Science of the Total Environment xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

A groundwater management plan for Stuttgart

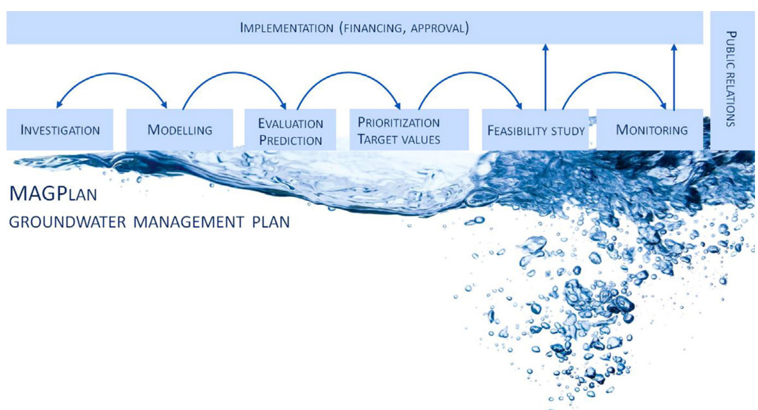
Sandra Vasin [a,*], Achim Carle [a], Ulrich Lang [b], Hermann Josef Kirchholtes [a]

[a] City of Stuttgart, Department for Environmental Protection, Gaisburgstr. 4, 70182 Stuttgart, Germany
[b] Ingenieurgesellschaft Prof. Kobus und Partner GmbH, Hessbruehlstr. 21, 70565 Stuttgart, Germany

HIGHLIGHTS

- Conventional and advanced investigation methods were used to delineate plumes.
- Transient 3D numerical transport model was built to simulate scenarios.
- Contaminated sites were prioritized according to their influence on a receptor.
- Groundwater management plan defines the necessary remediation measures.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 August 2015
Received in revised form 15 October 2015
Accepted 15 October 2015
Available online xxxx

Keywords:
Management plan
Groundwater
Volatile chlorinated hydrocarbons
Remediation
Priority
Target values

ABSTRACT

In general, groundwater in urban areas is exposed to anthropogenic influence and suffers from concentrations of contaminants. Stuttgart, as a highly industrialized city, has more than 5000 contaminated sites which might influence the Stuttgart's mineral water quality. Despite tremendous efforts and intensive single site orientated remediation since 1984 in downtown, the mineral springs were still affected with chlorinated hydrocarbons at low concentrations. Therefore, the applied practices of environmental management and measures for mitigation of pollution sources were not sufficient and had to be adjusted.
The main goal of this study is to define an integral remediation plan (a groundwater management plan), focusing on the key sources of chlorinated solvents which are relevant for the mineral springs.
For the large-scale investigated area of 26.6 km^2 and eight aquifers, an extensive investigation and characterization methods were used in order to delineate the contamination plumes. By means of a 3D numerical model, the prioritization of the contaminated sites could be performed. Five contaminated sites with high remediation priority and need for optimized or additional remediation efforts were determined. For those five contaminated sites feasibility studies were performed which resulted in recommendation of remediation measures with total costs of more than 12.5 million euros.
The proposed strategy and approach are suitable for multiple sources of contamination. Only in this way, the contributions of single contaminated sites to the total groundwater contamination can be identified and local

* Corresponding author.
E-mail addresses: sandra.vasin@gmail.com (S. Vasin), achim.carle@stuttgart.de (A. Carle), lang@kobus-partner.com (U. Lang), hermann.josef.kirchholtes@stuttgart.de (H.J. Kirchholtes).

http://dx.doi.org/10.1016/j.scitotenv.2015.10.078

remediation measures with their spatial impact simulated. Due to very complex geological conditions, technically there is no alternative to this strategy in order to achieve the contamination reduction in groundwater.

1. Why do we need a management plan?

Stuttgart is one of the few large cities in Europe where mineral water springs. The Stuttgart mineral water is widely used for spa and medical purposes. Nineteen springs discharge about 44 million liters of highly mineralized and carbogaseous water each day. Mineral springs of Stuttgart are, just after Budapest, the second largest European sources. Due to their vulnerability, they are protected as economical, natural and cultural assets (Ufrecht, 1999).

The usage of volatile chlorinated hydrocarbons (CHC) in Stuttgart over several decades has caused a severe groundwater contamination as well as a contamination of the mineral springs. As a consequence this has initiated the intensive site specific investigation and remediation measures, which have started thirty years ago. These measures have resulted in the removal of about 25,000 kg CHC in the inner city of Stuttgart (Landeshauptstadt Stuttgart, 2003). Despite these tremendous efforts, the contamination of the deeper aquifers has not changed significantly. Since 1988 no sustained decline in CHC concentration in the mineral springs could be observed and they are still affected at a low level, exemplary see Fig. 1. This indicated that the mechanisms of lateral and vertical CHC migration between the complex structured layers of the Keuper and the mineral water-bearing layer of the upper Muschelkalk were not fully understood. Therefore, the applied practices of environmental management and measures for mitigation of contamination sources were not sufficient and had to be adjusted.

Building on these premises, the management plan for groundwater remediation applies the concept of areal (or integral) management of contaminated sites, in contrary to the traditional approach of separately investigating single sites. It focuses on the spatiotemporal analysis of CHC migration and the associated degradation and transformation processes between the contamination sources and the mineral springs. Furthermore, the management plan is considering the fact that the pollution might originate from several sources. It gives the authorities a good basis for the future work in protection of groundwater, especially for controlling the contamination in the mineral springs and their water-bearing aquifer. The groundwater management plan became binding through the involvement of the responsible boards and agencies (Vasin et al., 2013).

2. Materials and methods

The investigated area of 26.6 km^2 comprises the downtown area of Stuttgart city, with very complex geological structure. The subsurface comprises eight groundwater layers, many tectonic structures and karstic aquifers. Moreover, contamination migration is not influenced just by nature, but also by anthropogenic structures typical for urban areas, such as numerous tunnels and wells. To fully understand the system, flow, contaminant transport and related processes, an intensive investigation of the whole investigated area has been performed. At the beginning of the project, in total 182 possible contaminated sites in the investigated area have been identified, see Fig. 2.

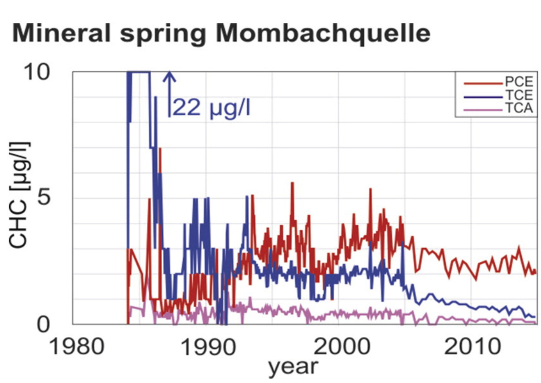


Fig. 1. CHC concentration distribution in the mineral spring Mombachquelle.

The overarching principle of the integral groundwater management is an iterative–adaptive approach with a gradual improvement of the level of knowledge, see Fig. 3. After each knowledge level is to question, which strategies and methods are appropriate or have to be adjusted in order to fill in the knowledge gaps (LUBW, 2014). In this way, additional investigations to decrease local gaps of data can be defined. However a complete and comprehensive description of a system will be not possible due to technical and financial limitations.

Conventional investigation methods, such as drillings (18), drill core analysis (18), organic carbon in rock (92), Packertests (45), water level measurements (350), water sampling (400), chemical analysis (434) and integral pumping tests (22) were performed (Ufrecht et al., 2015a). Due to the complex hydrogeological conditions, new and advanced investigation strategies and methods were applied, which in combination allowed for multiple lines of proof. These innovative methods applied were: isotopic analysis (144), micro element analysis (358), tracer tests (with fluorescence, freons, sulfur hexafluoride) and microbiological analysis (14) with a methodology to verify microbial degradation processes in a comprehensive interpretation of data evaluation, results of filed investigations and laboratory methods. The results of microbiological characterization enabled defining the microbial degradation zones, laid down in milieu maps which were used as parameter input in the numerical model. Furthermore, a combination of C-CSIA (compound specific isotope analysis for carbon isotopes) and a new method, called Cl-CSIA (compound specific isotope analysis for chlorine isotopes) was applied (Ufrecht et al., 2015a).

The hydrogeological conditions and chemical mechanisms derived from this approach, as well as from extensive already existing data sets, were combined in a conceptual model. The conceptual model consists of two modules, i.e. (i) the conceptual aquifer model describing the hydrogeological system and (ii) the conceptual contaminant model describing the chemical processes in the system. Furthermore, important elements of the conceptual contaminant model are so-called "profiles" with substance specific information on 19 sites, as presented in Fig. 2 (red dots), see Ufrecht et al. (2015b). These sites have been identified to have a high contamination input and a significant influence on the CHC contamination of the deeper aquifers. Thus, their contamination spreading has been investigated in detailed. As an example, the geological conditions, groundwater flow and contamination spreading at the site no. 9 are shown in Fig. 4.

Based on the conceptual hydrogeological model, a 3D numerical model with in total 17 layers was built to simulate the transient CHC-species transport in groundwater, accounting for degradation and transformation processes. For the flow calculation a finite difference software MODFLOW was used (Harbaugh, 2005). The transport model was calculated by MT3D99 (Zheng, 1990) and enhanced accounting for degradation and transformation processes in a so called multi-species model (Zheng and Papadopulos, 1999). The calibration of transport was performed for the period from 1960 to 2010 by comparing observed and calculated CHC concentration time series in an iterative process by varying the relevant parameters: horizontal and vertical hydraulic conductivities, input of contaminants (release rates) at contaminated sites in

Please cite this article as: Vasin, S., et al., A groundwater management plan for Stuttgart, Sci Total Environ (2015), http://dx.doi.org/10.1016/j.scitotenv.2015.10.078