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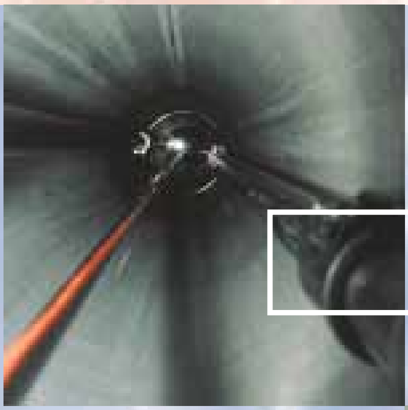
Ground Water Research in Practice



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Editorial

Ground Water Research in Practice

Lead Article

Research Reports

Forum

In Brief

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Ueli Bund
Vice-Director of the EAWAG

Ground water plays an important role in the natural hydrologic cycle. It is essential for nature and indispensable to humans as a source of drinking water. Through infiltration of rain and river water, it is naturally renewed and may be continuously used. In Switzerland ground water quality is generally very good. Soil coverage layers hinder acute contamination, and by taking appropriate measures gradual pollution can be prevented, too.

Ground water aquifers offer very special living conditions. During the course of evolutionary history, the porous systems were colonised from both, fresh waters and the sea. The immigrating species developed many specialised physiological characteristics that enable them to survive in the subsurface. The springs through which ground water escapes to the surface have a special emotional significance to human beings. They provide harmonic, balanced habitats for species that originate both in the ground water and in surface waters. Many organisms in springs are extremely sensitive to human interference. Unfortunately, very few untouched springs remain in the densely populated Swiss Plateau. It takes years to recolonise ecosystems that have been negatively impacted

Ground water often remains in the subsurface for very long time periods. Not managing it properly can have serious long-term consequences. This has been shown in many cases throughout the world. From an ecological point of view, quantitative overexploitation and qualitative degradation are often practically irreversible. Compensation measures taken to safeguard water supplies demand enormous technical and financial outlays. In many places, this is not possible to maintain on a long-term basis, if at all. Furthermore, such compensation measures may not be suitable for restoring biodiversity.

To properly safeguard ground water on a long-term basis, not only must the processes affecting quantity and quality be thoroughly understood, but adequate legislative, planning, technical and economic measures have to be taken. The EAWAG is making every effort in this direction through research, consulting and teaching. The results of these activities for the ground water were presented in the fall of 1999 at the EAWAG information seminar. The EAWAG mission is to provide an interface between science, practice and society with the goal of continuously improving the concepts and technologies for water use. Part of this is conflict management between the various interests involved – ecological, economic and social.

The EAWAG information seminars may be considered as a litmus test for these ambitious goals. In this issue of EAWAG news, you will find the presentations of the seminar on ground water. I was personally very impressed by the high standard of the contributions and the commitment of the mostly young lecturers. I am confident this issue may serve you as a valuable source of information.

Ueli Bund

Ground Water: From Drinking Water Reservoir to a Water Body

Ground water plays an important role in Switzerland, both as a source of drinking water and as an integral component of the natural hydrologic cycle. Even though the original practices for protecting ground water have successfully overcome some of the more traditional problems, they must now be extended to include recharge zones in order to insure adequate protection from persistent chemical contamination. As illustrated by comparing water consumption to ground water regeneration in Switzerland's most densely populated areas, a surplus of drinking water should not be taken for granted. The sustainable utilization of ground water must, therefore, be ensured by employing modern resource management practices.

About 80% of Switzerland's drinking water comes from ground water (both pumped and spring water). Of this total, 48% can be used without any treatment, while 41% must be disinfected on a single-stage basis (UV irradiation or chlorination). This is fortunate since many smaller communities normally lack the know-how and financial resources to operate large water treatment plants. Only about 10% of the country's ground water has to undergo multi-stage treatment in order to meet stringent Swiss drinking water quality criteria; this applies to karst water and anoxic ground water in particular.

Natural Ground Water Regeneration Processes

Until recently, ground water was regarded as an underground reservoir that is virtually sealed off at both the top and bottom; consequently, it was thought to be in only very limited contact with the aboveground environment. It was only after ground water contamination by anthropogenic chemicals was documented that this view changed. As a result of these discoveries, ground water is now acknowledged to be an integral part of natural water systems and a component of the hydrological cycle (Fig. 1).
Ground water is mainly formed by the infiltration of rain and river water. In the transition zones between surface water and ground water, numerous physical, biological and chemical processes take place which have a profound effect on ground water composition. The Swiss practices of ground water protection take into account all of these processes, including self-purification of the infiltrating water.

Ground Water Regeneration with and without Oxygen

As rain water infiltrates through unsaturated soils into the ground water, naturally occurring organic materials are oxidized by microorganisms (aerobic respiration). The carbonic acid formed during this oxidation process then reacts with limestone to cause ground water hardening (cf. paper by J. Zobrist, p.15). Exchange processes with the atmosphere usually guarantee the presence of sufficient oxygen, therefore, aerobic ground water regeneration is the norm in Switzerland.

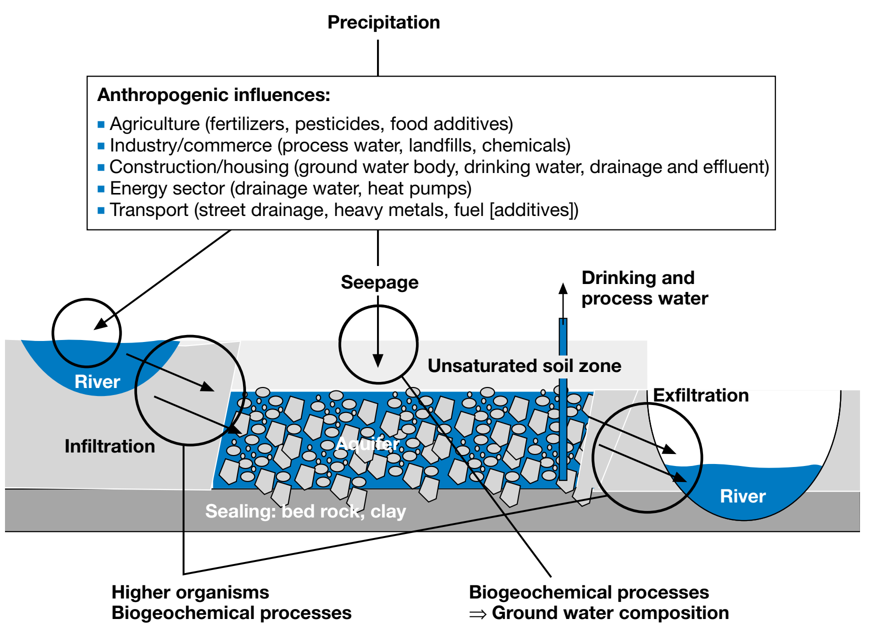
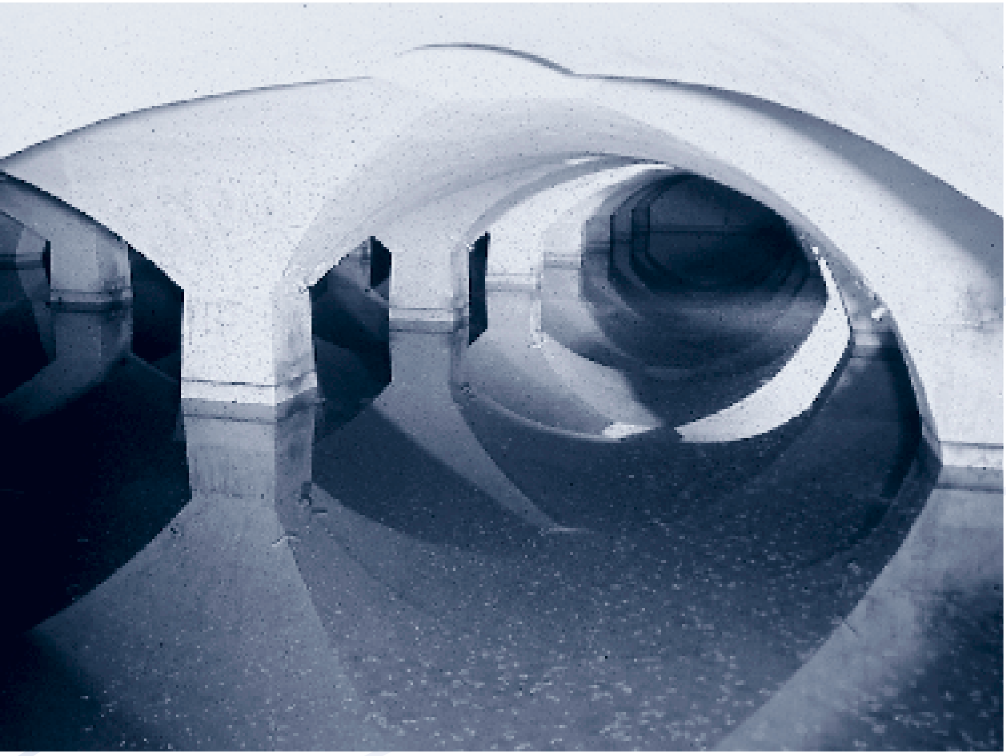


Fig. 1
Ground water as an integral part of the water cycle: natural regeneration processes and anthropogenic influences.



IWB, Basel

Drinking water reservoir. About 80% of Switzerland's drinking water comes from ground water (both pumped and spring water). Although Switzerland is often called the water tower of Europe, our ground water still has to be managed with care.

In the infiltration zone between surface water and ground water, a wide variety of small animals live on the dissolved nutrients (cf. paper by T. Gonser, p. 6), whose concentrations and availability largely determine the numerous biogeochemical processes that occur. Similar processes occur during the exfiltration of ground water into surface water.

During the infiltration of river water, atmospheric oxygen is often excluded. With a high concentration of ammonium or dissolved organic substances, available oxygen is rapidly consumed, resulting in a sequence of reductive processes (cf. J. Zobrist, p. 15). This is known as anaerobic ground water regeneration.

Ground Water Protection

In densely populated areas, as is common in many parts of Switzerland, anthropogenic influences may be superimposed on these natural processes of ground water regeneration (Fig. 1). Undesirable substances may thus enter the ground water from agriculture, industry, commerce, construction, energy production, and transportation. Substances such as fertilizers and pesticides, seepage from landfills, runoff, and street drainage can infiltrate directly through unsaturated soil zones, while other contaminants such as sewage effluent infiltrate mainly via river water.

To minimize the negative effects of anthropogenic activities, a comprehensive ground water protection policy has been instituted in Switzerland. In ground water collection zones, the use of fertilizers and pesticides and the handling of chemicals, etc. are restricted or prohibited altogether in order to preserve the self-purification capacity of the aquifer. Water protection zone 2 is generally established so that infiltration through this regime takes at least 10 days, which is normally long enough for self-purification and decomposition of biologically degradable substances. If this is not enough to ensure high quality drinking

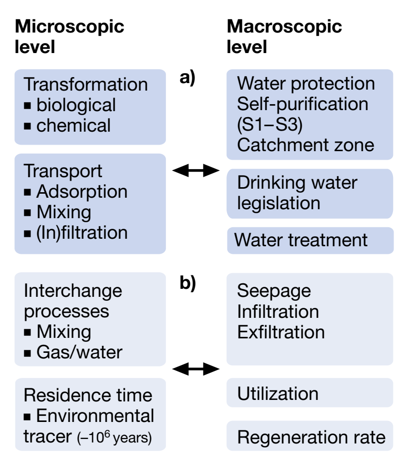


Fig. 2
a) Qualitative and b) quantitative aspects of ground water. A thorough knowledge of physical, chemical and biological processes at the *microscopic* level is essential for understanding the *macroscopic* system by which ground water becomes drinking water.

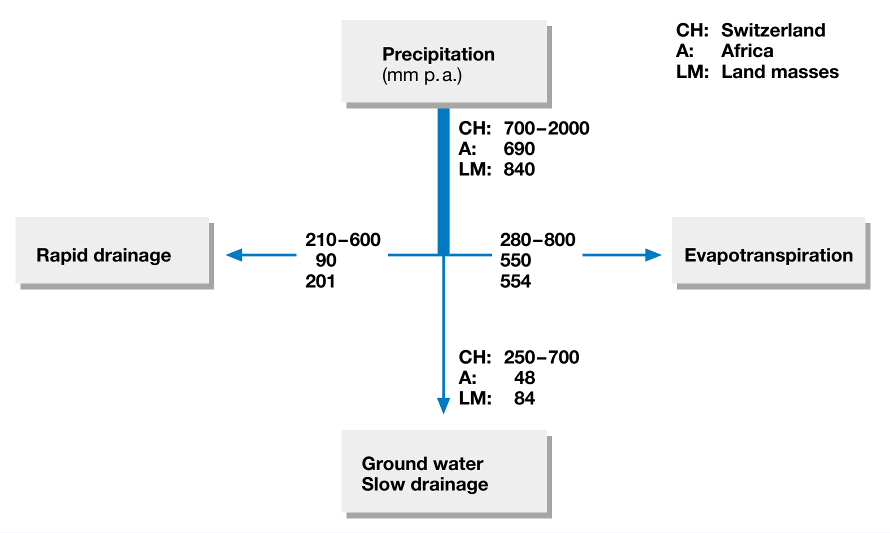


Fig. 3
Average ground water regeneration rates in Switzerland, Africa and global land masses compared with drainage and evaporation rates. Precipitation seepage into the ground water is clearly above average in Switzerland.

water, a number of drinking water treatment methods can then be employed.

Drinking water protection in Switzerland is based on three main principles (Fig. 2a):

- Ground water protection
- Self-purification capacity of water resources
- Drinking water treatment

This macroscopic approach is based on microscopic processes, which must be examined in depth to allow a reliable assessment of how pollutants behave in the subsurface (cf. papers by S. Hug, p. 19, J.R. van der Meer, p. 24, S. Haderlein, p. 21).

While the original protection zone concept successfully overcame the traditional problems of hygiene and degradation of organic pollutants (e.g., mineral oils), it was soon found to be inadequate against persistent chemicals such as pesticides, chlorinated solvents, etc. The new ground water protection policy, therefore, extends existing practices to include catchment and infiltration zones, thereby accounting for 90% of permitted ground water utilization (cf. E. Hoehn, p. 27). In order to put this extended policy into practice, it will be necessary to prepare suitable legislation over the next few years.

Ensuring Sustainable Ground Water Utilization

The quantity of ground water available for utilization largely depends on seepage, infiltration and exfiltration rates (Fig. 2b). This macroscopic level comprises the interplay of microscopic interchange processes such as mixing, gas-water interchange, etc. which can be investigated using environmental tracers (cf. R. Kipfer, p. 12). For example, the age of ground water can be determined within a range of years or millions of years. From this information, the regeneration rate can be derived, and the maximum amount of sustainable ground water utilization may be calculated. Such methods are indispensable for modern ground water management, though they are not yet in widespread use.

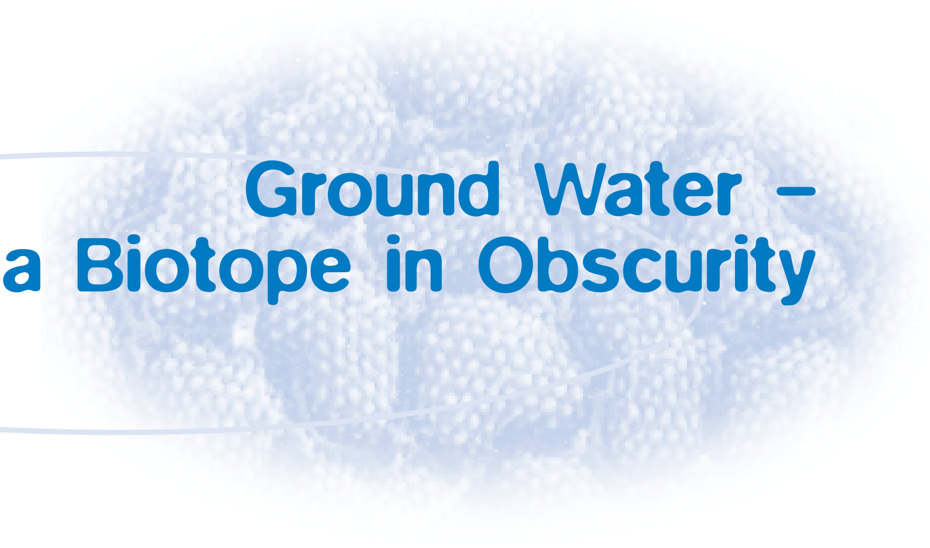
Engineering Science, EAWAG

Parade of rain gauges.

Although Switzerland is often called the water tower of Europe, our ground water still has to be managed with care. About 30% of precipitation in Switzerland rapidly flows away; another 40% evapotranspirates from the vegetation. The remaining 30% seeps slowly into the ground water (Fig. 3), a very high percentage by international comparison. The average in Africa is only 7%, while the global mean is around 10%. Depending on weather conditions, about 250 to 700 mm of annual precipitation in Switzerland seeps into the ground water (international average = 84 mm; Africa = 50 mm). On the other hand, average drinking water consumption in the heavily populated areas (i.e., 500 people per square kilometer) is around 125 mm of precipitation or 250 cubic meters per person per annum, which includes industry, commerce and services. In contrast to the widespread notion that Switzerland has unlimited drinking water supplies, consumption in the highly populated regions is about the same as that which is replaced by precipitation. In similarly populated areas with much lower ground water regeneration rates, ground water depletion is expected.

In order to ensure qualitatively and quantitatively sustainable utilization of our valuable ground water resources, modern assessment methods must be applied more systematically. The articles in this issue of EAWAG news give a good overview of the state-of-the-art.

Urs von Gunten studied chemistry at the ETH Zurich and was awarded his doctorate in 1989. He conducted postdoctoral research in biogeochemistry at the EAWAG, and has been working since 1992 on drinking water treatment (oxidation and disinfection processes). He has led a research team in this field since 1995. In 1998, he was appointed head of the Chemistry Department. This year (2000) he assumed leadership of the Department for Water Resources and Drinking Water.



Ground Water – a Biotope in Obscurity

Since ground water generally resides at a depth where sunlight cannot penetrate, photosynthesis does not occur; consequently, neither organic substances[1] nor oxygen are produced. Energy and oxygen for the ground water ecosystem, therefore, must be provided from the surface. For this reason, hydrological interchange between the surface and the ground water are indispensable to the functioning of ground water ecosystems.

Microorganisms in the ground water biotope have adapted to two main problems:
1. How to survive under such conditions?
2. How and where to participate in the interchange of matter and energy with the environment above ground?

The essence of ground water ecology, therefore, lies in the biological strategies employed to utilize the interchange of matter and energy between surface water and ground water (Gibert et al., 1994). To clarify ground water ecological systems, it is first necessary to explain the nature of the ground water biotope and how the hydrological interchange process occurs.

There are three main types of ground water biotopes, each with different interchange characteristics:
1. Fissured aquifer
2. Karstic aquifer
3. Porous aquifer

The following discussion is restricted to the two primary types of aquifers: karstic and porous.

Characteristics of Life Forms in Karstic Aquifers

Karstic aquifers are formed in limestone strata by carbonate dissolution, typically as large cavities and caves. Their structure is, however, heterogeneous, both in size and distribution. Due to the existence of large cavities the residence time of the water is usually very short.

Ground water research started in 1768 with Laurenti's discovery of the blind, non-pigmented salamander *Proteus anguinus* in the karstic caves of Slovenia. Later, Luca Cec discovered the beetle *Leptodirus hohenwarti,* likewise blind and non-pigmented. Since it had been assumed until then that no life existed underground, these discoveries triggered a spate of biospeleological cave research in the second half of the nineteenth century (Camacho, 1992). Among other findings, this work suggested that subterranean life forms generally adapt to their environment in several characteristic ways:

- Eyes are either underdeveloped or completely missing.
- Organisms are unpigmented, white or transparent.
- Largely dependent on tactile senses, they have long appendages and, in particular, antennae.
- Life forms in karstic systems can be very varied and complex.
- The distribution of karstic subterranean life forms is usually very limited; this endemism is due to the fact that most karstic zones are geologically isolated, and the organisms adapt to the specific limestone dissolution conditions in each zone.
- Modern research findings also show the important role played by chemical communication, both between the organisms of each species and between different species.

The "Interstitial Highway"

Ground water collections in the sedimentary deposits of river valleys are known as porous aquifers. They comprise relatively small cavities, with widely varying grain sizes and pore size distributions depending on their sedimentary origin. On a small scale (mm to m), they are very heterogeneous; however, on the 100 m to km scale, their pore size distribution is relatively homogeneous. Water residence times can vary from days or weeks up to centuries or even millennia (cf. R. Kipfer, p. 12). Due to this wide variation in flow and residence times, the physiochemical biotope conditions in porous aquifers are widely varied on all scales.

Porous aquifers comprise unconfined systems with an interlinked cavity system along the river bed. On an evolutionary time scale, this "interstitial highway" (Ward & Palmer, 1994) allows the influx and enormous spread of organisms, both from limnetic and marine environments. Their adaptation to the ground water biotope is, however, a "one-way street"; while various surface organisms have adapted to ground water conditions over the ages, the opposite has never happened. Ground water biotopes can thus be regarded as the "black holes" of evolution (Kornicker, in publication).

Characteristics of Organisms in Porous Aquifers

River beds in their upper reaches are typically coarse-structured with relatively large interstitial spacing, while the lower reaches are mainly comprised of fine sediments with smaller cavities. In Switzerland's coarsely structured ground water systems, largely created by mountain streams, the *Proasellus* (Isopoda) and *Niphargus* (Amphipoda) species are often found. They are typically non-pigmented, without eyes, and smaller than their relatives at the surface, *Asellus* (Isopoda) and *Gammarus* (Amphipoda). Some typical life forms in the finer sediments are shown at the top of Figure 1. They

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[1] **Except for chemolithoautotrophic production in some karstic caves.**

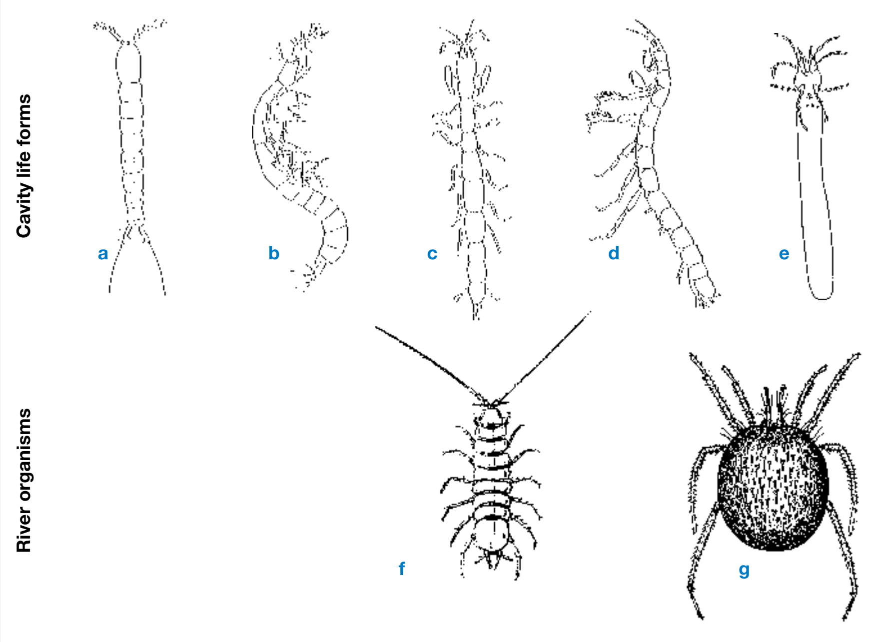

Fig. 1
Typical life forms in ground water cavities compared with some river organisms in the same zoological group (from Husmann, 1978).

Ground water cavity life forms: a) *Parastenocaris* (Copepoda), b) *Leptobathynella* (Bathynellacea), c) *Microcerbus* (Isopoda), d) *Ingolfiella* (Amphipoda), e) *Wandesia* (Acari)

River organisms: f) *Asellus* (Isopoda), g) *Libertia* (Acari)

all exhibit the characteristics of ground water biotope species: blind (no eyes), non-pigmented, relatively small, relatively short legs, wriggling motion in many cases, and elongated bodies. By comparison, the bottom of Figure 1 shows river organisms belonging to the same group.

Organic material entering ground water from the surface is first absorbed by the biofilm, a complex layer on the sediment composed of various microorganisms and their excretions. This biofilm, and partly the organic material itself, serve as nourishment for the multicellular, particle-consumers below. To compensate for limited nutrients and low oxygen concentrations underground, these life forms have adapted by developing slower metabolic rates and relatively low oxygen requirements (Malard & Hervant, 1999). As a result of these slower physiological processes, underground life forms live longer than their surface relatives.

In general, there are no particular nourishment patterns among ground water life forms and almost no specific predator-prey relationships. These organisms have developed the ability to make the most of whatever crosses their path, and the food chain in ground water is correspondingly short. As a whole, these organisms are highly environment-specific, but food generalists. Figure 2 summarizes the characteristic features of life forms that inhabit porous aquifers.

Distribution of Underground Life Forms

Beneath riverbed sediments (Fig. 3), the density of individual life forms generally decreases rapidly with depth. This is hardly surprising, since all oxygen and organic materials come from the surface. Life forms near the top of the ground water are mainly epigean river organisms penetrating from the surface. Lower down comes first a transition zone with genuine ground water organisms (hypogean) as well as epigean forms. This is where the hypogean life forms are usually most varied and frequent. Only at greater depths are exclusively hypogean organisms found, usually in low densities.

This distribution of organisms is due to their varying relationships with the underground environment and their different life cycles (Fig. 4). On the surface of river sediments, we find organisms which depend on flowing water (rheobion, stygoxene; e.g., Simuliidae). Other organisms, such as a good many chironimids, Plecoptera and Ephemeroptera, spend most of their life cycle below ground mainly in the egg and primary larval stages (stygophilic). There are, however, species of Plecoptera (such as some *Isocapnia* types) which spend almost their entire life underground. They do penetrate quite a way up into the sediment, but only for hatching, mating or laying eggs near the surface (amphibiont).

There are also life forms that are adapted to living in the transitional zone between river water and ground water (hyporheobiont); they neither come to the surface nor penetrate deeply into the ground water. Some organisms spend their entire life cycle in this transitional zone (permanent Hyporheos). The "genuine ground water organisms" (stygobiont, phreatobiont), such as *Salentinella* and *Troglochaetus,* live exclusively in deep ground water cavities.

The physiochemical characteristics of the transitional zone result from numerous factors that slowly change according to depth; they depend on the specific hydrological

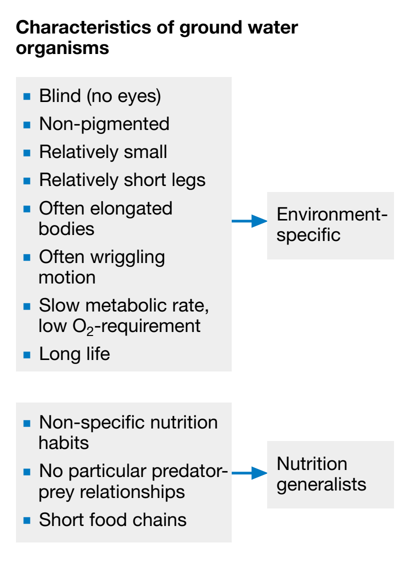

Fig. 2
Characteristic features and adaptation forms of ground water organisms in porous aquifers.

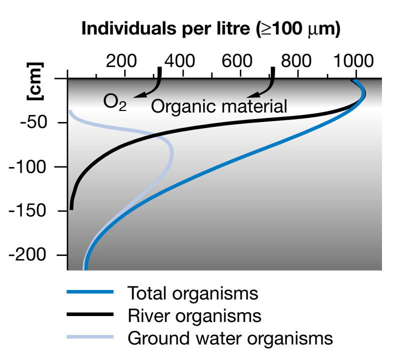

Fig. 3
Typical depth distribution of fauna in a river sediment.

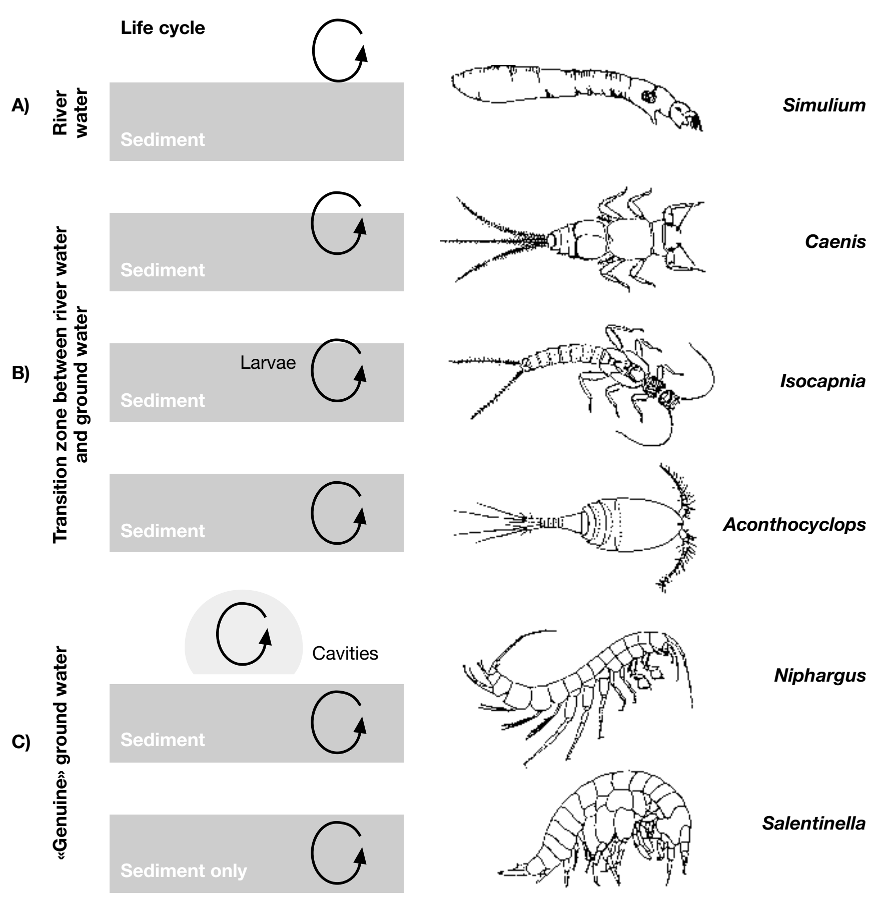

Fig. 4
Distribution of ground water fauna according to phenology and presence or absence in ground water biotopes (from Gibert et al., 1994).

A) Stygoxene organisms not found in ground water.

B) Stygophile organisms, which spend part of their life cycle in ground water or only in the transitional zone between river water and "genuine" (phreatic) ground water.

C) Stygobiont organisms, which spend their entire life cycle in ground water.

conditions and history of the drainage water. The species of ground water organisms living here depend on their inherent characteristics and life requirements. Wherever the infiltration of surface water into ground water dominates, surface life form characteristics penetrate to greater depths than in zones of ground water exfiltration. That is why epigean organisms can be found at greater depths in infiltration zones than in exfiltration zones. On the other hand, hypogen organisms can live very near the surface in exfiltration zones such as springs (cf. Zollhöfer, p. 9). In infiltration zones, more organic material generally penetrates to a greater depth. With regard to organisms, the distribution of organisms depends more on the availability of organic material than on the absolute amount present. The higher the content of fine inorganic particles, however, the lower the availability to organisms. Decisive to the presence or absence of organisms is, therefore, the ratio of fine organic particles to fine inorganic particles (Brunke & Gonser, 1999).

No precisely definable biotic composition, therefore, exists in ground water near the surface. Instead, from river to ground water, there is a gradual transition between various kinds of organisms. Their distribution depends on specific physiochemical conditions that are determined by hydrological interchange with the surface (Brunke & Gonser, 1999). In any case, the distribution of organisms in ground water is very heterogeneous.

Although a number of principles have been identified and various concepts have been proposed to explain the occurance of organisms found in alluvial ground water (Ward et al., 1998), our knowledge of their biotic composition is still very rudimentary (Ward & Palmer, 1994). To date, only a few aquifers have been investigated in detail. The importance of biological interactions for the obscure ground water ecosystems are still largely unknown.

Tom Gonser
works on river and ground water ecology in the Department of Limnology at EAWAG.
After studying in Freiburg, Breisgau and Constance, he worked in Chile for three years where he received his doctorate. His postdoctoratal work involved ground water investigations in Montana (U.S.A.).

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Springs – the Forgotten Biotope

Springs have always been poetically appealing, but they are also fascinating biotopes at the interface between streams and ground water. They harbor innumerable unique organisms, whose environment has thus far been almost completely neglected in Switzerland, both from the scientific and water management points of view. The effective protection of these highly sensitive ecosystems depends not only on tougher legislation, but also on a detailed inventory of all the natural springs that still exist.

Environmental and landscape protection in Switzerland, whether at the national or cantonal level, to date has taken almost no account of springs. The Water Protection Act (GSchG) specifically applies to "all surface and subterranean watercourses" and thus protects "spring and ground water together with bedding, coverage and storage strata". This law also serves to "safeguard drinking and process water supplies". As a result, the designated spring protection zones in the various cantons protect only the water supplies as such, but not the biotopes in these zones. Furthermore, springs which dry up for 18 days per year or longer are not considered watercourses according to GSchG (Art. 4i). In other words, the Water Protection Act does not apply to most of the springs in the Jura Mountains and the tertiary sandstone hills of the Swiss midlands.

While ground water and surface watercourses are subject to cantonal law, springs are excluded. According to Art. 704 of the Swiss Civil Code, springs are classified as the private property of the respective landowner. Spring watercourses cannot, therefore, be designated as public property until they have crossed the boundary of the estate in question.

Perfect Peace

Spring biotopes are a much more stable and balanced environment than any other above ground. Seasonal influences are considerably reduced, and river floodwaters with bedload movement do not occur here. The flow from many springs in river valleys is almost constant throughout the year, and the water temperature remains within a few degrees of the mean annual air temperature. In fact, the same spring which provides us with cool drinking water on hot summer days becomes a veritable oasis of warmth during the frosts of winter.

From a biological point of view, springs represent the interface between streams and ground water. Their biotic composition is, therefore, made up of ground water organisms as well as stream and pond species, depending on the hydrological conditions. Spring biotopes also harbor specialized species: a whole range of species has adapted to the pure and low-nutrient environment of springwater and they are correspondingly sensitive to any kind of perturbation. Thus so far some 1500 different species have been identified in European spring habitats whereof 465 (31%) are crenobiontic or crenophilic, i.e. their occurrence is more or less restricted to spring ecosystems. An initial biological investigation of 34 natural springs in the Swiss Jura Mountains and Swiss Plateau revealed about 160 visually identifiable species.

Landscape Jewels Lost Forever

Most of Switzerland's springs have been drained over the last century. Compared to springs that existed in 1884, only 1.2% of those in the midlands and 4.8% of those in the Jura still flow aboveground. Furthermore, most of the remaining springs have been restructured to a greater or lesser extent, whether for pasturization or enclosure reasons. Natural springs no longer exist in most of the Swiss midlands, and even in the remotest Jura valleys, they are now a rarity.

The draining of springs was promoted and subsidized for years to help intensify agriculture and forestry operations, but is now prohibited for landscape protection reasons. Despite general recognition of these past mistakes, we are still, however, waiting for restoration measures and public access to springs in the most seriously affected areas.

A Spring is not Just a Spring

Springs in the Swiss midlands and Jura can be divided into six categories according to habitat. Four of these occur in mountainous regions, and two in the alluvial plains and river valleys (Fig. 1).

Mountain springs

(Jura and tertiary sandstone hills of the Swiss midlands)

- Karst rheocrenes (karst springs)
- Lime-sinter rheocrenes
- Unsintered rheocrenes
- Linear springs

Alluvial springs (river valleys)

- Alluvial rheocrenes
- Limnocrenes (pond springs)

The fauna in karst rheocrenes comprises of a high proportion of organisms flushed out of the ground water, such as the amphipod *Niphargus* c.f *puteanus* and the springwater snail *(Bythiospeum diaphanum).* Due to ongoing calcium sedimentation, living conditions on the lime-sinter rheocrene terraces are extreme, and only very few species, such as the spotted salamander *(Salamandra sp.),* can survive. Unsintered rheocrenes, on the other hand, provide habitat

Fig. 1
Mountain springs (Jura and tertiary sandstone hills in the Swiss midlands)
a) Karst rheocrenes, b) Lime-sinter rheocrenes, c) Unsintered rheocrenes, d) Linear springs

Alluvial springs (river valleys)
e) Alluvial rheocrenes, f) Limnocrenes (pond springs)

for a wide variety of species including most of those specific to spring environments. In linear springs, mud organisms like *Cordulegaster bidentatus,* a rare species of dragonfly with luminous green eyes, are commonly found.

Alluvial rheocrenes are the only springs in this region where water plants and fish, such as the bullhead *(Cottus gobio),* are found. Pure spring water also provides the right environment for trout to raise their offspring under natural conditions. No large natural pond springs (limnocrenes) exist in the Swiss Jura and midlands; the most comparable habitats are dammed pond springs, where the fauna is comparable with that in pools.

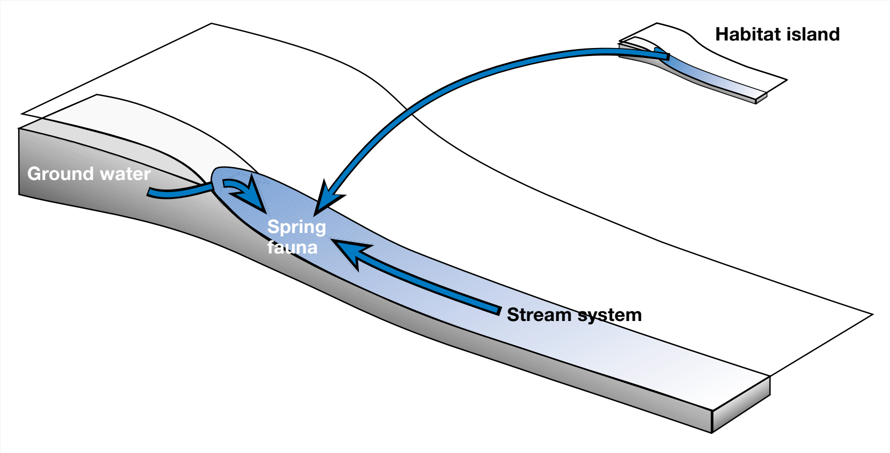

Fig. 2
All three immigration routes into the insular spring biotope are important.

The Challenge of Resettlement

How well can springwater fauna resist perturbation? And how do they manage to survive? These are two of the most challenging questions related to the structure and function of such biotopes. Thus so far, research findings in this direction are virtually non-existent.

Since springs are insular biotopes, it is difficult for many organisms to reach and establish themselves in newly formed spring environments. This is particularly true in cases where the nearest intact spring is some kilometers away. How these small creatures, many of which cannot fly, manage to reach a new spring habitat will certainly remain one of nature's secrets for some time to come; however, recent investigations carried out by the EAWAG give

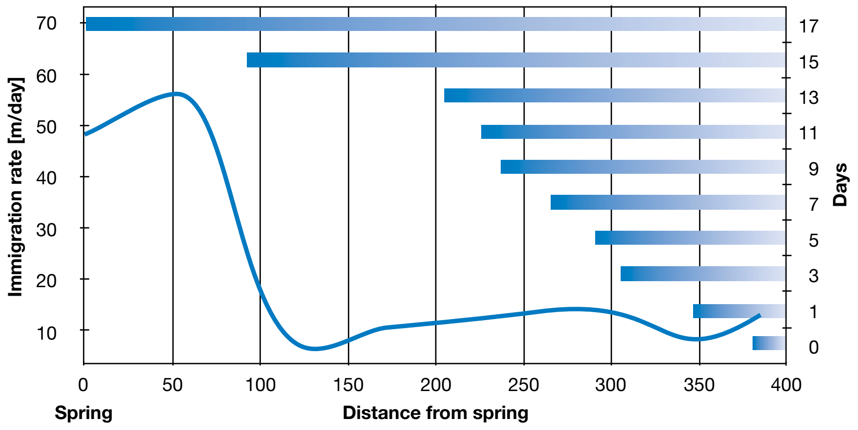

Fig. 3
Upstream immigration of the amphipod *Gammarus fossarum* in a new spring stream 400 m long.
Right ordinate: immigration distance and number of days taken; after 17 days the spring was reached.
Left ordinate: immigration rate [m/day].

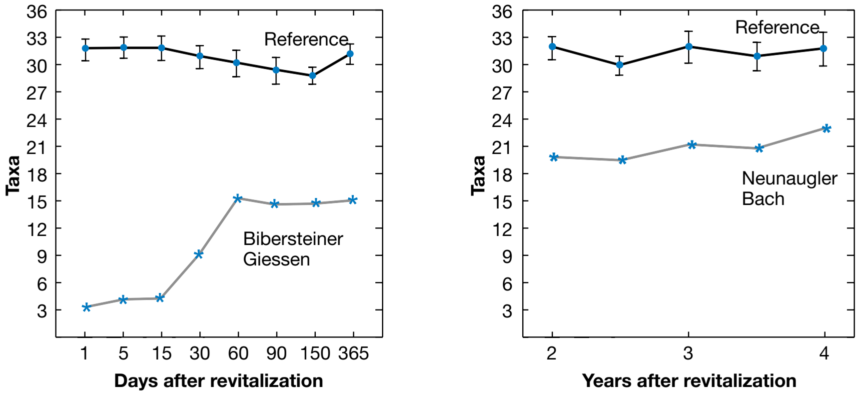

Fig. 4
Increase in number of taxa in two revitalized alluvial rheocrenes in the Aare catchment area, northern Switzerland. Species immigration in the first two years (left: Bibersteiner Giessen) and 2 to 4 years after revitalization (right: Neunaugler Bach).

some indication of the mechanisms involved in repopulating a spring biotope.

Slow Increase in Species Variety

Near Rohr in canton Aargau, two springs have been recreated by excavation. For the re-establishment of fauna, it was concluded that all three main immigration channels were of prime importance over the first 60 days (Fig. 2):

- Vertical immigration from ground water,
- Upstream immigration into the spring,
- Aerial immigration.

Only one day after the spring had been re-excavated, *Niphargus sp.* and meiofauna were found. This initial repopulation by ground water fauna remained fairly constant during the first two weeks, but after 17 days, was significantly displaced or reduced by the upstream immigration of *Gammarus fossarum* migrating upstream at a mean rate of 22 m/day (Fig. 3). The first eggs laid by insects, such as the chironomid *(Krenopsectra sp.),* were observed after 30 days. Other species of mayflies *(Ephemeroptera)* and caddis flies (Tichoptera) followed.

During the first two months, a total of 15 species immigrated to the recreated spring, after which the increase remained at this level for about one year (Fig. 4). This slow increase trend was also observed in the nearby "Neunaugler Bach", where the number of taxa increased from 20 to 23 groups between the second and fourth year after revitalization. This is still far fewer species than in comparable natural springs which were used as a reference. Clearly, the repopulation of springs is a much slower process than had been previously assumed from river biotope studies.

Spring Damage by Pasturization

A very different picture was revealed by the natural redevelopment of a perturbed spring in the Swiss Jura. The spring and its surroundings had been bogged down by pasturization, and the resulting spring outflow was a bog. In order to protect the spring from pasturization effects, it was fenced off. Even this simple measure brought improvement within the first year. The spring outflow turned into a clearly defined stream, and the surrounding land became drier and firmer. Gravely stretches started to form, thus promoting species diversity in the spring biotope. Within 18 months, the number of species increased from 9 to 23 Taxa (Fig. 5), including river species such as stoneflies (Perlodes jurassica). Although the proportion of spring-specific species was not yet as high after this time as in the reference springs, a comparably high number of species was established surprisingly quickly.

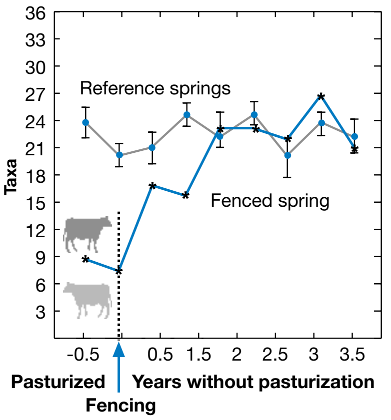

Fig. 5
Increase in number of taxa after fencing off a pasturized spring in the Swiss Jura Mountains.

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Ground Water – a Journey Through Time

New tracer methods show that ground water renewal rates can vary from days to millions of years. Even in Switzerland, the "water tower of Europe", very "old" ground water is substrated from deeper aquifers. Dating back to the last Ice Age, this ground water is not renewable; therefore, the water resource is depleted in terms of mining.

Ground water not only moves through space, but it also evolves in time. The average ground water renewal time worldwide is 1500 years. Much more notable, however, is the fact that this renewal rate can vary over 5 orders magnitude. In zones with direct river infiltration, ground water renewal times are only a few days. In arid zones, on the other hand, ground water renewal may take hundreds of thousands of years, whereas stagnant ground water in porous strata may even be as old as the rock itself. Sustainable ground water utilization has to be ultimately based on the typical water renewal rate in the region concerned, which has to be determined individually for each ground water system. It has to be noted that in general, the ground water renewal time represents the center of age distribution being determined by all water flow lines that end up in a specific ground water well.

Inadequate Interpretation Due to Inadequate Data

In general the ground water residence time or the ground water age, e.g. the time elapsed between ground water re- and discharge, is determined by numerical models that calculate the ground flow field out of the hydraulic conditions. However, it turns out to be very difficult to identity and to determine the essential physical parameters that actually control ground water transport. Since the data available for model definition is always far less than that actually required, to physically constrain a ground transport model can principally never be precisely simulated. As a result, while ground water models may correctly reproduce the hydraulic data, the fundamental processes involved controlling ground water evolution might be completely misinterpreted. For example, due to this lack of conceptual knowledge, neither the typical renewal times nor the mixing between young and old ground water may be adequately taken into account.

EAWAG

Participants in the "Science et Cité" roundtable discussion comparing drinking water samples. One sample is young surface ground water, while the other comes from ground water 200 meters deep and 30 000 years old.

Complementing Spring Data with Tracer Methods

In contrast to numerical ground water models based on hydraulic data such as piezometer readings, transient tracer based methods enable the determining of ground water renewal (rates), the average ground water residence time and the mixing between different ground water components. Thanks to their complementary sensitivity, these tracer methods reveal the conceptual weakness of ground water models and help to adapt them accordingly.

In order to reduce the uncertainty of ground water models, innovative approaches combine numerical simulations with tracer based ground water dating which rely on the analysis of naturally occurring time sensitive trace substances in ground water. The substances normally used are inert both chemically and biologically, but their concentrations do change over time either due to radioactive decau/accumulation (tritium, rare gas isotopes) or due to time depended input functions (tritium, chloro-fluoro-hydrocarbons, CFC).

If the characteristic time scale on which the concentration of a transient tracer changes over time is comparable, this method is often suitable for accurately determining the average ground water age. Modern tracer methods can be used to date young ground waters with residence times between days and few decades as well as to date stagnant ground waters that recharge over millions of years if they renew at all.

(Ground) Water and Riparian Forests in the Blenio Valley

The flood plains in Valle Blenio in Switzerland are of national importance. The sizes of these woods of the still active floodplains have been continuously decreasing over the last years, but the responsible processes remain unknown. Within the framework of an extensive EAWAG research project to investigate the ecological impact of storage power plant operations (Ökostrom project, cf. EAWAG news 47), hydraulic conditions in the riparian zone were investigated. The main point of interest here was whether ground water in this zone is fed and renewed by local infiltration from the main river (Brenno). To this end, the ground water age was measured every three months by sinking several boreholes in the center of the zone; additional data was provided by chemical analysis (Fig. 1, left).

It was found that ground water ages here vary both according to season and location. Seasonal fluctuation is common, with ages up to a few years in winter – even near the Brenno River – much younger ground water in spring and summer, and steadily increasing in age again in the autumn.

Ground water age was also found to vary as function of depth and can be divided into two basic kinds. During the summer, the ground water near the surface is young, but the age and mean dwell time nine meters down correspond to the situation in winter. These seasonal fluctuations and age gradings according to depth are attributable to the melting snow in spring and summer, which mixes fresh surface water into the upper ground water level which, in turn, forms a layer on top of the old ground water, which is not formed locally.

Chemical analyses suggest the same chronological pattern (Fig. 1, right). In the spring and summer, the chemical composition of the ground water largely corresponds with that of the meltwater in the tributary streams. In the winter, the ground water in this zone has a much higher mineral content, similar to the highly gypsiferous old ground water emerging as springwater from the Brenno alluvial plain. Ground water in the riparian zone is thus a mixture of young, weakly mineralized meltwater from the valley slopes and old subterranean ground

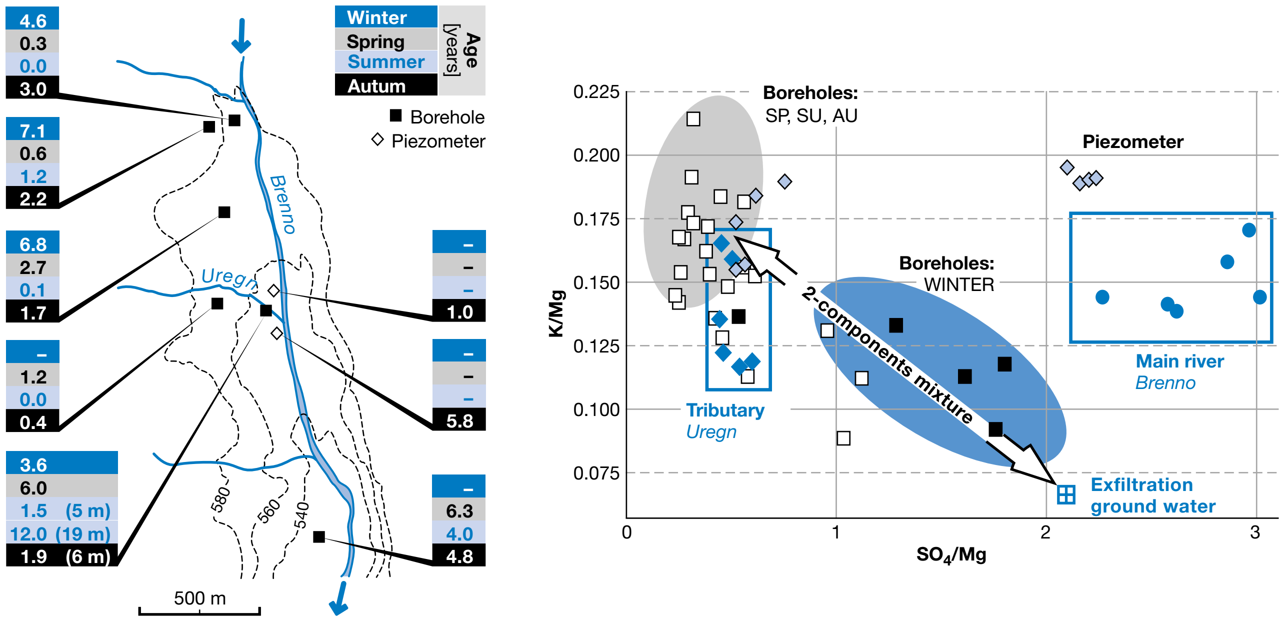

Fig. 1
Ground water in the central riparian zone of the Blenio valley is a mixture of two well-defined types. One of these components comprises ground water near the surface, which filters in as meltwater from the valley slopes. This locally formed ground water has a short dwell time (age ~"0") and is chemically similar to the tributary streams which are likewise fed by meltwater ("lateral inflow", "Boreholes: SP, SU, AU").
The freshly formed ground water forms a layer in the riparian forest zone on top of the heavily mineralized old ground water, which emerges as sulfurous springwater in the Brenno valley. The lower level ground water not formed locally ("exfiltration groundwater") has a longer dwell time (several years) and much higher mineral concentrations. Accordingly, the boreholes deliver fresh, weakly mineralized ground water in spring and summer at high piezometer readings ("Boreholes: SP, SU, AU").
In winter ("Boreholes: Winter"), the levels are significantly lower and the ground water is much older, since it then comes mainly from a lower level ("exfiltration ground water"). Almost no river water from the Brenno ("main river") can be detected geochemically in the riparian zone. This indicates that the Brenno only influences ground water dynamics in this zone indirectly, as outfall for regulating the ground water level.

Armin Peter, EAWAG

River meadow along the middle Brenno River.

water with a high sulfate content (Fig. 1, bottom). The river itself appears to have only a very indirect though large-scale influence on the ground water in this zone, possibly for regulating the ground water level.

Ice Age water in the Upper Glatt Valley

In contrast to the unconfined ground water near the surface, the renewal rate of subterranean ground water is much slower. Important in this regard is the limited extent of aquifer. Although extending only for some kilometers, the deep artesian ground water system in the upper Glatt valley contains water dating back to the last Ice Age (Fig. 2). Since the solubility of inert atmospheric gases depends, among other things, on the ground temperature at the time of ground water formation, tracer methods not only provide data on ground water age, but also on the climatic conditions during ground water infiltration. By this means, it has been found that the mean annual temperature in the upper Glatt valley during the last Ice Age was more than 5 °C lower than it is today (Beyerle et al., 1998).

It is notable that the ground water age increases by more than 10 000 years in less than one kilometer, although total age difference over the 10 km long aquifer is only 30 000 years. This age jump at the zenith of the last Ice Age is too great to be attributable to inadequate borings. The data show rather that glaciers and permafrost fundamentally changed the hydrological conditions during this last glacial maximum, thus greatly reducing ground water formation.

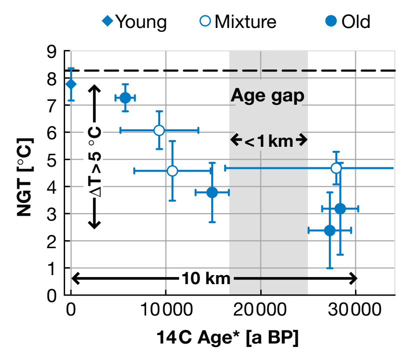

Fig. 2.
The upper Glatt valley aquifer, only 10 km long and about 100 m deep, contains young ground water near the infiltration zone (young: ◆), but at the lower end, it contains water which infiltrated more than 30 000 years ago (old: ●, ○). Since the solubility of inert atmospheric gases depends very much on temperature, the high inert gas concentrations in the old ground water suggest that the mean annual temperature in the upper Glatt valley during the last Ice Age was more than 5 °C lower than it is today (8.3 °C, broken line).
It is notable that between two borings only about 1 km apart, the ground water age abruptly increases from 15 000 to 25 000 years. This "age gap" is attributable to the fact that that glaciers and permafrost during the last glaciation (18 000 years ago) fundamentally changed the hydrological conditions, thus greatly reducing ground water formation.

Nonsustainable Water Utilization

Although the upper part of the Glatt valley aquifer between Uster and Hegnau contains Ice Age water, the lower end of the same strata near Dübendorf now contains relatively new ground water. Since the beginning of the 1990s, when drinking water was first extracted from the subterranean Glatt valley aquifer, the chemical composition of the ground water has changed continuously. While the water was previously reductive and free of tritium, it now contains both oxygen and tritium. At the same time, the ground water level in the subterranean aquifer has fallen sharply. Clearly the first ground water to be extracted was old and virtually nonrenewable, thus depleting the Ice Age resources. These hydraulic changes enabled young ground water near the surface to penetrate to the lower levels, where it now makes up most of the water that is extracted.

While the chemical composition of the ground water has changed due to extraction, there has been no change in drinking water quality. This example shows, however, that in Switzerland too there are ground water reserves that are not renewable on the human time-scale; they must, therefore, be considered non-renewal resources.

In the future, modern tracer methods, in combination with innovative ground water simulation models, will help to clarify the physical and temporal limitations of our water resources. This should lay the foundation for utilizing ground water resources on a truly sustainable basis.

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Co-authors: Werner Aeschbach-Hertig, Urs Beyerle, Johannes Holocher

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Ground Water Quality – the Result of Biogeochemical Processes

Microbiologically mediated redox processes are regulated by the ratio of accessible oxidizing agents to the amount of available and degradable organic substances in the subsurface. The resulting biogeochemical conditions induce further chemical and microbial transformation of contaminants. The origin of nitrates in ground water may be determined by the isotope ratio $\delta^{15}N$ to $\delta^{18}O$.

As rainwater seeps through unsaturated soil into ground water aquifers, its chemical composition changes drastically (Fig. 1). When organic materials are decomposed in the soil via mineralization, carbon dioxide (CO_2) is formed which, in turn, dissolves in the water and reacts with the rock-forming minerals, carbonates and silicates. These weathering reactions and the dissolution of evaporites determine the concentrations of the main components in ground water: calcium, magnesium, hydrogen carbonate, sulfates and silicic acid). In unpolluted aquifers, these geochemical processes also control sodium, potassium and chloride.

In order to achieve a hardness of 25 frz. H° (250 g $CaCO_3/m^3$) in one cubic meter of rainwater, which is typical for Swiss conditions, 70 grams of organic carbon (org C) must be decomposed. For this amount of carbon, microorganisms require 200 grams of oxygen, which is contained in the air of about two cubic meters of soil or in about 20 cubic meters of oxygen-saturated ground water. Despite this enormous oxygen consumption, the natural exchange of gases between the atmosphere and the subsoil is so great that most aquifers near the surface in Switzerland still contain oxygen.

Tracing Nitrates

Nitrate (NO_3) concentrations in ground water depend on the mineralization of organic nitrogen (org N) as well as on the nitrification of ammonia (NH_4). Surplus nitrate that is not absorbed by plants is washed into the ground water. Measurement of the isotope ratios ^{18}O to ^{16}O and ^{15}N to ^{14}N in nitrate allows conclusions to be drawn with regard to the origin of nitrate in ground water (Fig. 2) [1, 2]. Such data can be used to establish and to evaluate ground water protection measures.

Nitrate mainly originating from the decomposition of organic nitrogen in manure or in sewage has $\delta^{15}N$ values around +8 to +13‰ and $\delta^{18}O$ values around zero. This is in contrast to $\delta^{15}N$ values around 5±3‰ of nitrate formed by the mineralization of natural organic nitrogen in agricultural soils. This $\delta^{15}N$ value, coupled with high nitrate concentrations, indicates that the decomposition of organic nitrogen in the soil has been accelerated by agricultural practices.

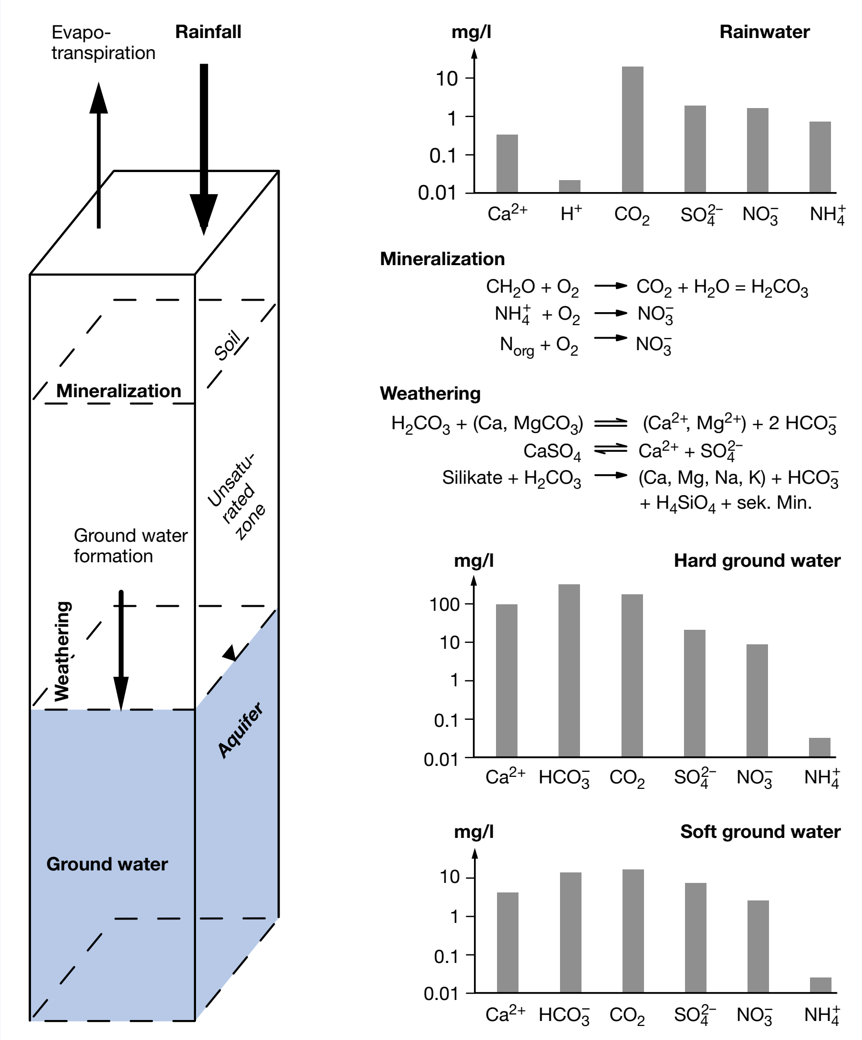


Fig. 1
Schematic representation of concentration changes during rainwater seepage into ground water and the major associated regulating processes.

Mineral fertilizers such as nitrate or ammonium have significantly different $\delta^{15}N$ and $\delta^{18}O$ values.

Atmospheric nitrogen alters isotope ratios in the soil. Near forest springs, for example, the $\delta^{15}N$ and $\delta^{18}O$ values are as low as in ammonium. Reliable tracing of the origin of nitrate requires a precise knowledge of agricultural practices in the catchment area.

Clearly Defined Sequence of Microbial Decomposition

During aerobic degradation of organic carbon, the bacteria present use oxygen directly as an oxidizing agent. Once the available oxygen has been consumed, other bacteria take over which use the remaining oxidants that are present in the aquifer during the course of a characteristic sequence of reactions (Fig. 3). The most important of these oxidizing agents are nitrate, sulfate and carbon dioxide dissolved in water, as well as solid manganese and iron (hydr)oxide. In chemical terms, microbial decomposition involves the transfer of electrons by bacteria from the organic carbon (the electron donor) to the oxidizing agent (the terminal electron acceptor) [3].

These reactions take place in a typical sequence, which is governed by the chemical energy released during each reaction. Energy output is greatest during the first reaction, and diminishes steadily thereafter (Fig. 3). This energy deliberated is used by the bacteria for their metabolism and growth. The oxidizing agents and products of the redox processes can serve as redox indicators in waters. From their presence or absence, the status of redox processes and conditions in the aquifer may be inferred.

Decomposition Processes in Heavily Polluted Ground Water

Redox conditions in a sandy aquifer that is heavily contaminated with organic substances is illustrated in Figure 4 [4, 5]. The dominant indicators are shown as redox zones; their sequence in the direction of flow represents their chronological devel-

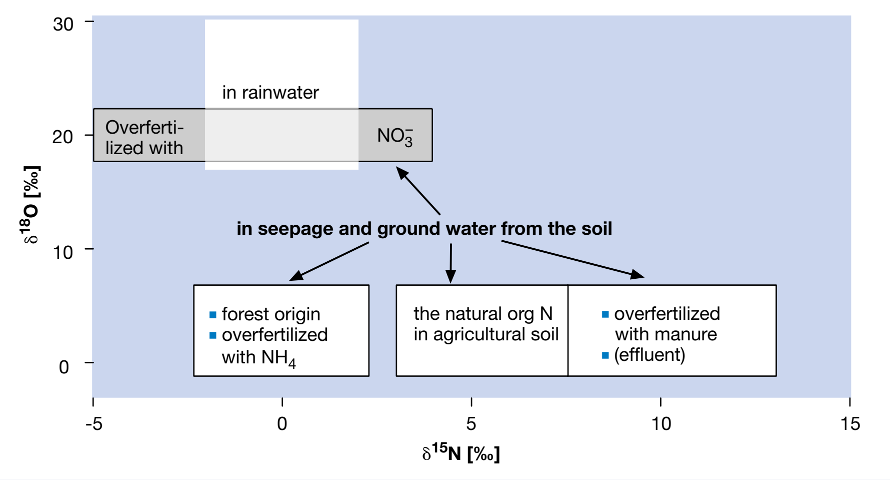


Fig. 2
Isotope ratios $\delta^{15}N$ and $\delta^{18}O$ in nitrate (NO_3^-) from various springs. $\delta^{15}N$ and $\delta^{18}O$ values in ‰ represent the isotope ratios relative to the respective international standards (Atmospheric N_2 or V-SMOV).

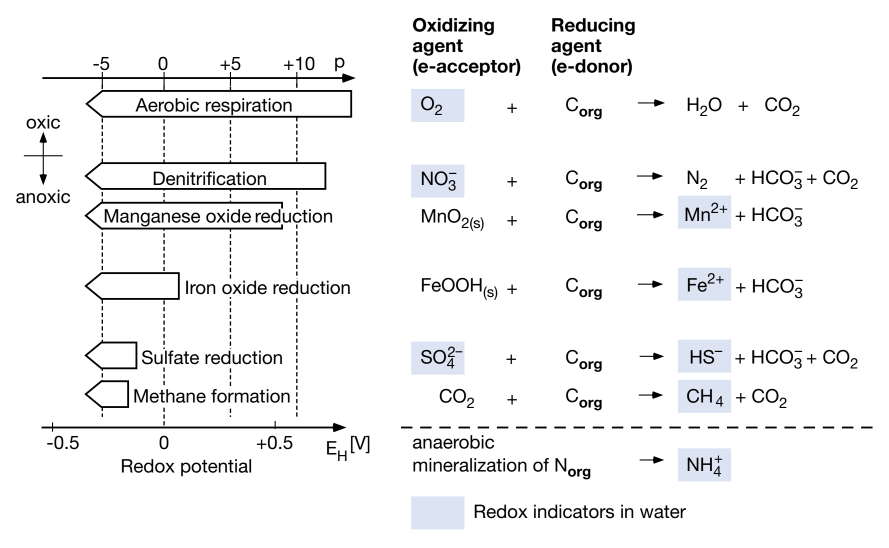


Fig. 3
Sequence of the major microbiologically mediated redox processes in aquatic systems.

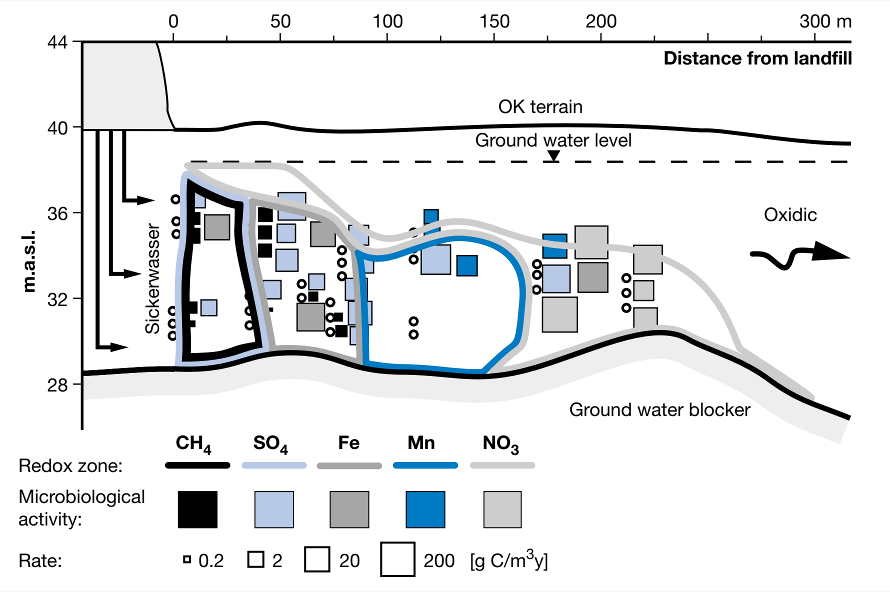


Fig. 4
Redox zones in ground water and microbiological activity in an aquifer. Longitudinal section through aquifer in Grindsted (DK) polluted with seepage water from a landfill. The numerous sampling points for redox indicators are not shown.

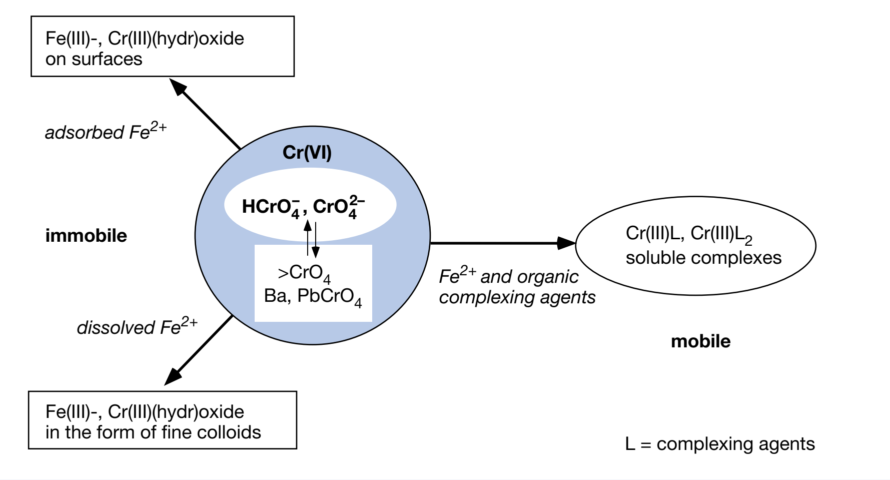


Fig. 5
Reaction diagram for chromate reduction by Fe(II) in an aquifer.

opment. Due to seepage of oxygen-free (anoxic) water containing sulfates out of the landfill for several years, the bacteria have used up all of the available manganese and iron (hydr)oxides in the immediate neighborhood of the landfill. In this zone, sulfate reduction and methane formation also take place. Further downstream, manganese and iron (hydr)oxides are still present, which are reduced dominantly here. In the end zone of the plume, nitrate washed in from the surface is denitrified at the top and front edge of the pollutant zone.

Quantification of Microbiological Activity

In order to quantify microbiological activity, small aquifer samples were analyzed in the laboratory together with the respective water samples. From the chronological development of redox process products, the oxidation rates of organic carbon were calculated for each reaction. The results of these calculations show that near landfill, iron oxide reduction takes place as well as methane formation and sulfate reduction (Fig. 4). Manganese oxide reduction and denitrification do not occur until further downstream in the ground water. In clay lenses within the denitrification zone, significant sulfate and iron oxide reduction are also observed.

These two investigations revealed spatial differences in the distribution of redox processes that are attributable to the differences in the two measuring procedures employed. For determining microbiological activity, all measurable redox processes in a small aquifer compartment were registered, i.e., on a small scale. Measurement of the redox indicators in water reflects the dominant redox process in a large compartment, i.e., on a large scale. This also includes the effects of transport and the secondary reactions of redox indicators.

The Significance of Redox Processes

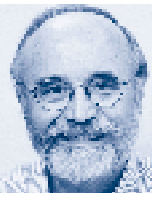
When oxygen has been consumed in a ground water system, its biogeochemical milieu changes drastically because the products of the redox processes initiate secondary geochemical reactions [6]:

- CO_2 reacts with the rock-forming minerals.
- Dissolved iron and manganese, Fe(II) and Mn(II), are precipitated by sulfide and carbonate.
- Any surplus sulfide dissolves iron and manganese (hydr)oxide reductively.

Additional chemical reactions are now known which do not take place under oxidizing conditions. For example, Fe(II) is also a reactive reduction agent that can react both with inorganic and organic pollutants [7]. Anoxic water must be treated before it can be used as drinking water, since dissolved manganese and iron are just as undesirable as sulfides for technical as well as taste reasons. From a microbiological point of view, anoxic ground water may contain anaerobic bacteria, which decompose organic pollutants that are not persistent in the presence of oxygen [8].

Chromate Reduction by Fe^{2+}

Chromate (CrO_4) is an inorganic contaminant found in industrial waste. It is readily soluble and, therefore, leaches into ground water. Under anoxic conditions it is reduced in the presence of Fe(II) to chromium(III) hydroxide [9, 10]. If the Fe(II) is sorbed on particles, such as silicates or iron (hydr)oxide, the chromium hydroxide attaches itself to these particles (Fig. 5). During reduction with free Fe(II), fine colloids of chromium hydroxide are formed which also attach themselves to solid phases; in such cases, the chromate is immobilized by reduction. If the ground water also contains high concentrations of organic pollutants, especially complexing agents, soluble compounds of chromium(III) are formed during chromate reduction; in such cases, the chromium remains mobile. If it is transported in this form to oxygenated zones, it may be oxidized (e.g., via manganese oxide) to reform toxic chromate.



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Arsenic Contamination of Ground Water: Disastrous Consequences in Bangladesh

Bangladesh is currently confronted with what is probably the largest case of mass poisoning in the history of humankind. About one third of her 125 million inhabitants are being slowly poisoned by drinking water that contains arsenic. The consequences have already affected tens of thousands: skin discoloration, ulcers, and cancer of the skin, lungs and intestines. Experts both in Bangladesh and at the World Health Organization (WHO) suspect that nearly 20 million people are, to a greater or lesser extent, already suffering from arsenic poisoning. If non-polluted drinking water supplies are not restored soon, arsenic poisoning might soon be the most frequent cause of death in Bangladesh. EAWAG scientists are presently concentrating on the development of a simple solar arsenic-removal-procedure (SORAS).

In Bangladesh, more than 90% of the population now drinks ground water. Previously, their drinking water supplies came from rivers and lakes, which continuously caused epidemics of cholera and diarrhea. The transition to drinking ground water, which started about 30 years ago, was quite rapid since it only took one day for a few workers to drive steel piping through the soft sediments to depths from 5 to 50 meters; the ground water was then simply pumped by hand to the surface. During the so-called "drinking water decade" (1980–1990) supported by the WHO and UNICEF, about three million ground water boreholes were sunk throughout Bangladesh. This drastically reduced the waterborne-disease epidemics, but the current arsenic crisis overshadows that success. The first cases of arsenic poisoning reportedly occurred between 1987 and 1992 in northeastern Bangladesh. Almost no official attention was paid to the problem until various organizations insisted and an international conference was held in Dhaka in 1998.

Arsenic Contamination – a Worldwide Problem

Ground water used for drinking is contaminated by arsenic in many parts of the world (Fig. 1). In some cases, this situation is attributable to human causes such as mining, fungicides, pesticides, and timber preservatives. Mostly, however, the cause is natural arsenic which occurs in the subterranean strata.

Arsenic can be dissolved in water-bearing sediments through biogeochemical processes, thus polluting ground water, springs and rivers. While the arsenic content in the Pacific Ocean is only 1.5 µg/liter, it varies in lakes and rivers from less than 1 µg/l up to several thousand µg/l. For humans 150–300 mg of arsenite (As_2O_3) are deadly, but it is not as easy to determine the chronic poisoning dose based on daily intake in food and water. This depends on numerous factors such as the nutrition, general health care, age, sex and genetic preconditions.

The maximum limit currently set for arsenic content in drinking water is 50 µg/l in most countries, including Switzerland, but in many parts of the world this limit is exceeded. Based on epidemiological studies, the WHO recommends setting a lower limit of 10 µg/l, so that many regions now must be regarded as problematic. Arsenic concentrations of 10–50 µg/l are found in Switzerland, for example in Astano (TI), as well as in Alsace and many other parts of Europe. According to the latest findings, arsenic is one of the most problematic water contaminants worldwide.

Arsenic in surface water occurs in two states of oxidation:

- in the trivalent form As(III), mainly as arsenite (up to pH 7 as H_3AsO_3)
- in the pentavalent form As(V), mainly as arsenate (from pH 7 as $H_2AsO_4^-/HAsO_4^{2-}$).

There are also numerous organic arsenic compounds formed by microbial activity and by metabolic processes in humans and animals.

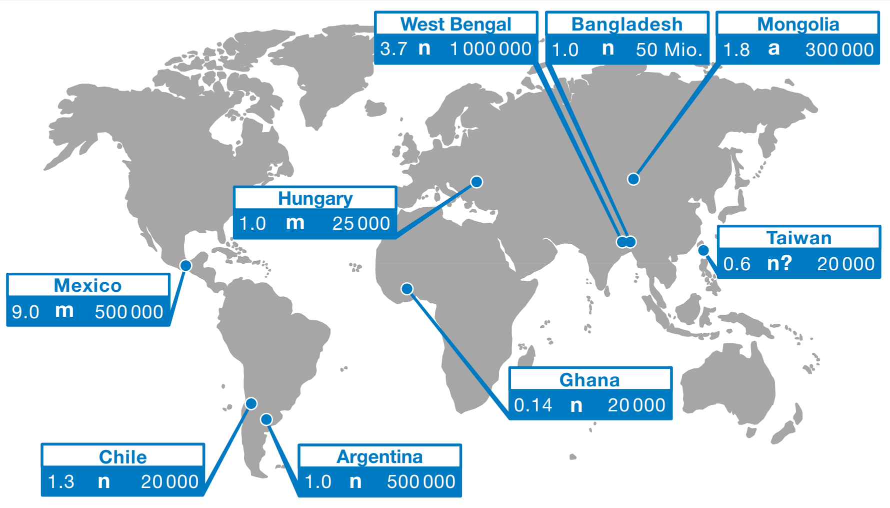


Fig. 1
Regions with high arsenic concentrations.
On the left in each box is the maximum detected arsenic concentration in mg/l. The suffix indicates the type of source (n = natural, m = mining, a = agriculture). The number on the right shows how many people are affected.

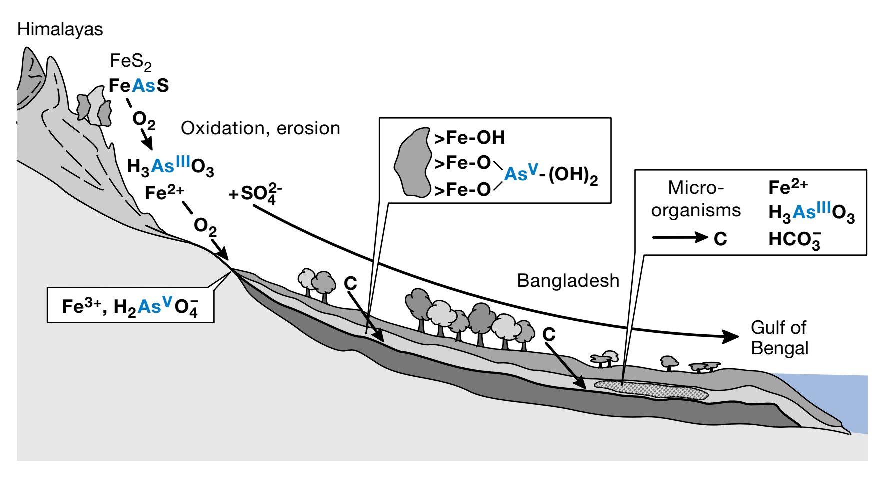


Fig. 2
Natural sources and distribution of arsenic in Bangladesh.

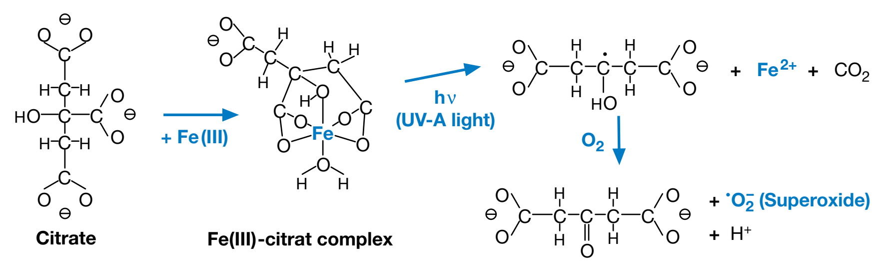


Fig. 3
Photochemical generation of oxidizing oxygen species with absorption of UV-A light by Fe(III) complexes.

Chemical transformations and the properties of various arsenic compounds determine not only the transport and distribution of arsenic in the environment, but also the most effective ways of reducing its content in drinking water. Figure 2 shows how transport and erosion processes since the last Ice Age might have brought arsenic into the Bangladeshi ground water, according to generally accepted hypotheses. The primary sources of arsenic are ores such as arsenopyrite (FeAsS) found in the Himalayas. They are oxidized in the atmosphere, or by water containing oxygen, to release As(III), Fe(II) and sulfate. In the presence of oxygen at neutral pH values, Fe(II) is oxidized within a few minutes or hours to Fe(III)(hydr)oxides. Within days, As(III) is also oxidized to As(V). $H_2AsO_4^-/HAsO_4^{2-}$ adsorbs to Fe(III)(hydr)oxides, with which it is deposited in sediments, while the sulfate is washed out.

Since As(V) in Fe(III)(hydr)oxide is practically insoluble, it does not pollute water. The Bangladesh flood plain contains a great deal of organic material, however, which provides nutrition for microorganisms. When all available oxygen has been consumed, the microorganisms set about to reduce the Fe(III)(hydr)oxides, whereby the Fe(II) and As(V) are released and then reduced to As(III). These processes explain the ground water composition: anoxic, 200–400 mg/l HCO_3^-, 0–20 mg/l Fe(II), 0–2000 µg/l As(III) and As(V), <3 mg/l sulfate. The iron and arsenic content are usually correlated.

Removing Arsenic

To remove arsenic, the As(III)release process must be reversed. This is done in industrial plants by oxidizing As(III) with chlorine, hypochlorite, ozone or other oxidizing agents which results in the formation of As(V); Fe(II)-, Fe(III)- or Al(III) salts are additionally used as flocculation agents. As(V) adsorbs strongly into the Fe(III)- or Al(III)-hydroxides, with which it is then precipitated and removed. In industrialized nations, it is possible to reduce the As-content to <10 µg/l, thereby eliminating all health risks. For financial reasons, and due to the completely decentralized drinking water supply system, large industrial decontamination plants are not possible in Bangladesh. Instead, technologies are required with which small communities and villages can decontaminate their own drinking water at the lowest possible cost.

Most of the arsenic-polluted wells in Bangladesh contain sufficient iron for successful decontamination. The As(III) must first be oxidized as completely as possible, and afterwards the As(V) adsorbed to the Fe(III)(hydr)oxide can be removed by flocculation and precipitation or by filtration.

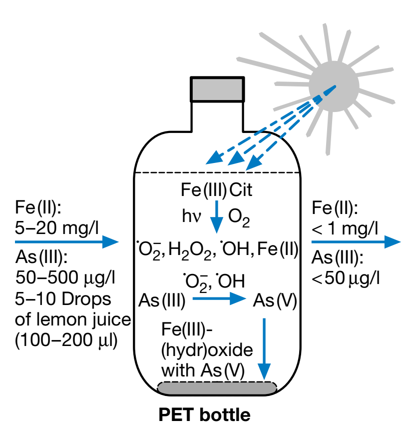


Fig. 4
Solar oxidation and arsenic removal in PET bottles.

Purification by Sunlight

Some years ago, an Australian team patented a process for the photochemical oxidation of As(III) in strongly acidic mining effluents. However, this process is not suitable for the Bangladeshi ground water, which is neutral (pH 7). Organic ligands, especially polycarbonic acids, are known to form photoactive complexes with Fe(III). Earlier EAWAG studies on the photochemical reduction of toxic chromium(VI) to the far less toxic Cr(III) demonstrated that citrate, which is found in numerous fruits, is very active even at pH 7. Figure 3 shows the formation of Fe(III)-citrate complexes and the photochemical generation of oxidizing oxygen species such as superoxide ($^{\cdot}O_2^-$).

Along the same lines as the successful SODIS water disinfection process, a small team of EAWAG chemists and engineers started development work last year on a practical method for removing arsenic from drinking water in Bangladesh. The new SORAS process (Solar Oxidation and Removal of Arsenic, Fig. 4) is amazingly simple. Citrate or lemon juice is added to the

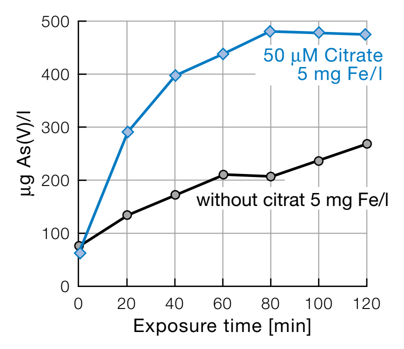
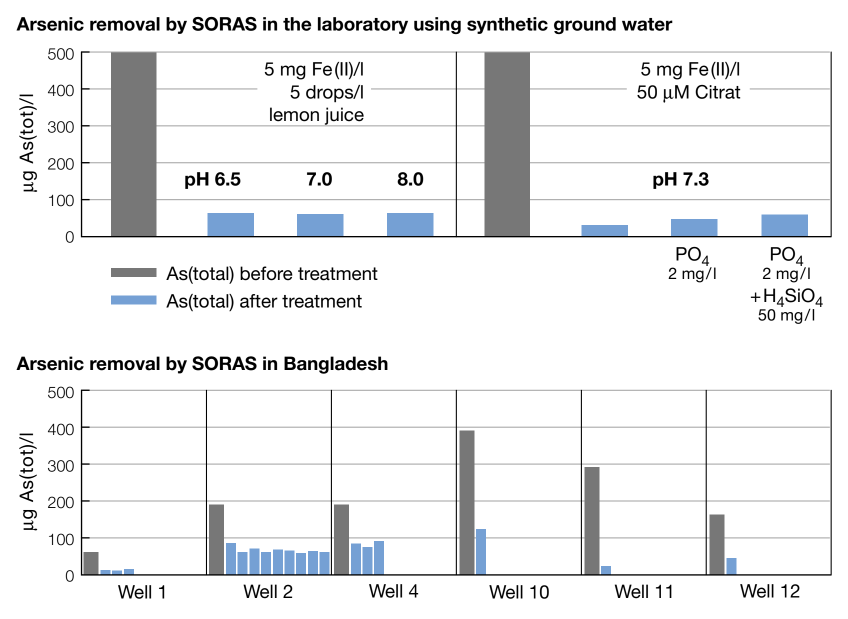


Fig. 5
Acceleration of As(III) oxidation by citrate at pH 7.


Arsenic removal by SORAS in the laboratory using synthetic ground water

Arsenic removal by SORAS in Bangladesh

Fig. 6
Arsenic removal rates in laboratory tests and field trials.

water, which is transferred into PET bottles and left in the sun for some hours. The bottles are then placed upright and left overnight, after which the purified water is either decanted from the precipitated Fe(III)-(hydr)oxide particles or passed through textile filters.

In order to reproduce Bangladeshi conditions in the laboratory, synthetic ground water was used that contained known concentrations of Ca, Mg, HCO_3, As, Fe as well as silicate, phosphate and dissolved organic carbon. Adding 500 µg/l As(III) and 5 mg/l Fe(II) to the air-saturated water creates a situation similar to that of anoxic ground water saturated with air by shaking for one or two minutes. Once 50 µM citrate or 3–6 drops of lemon juice per liter have been added, the water is poured into PET bottles and exposed to UV-A lamps (ca. 80 mW/m^2). In the presence of citrate, the As(III) is quickly oxidized to As(V), as shown in Figure 5. Another advantage of adding citrate is that the Fe(III) in the treated water flocculates rapidly and is easily removed by precipitation.

Optimization for Practical Use

Comparison of the laboratory tests with field trials in Bangladesh (Fig. 6) indicate significant differences in the results. At pH values of 6.5 to 8.0, the arsenic removal efficiency in the laboratory was 80–90%, while removal efficiencies in the field varied widely. There is a possibility that phosphate (0–2 mg/l) and silicate (up to 70 mg/l) in the Bangladeshi ground water may have influenced the arsenic removal, but this was not confirmed in the laboratory where neither phosphate nor silicate had a large effect on photo-oxidation. Although these ions compete with the adsorption of arsenate in Fe(III)(hydr)oxides, the removal of As(V) in the presence of 5 mg/l Fe was only slightly affected.

It may be possible to optimize the SORAS process by adding citrate at different times to allow for dark periods before exposure to sunlight, by changing the exposure period, or by repeatedly adding citrate. The reasons for these various possibilities is that during the aeration and exposure of the ground water to sunlight, several reactions take place both in parallel and in sequence. Even in the dark, Fe(II) is oxidized within 10 to 60 minutes to numerous Fe(III) species, as shown by the turbidity and brown coloration [formation of Fe(III)(hydr)oxides]. The composition of the water changes continuously during this time. Both in the dark, and even more so in sunlight, many oxidation and reduction reactions are possible. Based on a complete list of reactions, the system could be numerically simulated and optimized by computer methods; but this is presently only possible to a limited extent due to the large number of reaction constants that are still unknown.

Research Needed for Optimized Technology

Reactions greatly involving iron and manganese oxidations and reductions affect the distribution of contaminants and hence the quality of ground water. If the relevant reactions are known, the water quality can be improved by appropriate measures, both before and during drinking water extraction. By injecting oxygen into the sediments around boreholes, for example, the iron and manganese content in water can be reduced, and possibly the arsenic content as well. Solar treatment methods have great potential for disinfecting drinking water and for removing inorganic and organic pollutants.

The development of appropriate technologies depends, however, on a detailed knowledge of the basic reactions involved in complex technical processes. While simple technologies must be used in developing countries, well-equipped laboratories in the industrialized world are needed to acquire the necessary knowledge. In the long term, high-capacity water treatment plants will have to be installed in developing countries, at least in heavily urbanized regions. This will, of course, necessarily depend on know-how and teamwork with the industrialized nations.

Stephan Hug
is a Ph.D. chemist and has been at EAWAG since 1992. His research focus is the influence of geochemical processes on water resource quality.

Co-authors: Martin Wegelin, Daniel Gechter, Laura Canonica

Information on the arsenic crisis in Bangladesh:
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Underground Chemical Spies

Only rarely under natural conditions do chemical reactions completely decompose organic pollutants; however, abiotic transformation processes can decisively affect the distribution, availability and mobility of ground water contaminants. EAWAG's innovative approach to research on the interplay between chemical and biological processes in ground water pollutant decomposition heralds novel prospects for decontamination.

Ground water contamination by pesticides, fuel oil and solvents and the like must not only be investigated with regard to their origins, but also with regard to transport and decomposition mechanisms. Given adequate knowledge of the subsurface self-purification processes, the long-term behavior of ground water contaminants can be assessed and natural transformation processes optimally utilized. Decontamination costs can thereby be reduced or even completely avoided.

The persistence of organic contaminants is often assessed solely on the basis of their biodegradability; however, the fate of many pollutants below ground is largely determined by chemical reactions with matrix components or ground water. Although under natural conditions such chemical reactions seldom do decompose organic pollutants completely into harmless products, they do change the product spectrum and control their binding into the aquifer matrix. Chemical processes, therefore, affect the transport of organic contaminants through ground water as well as their biodegradability and bioavailability.

Chemistry and Biology Hand-in-Hand

Some fundamental aspects of the interplay between chemical and biological decomposition of ground water contaminants are shown in Figure 1 for the herbicide Propanil. In the aquatic environment, this pesticide decomposes into propionic acid and dichloraniline; in the presence of oxygen, both of these products are biodegradable. By chemical reaction, however, dichloraniline can permanently bind to natural organic material and thus conversely, be protected from microbial or chemical decomposition. Oxidative coupling may turn dichloraniline into a highly toxic azoxy compound. Under anoxic conditions, dichloraniline is quite mobile and difficult to remove by internal processes in the ground water.

As illustrated by this example, ground water contaminants are simultaneously affected by physical, chemical and biological processes, whose relative time-scales determine the toxicity and fate of the substance in question. Furthermore, these transformation reactions do not always lead to harmless end products. To reliably estimate the long-term behavior of soil and groundwater contaminants, detailed knowledge is required not only of the reactivity of the substances of concern and their transformation products, but also of the matrix components under the predominant milieu conditions.

Molecular Spies in the Underground

Data on the degradability and toxicity of environment contaminants can often be determined from their chemical structure or from standard laboratory procedures. It is far more difficult, however, to gain information on reaction conditions at any particular location in the subsurface. This problem lies, on the one hand, in the confusing variety of possible reaction partners in the subterranean milieu and on the other hand, in the poor accessibility for sampling of the subsurface.

To make direct observations of subsurface processes, numerous expensive boreholes are required along the contaminated area. Even though borehole samples usually deliver useful data on ground water composition, only very limited information can be derived about the composition and reactivity of the aquifer matrix. Furthermore, at least in anoxic ground water, installation of boreholes can interfere with in situ reactions by admitting oxygen to the system.

Innovative approaches to observe subsurface reaction conditions are, therefore, needed. One such novel concept utilizes

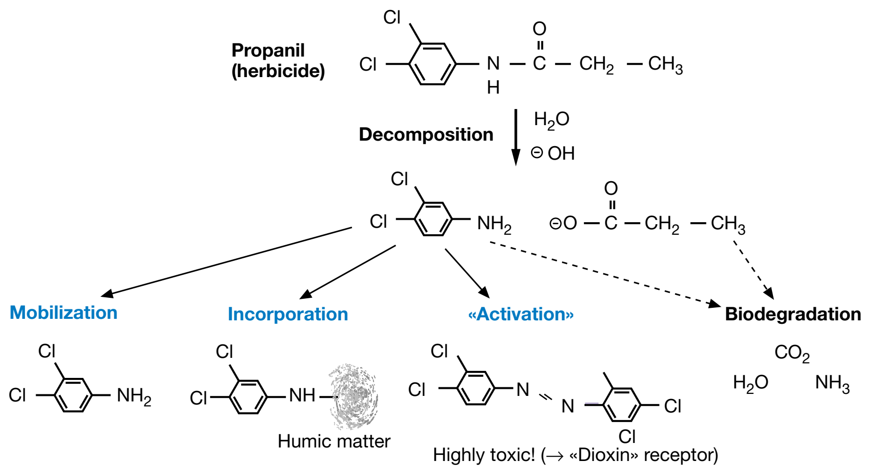

Fig. 1
Interplay between chemical and biological processes in the subsurface as illustrated by the pesticide Propanil.

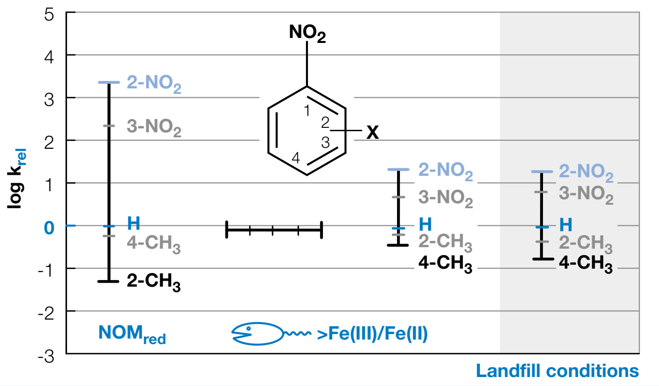

Fig. 2
Exploring subsurface reaction conditions using reactive tracers. Comparison of reaction characteristics in model systems [reduced natural organic material (NOM_{red}); microbial transformation; reduction with adsorbed Fe(II)] and in a contaminated landfill aquifer matrix.

the characteristic changes left on a set of dissolved substances by the processes taking place in the subsurface. The substances used either already exist in the ground water or are injected in small concentrations. On their way from the injection to the extraction point, they “sample” the entire biogeochemical milieu in the ground water and aquifer. By reacting with solids as well as with the liquid phase, these so-called reactive tracers deliver genuine *in-situ* data along the entire flow path with minimal system interference. One precondition for using this method is that the set of tracers must react or interact in a characteristic way with each of the main subsurface reaction partners. This can be determined, for example, on the basis of product distribution, relative reaction rates or extent of sorption of the reactive tracer.

Self-Purification of Contaminated Ground Water

The reactive tracer concept for determining the predominant reaction partners in anoxic ground water was developed in our laboratory and tested in a geochemically complex aquifer. Biogeochemical processes in anaerobic (oxygen-free) ground water produce numerous reduction agents such as reduced natural organic material (NOM), various Fe(II) species and hydrogen sulfide. The reactivity of reducing agents like Fe(II) greatly depends on whether they are dissolved in the ground water or bound to surfaces [1]. Some of these mainly biogenic reduction agents are capable of transforming substances such as halogenated hydrocarbons and nitro-aromatic substances (NAS).

In cooperation with a research team at the Danish Technical University, the reactivity of five nitro-aromatic substances (NAS) was used to probe for the predominant reduction agents in the ground water downsteams of a landfillsite in Denmark (field system) [2]. Based on the results of well-defined model systems [3], criteria were derived for identifying the various reducing agents based on their reactivity and product formalian with NAS.

Research Focus: Iron-Reducing Conditions

In contaminated ground water, anaerobic microorganisms often dominate the biogeochemical processes. Due to the lack of molecular oxygen these microorganisms use alternative oxidation agents, often trivalent iron which exists in practically all ground water as iron oxides. Due to the activity of iron-reducing microorganisms, highly reactive surfaces are generated on such minerals, enabling them to react with reducible pollutants which are difficult to degrade biologically. EAWAG research on the interplay of biological and chemical processes in decomposing contaminants under iron-reducing conditions, both in the laboratory and in the field, provides data allowing for a better understanding of the possibilities and limits of natural and stimulated self-purification processes in contaminated ground water.

Comparison of the results of the field experiment with those obtained in model systems (Fig. 2) indicated that the predominant reducing agent for NAS in the aquifer was Fe(II) attached to iron oxides. The reaction patterns of the reactive tracers for direct biotransformation and for reaction with reduced organic material (NOM) was very different from that with surface-bound Fe(II), which was almost identical to the pattern observed in the aquifer. Other observations including similar reaction products in field and model tests as well as similar of NAS in sterilized and biologically active aquifer samples confirm the dominance of adsorbed Fe(II) as a reduction agent in the ground water of the anaerobic landfill.

These investigations demonstrate that coupled biological and chemical processes at the mineral-water interface can determine in the subsurface reaction conditions, and hence the long-term behavior of contaminants. Such processes are difficult to detect *in situ* by classical methods. Under complex milieu conditions in particular, reactive tracers represent a promising approach for exploring transformation processes in ground water. Knowledge of the reactive subsurface species as identified by the tracers allows predictions about the behavior of other contaminants to be made, provided that they are transformed by similar processes. Only if the relative significance of chemical and microbial processes is known, is it possible to estimate the long-term behavior of contaminants and to assess and enhance natural affimation in the subsurface process.

Stefan Haderlein
Studied geoecology at Bayreuth University and engineering and water pollution control at ETH Zurich. He was awarded a gold medal for his 1992 doctoral dissertation at the ETH Zurich. He established an EAWAG research team on “Transport and transformation of organic contaminants in ground water”. After a research term at MIT, he was awarded the *Venia Legendi* for environmental chemistry from ETH Zurich in 1998. Since January 2000, Stefan Haderlein has led the EAWAG contaminant hydrology team in the department for “Water resources and drinking water” (W+T).

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Ground Water Pollution – the Limits on Biodegradability

Every year in Switzerland about 1500 tons of pesticides, herbicides and fungicides are released into the environment. Traces of these substances have been found in various Swiss ground water samples. Microorganisms can decompose a good many of these chemicals into harmless substances, but to eradicate the remaining contamination, the chemical compounds must be biodegradable. Biodegradability studies suggest that a combination of microbiological and physical-chemical factors determines whether or not pollutants will disappear.

Natural self-purification processes depend on the ability of microorganisms to decompose large and complex organic compounds into smaller and simpler components. Microorganisms use these organic compounds as nutrition to provide energy for their metabolism and reproduction processes. The number of compounds which can be decomposed by an individual species of microorganism is limited, but luckily there is an enormous variety of microorganisms with different decomposition abilities.

Delicious Poison

Microorganisms even enjoy compounds generally regarded as toxic. The solvent toluene, for example, is rapidly decomposed by several microorganisms into carbon dioxide and water. Although they are purely technical products, some herbicides such as 2,4-dichlorphenoxyacetic acid (2,4-D) are almost a delicacy to some types of bacteria. These recognize 2,4-D as food, consume it and, at the same time, activate a specific metabolic mechanism (Fig. 1). It is comprised of a half dozen specific enzymes inside the bacterial cell which digest the herbicide and start a chain of biochemical reactions finally converting it into carbon dioxide, chloride and water. The environmental hazard posed by 2,4-D is thereby eliminated.

Inedible Innovations

Microorganisms are not successful in every case. They may not recognize the substance concerned as food, for example, or they may lack the enzymes required for decomposing it. Such contaminants can take a very long time to disappear completely from the environment, if at all. Many of the chemical compounds developed and produced in the past were new to microorganisms and, therefore, took a long time to decompose. In particular, compounds with innovative structures or high-stability chemical derivatives were not similar enough to natural substances normally encountered

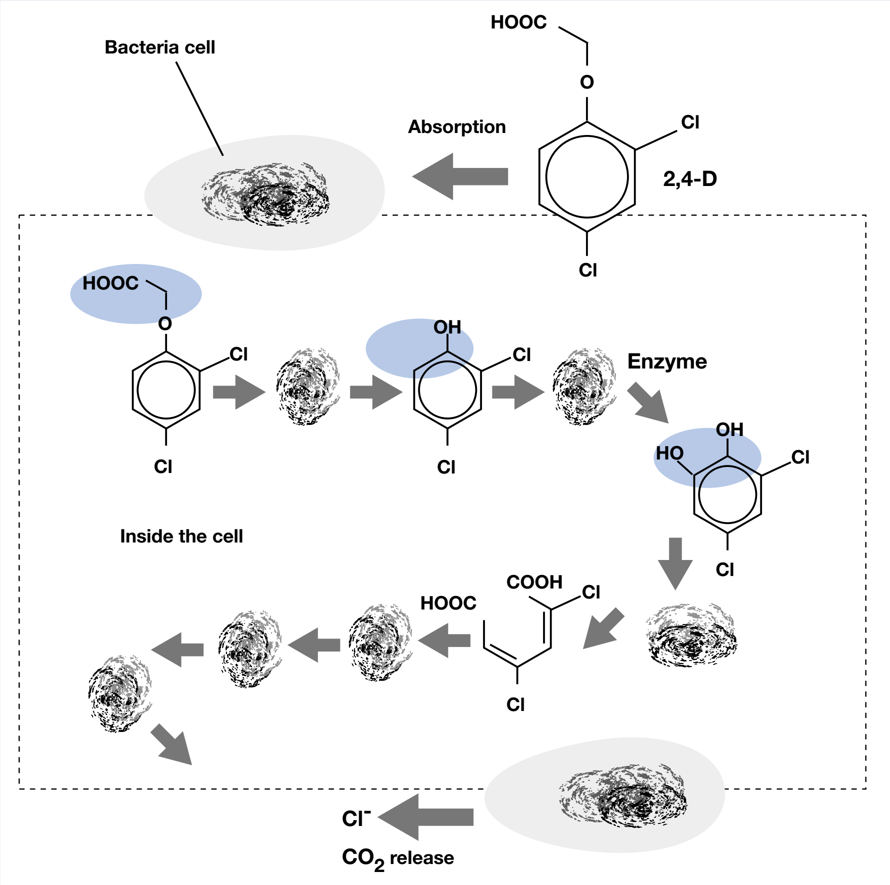


Fig. 1
The degradation pathway of 2,4-D is comprised of half a dozen specific enzymes (shown here as circular structures) inside the bacterial cell, which stepwise decompose 2,4-D to form carbon dioxide, chloride and water.

Walter Wagner, EAWAG

Agriculture as a source of ground water pollution.

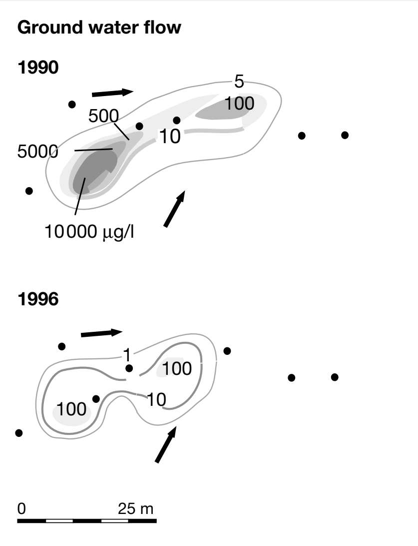


Fig. 2
Spontaneous decomposition of chlorobenzene ground water pollution in the U.S.A.. Within 6 years, most of the chlorobenzene was decomposed by re-adapted subterranean bacteria (the lines indicate zones of equal chlorobenzene concentration; the triangles designate the various ground water borings; figure taken from [3]).

by bacteria. Examples of such compounds include atrazine, hexachlorocyclohexane and bentazone. Likewise, different enantiomers (i.e. stereo-isomers of compounds like mecoprop) may exhibit different biodegradability. By requiring the chemical industry to test new products for biodegradability and toxicity, this type of environmental pollution has been somewhat reduced; nonetheless, new kinds of persistent chemicals are still being introduced.

Adapting to New Delicacies

It has been repeatedly found that after a certain time, bacteria get used to new chemicals. For example atrazine, which not long ago was regarded as non-biodegradable, now seems to be attracting bacteria to some extent. EAWAG studies of bacterial activity in polluted ground water clearly reveal an adaptation strategy among microorganisms. This is attributable to the characteristic mechanisms of bacteria which allow for a so-called horizontal gene transfer between them, thereby endowing the recipient with characteristics of the donor organism.

Annual monitoring of ground water at a site in the U.S.A. polluted with chlorobenzene (Fig. 2) showed that contamination can slowly decrease even without intervention. By comparing the bacterial population in the contaminated zone with that outside the zone, it was concluded that specific bacteria developed in the polluted bed strata. By horizontal gene transfer, these bacteria had acquired some of the characteristics of others and were now able to completely decompose chlorobenzene. Since those bacteria able to decompose chlorobenzene most rapidly found the most favorable conditions here, the chlorobenzene had a selective effect.

Whetting the Appetite

For the successful decomposition of environmental contaminants, an additional biological factor is required which cannot be easily manipulated – time. Bacteria need a certain time for their metabolism to adjust to environmental changes, and it takes a while until they have synthesized all enzymes needed to decompose a new chemical. Growth experiments in the laboratory have shown that this activation process involves a complex interplay of mechanisms. It is this process which decides how quickly and how well bacteria can decompose a new substance.

Two examples illustrate this process:

- A test tube is filled with liquid containing a dissolved pollutant. To this is added a large quantity of bacteria which have adapted their metabolism to decompose this substance. The test tube is now aerated by shaking to provide the bacteria with oxygen. The pollutant is then completely decomposed in a relatively short time.
- In the second case, the experiment is carried out with bacteria whose metabolism is not yet adjusted to decomposing this particular pollutant. It can now be determined if they do this nevertheless, and to

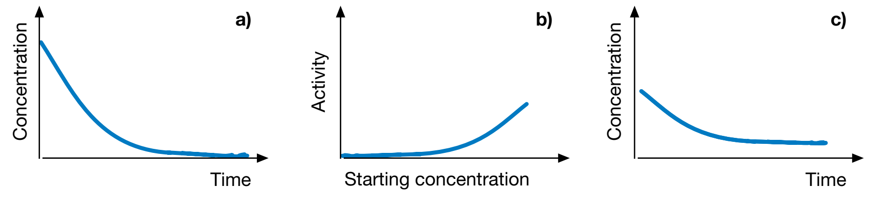
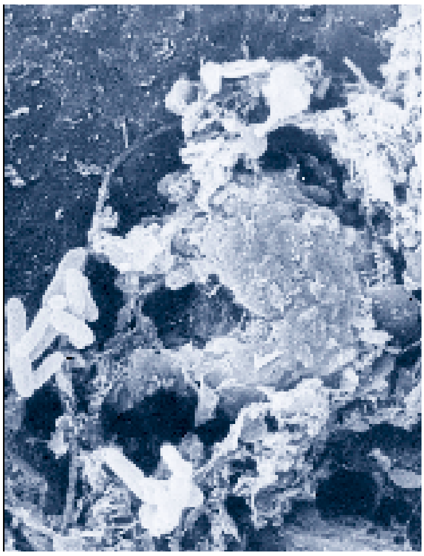


Fig. 3
a) Under optimal laboratory conditions with sufficient active bacterial cells, compounds are degradable down to the last molecule.
b) To activate bacterial cells, a certain concentration of pollutant is often necessary.
c) In dynamic systems such as columns, even active cells cannot obtain complete decontamination, since pollutant transport to the bacterial cells is limited.

what extent decomposition depends on concentration of the contaminant (Fig. 3). Interestingly, in many cases, their readjusted metabolism is not activated until a certain threshold concentration is reached. For bacteria in their natural environment (e.g., subsurface), this may mean that, even though they are able to decompose a certain pollutant, its concentration may be too low to activate their readjusted metabolism. In such cases decomposition is very slow, if at all.


Jan Roelof van der Meer, EAWAG

EM image of a group of bacteria.

Getting to the Table

The last requirement for optimal decomposition seems trivial: bacteria need to reach their food. Although many can swim small distances with the help of their flagella, in subterranean environments they tend to adhere to particles. In other words, the food, the pollutant molecules, has to be transported to the bacteria.

How does a herbicide applied on the soil reach the decomposing bacteria located 10 cm or deeper? Or vice-versa: how is a herbicide decomposed after being flushed to a depth below the habitat of the decomposing bacteria? On the microscopic scale of bacteria, they depend on transport by water diffusion on a boundary layer about 1 µm thick. This means that some of the dissolved pollutant substrate may not be decomposed, since it cannot reach the bacteria by diffusion.

To ensure the biodegradability of pollutants, they must easily be able to reach the bacteria responsible for decomposition. In the absence of such bacteria, these can be inoculated locally (on the ground). Pollutants that are practically non-biodegradable should either be prohibited or tolerated to a certain extent.

Jan Roelof van der Meer Geneticist and lecturer in environmental sciences at the ETH Zurich. Research activities at the EAWAG focus on bacterial adaptation in the environment and applications of specific bacteria for decomposing environmental contaminants.

Coauthor: Hans-Peter E. Kohler

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Swiss Transdisciplinary Award to EAWAG Team

The EAWAG "Ökostrom" project team led by *Bernhard Truffer* has won the first Swiss Transdisciplinary Award. Prizes worth CHF 50 000 in total were awarded during the International Transdisciplinarity Conference at the ETH Zurich.

Chaired by Professor *Heidi Diggelmann,* President of the Swiss National Research Council, the jury awarded prizes for each project illustrating one aspect of transdisciplinarity particularly well. The EAWAG "Ökostrom" project, which establishes criteria for environmentally-friendly power generation, was awarded the CHF 15 000 prize for social relevance. All members of the "Ökostrom" project team (past as well as present) received a citation for outstanding contributions in transdisciplinary research. Two prizes were also awarded for German and Austrian projects. The prize money was donated by the Gerbert-Rüf Foundation.


Ueli Bundi, EAWAG

Drinking Water Well Catchment Zoning

To protect the potability of ground water supplies, the revised Water Protection Act in Switzerland now divides inflow into subsurface (Z_U) and surface (Z_O) zones. In many cases, rough estimates are adequate for dimensioning Z_U zones. With regard to the infiltration of river water and subsurface flow from valley slopes into ground water, however, such estimates are inadequate.

Extension of the Protection Concept

Since January 1999, the new Water Protection Act (GSchV) has been in force in Switzerland. Amongst other aspects of the law, it prescribes the protective zoning of intakes to ground water for drinking purposes. The critical intake zones are divided into three categories:

- Subterranean (A_U) and surface (A_O) water protection areas,
- Subsurface (Z_U) and surface (Z_O) inflow zones,
- Ground water protection zones I–III.

The water protection categories and zones are virtually unchanged from the existing regulations, while inflow zones Z_U and Z_O are new elements in the protection legislation. These zones serve for “the protection of water quality in existing and planned ground water wells in the public interest, if the water is contaminated by pollutants which cannot be adequately decomposed or excluded, or if there is any significant risk of pollution”.

Dimensioning of the Z_U zone is based on well known, simplified assumptions, as follows:

- A homogeneous isotropic aquifer of infinite length,
- Stable ground water flow in the horizontal direction.

The Z_U zone can thus be represented in parabolic form (Fig. 1).

Problems with Inflow Zoning

In the perialpine valleys with glaciofluvial gravel aquifers, there are at least two problematic cases where this simplified approach is inadequate:

- Infiltration of polluted river water into the ground water, e.g., below sewage treatment plant outlets,
- In flow of subsurface waters from valley slopes, polluted, e.g., with fertilizers.

In both of these cases, more detailed investigations are needed. Apart from conventional boring, hydrochemical and geophysical methods, modern techniques such as tracer investigations and computer simulation are now available. Examples are given here of how these two cases can be examined.

a) Infiltration Flow in the Töss Valley

Situated in the gravel of the central Töss valley south of Winterthur (Linsental region) are several large drinking water wells belonging to Winterthur water works (including the Sennschür and upper Au wells). In the 1950s, ground water conditions were investigated in this area. Based on numerous piezometer measurements, isohypsic ground water contour lines were plotted both with and without pumping. These results were interpolated manually and recorded on maps. It is not clear from the drawings whether or not inflow during pumping is exclusively from the Töss. The assumption that exclusively fresh water infiltrates into the well is probably an erro-

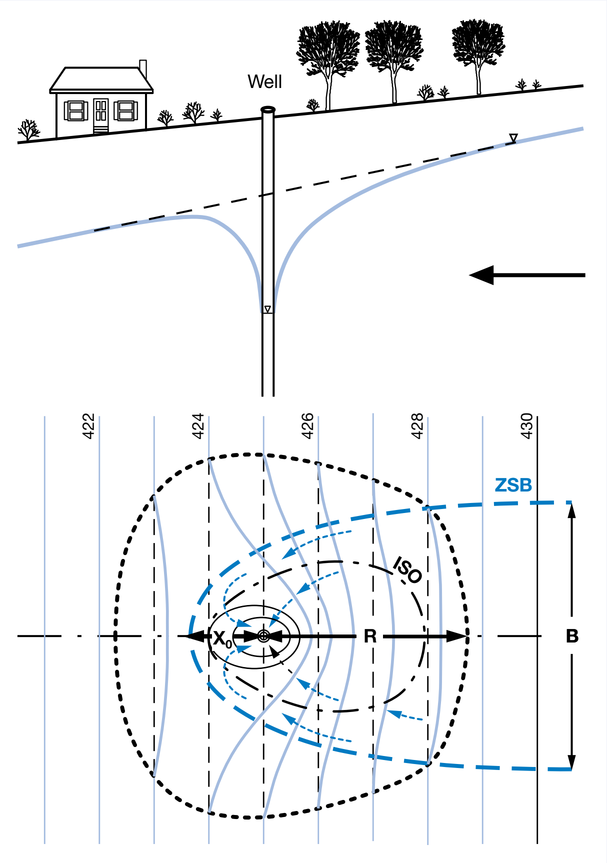

Fig. 1
Well catchment zone with and without pumping.

Top: Cross-sectional view

Bottom: Plan view, ground water flow from right to left (from Richter & Lillich, 1975, modified).

Continuous lines: Isohypsic ground water contour lines during pumping, elevations in m.a.s.l.

Plan view

Dotted arrow: Streamlines during pumping;

Dotted zone: Cone of influence during pumping

Continuous blue lines in dotted zone: Isohypsic contour lines during pumping;

Broken lines: Isohypsic contour lines without pumping;

Dashed parabola: Well catchment zone (ZSB);

Dot-dash: Lines of equal residence time to reach the well (isochronic contour lines, ISO)

X_0: Distance of well from stagnation point;

R: Upstream extent of cone of influence on flow centerline

B: Maximum width of well catchment zone

neous impression given by the horizontal two-dimensional representation. It is much more likely that ground water also flows in from a deeper level below the river Töss. This inflow either originates from further upstream in the Töss valley or comprises of "genuine" ground water fed by rainwater or tributaries. Ground water dating by tracers (e.g., inert gases; Hofer et al., 1998; Beyerle et al., 1999) supports this assumption. A two-dimensional vertical representation of hydraulic conditions would partially correct this illusion, but the oblique flow paths (from a direction oblique to the vertical plane) would still be shown incorrectly. For a correct representation of the mixing ratios and residence times of the various ground water types, a three-dimensional model is required.

During the course of a dissertation at the ETHZ and the University of Berne (Mattle, 1999), a mathematical model with five layers was compiled. Apart from the ground water contour and flow data acquired earlier, the above-mentioned dating methods were used for the first time to calibrate this model. Figure 2 shows the Töss underflow and mixing of various ground water types. One drawback of the 3-D representation is that the position of the individual streamlines is only valid to a limited extent. It is better to check the average residence time of the ground water against tracer measured data, since the position of the streamlines greatly depends on the aquifer permeability and its spatial distribution.

b) Lateral Ground Water Inflow in the Klettgau Region

The Klettgau region in the canton Schaffhausen is likewise a gravel plain, but without significant surface water flow in the valley. The ground water originates almost exclusively from rainfall seepage and lateral inflow. Drinking water in the wells, in particular the wells Chrummenlanden near Neunkirch, and Trasadingen, is contaminated by anthropogenic nitrate, and in Trasadingen by geogenic sulfate. For this region, a 2-D model of ground water flow was compiled and calibrated using ground water level and permeability measurement data (Oekogeo, 1999; Bühl and Tietje, 1999). Comparison of hydrochemical data and ground water levels revealed significant lateral inflow to both wells from karstic zones on the edge of the valley. In the case of Chrummenlanden well, mathematical modeling showed residence times of part of the ground water in the valley floor of only about five months. The model did not enable an assessment of:

- the proportion of lateral inflow in the pumped ground water,
- the depth of surface inflow from valley slopes,
- the outer limit of the well catchment zone Z_U.

As with infiltration flow, therefore, lateral inflow problems can be better solved with a 3-D presentation.

Cost Relevance of the Outer Z_U Limit

For an accurate estimation of the outer Z_U limit, a detailed knowledge of the flow system is required. In cases such as the two examples described here, mathematical simulation by stochastic methods compensates to some extent for the inaccuracy of the modelled Z_U limit (e.g., Vassolo et al., 1997). The accuracy of the calculated Z_U limit increases according to the amount of data available. If twice as much data is available, the probability area of the Z_U limit location is reduced by about half.

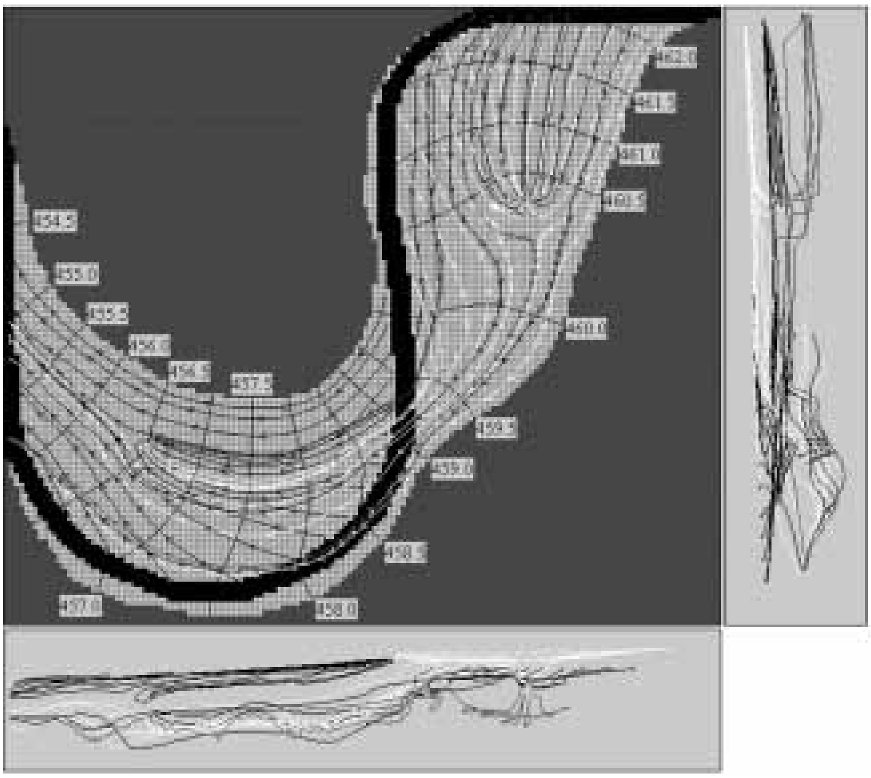

Fig. 2
Plan and cross-sectional views of stationary flow conditions during pumping at Linsental, Winterthur. The two different grey shadings indicate various streamlines (third and fifth layers of the Töss model). (Graphic: Mattle, 1999)

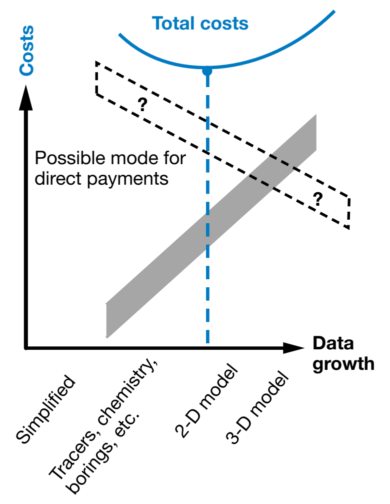

Fig. 3
Overall cost estimate for Z_U zone delineation: Relationship between data acquisition costs for more detailed survey (upward sloping grey zone) and resultant savings in water protection costs, e.g., for direct payments (downward sloping dashed zone).
The Töss ground water in the Linsental provides drinking water for the city of Winterthur.


Walter Wagner, EAWAG

The Töss ground water in the Linsental ensures the drinking water supply for Winterthur.

In other words, the outlay involved in estimating the outer Z_U limit is highly cost-relevant. The overall costs of protection measures in the Z_U zone are made up of survey costs together with actual protection costs such as in the form of direct payments to farming operations. These two cost elements are interrelated. The additional outlay required for enhanced data and greater accuracy in determining the outer Z_U limit must be compared with the expenditure incurred by a lack of detailed knowledge (Fig. 3). By balancing these two cost elements – survey costs and outlay for protection measures – overall costs can be optimized.

Better Survey Methods and Implementation Support Required

The EAWAG sees a need for greater accuracy in delineating the well catchment zone, Z_U, in cases of infiltration or lateral inflow. More detailed studies are required in such cases to ensure the well-integrated quality assurance of water resources. This involves:

- the determination of measuring methods, e.g., for the main parameters of residence time distribution and mixing ratios,
- implementation support for Z_U and Z_O zoning in these two problem cases.

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Co-authors: Norbert Mattle (Institute for Hydromechanics and Water Resources at the ETH Zurich, University of Berne, Physics Institute, Berne) and Herbert Bühl (Oekogeo AG, Schaffhausen).

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Drinking Water from Karstic Springs – a Case for Membrane Technology

Membrane technology opens up new, cost-effective ways of treating spring water in karstic zones. Experimental trials with various membrane processes for treating heavily turbid karstic springwater produced high quality drinking water in all cases; however, membrane life and application scope may be limited by fouling. The most suitable treatment process tested was found to be ultrafiltration, possibly in combination with activated powdered carbon.

Karstic Springwater Problems

Karstic springwater raises various quantitative and qualitative problems. The Swiss Jura is a typical region where small communities are faced with water contamination either of natural origin (turbidity and sulfates) or caused by human activities (landfill seepage water, agriculture). The main water quality problems are turbidity, high bacterial counts, parasites, bad taste and odor, excessive nitrate and ammonium content, and high local concentrations of chlorinated hydrocarbons or pesticides. Most of these springwater quality parameters depend on weather conditions, with widely stochastic variations.

In order to comply with drinking water quality requirements, such springwater is normally purified in complex treatment plants. The multiple stages involved include flocculation, filtration, ozonation, activated carbon filtration, and mains protection measures. By using membrane technology, the complexity of this treatment can be greatly simplified. Although used relatively little so far for drinking water treatment, membrane technology is rapidly developing and shows significant cost and technical advantages which will lead to more widespread applications in the near future.

Membranes on the Test Rig

Findings so far indicate that membrane performance depends very much on water quality. Membrane life is decisively affected by variable quality parameters such as particle size distribution, molecular size distribution of dissolved organic substances and concentration of dissolved salts. Local pilot trials for at least one year are, therefore, very important in order to assess the performance and cost-effectiveness of large-scale treatment plants using membrane technology.

In Cornol, a Swiss Jura community of about 800 people, three pilot plants of various makes (Table 1) were tested for two years to compare the hydraulic and qualitative performance of micro-, ultra- and nanofiltration, with particular attention paid to membrane blockage.

Membrane Plant Operating Modes

Apart from the central membrane module, the other elements of a membrane water treatment plant include coarse prefiltering, the pressure boosting pump, storage basin for treated water (permeate) and reverse flushing pump. Contaminants are held back and concentrated by the membrane. In direct filtration or dead-end mode, permeate is produced without recirculation. During the course of time, a layer of particles forms on the membrane and increases the transmembrane pressure. This layer can only be removed by reverse flushing.

To minimize layer formation on the membrane, the concentrate is often recirculated through the module together with the springwater. This generates strong tangential flow on the membrane surface, which keeps most of the turbid material in suspension and thereby helps to prevent layer formation. In this cross-flow mode, long operating times or high loadings are possible. Despite regular flushing, however, a slow reduction of permeate flow and increase in operating pressure cannot be avoided. From time to time, flushing with detergents, oxidizing agents and other chemicals is needed in order to restore the original membrane throughput.

Micro and ultrafiltration can also be combined with activated carbon powder additive in the intake. This adsorbs organic microcontaminants, which are then removed by the membrane together with the activated carbon.

Micro-, Ultra- and Nanofiltration

The finer the membrane pores,

- **the smaller the particles filtered out**
- **the lower the membrane throughput (membrane flux)**
- **the higher the transmembrane pressure (energy outlay).**

***Microfiltration* with pore diameters around 0.2 µm removes turbidity particles and can also eliminate bacteria.**

***Ultrafiltration* with pore diameters around 0.01 µm eliminates the finest turbidity particles including viruses and large organic molecules.**

***Nanofiltration* with pore diameters around 0.001 µm removes hardening salts (Ca^{2+}, Mg^{2+}), undesirable anions (NO_3^-, SO_4^{2-}) and smaller organic molecules; however, the water must first be filtered free of solid particles.**

	Microfiltration Memtec	**Ultrafiltration** Aquasource	**Nanofiltration** Filmtech Dow
Membrane material	Polypropylene	Cellulose derivative	Polyamid
Pore size [µm]	0,2	0,01	≈ 0,001 (200 Dalton)
Module type	Capillary module	Capillary module	Spiral module
Operating pressure [bar]	1–3	1–3	8–9
Purified water output [l/m^2·h]	300	240	40

Table 1
Characteristics of the tested membrane filtering processes.

	Microfiltration	**Ultrafiltration**		**Nanofiltration**
			+ ACP*	
Turbidity	97–100%	97–100%		–
Bacteria	100%	100%	100%	100%
Viruses	2–3 log	>7 log	>7 log	>7 log
DOC	12%	12%	40%	90%
Trichlorethylene	0%	0%	75%	90%
Perchlorethylene	0%	0%	80%	90%
Atrazine	0%	0%	98%	90%
Calcium	0%	0%	0%	95%
Sulfate	0%	0%	0%	99%
Nitrate	0%	0%	0%	35%

log = reduction over number of logarithmic units

Table 2
Elimination of various contaminants by different membrane filtering processes.

	Microfiltration		**Ultrafiltration**		**Nanofiltration** (after microfiltration)
Operating mode	Dead-end	Cross-flow	Dead-end	Cross-flow	Cross-flow
Initial flow (purified water)	300	–	240–	–	40
Low turbidity (<10 FTU)	125	85	120–140 110 (+ ACP*)	90	33
Medium turbidity (10–60 FTU)	80	75 (+ ACP*)	–	75 90 (+ ACP*)	–
High turbidity (>60 FTU)	60	–	–	60	–
Operating problems	Fouling by colloids		Fouling organic materials		Efficient pretreatment and acid dosing required

* ACP = activated carbon power additive, grain size approx. 15 µm

Table 3
Permeate flux in liters/(m^2·h) under various operating conditions (at 20 °C).

Filtering Capacity

The filtering capacities attained with this system are summarized in Table 2. The main difference between micro- and ultrafiltration lies in the separation of extremely small particles such as viruses. Nanofiltration requires a good deal more outlay, but is much more effective in removing hardening salts, sulfates, nitrates and organic micro-contaminants. Activated carbon powder additive significantly improves both micro- and ultrafiltration performance for removing dissolved organic substances.

Turbidity Peaks Accelerate Membrane Fouling

Short- or long-term membrane blockage due to fouling is attributable to various mechanisms. As long as flushing effectively restores the original membrane throughput or transmembrane pressure, operation can continue without problems. But if membrane performance gradually declines despite chemical flushing, operation will be seriously affected and membrane life will be shortened. Long-term fouling can be minimized by suitable pretreatment of the springwater, modification of the flushing procedure, and/or reduction of membrane throughput.

Both micro- and ultrafiltration are sensitive to the characteristic turbidity peaks of springwater in karstic locations. The steep rise in turbidity, from <1 FTU to more than 150 FTU, within only a few hours rapidly increased transmembrane pressure to peak levels during the trials. Despite intensive flushing, membrane fouling could not be prevented.

Various Fouling Mechanisms

If a closer look is taken at fouling phenomena, it is seen that for each process, different mechanisms are responsible. Springwater analysis during turbidity peaks revealed that a good many particles are less than 0.2 µm in diameter. Since this is smaller than the microfilter pores, they are able to penetrate the membrane. Some of them remain blocked in the pores, thus starting an irreversible fouling process. The more turbulence peaks, the greater the fouling; even chemical flushing does not fully regenerate membrane performance.

Ultrafiltration membranes with a pore size of 0.01 µm can hold back extremely fine particles. Measurements revealed that at peak turbidity values, the concentration of dissolved organic compounds (DOC) increases accordingly. Preliminary measurements with almost DOC-free water indicated trouble-free filtering of solids concentrations up to 1500 mg per liter (about 900 FTU) without affecting permeate flow. But under actual conditions, membrane blockage had already occurred at turbidity levels >60 FTU. These results suggest that fouling processes due to DOC are critically important in ultrafiltration. The typical behavior of ultrafiltration membranes during a series of turbidity peaks is shown in Figure 1 on the left. As indicated by the membrane throughput curves, operation can be continued by changing over from dead-end to cross-flow mode and reducing the operating throughput (with flushing every 30 minutes).

Combining membrane filtration with activated carbon powder additive is beneficial, particularly in the case of ultrafiltration be-

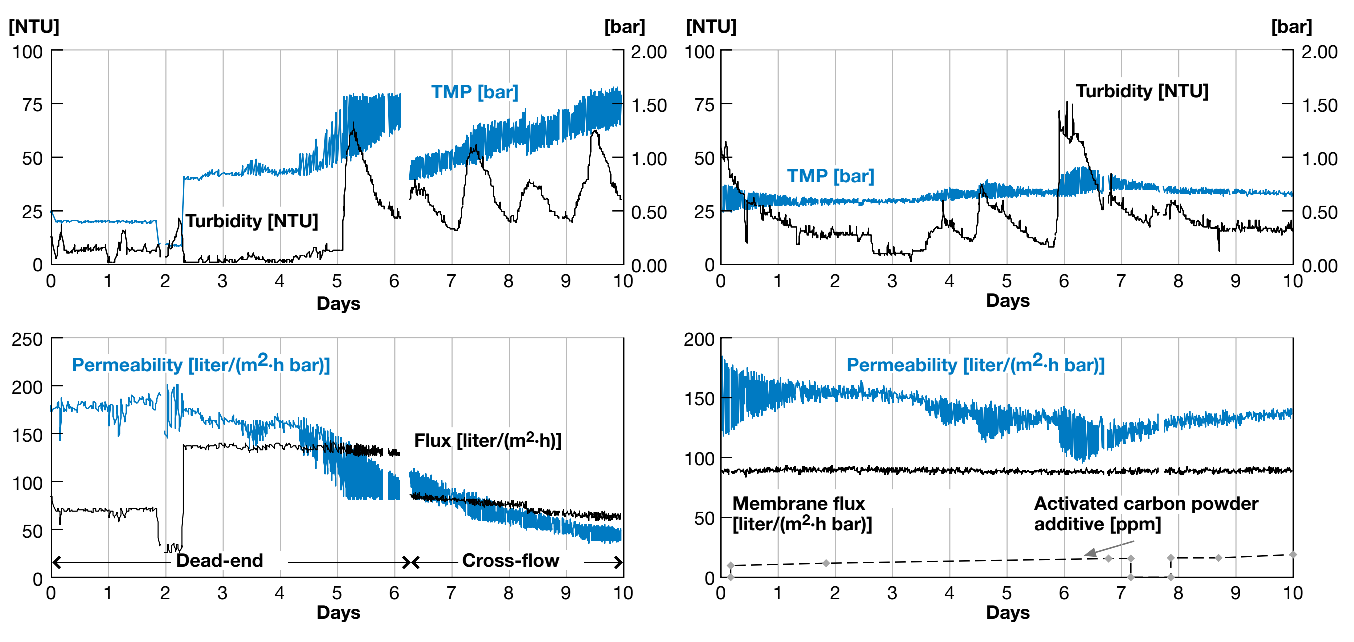

Fig. 1
Transmembrane pressure differential and specific permeate flux through ultrafiltration membrane during frequent turbidity peaks.
Left: operation adjustment by flux regulation and cross-flow mode switching. Right: reduction of fouling by activated carbon powder additive.

cause some of the DOC is absorbed to the carbon along with organic contaminants like trichlorethylene, perchlorethylene and atrazine. This not only increases permeate throughflow, but also improves filtering performance (Fig. 1 on the right).

Precleaning Requirements for Nanofiltering

Nanofiltering trials clearly showed that trouble-free operation is only possible with adequate precleaning measures, such as by microfiltration or, better still, ultrafiltration. The extremely fine nanofilter membranes with pore sizes around 0.001 µm (i.e., 200 Dalton) are sensitive to microparticles of all kinds. Even turbidity in the microfiltration permeate during springwater turbidity peaks increases nanofilter membrane fouling. To minimize fouling due to colloids and precipitation products, the pH must be artificially reduced with chemical additives.

Well Proven in Karstic Regions

Figure 2 shows annual cost estimates for small waterworks as a function of plant size. The overall validity of these cost estimates is not very high, however, since no data on large plants is yet available in Switzerland.

For satisfactory long-term use of membrane filtration in drinking water supply systems, the technology, performance capacity and cost-effectiveness must be carefully assessed in each case. Basically, membrane technology is competitive with conventional systems where complex treatment is required. Cost-benefit analyses are needed according to individual application, however, taking adequate account of uncertain membrane life.

These semi-full-scale trials in the karstic region of the Swiss Jura demonstrated that qualitatively unstable springwater can be treated satisfactorily by membrane technology for drinking purposes. The fouling problems encountered demand careful ongoing adjustment of membrane throughput and other operating parameters according to springwater quality. The most cost-effective and reliable process appears to be ultrafiltration combined, if needed, with activated carbon powder additive.

Markus Boller
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Co-author: Roberto Pianta (engineering research in drinking water treatment, particularly membrane technology, within the EAWAG Department for Urban Water Management).

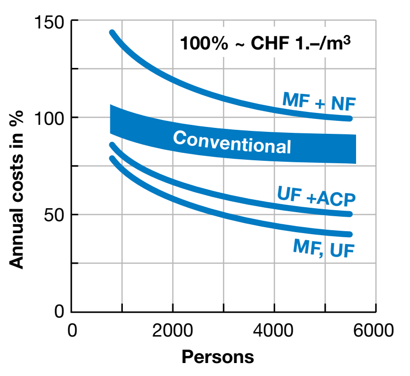

Fig. 2
Cost comparison of conventional treatment technology with various membrane filtering processes.
MF = Microfiltration
UF = Ultrafiltration
ACP = activated carbon power additive
NF = Nanofiltration

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The project "Membrane Technology in Water Treatment" was conducted in Paris in collaboration with the engineering firm RWB in Porrentruy, VA TECH WABAG AG in Winterthur, and Lyonnaise des Eaux (CIESEE). It was supported by BUWAL, the cantons of Jura, Bern, Baselland, Baselstadt, Solothurn and by SVGW.

From Ivory Tower to Glass House

Revealing the Mysteries of Science to the Public

The first roundtable discussion held by the "Science et Cité" Foundation launched an experiment in "interstellar communication". By putting researchers and laypersons in direct contact, it is hoped that new ways of reaching mutual understanding can be found. The first steps taken in this direction last February in Dübendorf and on the Uetliberg, Zurich's doorstep mountain, were very promising.

The people arriving at the EAWAG on February 4, 2000 certainly seemed out of place, at least at first glance. But the well-dressed elderly gentleman, the curly-haired lady with the pink pullover and the young man in jeans soon found their way to the lecture room. EAWAG Director Alexander Zehnder then told them why they had been asked to come: his researchers had decided to get together with "ordinary" citizens and talk about their work. The idea was to share in unravelling the mysteries of science and reach a common understanding of their meaning and purpose. This was only the beginning – there will be nine more such days over the next three years.

This intensive type of personal discussion between scientists and the public is quite unique, at least in Switzerland. Launched by the "Science et Cité" Foundation as a new form of communication, the "roundtable" pilot project is led by the well-known journalist Rosmarie Waldner. To ensure maximum benefit from project findings, the dialogue is being evaluated by a sociologist from the faculty of scientific research in Zurich. If the experiment is a success, other scientific institutions – whether in industry or the academia – will also sit around the table with laypersons.

Objectives of the "Roundtable" Project

"Science et Cité" was founded in 1998 by the Swiss Academies, the Swiss National Science Foundation, and the Vorort and Silva-Casa Foundations. President of the Foundation board is Charles Kleiber, State Secretary for Science Policy. In view of the social changes brought about by scientific and technical innovations such as gene technology, telecommunications and information technology, there is an urgent need to find new forms of dialogue between science and society. It is for this purpose that "Science et Cité" was founded: to inform ordinary people about ongoing scientific work in understandable terms. Furthermore, "Science et Cité" will search for new ways of reaching a mutual understanding between laypeople and experts on the methods, goals, advantages and drawbacks of scientific activities. Within the framework of its CHF 1 million annual budget, the Foundation has already launched various forms of dialogue.

"I find this dialogue attempt very exciting and can hardly wait to see how it turns out", admitted Alexander Zehnder to his guests. He selected a dozen or so people at EAWAG – ranging from laboratory apprentice to doctoral students, from technician to professor – to take part in the project. The citizens involved were chosen on behalf of "Science et Cité" by a public opinion analysis institute in Zurich. Emphasis was placed on obtaining the widest possible mixture of ages and professional backgrounds with equal representation of both genders.

A Good Start

The first few hours were spent getting to know the EAWAG and some of its projects. The laypersons taking part in the first roundtable discussion were fortunate – the EAWAG deals with the scientific, economic and social aspects of something which runs through their fingers every day: water.

They heard, for example, that every one of us uses in our homes an average of 50 000 liters of water per year. Industry uses the equivalent of 250 000 liters per person per year, while agriculture uses about four times as much. And how many people know that it takes 10 000 liters of water to produce a single kilogram of meat? Then came the first questions: Why don't we use more seawater? What can be done about rusty drain pipes? Why are our rivers and lakes still being poisoned by chemicals?

The Next Stage

Toward the end of the second day, after several rounds of discussion on numerous themes, a common focus started to emerge for the next stage of the process. It was decided to hold the next meeting in early July at the EAWAG's Kastanienbaum Laboratory on the Lake of Lucerne, focusing on problematic chemicals in wastewater and in effluents. The goal of the meeting will be to find ways of accelerating a change in attitude in both industry and consumers, while promoting a wider awareness of ecological problems.

When everyone finally left this first roundtable discussion in the evening, they were all quite tired but nevertheless in a good frame of mind. "I would never have thought such a simple theme as 'water' would have resulted in so many problems and questions", commented one of the office employees. The EAWAG doctoral student was even more astonished: "Only yesterday everyone was sitting there open-mouthed, and this afternoon they were already using terms like 'grey water' and 'aquifers' – as if they had been doing it all their lives". It would seem, indeed, that the first stretch of this new path has been trodden very successfully.

(Report by Herbert Cerutti, NZZ editor)

Fabian Scheifele, EAWAG

Publications and Books

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2625 **Suter M.J.-F., Riediker S., Schwoerer V.G.** (1999): Bestimmung von aromatischen Sulfonaten in Deponiesickerwasser und Grundwasser. Schrr. Biologische Abwasserreinigung 11, Kolloquium 7./8.6.1999, TU Berlin, S. 41–56.

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Fresh Ideas

In response to an invitation for fresh ideas for the improvement of water supply and sanitation in developing countries, the SODIS (Solar Water Disinfection) project submitted by the EAWAG/SANDEC has won first prize in the international competition.

This prize was awarded to project leader *Martin Wegelin* and *Christina Aristante* (Indonesia), representing one of our southern partner organizations at the Word Water – Forum in The Hague. The jury selected the SODIS project from more than 60 entries based on two decisive features:

- "Scientific development of solar disinfection",
- "Exemplary combination of high-ranking laboratory research with the practical application of results to improve drinking water quality for the world's poorest people in developing nations".

This award was only possible thanks to years of close teamwork among engineers, chemists, biologists, hygienists, sociologists and technicians, both within the EAWAG and with our southern partner organizations.

Hearty congratulations to all concerned and sincere thanks to the Directorate for Development and Cooperation (DEZA) for ongoing financial support of the SODIS project. The CHF 80 000 prize money will be used exclusively for the further development of SODIS technology in Asia, Africa and Latin America.

SIMAVI, Holland

From left to right: Margaret Mwangola, Christina Aristante, Martin Wegelin.

Patricia Holm Wins the Bern Environmental Research Award

Congratulations to our PD team member *Dr. Patricia Holm,* leader of the "Fishing Net" study that focuses on the decline of fish populations in Switzerland. She won the Bern Environmental Research Award in December 1999 with her habilitation dissertation entitled: "The Fish as Bioindicator: The Effect of Environmental Influences on Selected Molecules, Cells and Organs". This prize is awarded every two years to researchers who make outstanding contributions to a better social understanding of environmental problems.

Patricia Holm studied biology and sport sciences at Heidelberg University, where she also earned her doctorate in biology. After working for a biotechnology consulting firm, she embarked on a two-year postdoc in neurobiology at the ETH Zurich. She then became senior assistant in the interfaculty coordination department for general ecology at the University of Bern, and in 1994 was awarded a grant by the Federal support fund for young researchers. She carried out this research work at the Fish and Wildlife Medicine Center of the Institute for Animal Pathology. Dr. Holm joined the EAWAG in August of 1999.

The EAWAG at the Hanover Fair

Together with the other ETH institutions, the EAWAG participated in the International Hanover Fair 2000 for industry, automation and innovation. Widespread interest was raised by the selected projects, and some valuable contacts were made.

More attention must be paid in the future to knowledge and technology transfer from the universities to practice. This is the firm conviction not only of the EAWAG but of the ETH as a whole, whose governors took the initiative, together with other Swiss partners, to participate with the six other ETH institutions at the Hanover Fair from 20–25 March 2000.

The professionally designed ETH pavilion provided the EAWAG with an ideal setting for showing the public our mission and goals, and giving some insight into our research activities. In keeping with the technological theme of the fair, the EAWAG project on biosensor organisms was presented. It investigates various methods of determining environmental pollutant concentrations using living organisms as sensors and raised widespread interest among visitors. All the more because these methods can also be used for technical measurement purposes as well as for environmental analysis applications.

Participation at the Hanover Fair was a new and rewarding experience for the EAWAG. It seems that direct contact between researchers and industry is still unusual; however, the large number of visitors to the ETH exhibit clearly illustrates the keen interest of industry in new research findings. The Hanover Fair provided us as researchers with stimulating feedback on market needs which will certainly generate new ideas and incentives for future work.

EAWAG