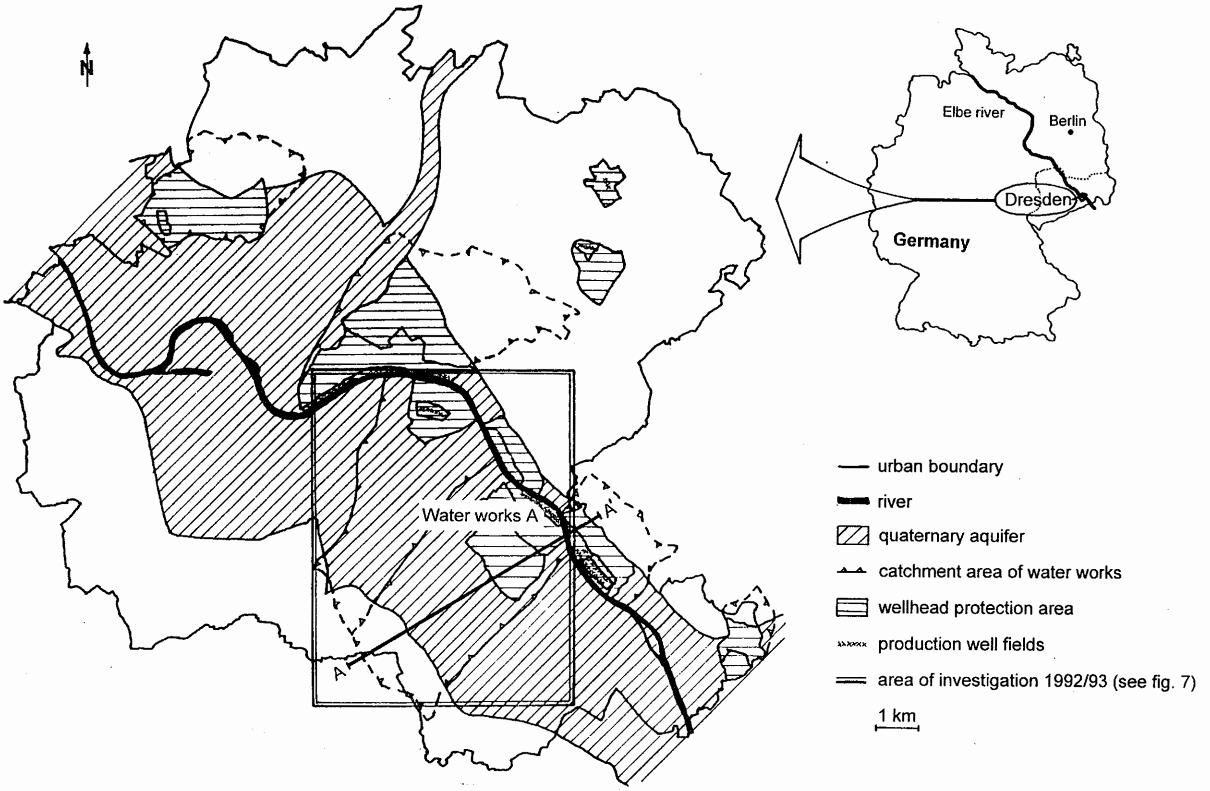

Figure 1. Location of Dresden, Germany, showing area of investigation, extent of Quaternary aquifer, catchment area of water works, wellhead protection area, production well fields, and line of section A-A' (section shown in figure 2). Based on environmental reports (Amt für Umweltschutz, 1992-93).

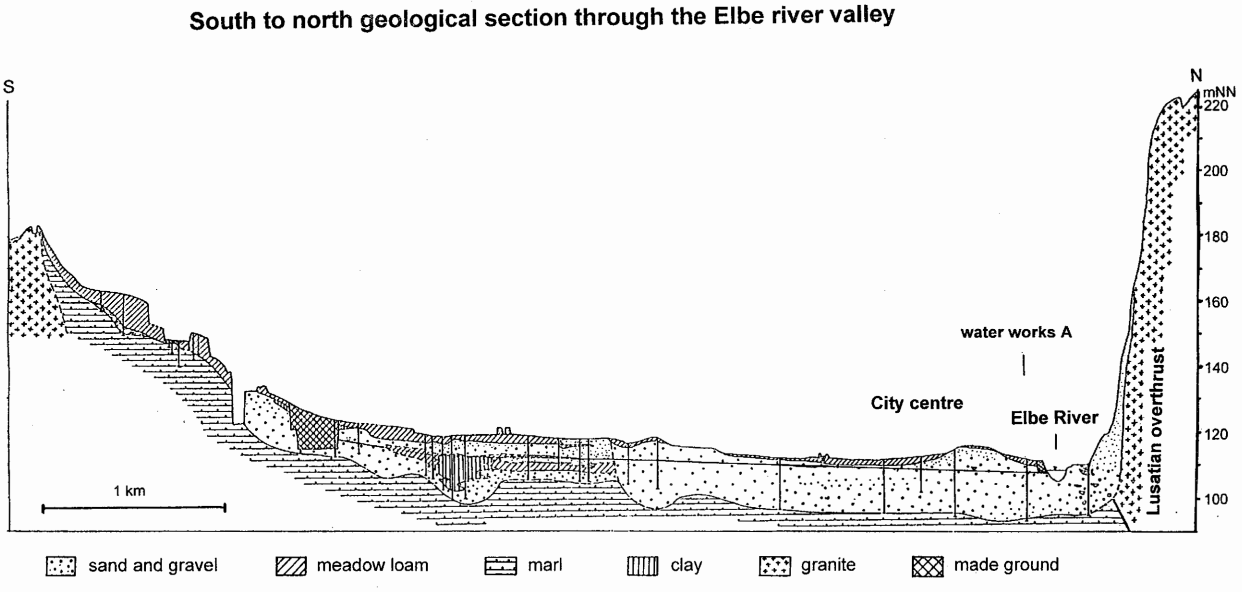

Figure 2. Geologic section A-A' across the Elbe River valley. Line of section shown in figure 1.

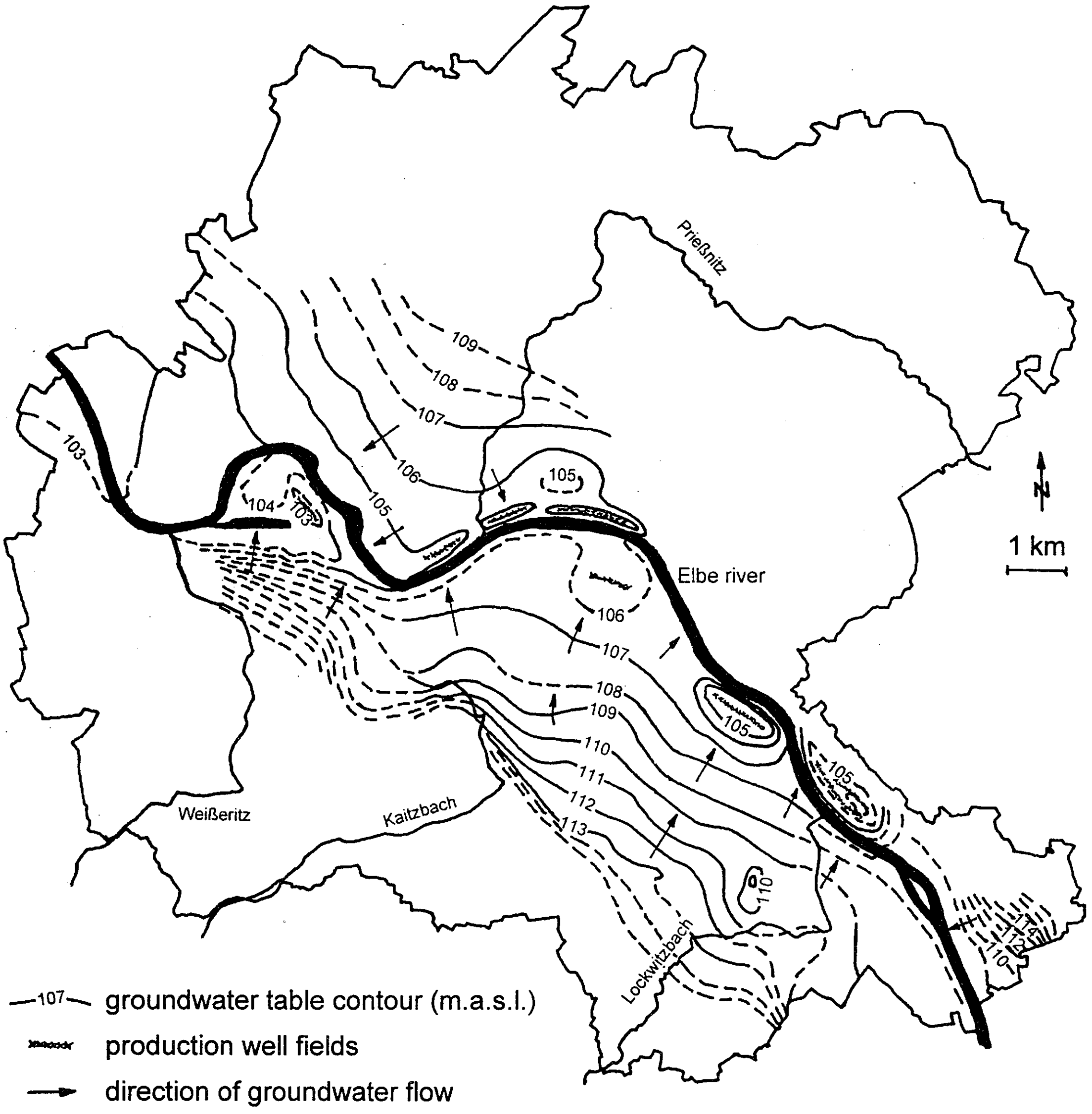

Figure 3. Water-table elevations, Dresden, 1991.

Table 1. Total drinking-water production and sources of raw water, Dresden.

Year	Total drinking-water production (10^3 m^3/a)	Sources of raw water (%)		
		Storage reservoir	River-bank infiltration and artificial recharge	Ground-water
1986	75,375	47.1	38.7	14.2
1991	57,935	31.2	49.6	19.2
1994	40,390	65.4	31.3	3.3

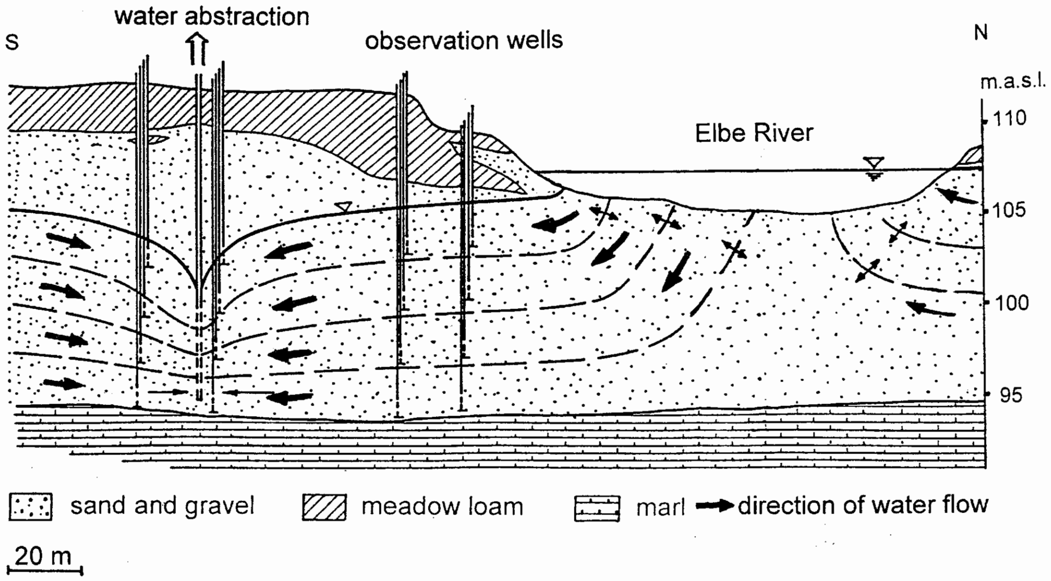

Figure 4. Geologic section at water works A, showing abstraction and observation wells and generalized directions of groundwater flow.

IMPACT OF URBANIZATION ON GROUNDWATER RECHARGE

In urban areas, the water-supply and sewerage systems and irrigation become additional factors affecting groundwater recharge (Lerner, 1990). Land-surface sealing results in reduced direct infiltration, lower evaporation, and increased surface runoff. The mean long-term precipitation in Dresden is 724 mm/a. Evaporation is about 380 mm/a in the city, which is less than in the surrounding rural areas where evaporation is about 410 mm/a (Amt für Umweltschutz, 1993).

The reduction in groundwater recharge for the Quaternary aquifer due to surface sealing results in a mean recharge rate of 5.8 L/s/km^2, compared with 7.5 L/s/km^2 for unsealed areas (table 2). Groundwater-recharge data are from studies by the water company and calculated by the method of Glugla et al. (1976). The quantification of leakage of water mains and sewers is very difficult. TV-inspection of sewers shows damage, but the resulting leakage rate cannot easily be determined. The leakage rate of 18 percent for water mains in Dresden is the result of calculations based on metered water output of water works and metered water consumption, and on investigations of 20 percent of the water-main system. Infiltration of groundwater and inflow of surface water from channeled creeks into the sewerage system even during dry periods have been proved by sewage water analyses, which show significant decreases in COD and conductivity. The leakage rate of five percent for sewers is an approximation for the total city area, based on these observation, on results from TV inspections of sewers made by the water company, and on groundwater-level considerations. This value varies considerably at the local scale. Leakage of septic tanks and water input from park irrigation were estimated from data from Lerner (1990).

Data in table 2 show that for the city of Dresden additional urban sources of recharge nearly compensate the effects of surface sealing. In Dresden, urbanization has not caused significant changes of the groundwater level. Observed fluctuations are dominated by natural factors, principally precipitation and river-water level. But at the local scale, rising groundwater levels are occurring as a result of decreasing groundwater abstraction. Deep foundations of new buildings, such as supermarkets and parking garages, act as underground barriers to groundwater flow in the direction of the river; these features cause local groundwater rises, unless measures are taken to compensate the barrier effect.

IMPACT OF URBANIZATION ON GROUNDWATER QUALITY

During a comprehensive groundwater-quality study for the city of Dresden in 1991-95, groundwater samples from existing observation wells and production wells were analyzed for many parameters (Amt für Umweltschutz, 1992). The results were published in maps that show only computer-calculated contour lines of concentrations. The maps give a general view of the

Table 2. Sources and rates of groundwater recharge, Dresden, 1993-94.

Parameter and units	Value	Remarks
Area (km^2)	226	--
Sealed area (%)	30	--
Inhabitants (1994)	470,681	--
Mean water demand (m^3/s)	1.4	= 1.21 x 105 m^3/d
Corrected precipitation, P (mm/a)	724	1901-50 (50-year series)
Evapotranspiration, ETR (mm/a)	380	--
Surface runoff, RO (mm/a)	170	--
Natural recharge (mm/a)		
To Quaternary aquifer (p1)	183	over 212 km^2
To Cretaceous aquifer (p2)	252	over 13.6 km^2
Recharge from urban sources (mm/a)		
Leakage from water mains (18%)	35	= 2.2 x 104 m^3/d
Leakage from sewers (5%)	10	5% of water demand; excludes storm sewers
Septic tanks	2.8	15,000 inhabitants, and assuming 110 L/head/d and 50% leakage
Public-garden irrigation, firefighting, public road cleaning	1.4	470,000 inhabitants, and assuming 1.5 l/head/d
Total recharge (mm/a)		
Natural (weighted sum of p1 and p2)	187	Mean for city area
From urban sources	49.2	21% of total; nearly compensates for reduction of natural recharge due to sealing
Total	236.2	--

situation, but they ignore variations with depth and the interaction of groundwater and river water (figs. 5 and 6). The extent of contamination is overemphasized by single high-concentration values. Urban impact is indicated for more than 80 percent of all the samples by high concentrations of sulphate, boron, adsorbable organic halogens (AOX), and halogenated organic volatiles (HOV). A more detailed groundwater-quality study in 1992-93 for the catchment area of water works A (fig. 1) included sampling of 18 observation wells and 56 production wells (Amt für Umweltschutz, 1993).

The results of the earlier studies (Amt für Umweltschutz, 1992 and 1993) and of the author's investigations are discussed in more detail below. In general, the temperature of groundwater beneath residential districts in the city where central heating is used is 2-3 degrees higher than beneath districts dominated by individual gas and coal heating (fig. 5). Dissolved oxygen contents range from 4-8 mg/L. Concentrations of more than 8 mg/L occur near the Elbe River and in non-polluted groundwater that flows from the north. Anoxic conditions were observed at local contaminated sites and gas works.

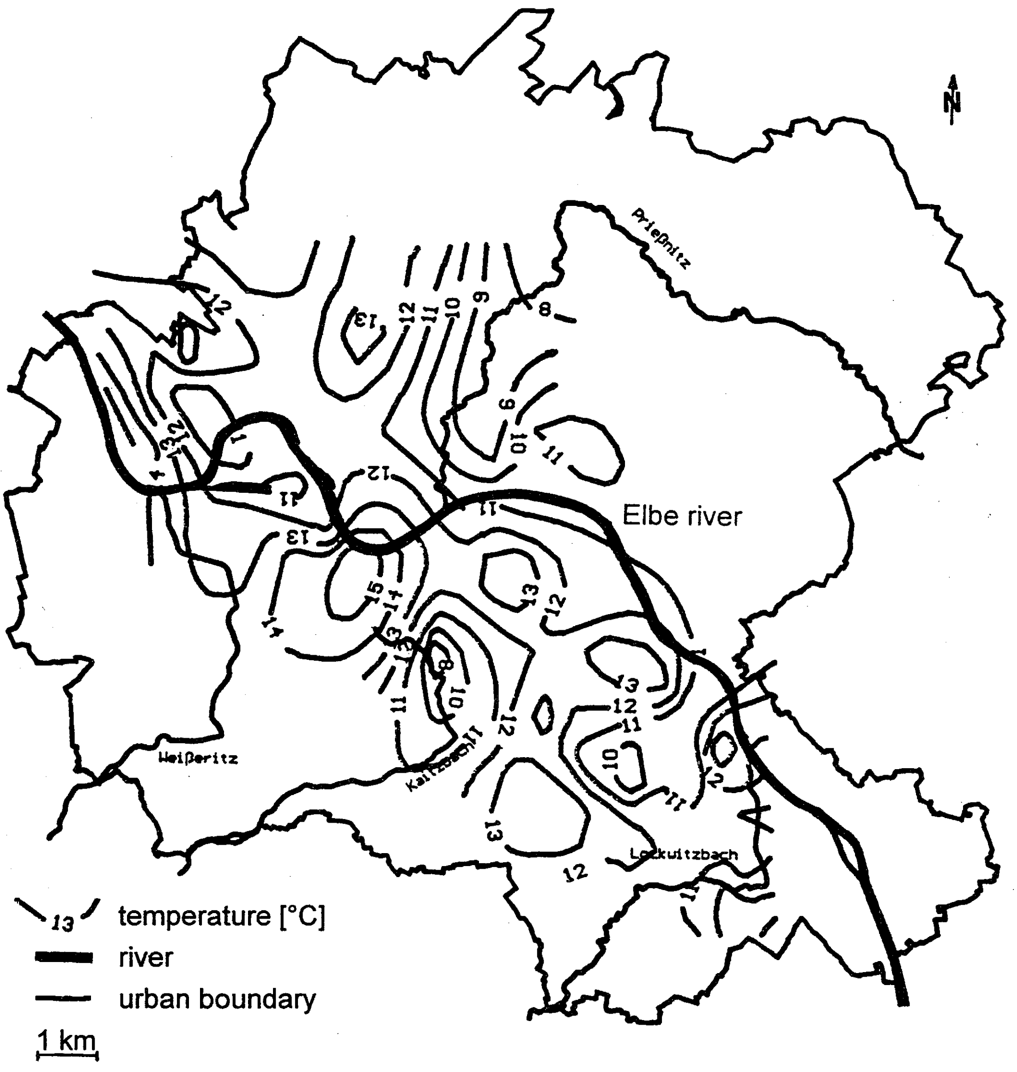

Figure 5. Temperature of groundwater, Dresden, 1992 (Amt für Umweltschutz, 1992).

Measured conductivity is generally between 400 µS/cm (forest area) and 1,000 µS/cm (fig. 6). Conductivity values exceeding 1,000 µS/cm are correlated with high concentrations of sulphates and nitrates. Maximum values occur beneath and downstream of areas where rubble from ruins and waste was dumped. The pH value of groundwater is neutral to weakly acid, mostly 6.4-7.

The dissolved organic carbon (DOC) content is 2-3 mg/L. Near the river, concentrations are as much as 5 mg/L, due to river-water infiltration during floods or due to pumping.

Sulphate concentrations vary greatly and range from 100-600 mg/L. Sources of sulphate concentrations of more than 240 mg/L are principally due to builders' rubble, waste dumps, and ground infilling.

High nitrate concentrations, as much as to 150 mg/L NO_3 at the outskirts, are caused by vineyards and gardening along the hills. Groundwater pollution by nitrates near the city centre are from market gardens with greenhouses and gardening centres. For large areas of the city, nitrate concentrations in groundwater exceed the limit for drinking-water quality and range from 50-80 mg/L NO_3. These values are relatively low compared with nitrate concentrations of more than 100 mg/L that often occur in rural areas with intensive agriculture. The decrease in nitrate concentrations downstream of contaminated sites parallels low oxygen concentrations and indicates microbiological denitrification. Denitrification rates are highest at sites of induced river-bank infiltration, due to infiltration of river water containing high DOC contents.

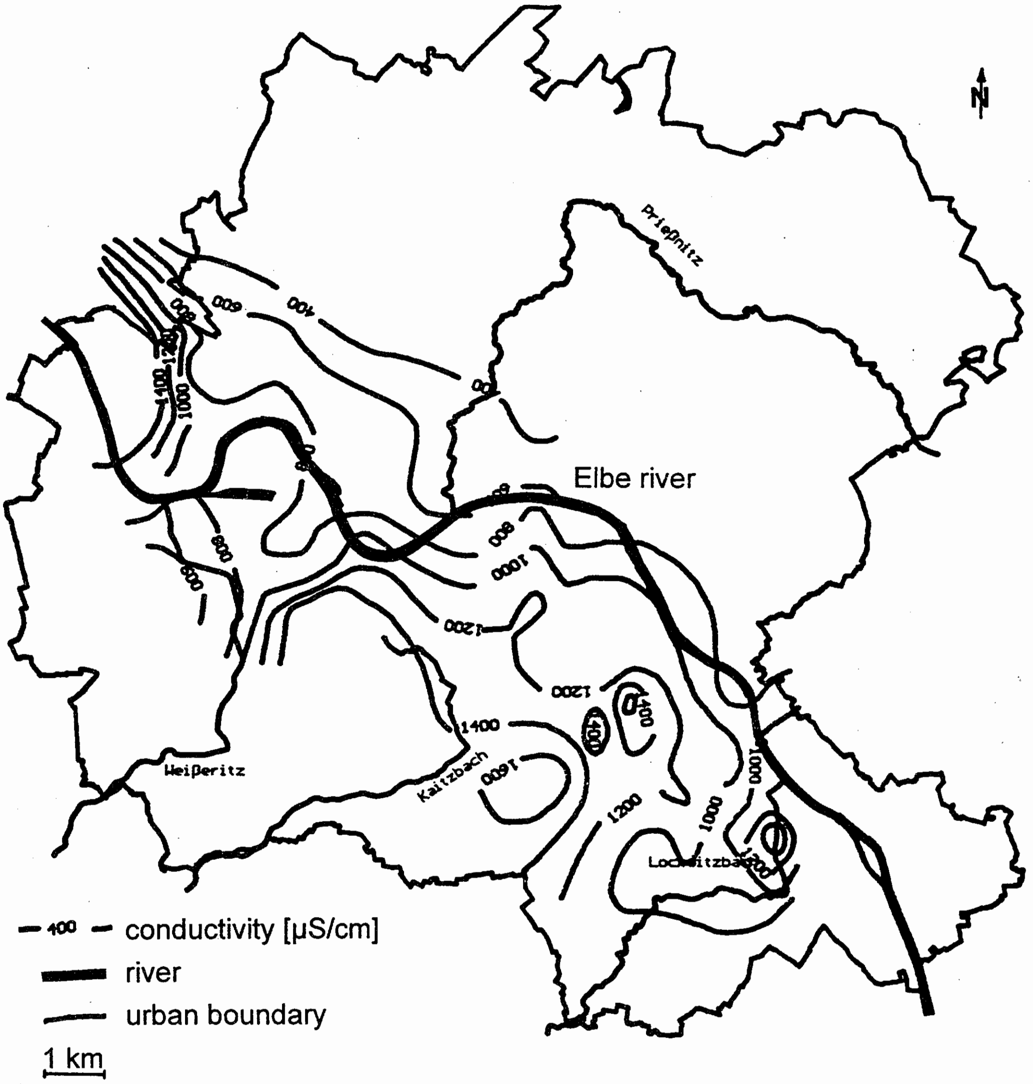

Figure 6. Conductivity of groundwater, Dresden, 1992 (Amt für Umweltschutz, 1992).

The mean boron concentration is about 300 µg/L. The limit of 1 mg/L given in the German guidelines for drinking-water quality is exceeded in samples from only a few observation wells. No evidence exists that leaking sewers are causing high boron concentrations. High concentrations are, therefore, probably a result of inputs from former channels (waste-water discharge) and waste disposal.

The most important and widespread pollution is caused by halogenated organic volatiles. In all observation wells investigated in Dresden, tetrachloroethene (PCE) is above the detection limit of 0.1 µg/L. The mean concentration of PCE is 168 µg/L. Figure 7 shows the distribution of PCE concentrations. The highest PCE concentration observed was 3,500 µg/L. The mean trichloroethene (TCE) concentration is 65 µg/L, and the mean cis-1,2-dichloroethene concentration is 5 µg/L. The samples were mostly from the lower and middle layer of the Quaternary aquifer. Figure 8 gives the concentration versus depth below ground for observation wells MP 1 to MP 6. The differences among measured concentrations at various depths demonstrate the need for depth dependent groundwater sampling.

Within the catchment area of water works A, the annual use of PCE and TCE exceeded 80 t/a and 140 t/a, respectively. For this area, the major sources of contamination were identified. Industrial sources were dry cleaning and production of electrical instruments, cameras, machines, lubricants, and plastics; other potential polluters were car repair shops, a forge, and a hospital. The higher concentration and greater extent of The higher concentration and greater extent of PCE

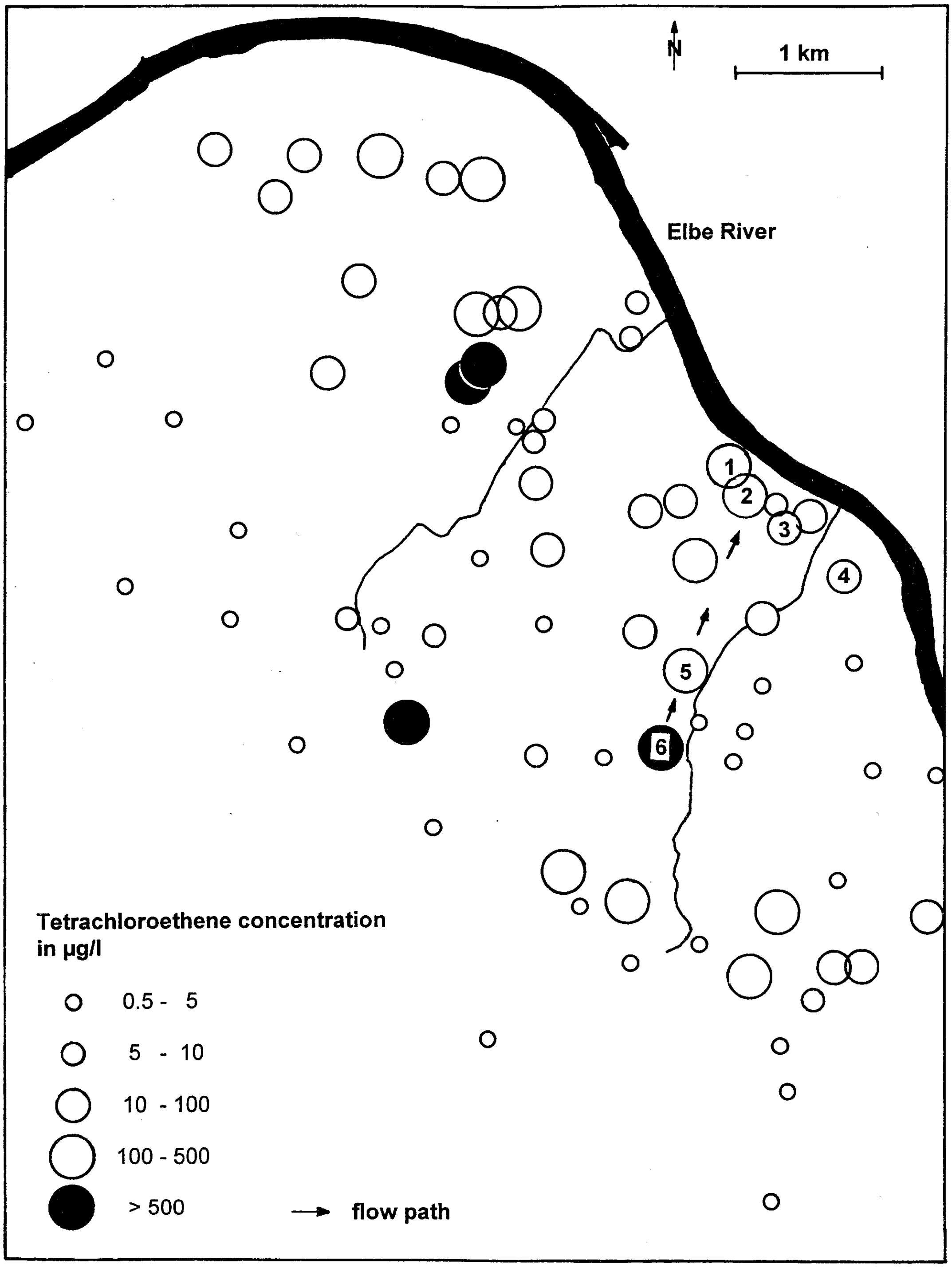

Figure 7. Distribution of tetrachloroethene concentration in the catchment area of water works A. Based on environmental reports (Amt für Umweltschutz, 1992, 1993) and on additional investigations. Numbered points (1-6) refer to well data (MP1-MP6) shown in figure 8.

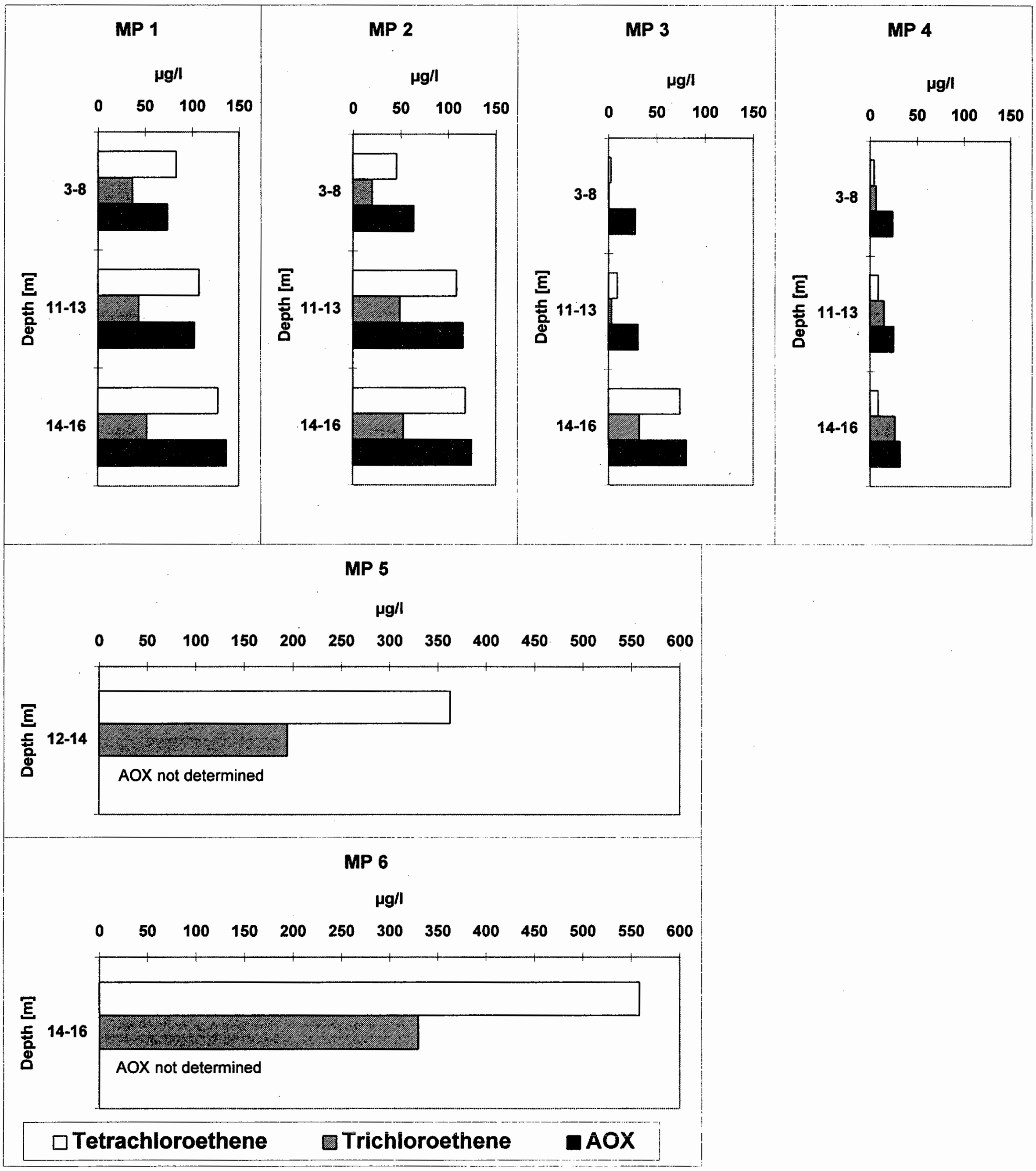

Figure 8. Distribution of tetrachloroethene, trichloroethene, and AOX concentrations in groundwater near the Elbe River, 1993-94. Sampling locations are shown in figure 7.

pollution compared to TCE is not in agreement with its amount of use. This result is different from that of the Birmingham groundwater study (sandstone aquifer), where TCE was the main contaminant. There, 78 percent of boreholes had detectable levels, which is in agreement with its wider use, whereas PCE values were much lower (Rivett et al., 1990). Higher PCE values in Dresden probably are a result of its higher persistence. Whereas no biodegradation of tetra- chloroethene occurs in aerobic environments, trichloroethene can be dehalogenated under aerobic conditions (Toussaint, 1994; Cook, 1988).

In Dresden, groundwater is mostly aerobic. Because of the low organic load of the aquifer material (coarse sands and gravel), no significant retardation and degradation takes place. A decrease in groundwater pollution can only be achieved if the known major contaminated sites are remediated. At many sites, significant amounts of contaminants still exist within the unsaturated zone, and these will be leached in the future. Even in the case of intensified remediation, it will take more than 10 years to get a significant improvement of groundwater quality, because of the long-term and widespread pollution.

The sum parameter Adsorbable Organic Halogens (AOX) was useful for primary inventories (ATV, 1993) and control of groundwater quality. AOX includes all adsorbable halogenated organic compounds of a water sample. The AOX value is expressed in micrograms per liter of Cl. This expression makes it easy to calculate potential AOX values for known concentrations of chlorinated hydrocarbons and so to control analytical results (fig. 9). The background value of AOX is about 10 µg/L. AOX concentrations of more than 40 µg/L are considered to be critical. The advantage of AOX analysis is that a wide range of pollutants is included. For example, in 1991 the Elbe River water showed high AOX concentrations. However, from a measured AOX concentration of 100 µg/L, only 10 percent could be identified as individual organic compounds.

Large amounts of halogenated compounds (in particular from paper-mill effluents) were not detected by common analytical methods, including gas-chromatography. In contrast, of 100 µg/L detected in groundwater samples, about 90 percent can be identified with the two compounds PCE and TCE (fig. 9). This important result demonstrates that no significant amounts of other, non-detected adsorbable halogenated organic compounds exist that are causing groundwater pollution. Remediation strategies can thus be concentrated on the removal of tetra- and trichloroethene. At high concentrations of PCE and TCE, the measured AOX values were below the calculated values (fig. 9), which suggests that special handling of AOX samples is needed to prevent losses.

Concentrations of aromatic compounds are generally low. The highest toluene concentration of 4 µg/L was observed at a gas works site. At some local sites, pollution by phenols and oils was detected. Heavy metals and pesticides are of little importance in Dresden groundwater.

The methods for evaluation of field data should be chosen according to the aim of the study. One way to make a global assessment of urban impacts on groundwater quality is to obtain natural background values for groundwater quality from long-term monitoring of undisturbed groundwater under the same hydrogeologic conditions. In areas with high population density, industry, agriculture, and forest management, reliable background values are difficult to obtain. If standard values (e.g., drinking-water standards or guideline values of the World Health Organisation) are used for data evaluation, site-specific characteristics need to be considered (e.g., geogenic background, water inflow from other areas or aquifers, and surface-water/groundwater interactions).

For small numbers of samples, average values can be inappropriate for impact assessment, because the highest values (e.g., measured tetrachloroethene concentration of 3,500 µg/L in Dresden groundwater) can have too much influence on the average. A better way is to calculate percentile values and present all data as boxplots. Such a presentation, shown in figure 7, is more suitable than calculating concentration contours. This form of data presentation was used also by Rivett et al. (1990), in order to show urban impacts on groundwater quality in Birmingham. Lloyd et al. (1991) summarized contamination of groundwater in Birmingham by chlorinated solvents by giving the proportions (percent) of 59 samples from boreholes exceeding 1 µg/L, 10 µg/L, and 100 µg/L. In a survey of 15 Japanese cities, chlorinated solvents were detected in about 30 percent of all wells tested (Hirata et al., 1992). Wurl et al. (1995) used cluster analysis to classify groundwater types and to demonstrate geogenic and anthropogenic impacts on groundwater quality.

Further steps are proposed to compare the urban impacts in different areas or cities. Even percentile values can overestimate contamination, because production wells at industrial sites are often polluted by nearby sources, and because monitoring wells are installed at greater densities in areas of contamination. The most correct but complicated method is to assign single samples (wells) to relevant areas and use geohydraulics to get area-weighted values. The result can also be improved by designing a grid for the city, similar to

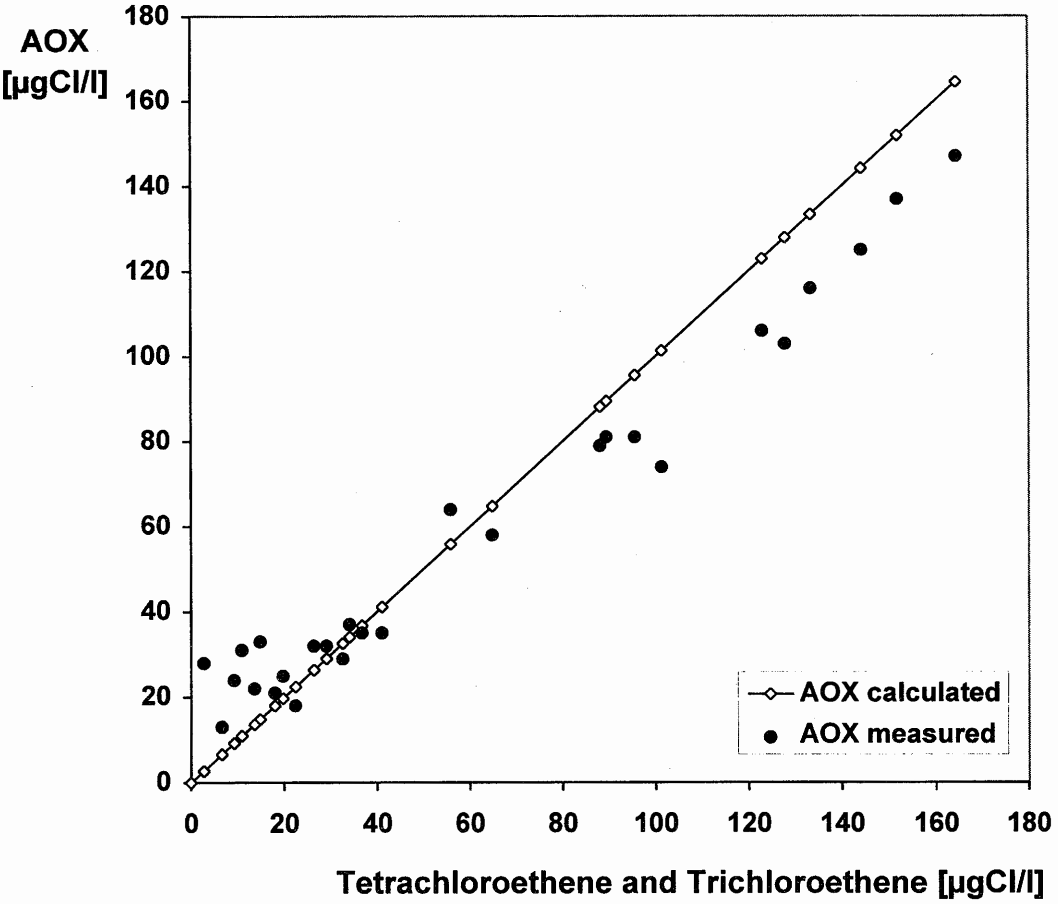

Figure 9. Relationship between AOX concentrations (observed and calculated) and observed tetrachloroethene and trichloroethene concentrations for observation wells MP1-MP4, 1993-94.

methods for groundwater recharge determination, and then calculating mean values for each grid element as a base for calculating percentile values for the total area.

Evaluation schemes that have been designed for the evaluation of groundwater contamination from contaminated sites can also be applied or adapted for urban-impact assessment. Dittrich et al. (1993) applied the method of Kerndorff (1990) to the data for the catchment of water works A. The detection frequency of single compounds was determined (table 3).

Percentile values c_{25}, c_{50}, c_{75}, and c_{90}, indicating concentrations with 25, 50, 75, and 90 percent exceedence, were determined for the most important compounds. Concentration values corresponding to these percentile values were used as impact-class limits. Kerndorff (1990) proposed the following impact classes:

0 - 25 %	low impact
25 - 50 %	impact
50 - 75 %	significant impact
75 - 90 %	strong impact
90 - 100 %	extreme impact

Table 4 shows the resulting classes from the data set for the catchment area of water works A and gives drinking-water limits for comparison. These impact classes can be presented in maps for single compounds as well as for sets of parameters, in order to get an integrated figure.

A wide variety of methods can be used to rank contaminated sites for remediation priority. Canter et al. (1987) give a survey of empirical assessment methodologies (e.g., hazard-ranking system, site-rating methodology, numerical-rating scheme DRASTIC) and

Table 3. Ranking of detected organic compounds (Dittrich et al., 1993).

Rank	Compound	Detection limit (µg/L)	Detection frequency (n = 74)	
			Number	Percent
1	tetrachloroethene	0.1	74	100.0
2	trichloroethene	0.1	69	93.2
3	trichloromethane	0.1	65	87.8
4	tetrachloromethane	0.1	39	52.7
5	cis-1,2-dichloroethene	4.0	15	20.3
6	toluene	0.1	14	18.9
7	benzene	1.0	12	16.2
8	trans-1,2-dichloroethene	5.0	5	6.8
9	m,p-xylene	0.1	3	4.1
10	bromodichloromethane		3	4.1
11	ethylbenzene	0.1	3	4.1
12	dibromochloromethane	--	2	2.7
13	tribromomethane	1.0	2	2.7
14	phenanthrene	0.1	1	1.4
15	dichloromethane	10.0	1	1.4
16	1,1,1-trichloroethane	0.1	1	1.4
17	1,1,2,2-tetrachloroethane	--	1	1.4
18	naphthalene	0.1	1	1.4

groundwater-quality standards. Aspects such as quantification of input of contaminants, groundwater vulnerability, groundwater contamination, mobility, degradation and toxicity of contaminants, flow direction, flow velocity, groundwater use, and others need to be included in the risk assessment. The measured data for the catchment area of water works A were evaluated using the "Dresden Model", which is a weighting system that includes many of these aspects (Dittrich et al., 1993). The resulting priorities for remediation indicate that sites contaminated by PCE and TCE are at the top.

Due to significant groundwater pollution within the catchment of the water works, the wisdom and design of well-head protection areas in cities has become a subject of discussion (Luckner and Riess, 1992; Piechniczek, 1994; Thomsch and Korndörfer, 1995). The question of whether protection zones should be abandoned or further groundwater abstraction be prohibited has not yet been resolved.

Groundwater in the sandstone aquifer at a depth of more than 200 m might be expected to have very low vulnerability to pollution, with protection given by the extensive marls. But pollution by halogenated organic compounds and nitrates has already been observed in many boreholes. This occurrence indicates fissure flow or short-cut flow of polluted groundwater from the Quaternary aquifer, perhaps through abandoned boreholes.

CONCLUSIONS

A changing groundwater balance is not a problem in Dresden. Groundwater levels are more affected by the natural water level of the river and by precipitation than by current water abstractions, surface sealing, or leakage of water mains and sewers.

The principal quality problem is widespread groundwater pollution by tetrachloroethene and trichloroethene. Remediation is expensive and should be concentrated on the main point sources. Further leaching of contaminated soil in the unsaturated zone should be prevented. Other chlorinated solvents are widespread but are usually at low levels. Contamination by other organic

Table 4. Impact classes and drinking water standards of the most important parameters, n=74 (Dittrich et al., 1993)

Parameter or compound	Units	Impact class					WHO drinking-water guidelines	German drinking-water standards
		Low impact (c_{25})	Impact (c_{50})	Significant impact (c_{75})	Strong impact (c_{90})	Extreme impact ($>c_{90}$)		
conductivity*	µS/cm	500	1,000	1,500	2,000	> 2,000	-	2,000
sulphate*	mg/L	150	210	270	350	> 350	400	240
nitrate	mg/L	35	50	60	75	> 75	10	50
boron	mg/L	0.1	0.2	0.3	0.4	> 0.4	-	1.0
AOX	µg/L	20	50	150	500	> 500	-	-
tetrachloroethene	µg/L	2.7	6.8	32	320	> 320	10	10**
trichloroethene	µg/L	1.8	8	40	140	> 140	30	10**
tetrachloromethane	µg/L	0.2	0.7	1.0	3.5	> 3.5	3	3
trichloromethane	µg/L	0.6	0.9	2.2	3.6	> 3.6	30	10**
1,2-cis-dichloroethene	µg/L	5	12.5	25	100	> 100	-	
benzene*	µg/L	1		10		> 10	10	

* Classes not formed statistically

** 10 µg/L for sum of tetrachloroethene, trichloroethene, dichloromethane, and 1,1,1-trichloroethane

contaminants is low. The sum parameter AOX is useful for primary inventories and control of groundwater quality. High AOX values correlate with PCE and TCE concentrations, indicating that no significant amounts of other adsorbable halogenated organic compounds occur. High concentrations of sulphate are below and upstream of dumped material (builders' rubble and waste) and infill. Nitrate input is from market gardens and gardening. Many market gardens with greenhouses have been shut down during the last few years, reducing the future nitrate input. In Dresden, inputs of heavy metals and pesticides to groundwater are small.

The results show that major impacts on groundwater quality are, according to their importance:

1) spillages at industrial sites and other places of use;
2) disposal and storage of waste;
3) gardening and market gardens with greenhouses;
4) leaking sewers and septic tanks; and
5) spillages during transportation of chemicals.

The available data allowed only a limited survey of urban impacts on groundwater balance and groundwater quality in Dresden. Further investigations should be done to determine the leakage rate of sewers, its impact on groundwater quality, and the depth variations of groundwater quality.

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