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## Veröffentlichungen zu angewandt-wissenschaftlichen Studien mit Bezug zum Grundwasser der Schweiz

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**BAFU / 03.02.2012**

# Abstracts

## Fachartikel Schweiz

### 1. Auswirkungen des Klimawandels auf das Grundwasser - Erster Bericht der Arbeitsgruppe "Grundwasser und Klima"

Die Arbeitsgruppe «Grundwasser und Klima» der Schweizerischen Gesellschaft für Hydrogeologie (SGH) will mögliche Auswirkungen der Klimaänderung auf das Grundwasser frühzeitig erfassen. Sie versteht sich als Bindeglied zwischen Forschung und Praxis. Die Wissenschaft ist zurzeit sehr aktiv, und die Behörden benötigen für die Sicherstellung der Trinkwasserversorgung Entscheidungshilfen für ihre Bewirtschaftungskonzepte. Als Koordinationsstelle sammelt die Arbeitsgruppe Datenreihen, die Hinweise liefern über Änderungen im Grundwasser infolge des Klimawandels und deren Ausmass heute und in naher Zukunft. Weiter begleitet sie die Auswertung der Datenreihen. Beobachtungen aus dem Hitzesommer 2003 und erste Auswertungsergebnisse zeigen, dass Grundwässer, die stark durch die Infiltration von Flüssen gespeist werden, bereits auf Klimaänderungen reagieren.

### 2. Pestizidrückstände im Grundwasser des Kantons Jura

Das Kantonale Labor hat Analysen von Pestizidrückständen, Nitrat, Metallen und flüchtigen organischen Substanzen in den 119 Grundwässern durchgeführt, die potenziell als Trinkwasser benutzt werden. Nur sechs Quellen und ein Brunnen überschritten die Maximalwerte für Pestizide und Metabolite. Die Nitratgehalte waren nicht nur tiefer als der Toleranzwert, sie hielten auch das Qualitätsziel ein. Nur eine Quelle zeigte Überschreitungen bei Blei und Aluminium. Bei drei Wässern lagen die VOC über den Normen. Diese Resultate sind beruhigend und erlauben dem Konsumenten, dem Wasser am Hahn zu vertrauen.

### 3. Transformationsprodukte von organischen Mikroverunreinigungen - Untersuchung von Auftreten und Wirkung im Gewässer

Im Projekt «KoMet» wurde ein mess- und modellbasiertes Vorgehen entwickelt, um die Wichtigkeit von Transformationsprodukten von Mikroverunreinigungen für die schweizerische Gewässerqualität systematisch zu evaluieren. Für 62 untersuchte Pflanzenschutzmittel, Biozide und Arzneimittel wurden 51 Transformationsprodukte aufgrund ihres Auftretens in verschiedenen Gewässerproben als expositionsrelevant eingestuft. Während biologische Transformation den ökotoxikologischen Gesamteffekt typischerweise stark reduziert, wurden sechs Transformationsprodukte von abwasserrelevanten Verbindungen identifiziert, deren Wirkung auf Gewässerorganismen weiter abgeklärt werden sollten.

### 4. Dezentrale Enthärtung von Trinkwasser

Viel Kalk im Wasser, sprich hartes Wasser, ist in der Schweiz weit verbreitet. Eine zentrale Enthärtung würde aber nur privaten Haushalten dienen – also rund einem Fünftel aller Verbraucher. Ihnen ist eine dezentrale Enthärtung empfohlen, um den Komfort zu steigern, Waschmittel zu sparen und Haushaltgeräte zu schützen.

### 5. Nachhaltige Wassernutzung – Was das NFP 61 dazu beitragen kann

Infolge der Entwicklung gegenwärtiger sozioökonomischer, ökologischer und politischer Randbedingungen, die durch den Klimawandel noch verschärft werden, sind die allgemeinen Perspektiven für die Zukunft unsicher. Die Doktrin des Wirtschaftswachstums muss sich neuen Konzepten wie «Degrowth» und «Lebensqualität» stellen. Nur so können die Lebensgrundlagen, insbesondere die Wasserressourcen, erhalten bleiben. Das Nationale Forschungsprogramm (NFP-61) will einen substanziellen Beitrag zur Sicherung einer nachhaltigen Wassernutzung in der Schweiz liefern. Die Forschung wird ganzheitlich, stark inter- und transdisziplinär betrieben und der Umsetzung der Forschungsergebnisse in die Praxis wird grosses Gewicht beigemessen.

## **6. Inwertsetzung von Waldleistungen – Rechtliche Sicht**

Der Wald erfüllt für Mensch und Umwelt wichtige Funktionen. Eine davon ist die Reinigung und Speicherung von Wasser. Zum Erhalt der Funktionen sind weitreichende Schutzmassnahmen, insbesondere Nutzungseinschränkungen, erforderlich. Den Waldeigentümern können daraus Mehrkosten erwachsen. Eine Inwertsetzung von Waldleistungen ist gesetzlich jedoch nicht vorgesehen. Entschädigungen gibt es nur im Fall einer Enteignung.

## **7. Die neue Valser-Mineralquelle: Die St. Paulsquelle**

Dank umfangreicher Vorarbeiten konnte 2008/2009 die Valser St. Paulsquelle gefasst und so eine der höchstgelegenen kommerziell genutzten Mineralwasserfassungen der Schweiz erstellt werden. Das damit 2010 neu lancierte Mineralwasser «Valser Silence» weist mit einer Gesamtmineralisation von 220 mg/l im Vergleich zum klassischen Valser Mineralwasser eine deutlich geringere Mineralisation auf. Isotopen-hydrochemische Untersuchungen zeigen eine mittlere Verweilzeit des Wassers von 2-5 Jahren und ein Hauptinfiltrationsgebiet auf einer Höhenlage von 2100-2500 m ü. M. Intensive Validierungsuntersuchungen sowie Grundfluoreszenzanalysen zeigen eine überaus konstante und reine Qualität des gefassten Wassers, was insbesondere in Anbetracht der jahreszeitlichen Schüttungsschwankungen bemerkenswert ist. Der vorliegende Artikel gibt einen Überblick über die Resultate der zur Evaluation und Fassung des St. Paulsquelle ausgeführten geologisch-hydrogeologischen Untersuchungen.

## **8. GeORG sucht die Geopotenziale**

Ziel des Projekts GeORG ist der Aufbau eines geologischen 3D-Planungswerkzeugs, das als Instrument zur Charakterisierung des Untergrunds und seiner Geopotenziale dient. Bereits während der Aufbauphase wurde es als Grundlage für konkrete Fragestellungen beigezogen.

## **9. Ordnung im Untergrund**

Bei vielen Bauvorhaben endet der Planungshorizont an der Erdoberfläche. Für den Untergrund fehlen hingegen, mangels ausreichender Daten und Erfahrungen, meistens verbindliche Regeln. Seine Bedeutung als Träger von Infrastrukturen nimmt aber rasch zu. Deshalb ist die nachhaltige Planung der Nutzung des Untergrundes unabdingbar. Die Werkzeuge dazu sind geologische 3D-Modelle, die die erforderlichen Daten zur Verfügung stellen.

## **10. Öffentliche Quellen: nutzen UND schützen**

Quellen werden im Kanton Aargau rege zur Wassergewinnung genutzt. Um eine gute Wasserqualität zu gewährleisten, besteht für öffentlich genutzte Quellen eine Schutzzonenpflicht. Gemäss einer Gemeindeumfrage aus dem vergangenen Jahr weisen über 80 Prozent der öffentlich genutzten Quellen eine rechtskräftige Schutzzone auf. In einigen Gemeinden besteht aber noch Handlungsbedarf.

## **11. Trinkwasserqualität in der Nähe von Ablagerungsstandorten**

Verunreinigen Altlasten das Aargauer Trinkwasser? Diese Frage richten besorgte Einwohnerinnen und Einwohner gelegentlich an das Amt für Verbraucherschutz. Neuerliche Untersuchungen von Trinkwasser aus Grundwasserfassungen und Quellen in der Nähe von Ablagerungsstandorten haben ein erfreuliches Resultat ergeben: Keine Trinkwasserprobe enthielt problematische chemische Fremdstoffe in unzulässiger Konzentration.

### 12. Reactive transport modelling of Cr(VI) treatment by cast iron under fast flow conditions

The Cr(VI) reduction behaviour of five different types of grey cast iron shavings meant for construction of a permeable reactive barrier (PRB) in Thun, Switzerland, was investigated by performing batch and column experiments. Closed system batch experiments clearly demonstrated that the largest shavings also containing the largest spherical C inclusions, were best qualified for the PRB due to their fast Cr(VI) reduction rate. However, the column experiment performed with this type of material revealed that a complete and long term Cr(VI) treatment by the planned PRB was questionable due to the site-specific high groundwater flow velocities and the almost O<sub>2</sub> and CaCO<sub>3</sub> saturated aquifer conditions. The experimentally observed Cr(VI) breakthrough is explained as a result of a decline of reactivity provoked by a strong passivation by observed Fe hydroxides (FeOOH-polymorphs) and carbonates (calcite and aragonite). The column experiment was simulated using the reactive transport modelling code CrunchFlow. Iron cycling and intra-aqueous reactions were incorporated into a previously described reaction network in order to model the strong decline in reactivity of grey cast iron. All key parameters like aqueous species concentrations and mineralogical evolution of the column were successfully modelled. The modelling results confirmed that the observed Cr(VI) breakthrough was caused by surface passivation of the Fe shavings. Complete oxidation of the initially present mass of shavings is not predicted to occur during the expected PRB lifetime of several decades. The model seems to be robust, and it is expected that an application of the calibrated model in 2D to field sites will allow a quantitative evaluation for the performance of planned PRB's in such environments. (C) 2011 Elsevier Ltd. All rights reserved.

### 13. Large-scale tracer profiles in a deep claystone formation (Opalinus Clay at Mont Russelin, Switzerland): Implications for solute transport processes and transport properties of the rock

Natural tracers (Cl<sup>-</sup>) and stable water isotopes) in pore water of the Opalinus Clay and adjacent formations were studied in the motorway tunnel at Mont Russelin, Switzerland. The Opalinus Clay occurs in the core of an anticline which is cut by a complex system of thrust faults. Concentration profiles of natural tracers were taken from 17 boreholes along a 363 m long section. Pore waters of drillcore samples were analysed with indirect and direct methods. The Cl<sup>-</sup> and stable water isotope distribution in the pore water shows a regular and well defined profile, with a conspicuous decrease towards the overlying Dogger limestone aquifer. The highest Cl<sup>-</sup> values (approximately 23,000 mg/L) are found in the core of the anticline in Liassic claystones underlying the Opalinus Clay. To quantify the large-scale transport properties of the Opalinus Clay formation, a 2D transport model was constructed and used to reproduce the observed concentration profiles. The calculations indicate that the observed tracer distributions are consistent with diffusion as the dominant transport process. Groundwater flow in the overlying Dogger aquifer was initiated about 2-4 Ma ago, which is long after the folding of the Jura Mountains and probably coincides with the exposure of the aquifer to freshwater recharge following continued erosion of the anticline. The calculations suggest that tracer distributions are controlled by 1) the timing of freshwater recharge in the overlying limestone aquifer, 2) the shape of the anticline and 3) the magnitude and the anisotropy ratio of diffusion coefficients. (C) 2010 Elsevier B.V. All rights reserved.

### 14. Production, redistribution and loss of helium and argon isotopes in a thick sedimentary aquitard-aquifer system (Molasse Basin, Switzerland)

In a rock-water system an apparent residence time for He can be derived from the bulk He concentration in the rock and the porewater and the He production rate provided that (1) the system is at steady state and (2) the He flux from external sources is negligible. This second condition is crucial and needs to be assessed by identifying the various He-sources in a given hydrologic environment. He and Ar isotope abundances were investigated in whole rock samples and mineral separates of the alternating shale-sandstone rock sequence of the Permo-Carboniferous Trough (PCT) of the Molasse Basin in northern Switzerland. (4)He concentrations and (40)Ar/(36)Ar ratios in groundwater in the bounding aquifers are lower than those in PCT groundwaters, thus eliminating a possible external source of radiogenic noble gases. The elements producing radiogenic helium isotopes, U,Th and Li, are mainly concentrated in the shales, where

they reside in biotite, muscovite, clay minerals and organic matter. Contents of these elements as well as chronological and chemical data allow us to calculate maximum "closed system" He isotope concentrations and the retention coefficients, e.g.  $(^3\text{He}(\text{measured})/(^3\text{He}(\text{calculated})))$  ratios. As deduced from the low retention coefficients, almost all helium-3 that has been produced in these minerals since their deposition has been lost into the complementary reservoir, i.e. the porewater; the same conclusion is valid for  $(^4\text{He})$ . This is also indicated by the similarity between the calculated  $(^4\text{He})/(^3\text{He})$  production ratio of the shales and that observed in PCT groundwater ( $1.3 \times 10^7$ ). Moreover, similar  $(^4\text{He})/(^3\text{He})$  ratios are measured in quartz and plagioclase mineral grains from the sandstone layers, by far exceeding the production ratios derived for these minerals. Also, the measured concentrations of He isotopes (especially  $(^3\text{He})$ ) are higher than the calculated production capacities of these minerals. These observations suggest that some of the He produced in the shale and released from these rocks migrates via the porewater into the sandstone layers and penetrates further into some rock-forming minerals, such as quartz and plagioclase. Measurements of the migration rate of He atoms through quartz crystals showed that equilibrium between internal (gas-fluid vesicles) and external (porewater) He-concentrations is reached on a short time scale of  $\sim 10^4$  years at an in-situ temperature of approximate to 170 degrees C. The equilibrium allows the He concentrations in the porewater across the PCT sequence to be quantified using quartz crystals as detectors. For the PCT segment opened by the Weiach borehole these "quartz-derived" concentrations as well as those directly measured in PCT groundwaters are rather high implying a long residence time for the He-atoms in the PCT rock-porewater system, well exceeding  $10^7$  years. (c) 2011 Elsevier B.V. All rights reserved.

#### **15. A new energy and natural resources investigation method: Geneva case studies**

The Praille-Acacias-Vernets suburb, located in Geneva, Switzerland, is today considered as an outworn city area (2.3 km<sup>2</sup>). It consists of parking lots, industries, businesses and marshalling yards. The Geneva Government decided to remodel this suburb to effectively allow for city growth while complying with the highest energy efficient and environmental standards in urban development. A masterplan was accepted in spring 2007. It did not take into account the various energy and natural resources of the area at that stage. BG Consulting Engineers was thus mandated to assess a set of resources related to energy and environment, such as geothermal power or groundwater. For this purpose, a new investigation method was tested. It integrated the Deep City approach (Swiss Federal Institute of Technology, Lausanne), which promotes the sustainable use of urban underground resources. The BG method consisted in (1) establishing a geodatabase regrouping all available data (Geographic Information System), (2) identifying, localising and quantifying the different resources and (3) identifying and discussing all synergies and conflicts that might arise during their exploitation. This third step constitutes a real improvement allowing for anticipated decision making, thus avoiding future compatibility issues. Results of this study consisted in lists and maps of (1) raw resources, (2) technical and economical opportunities and constraints of exploitation, and (3) practical synergies and conflicts of exploitation. In addition, further necessary studies were identified along with synthetic scopes of work. Results were convincing and highly considered by the Geneva Government. For example, geothermal power resources were localised along with possible exploitation technologies and quantified extractable power. Synergies like combined exploitation of geothermal power and groundwater were also identified while conflicts such as spatial occupation were localised and discussed. These examples, among many others, validate this BG innovative method integrating the Deep City concept. (C) 2011 Elsevier Ltd. All rights reserved.

## **16. River restoration with complex hydrological and ecological interactions: the RECORD-Project**

River restoration is an essential means to enhance the dynamic stability of watercourses while concurrently improving habitat diversity and variability, as well as lowering long-term maintenance expenditures. Although the number of restoration projects has increased in recent years, scientific understanding is still limited with regards to the underlying principles determining how hydromorphological variability in restored river corridors relates to ecosystem functioning, biodiversity and (ground)water quality. In order to deal with the challenges of river restoration in a successful and efficient way, the mechanistic understanding of the coupled hydrological and ecological processes in near-river corridors has to be extended. Limitations in scientific progress in these areas have been particularly impaired by specific research rather than a multi-disciplinary endeavour that collaboratively investigates cause-and-effect relationships and re-examines historical assumptions and approaches. In the multi-disciplinary RECORD Project (Assessment and Modelling of Coupled Ecological and Hydrological Dynamics in the Restored Corridor of a River (Restored Corridor Dynamics)), we investigated coupled hydrological and ecological dynamics in a channelized and restored river section in northeast Switzerland by synthesizing physical, chemical, and biological experiments as well as modelling approaches. Hydrogeological research was focused on the infiltration processes of river water into aquifers. From the viewpoint of drinking water protection, it is of particular importance to determine which portion of the pumped water originates from the river and how long it takes to travel from the river to the pumping station. Therefore, we investigated the electrical conductivity and temperature of the water over a period of time, thereby gaining a tool for the quantitative analysis of mixing ratios and travel times.

## **17. Impact of tunneling on regional groundwater flow and implications for swelling of clay-sulfate rocks**

Tunnels play a key role in many transportation concepts. The swelling of clay-sulfate rocks leads to serious damage to many tunnels crossing such rock, producing great difficulties and high extra costs in tunnel engineering. The swelling is caused by the transformation of the sulfate mineral anhydrite into gypsum, entailing a 60% volume increase. The transformation involves anhydrite dissolution in water, transport of the solution with groundwater flow, and gypsum precipitation at a different location. Therefore, the knowledge of groundwater flow systems at the tunnel and adjacent areas is essential to better understand the swelling processes. The present study investigates the groundwater flow systems at the Chienberg tunnel in Switzerland before and after the tunnel excavation, based on numerical flow modeling. The models include faults and the hydrostratigraphic layering in the subsurface to assess the role of the hydrogeological setting. The results of this study indicate effects on groundwater flow caused by the tunneling, which may trigger rock swelling by favoring anhydrite dissolution and gypsum precipitation, including (1) increase of flow rates around the tunnel, (2) broadened, shifted and more distributed capture zones leading to a change in origin and age of groundwater, (3) access of groundwater from preferential flow paths (e.g. faults) due to the drainage effect of the tunnel, and (4) change in geochemical equilibrium conditions because of decreased pore water pressures in the tunnel area. (C) 2010 Elsevier B.V. All rights reserved.

### **18. Relation between hydrogeological setting and swelling potential of clay-sulfate rocks in tunneling**

In this study, an approach to estimate the swelling potential of clay-sulfate rocks in tunneling is presented. Swelling of clay-sulfate rocks leads to damage in tunnels that is difficult and costly to repair. Swelling is caused by the transformation of the sulfate mineral anhydrite into gypsum, which involves an increase in rock volume in a system open to water flow. Knowledge of the hydrogeological situation and the groundwater flow systems at the tunnel is essential to better understand the swelling processes. The present study was conducted for the Chienberg tunnel in Switzerland. It investigates the hydrogeological situation of four zones in this tunnel crossing the Triassic Gipskeuper formation. In two of them, heavy swelling occurred after tunnel excavation, while in the other two no swelling occurred. In addition, the groundwater flow systems before and after tunnel excavation are investigated based on numerical flow modeling. The findings suggest that in certain situations after tunnel excavation, depending on geological and changing hydraulic conditions, the excavation damaged zone around the tunnel provides a "hydraulic short circuit" between the weathered Gipskeuper and the anhydrite-bearing strata of the unweathered Gipskeuper. As a result, water from the weathered Gipskeuper gets in contact with anhydrite, triggering its transformation into gypsum and, thus, rock swelling. The results of the study may also contribute to improved swelling experiments in the laboratory and a more reliable planning of restoration measures in tunnels that are damaged by rock swelling. (C) 2011 Elsevier B.V. All rights reserved.

### **19. Saccharin and Other Artificial Sweeteners in Soils: Estimated Inputs from Agriculture and Households, Degradation, and Leaching to Groundwater**

Artificial sweeteners are consumed in substantial quantities as sugar substitutes and were previously shown to be ubiquitously present in the aquatic environment. The sweetener saccharin is also registered as additive in piglet feed. Saccharin fed to piglets was largely excreted and, consequently, found in liquid manure at concentrations up to 12 mg/L, where it was stable during 2 months of storage. Saccharin may thus end up in soils in considerable quantities with manure. Furthermore, other studies showed that saccharin is a soil metabolite of certain sulfonylurea herbicides. Sweeteners may also get into soils via irrigation with wastewater-polluted surface water, fertilization with sewage sludge (1-43  $\mu\text{g/L}$ ), or through leaky sewers. In soil incubation experiments, cyclamate, saccharin, acesulfame, and sucralose were degraded with half-lives of 0.4-6 d, 3-12 d, 3-49 d, and 8-124 d, respectively. The relative importance of entry pathways to soils was compared and degradation and leaching to groundwater were evaluated with computer simulations. The data suggest that detection of saccharin in groundwater (observed concentrations, up to 0.26  $\mu\text{g/L}$ ) is most likely due to application of manure. However, elevated concentrations of acesulfame in groundwater (up to 5  $\mu\text{g/L}$ ) may result primarily from infiltration of wastewater-polluted surface water through stream beds.

### **20. How Mobile Are Sorbed Cations in Clays and Clay Rocks?**

Diffusion of cations and other contaminants through clays is of central interest, because clays and clay rocks are widely considered as barrier materials for waste disposal sites. An intriguing experimental observation has been made in this context: Often, the diffusive flux of cations at trace concentrations is much larger and the retardation smaller than expected based on their sorption coefficients. So-called surface diffusion of sorbed cations has been invoked to explain the observations but remains a controversial issue. Moreover, the corresponding surface diffusion coefficients are largely unknown. Here we show that, by an appropriate scaling, published diffusion data covering a broad range of cations, clays, and chemical conditions can all be modeled satisfactorily by a surface diffusion model. The average mobility of sorbed cations seems to be primarily an intrinsic property of each cation that follows inversely its sorption affinity. With these surface mobilities, cation diffusion coefficients can now be estimated from those of water tracers. In pure clays at low salinities, surface diffusion can reduce the cation retardation by a factor of more than 1000.

### **21. Assessing Exposure to Transformation Products of Soil-Applied Organic Contaminants in Surface Water: Comparison of Model Predictions and Field Data**

Transformation products (TPs) of chemicals released to soil, for example, pesticides, are regularly detected in surface and groundwater with some TPs even dominating observed pesticide levels. Given the large number of TPs potentially formed in the environment, straightforward prioritization methods based on available data and simple, evaluative models are required to identify TPs with a high aquatic exposure potential. While different such methods exist, none of them has so far been systematically evaluated against field data. Using a dynamic multimedia, multispecies model for TP prioritization, we compared the predicted relative surface water exposure potential of pesticides and their TPs with experimental data for 16 pesticides and 46 TPs measured in a small river draining a Swiss agricultural catchment. Twenty TPs were determined quantitatively using solid-phase extraction liquid chromatography mass spectrometry (SPE-LC-MS/MS), whereas the remaining 26 TPs could only be detected qualitatively because of the lack of analytical reference standards. Accordingly, the two sets of TPs were used for quantitative and qualitative model evaluation, respectively. Quantitative comparison of predicted with measured surface water exposure ratios for 20 pairs of TPs and parent pesticides indicated agreement within a factor of 10, except for chloridazon-desphenyl and chloridazon-methyl-desphenyl. The latter two TPs were found to be present in elevated concentrations during baseflow conditions and in groundwater samples across Switzerland, pointing toward high concentrations in exfiltrating groundwater. A simple leaching relationship was shown to qualitatively agree with the observed baseflow concentrations and to thus be useful in identifying TPs for which the simple prioritization model might underestimate actual surface water concentrations. Application of the model to the 26 qualitatively analyzed TPs showed that most of those TPs categorized as exhibiting a high aquatic exposure potential could be confirmed to be present in the majority of water samples investigated. On the basis of these results, we propose a generally applicable, model-based approach to identify those TPs of soil-applied organic contaminants that exhibit a high aquatic exposure potential to prioritize them for higher-tier, experimental investigations.

### **22. Moving Targets, Long-Lived Infrastructure, and Increasing Needs for Integration and Adaptation in Water Management: An Illustration from Switzerland**

Switzerland provides an example of successful management of water infrastructure and water resources that was accomplished largely without integration across sectors. Limitations in this approach have become apparent; decisions that were formerly based only on technical and economic feasibility must now incorporate broader objectives such as ecological impact. In addition, current and emerging challenges relate to increasingly complex problems that are likely to demand more integrated approaches. If such integration is to be of benefit, it must be possible to redirect resources across sectors, and the synergies derived from integration must outweigh the additional cost of increased complexity.

### **23. Regime shift in groundwater temperature triggered by Arctic Oscillation**

Groundwater is the world's most important source of raw drinking water. However, the potential impact of climate change on this vital resource is unclear because of a lack of relevant long-term data. Here we statistically analyze over 20 years of groundwater temperature data from five Swiss aquifers fed predominantly by river-bank infiltration. The results reveal an abrupt increase in annual mean groundwater temperature centered on 1987-1988 that can also be observed in air and river temperatures. We associate this temperature increase with the Northern Hemisphere late 1980s climate regime shift (CRS), which itself is related to an abrupt change in the behavior of the Arctic Oscillation. Because temperature affects redox conditions in groundwater, groundwater biogeochemistry in aquifers fed by river-bank infiltration is likely to depend on large-scale climatic forcing and will be affected by climate change.

#### **24. 3D crosshole ERT for aquifer characterization and monitoring of infiltrating river water**

The hydrogeological properties and responses of a productive aquifer in northeastern Switzerland are investigated. For this purpose, 3D crosshole electrical resistivity tomography (ERT) is used to define the main lithological structures within the aquifer (through static inversion) and to monitor the water infiltration from an adjacent river. During precipitation events and subsequent river flooding, the river water resistivity increases. As a consequence, the electrical characteristics of the infiltrating water can be used as a natural tracer to delineate preferential flow paths and flow velocities. The focus is primarily on the experiment installation, data collection strategy, and the structural characterization of the site and a brief overview of the ERT monitoring results. The monitoring system comprises 18 boreholes each equipped with 10 electrodes straddling the entire thickness of the gravel aquifer. A multi-channel resistivity system programmed to cycle through various four-point electrode configurations of the 180 electrodes in a rolling sequence allows for the measurement of approximately 15,500 apparent resistivity values every 7 h on a continuous basis. The 3D static ERT inversion of data acquired under stable hydrological conditions provides a base model for future time-lapse inversion studies and the means to investigate the resolving capability of our acquisition scheme. In particular, it enables definition of the main lithological structures within the aquifer. The final ERT static model delineates a relatively high-resistivity, low-porosity, intermediate-depth layer throughout the investigated aquifer volume that is consistent with results from well logging and seismic and radar tomography models. The next step will be to define and implement an appropriate time-lapse ERT inversion scheme using the river water as a natural tracer. The main challenge will be to separate the superposed time-varying effects of water table height, temperature, and salinity variations associated with the infiltrating water.

#### **25. The Role of Prior Model Calibration on Predictions with Ensemble Kalman Filter**

This paper, based on a real world case study (Limmat aquifer, Switzerland), compares inverse groundwater flow models calibrated with specified numbers of monitoring head locations. These models are updated in real time with the ensemble Kalman filter (EnKF) and the prediction improvement is assessed in relation to the amount of monitoring locations used for calibration and updating. The prediction errors of the models calibrated in transient state are smaller if the amount of monitoring locations used for the calibration is larger. For highly dynamic groundwater flow systems a transient calibration is recommended as a model calibrated in steady state can lead to worse results than a noncalibrated model with a well-chosen uniform conductivity. The model predictions can be improved further with the assimilation of new measurement data from on-line sensors with the EnKF. Within all the studied models the reduction of 1-day hydraulic head prediction error (in terms of mean absolute error [MAE]) with EnKF lies between 31% (assimilation of head data from 5 locations) and 72% (assimilation of head data from 85 locations). The largest prediction improvements are expected for models that were calibrated with only a limited amount of historical information. It is worthwhile to update the model even with few monitoring locations as it seems that the error reduction with EnKF decreases exponentially with the amount of monitoring locations used. These results prove the feasibility of data assimilation with EnKF also for a real world case and show that improved predictions of groundwater levels can be obtained.

#### **26. Propagation of seasonal temperature signals into an aquifer upon bank filtration**

Infiltrating river water carries the temperature signal of the river into the adjacent aquifer. While the diurnal temperature fluctuations are strongly dampened, the seasonal fluctuations are much less attenuated and can be followed into the aquifer over longer distances. In one-dimensional model with uniform properties, this signal is propagated with a retarded velocity, and its amplitude decreases exponentially with distance. Therefore, time shifts in seasonal temperature signals between rivers and groundwater observation points may be used to estimate infiltration rates and near-river groundwater velocities. As demonstrated in this study, however, the interpretation is nonunique under realistic conditions. We analyze a synthetic test case of a two-dimensional cross section perpendicular to a losing stream, accounting for multi-dimensional flow due to a partially penetrating channel, convective-conductive heat transport within the aquifer, and heat exchange with the underlying aquitard and the land surface. We compare different conceptual simplifications of the domain in order to elaborate on the importance of different system elements. We find that temperature propagation within the shallow aquifer can be highly influenced by conduction through the unsaturated zone and into the underlying aquitard. In contrast, regional groundwater recharge has no major effect on the simulated results. In our setup, multi-dimensionality of the flow field is

important only close to the river. We conclude that over-simplistic analytical models can introduce substantial errors if vertical heat exchange at the aquifer boundaries is not accounted for. This has to be considered when using seasonal temperature fluctuations as a natural tracer for bank infiltration.

### **27. Validation of a Numerical Indicator of Microbial Contamination for Karst Springs**

Rapid changes in spring water quality in karst areas due to rapid recharge of bacterially contaminated water are a major concern for drinking water suppliers and users. The main objective of this study was to use field experiments with fecal indicators to verify the vulnerability of a karst spring to pathogens, as determined by using a numerical modeling approach. The groundwater modeling was based on linear storage models that can be used to simulate karst water flow. The vulnerability of the karst groundwater is estimated using such models to calculate criteria that influence the likelihood of spring water being affected by microbial contamination. Specifically, the temporal variation in the vulnerability, depending on rainfall events and overall recharge conditions, can be assessed and quantified using the dynamic vulnerability index (DVI). DVI corresponds to the ratio of conduit to diffuse flow contributions to spring discharge. To evaluate model performance with respect to predicted vulnerability, samples from a spring were analyzed for *Escherichia coli*, enterococci, *Clostridium perfringens*, and heterotrophic plate count bacteria during and after several rainfall events. DVI was shown to be an indication of the risk of fecal contamination of spring water with sufficient accuracy to be used in drinking water management. We conclude that numerical models are a useful tool for evaluating the vulnerability of karst systems to pathogens under varying recharge conditions.

### **28. Risikoorientierte Bewilligung von Erdwärmesonden**

Die Zahl an Erdwärmesonden nimmt in ganz Europa stetig zu. Wie mit anderen Technologien der Energiegewinnung sind auch mit Erdwärmesonden Risiken verbunden. Deshalb bedarf es Leitlinien als Grundlage für die Bewilligungsverfahren, die den Bau und Betrieb einer solchen Anlage regeln. Um dabei den zu erwartenden Nutzen gegen mögliche Risiken abwägen zu können, sind Kenntnisse über die hydrogeologischen Verhältnisse am Standort und die dort stattfindenden Prozesse erforderlich. Am Beispiel des Erdwärmenutzungskonzepts des Kantons Basel-Landschaft wird gezeigt, wie die Bewilligung von Erdwärmesonden differenziert geregelt werden kann, und wie die geologischen Merkmale einer Region in ein Erdwärmenutzungskonzept integriert werden können. Dabei werden insbesondere Karstgebiete, Gebiete mit der Gefahr des Gebirgsquellens und der Subrosion, Gewässerschutzbereiche, und Gebiete mit Grundwasserstockwerkbau oder gespannten Grundwasserverhältnissen berücksichtigt. Der Artikel will damit einen Beitrag zur derzeit stattfindenden gesellschaftlichen Diskussion über den Nutzen und die Risiken der un tiefen Geothermie leisten, indem er Risiken durch den Bau und Betrieb von Erdwärmesonden beschreibt, und Möglichkeiten aufzeigt, diese Risiken in der Bewilligungspraxis zu berücksichtigen.

### **29. Analysis of the impact of climate change on groundwater related hydrological fluxes: a multi-model approach including different downscaling methods**

Climate change related modifications in the spatio-temporal distribution of precipitation and evapotranspiration will have an impact on groundwater resources. This study presents a modelling approach exploiting the advantages of integrated hydrological modelling and a broad climate model basis. We applied the integrated MIKE SHE model on a perialpine, small catchment in northern Switzerland near Zurich. To examine the impact of climate change we forced the hydrological model with data from eight GCM-RCM combinations showing systematic biases which are corrected by three different statistical downscaling methods, not only for precipitation but also for the variables that govern potential evapotranspiration. The downscaling methods are evaluated in a split sample test and the sensitivity of the downscaling procedure on the hydrological fluxes is analyzed. The RCMs resulted in very different projections of potential evapotranspiration and, especially, precipitation. All three downscaling methods reduced the differences between the predictions of the RCMs and all corrected predictions showed no future groundwater stress which can be related to an expected increase in precipitation during winter. It turned out that especially the timing of the precipitation and thus recharge is very important for the future development of the groundwater levels. However, the simulation experiments revealed the weaknesses of the downscaling methods which directly influence the predicted hydrological fluxes, and thus also the predicted groundwater levels. The downscaling process is identified as an important source of

uncertainty in hydrological impact studies, which has to be accounted for. Therefore it is strongly recommended to test different downscaling methods by using verification data before applying them to climate model data.

### **30. Climate change and mountain water resources: overview and recommendations for research, management and policy**

Mountains are essential sources of freshwater for our world, but their role in global water resources could well be significantly altered by climate change. How well do we understand these potential changes today, and what are implications for water resources management, climate change adaptation, and evolving water policy? To answer above questions, we have examined 11 case study regions with the goal of providing a global overview, identifying research gaps and formulating recommendations for research, management and policy. After setting the scene regarding water stress, water management capacity and scientific capacity in our case study regions, we examine the state of knowledge in water resources from a highland-lowland viewpoint, focusing on mountain areas on the one hand and the adjacent lowland areas on the other hand. Based on this review, research priorities are identified, including precipitation, snow water equivalent, soil parameters, evapotranspiration and sublimation, groundwater as well as enhanced warming and feedback mechanisms. In addition, the importance of environmental monitoring at high altitudes is highlighted. We then make recommendations how advancements in the management of mountain water resources under climate change could be achieved in the fields of research, water resources management and policy as well as through better interaction between these fields. We conclude that effective management of mountain water resources urgently requires more detailed regional studies and more reliable scenario projections, and that research on mountain water resources must become more integrative by linking relevant disciplines. In addition, the knowledge exchange between managers and researchers must be improved and oriented towards long-term continuous interaction..

### **31. Exchange between a river and groundwater, assessed with hydrochemical data**

We describe the chemical composition of groundwater from an alluvial granular aquifer in a valley fill flood plain (River Thur Valley). The river flows along this valley and is mostly downwelling on its way, indirectly through an unsaturated zone in the upstream part, and directly through the water-saturated bed in the downstream part. River Thur has been channelized with barriers for more than a century. In 1992, the authorities started to restore a section of River Thur with riverbed enlargements. The land use in the flood plain and the seasonal and climatic conditions (e.g., hot dry summer 2003) result in alterations of the natural geochemical composition of the river water. This groundwater is partly to mainly recharged by bank filtration. Several wells exist near the river that draw groundwater for drinking. In some of these wells, the groundwater has a very short residence time in the subsurface of days to weeks. Bed enlargements and other operations for an enhancement of the exchange of water between the river and groundwater increase the contamination risk of the nearby wells. During bank filtration, the groundwater changes gradually its composition, with increasing distance from the river and with depth in the aquifer. From today's changes of the water quality during riverbank filtration, we tried to extrapolate to the groundwater quality that may arise from future river restorations. Today the groundwater body consists of a mixture of groundwater from the seepage of precipitation and from riverbank filtration. The main difference between river water and groundwater results from the microbial activity in riverbed and bank materials. This activity leads to a consumption of  $O_2$  and to a higher partial pressure of  $CO_2$  in the groundwater. Criteria for the distinction of different groundwater compositions are the distance of a well from the river and the subsurface residence time of the groundwater to reach this well.

### **32. Towards improved instrumentation for assessing river-groundwater interactions in a restored river corridor**

River restoration projects have been launched over the last two decades to improve the ecological status and water quality of regulated rivers. As most restored rivers are not monitored at all, it is difficult to predict consequences of restoration projects or analyze why restorations fail or are successful. It is thus necessary to implement efficient field assessment strategies, for example by employing sensor networks that continuously measure physical parameters at high spatial and temporal resolution. This paper focuses on the design and implementation of an instrumentation strategy for monitoring changes in bank filtration, hydrological connectivity, groundwater travel time

and quality due to river restoration. We specifically designed and instrumented a network of monitoring wells at the Thur River (NE Switzerland), which is partly restored and has been mainly channelized for more than 100 years. Our results show that bank filtration - especially in a restored section with alternating riverbed morphology - is variable in time and space. Consequently, our monitoring network has been adapted in response to that variability. Although not available at our test site, we consider long-term measurements - ideally initiated before and continued after restoration - as a fundamental step towards predicting consequences of river restoration for groundwater quality. As a result, process-based models could be adapted and evaluated using these types of high-resolution data sets.

### **33. An indicator approach to assessing and predicting the quantitative state of groundwater bodies on the regional scale with a special focus on the impacts of climate change**

An integrated approach for assessing the availability of groundwater under conditions of 'global-change' is presented. The approach is embedded in the DANUBIA system developed by the interdisciplinary GLOWA-Danube Project to simulate the interaction of natural and socio-economic processes within the Upper Danube Catchment (UDC, 77,000 km<sup>2</sup>) and located in parts of Germany, Austria, Switzerland and Italy). The approach enables the quantitative assessment of groundwater bodies (zones), which are delineated by intersecting surface watersheds, regional aquifers, and geomorphologic regions. The individual hydrogeological and geometrical characteristics of these zones are accounted for by defining characteristic response times and weights to describe the relative significance of changes in variables (recharge, groundwater level, groundwater discharge, river discharge) associated with different states. These changes, in each zone, are converted into indices (GroundwaterQuantityFlags). The motivation and particularities of regional-scale groundwater assessment and the background of GLOWA-Danube are described, along with a description of the developed methodology. The approach was applied to the UDC, where several different climate scenarios (2011-2060) were evaluated. A selection of results is presented to demonstrate the potential of the methodology. The approach was inspired by the European Water Framework Directive, yet it has a stronger focus on the evaluation of global-change impacts.

### **34. Effects of tectonic structures, salt solution mining, and density-driven groundwater hydraulics on evaporite dissolution (Switzerland)**

Subsurface dissolution (subsidence) of evaporites such as halite and gypsum can lead to extensive land subsidence. Recent land subsidences have been surveyed at six separate locations in northwestern Switzerland. The diameters of the affected surface areas range from 100 to 1,500 m, and corresponding subsidence rates reached more than 100 mm/year. Based on a geometrical model, three sites could be outlined where land subsidence can likely be attributed to salt solution mining. The effects of increased hydrostatic gradient due to both groundwater withdrawal and fluid density contrasts were evaluated in more detail for the remaining sites with a series of 2D density-coupled solute-transport simulations along an approximately 1,000-m-long and 150-m-deep 2D cross section. Simulation results indicate that the upconing process of saline groundwater into the main aquifer occurs under different distributions of subsurface parameters and hydraulic boundary conditions. For the presented setup, the simulations also revealed that the most sensitive factor for the dissolution rate is the structure or dip of the halite formation, which leads to an increase of dissolution rate with increasing dip. Due to the increased density of the brine, an intrinsic flow dynamic develops which follows the direction of the dip.

### **35. The importance of coupled modelling of variably saturated groundwater flow-heat transport for assessing river-aquifer interactions**

This paper focuses on the role of heat transport in river-aquifer interactions for the study area Hardhof located in the Limmat valley within the city of Zurich (Switzerland). On site there are drinking water production facilities of Zurich water supply, which pump groundwater and infiltrate bank filtration water from river Limmat. The artificial recharge by basins and by wells creates a hydraulic barrier against the potentially contaminated groundwater flow from the city. A three-dimensional finite element model of the coupled variably saturated groundwater flow and heat transport was developed. The hydraulic conductivity of the aquifer and the leakage coefficient of the riverbed were calibrated for isothermal conditions by inverse modelling, using the pilot point method. River-aquifer interaction was modelled using a leakage concept. Coupling was considered by temperature-dependent values for hydraulic conductivity and for leakage coefficients. The

quality of the coupled model was tested with the help of head and temperature measurements. Good correspondence between simulated and measured temperatures was found for the three pumping wells and seven piezometers. However, deviations were observed for one pumping well and two piezometers, which are situated in an area, where zones with important hydrogeological heterogeneity are expected. A comparison of simulation results with isothermal leakage coefficients with those of temperature-dependent leakage coefficients shows that the temperature dependence is able to reduce the head residuals close to the river by up to 30%. The largest improvements are found in the zone, where the river stage is considerably higher than the groundwater level, which is in correspondence with the expectations. Additional analyses also showed that the linear leakage concept cannot reproduce the seepage flux in a downstream section during flood events. It was found that infiltration is enhanced during flood events, which is attributed to additional infiltration areas. (C) 2010 Elsevier B.V. All rights reserved.

### **36. Radon and CO(2) as natural tracers to investigate the recharge dynamics of karst aquifers**

**Abstract:** This study investigated the use of radon ( $(^{222}\text{Rn})$ , Km a radioactive isotope with a half-life of 3.8 days, and CO(2) as natural tracers to evaluate the recharge dynamics of karst aquifer under varying hydrological conditions. Dissolved  $(^{222}\text{Rn})$  and carbon dioxide (CO(2)) were measured continuously in an underground stream of the Milandre test site, Switzerland. Estimated soil water  $(^{222}\text{Rn})$  activities were higher than baseflow  $(^{222}\text{Rn})$  activities, indicating elevated  $(^{222}\text{Rn})$  production in the soil zone compared to limestone, consistent with a  $(^{226}\text{Ra})$  enrichment in the soil zone compared to limestone. During small flood events,  $(^{222}\text{Rn})$  activities did not vary while an immediate increase of the CO(2) concentration was observed. During medium and large flood events, an immediate CO(2) increase and a delayed  $(^{222}\text{Rn})$  activity increase to up to 4.9 Bq/L and 11 Bq/L, respectively occurred. The detection of elevated  $(^{222}\text{Rn})$  activities during medium and large flood events indicate that soil water participates to the flood event. A soil origin of the  $(^{222}\text{Rn})$  is consistent with its delayed increase compared to discharge reflecting the travel time of  $(^{222}\text{Rn})$  from the soil to the saturated zone of the system via the epikarst. A three-component mixing model suggested that soil water may contribute 4-6% of the discharge during medium flood events and 25-43% during large flood events. For small flood events, the water must have resided at least 25 days below the soil zone to explain the background  $(^{222}\text{Rn})$  activities, taking into account the half-life of  $(^{222}\text{Rn})$  (3.8 days). In contrast to  $(^{222}\text{Rn})$ , the CO(2) increase occurred simultaneously with the discharge increase. This observation as well as the CO(2) increase during small flood events, suggests that the elevated CO(2) level is not due to the arrival of soil water as for  $(^{222}\text{Rn})$ . A possible explanation for the CO(2) trend is that baseflow water in the stream has lower CO(2) levels due to gas loss compared to water stored in low permeability zones. During flood event, the stored water is more rapidly mobilised than during baseflow with less time for gas loss. The study demonstrates that  $(^{222}\text{Rn})$  and CO(2) provides value information on the dynamics of groundwater recharge of karst aquifer, which can be of high interest when evaluating the vulnerability of such systems to contamination. (C) 2011 Published by Elsevier B.V.

### **37. Correlation of six anthropogenic markers in wastewater, surface water, bank filtrate, and soil aquifer treatment**

Six trace contaminants (acesulfame (ACE), sucralose (SUC), carbamazepine (CBZ), diatrizoic acid (DTA), 1H-benzotriazole (BTZ) and its 4-methyl analogue (4-TTri)) were traced from wastewater treatment plants (WWTPs) to receiving waters and further to riverbank filtration (RBF) wells to evaluate their prediction power as potential wastewater markers. Furthermore, the persistence of some compounds was investigated in advanced wastewater treatment by soil aquifer treatment (SAT). During wastewater treatment in four conventional activated sludge WWTPs ACE, SUC, and CBZ showed a pronounced stability expressed by stable concentration ratios in influent (in) and effluent (out) (ACE/CBZ: in45, out40; SUC/CBZ: in1.8, out1.7; and ACE/SUC: in24, out24). In a fifth WWTP, additional treatment with powdered activated carbon led to a strong elimination of CBZ, BTZ, and 4-TTri of about 80% and consequently to a distinctive shift of their ratios with unaffected compounds. Data from a seven month monitoring program at seven sampling locations at the rivers Rhine and Main in Germany revealed the best concentration correlation for ACE and CBZ ( $r(2) = 0.94$ ) and also a good correlation of ACE and CBZ concentrations to BTZ and 4-TTri levels ( $r(2) = 0.66$  to  $0.82$ ). The comparison of ratios at different sampling sites allowed for the identification of a CBZ point source. Furthermore, in Switzerland a higher consumption of SUC compared to Germany can be assumed, as a steadily increasing ACE/SUC ratio along the river Rhine was observed. In RBF wells a good correlation ( $r(2) = 0.85$ ) was again observed for ACE and CBZ. Both also showed the highest stability at a prolonged residence time in the subsurface of

a SAT field. In the most peripheral wells ACE and CBZ were still detected with mean values higher than  $36 \mu\text{g L}^{-1}$  and  $1.3 \mu\text{g L}^{-1}$ , respectively. Although SUC concentrations in wastewater used for SAT decreased by more than 80% from about  $18 \mu\text{g L}^{-1}$  to  $2.1 \mu\text{g L}^{-1}$  and  $3.5 \mu\text{g L}^{-1}$  in these outlying wells, the compound was still adequate to indicate a wastewater impact in a qualitative way.

### **38. Surface subsidence and uplift above a headrace tunnel in metamorphic basement rocks of the Swiss Alps as detected by satellite SAR interferometry**

Surface subsidence associated with the construction of a headrace tunnel in the Swiss Alps at more than 2000 m above sea level (a.s.l.) has been detected at two locations with satellite differential Synthetic Aperture Radar (SAR) interferometry. At the first location, a subsidence trough of about 4 cm in the satellite line-of-sight direction following the headrace tunnel axes has been measured between August 1995 and August 1996. Similar values from SAR data of ascending and descending orbits indicate displacements in the vertical direction of the movement. In the second case, a symmetric cone of depression with a maximum displacement of about 4 cm between 1995 and 1997 has been observed above the tunnel. Differences in the results from satellite SAR data of ascending and descending orbits indicate that the direction of displacement in this second case was not entirely vertical. Large-scale consolidation associated with pore-pressure reduction in the rock mass arising from tunnel drainage at about 200-400 m depth beneath the topographical surface is believed to be the contributing mechanism (Zangerl et al., 2008a, 2008b). Evidence for this process is based on pore pressure recordings in nearby deep wells. In both areas, the subsidence was followed by a small uplift of about one centimeter between 1997 and 1999, after the tunnel was cased with permeable concrete segments. This partial recovery is also visible in pore pressure records and can be related to the elastic components of rock mass deformation. (C) 2011 Elsevier Inc. All rights reserved.

### **39. Operational real-time modeling with ensemble Kalman filter of variably saturated subsurface flow including stream-aquifer interaction and parameter updating**

Urban groundwater is frequently contaminated, and the exact location of the pollution spots is often unknown. Intelligent monitoring of the temporal variations in groundwater flow in such an area assists in selectively extracting groundwater of drinking water quality. Here an example from the city of Zurich (Switzerland) is shown. The monitoring strategy consists of using the ensemble Kalman filter (EnKF) for optimally combining online observations and online models for the real-time characterization of groundwater flow. We conducted numerical simulation experiments for the period January 2004 to December 2007 with a 3-D finite element model for variably saturated groundwater flow. It was found that the daily assimilation of piezometric head data with EnKF results in a better characterization of piezometric heads than does a model which is inversely calibrated with historical data but not updated in real time. The positive impact of model updating with observations can still be observed 10 days after the update. These simulations also suggest that parameters (hydraulic conductivity and leakage) are successfully updated: 1 and 10 day piezometric head predictions are better with than without updating of parameters. Additional experiments with a synthetic model for the same site, in which the only difference is that certain parameter values are selected as the unknown "true" conditions, show that EnKF also successfully updates unknown parameters. However, this is only the case if spatially distributed hydraulic conductivities and leakage coefficients are jointly updated and if a damping parameter is used. The mean absolute error of estimated log leakage coefficients decreased by up to 63%; for log hydraulic conductivity a decrease of up to 27% was observed. From January 2009 the method has been operational at the Water Works Zurich and showed a remarkable performance until present (October 2010).

### **40. Analytical model for environmental tracer transport in well catchments**

In this paper, we present analytical solutions and discuss them for simplified groundwater systems with decaying environmental tracers such as  $(3)\text{H}$ , including the formation of a decay product such as tritiogenic  $(3)\text{He}$ . The developed solutions are applicable for shallow, unconfined groundwater systems, which can be conceptually described by a steady-state, two-dimensional, semiconfined groundwater flow model with constant thickness, recharge rate, and porosity. The prerequisite for the applicability of our solutions is that the pumping wells and observation wells at which tracer information is available are fully screened over the entire aquifer thickness. The sampling by pumping from such wells produces the complete mixing of water of different age and origin. The

application of our solution to the Baltenswil (Zurich, Switzerland) groundwater field site shows that the simplified model is able to catch essential dynamics of the transient concentration development of  $(3)H$  and  $(3)He$ .

#### **41. Effects of tunneling on groundwater flow and swelling of clay-sulfate rocks**

Swelling of clay-sulfate rocks is a major threat in tunneling. It is triggered by the transformation of the sulfate mineral anhydrite into gypsum as a result of water inflow in anhydrite-containing layers after tunnel excavation. The present study investigates the hydraulic effects of tunneling on groundwater flow and analyzes how hydraulic changes caused by excavation lead to water inflow into anhydrite-containing layers in the tunnel area. Numerical groundwater models are used to conduct scenario simulations that allow one to relate hydrogeological conditions to rock swelling. The influence of the topographic setting, the excavation-damaged zone around the tunnel, the sealing effect of the tunnel liner, and the geological configuration are analyzed separately. The analysis is performed for synthetic situations and is complemented by a case study from a tunnel in Switzerland. The results illustrate the importance of geological and hydraulic information when assessing the risk of swelling at an actual site.

## **Übersichtspublikationen**

#### **42. Urban Geology – Process-Oriented Concepts for Adaptive and Integrated Resource Management**

Urban subsurface resources and particularly urban groundwater are vulnerable to environmental impacts, and their rational management is of major importance. In this book a multidisciplinary team of specialists and scientists presents innovative process-oriented approaches to the sustainable use of these resources. The included case studies from northwestern Switzerland describe representative environments and are relevant for urban areas in general. They illustrate the protection of groundwater; river restoration; engineering and hydrogeological questions related to urban infrastructure and management concepts; as well as monitoring, modeling and remediation strategies for contaminated sites; problems caused by karst in urban environments; the use of shallow geothermal energy; and natural hazards such as flood events and earthquakes. It is demonstrated that modern quantitative earth sciences can contribute significantly in finding solutions concerning the sustainable use of subsurface resources in urban environments. The book is an invaluable source of information for hydrogeologists, geologists, urban planners, water supply engineers, and environmental agencies.

## **Fachartikel SGM 2011**

#### **43. Characterization of the Upper Muschelkalk aquifer in northeast Switzerland using laboratory physical properties and imaging techniques**

Deeply buried levels of the Triassic Trigonodus Dolomite Formation of the Upper Muschelkalk aquifer (Swiss Molasse Basin) show potential for geothermal energy exploitation and for geological storage of gas – whether permanent storage of waste  $CO_2$  (Chevalier et al., 2010) or seasonal storage of imported methane. All of these potential applications rely on high porosities and high permeabilities. Although some borehole intersections of the Formation look encouraging, very little is known about the regional distribution and magnitudes of porosity and permeability within the aquifer. In this context we are undertaking a quantitative and qualitative characterization of the porosity and permeability of the Trigonodus Dolomite using a variety of analytical techniques, including SEM imaging, He-pycnometry, mercury porosimetry, thin-section petrography, x-ray computer tomography (CT), as well as ultrasonic velocity and permeability measurements. These laboratory analyses will be integrated with field scale geophysical observations and laboratory geochemical and isotopic investigations. ...

#### **44. Effect of climatic forcing on nitrate concentrations in groundwater based on changing recharge rates**

Climate changes can have an impact on the sustainability of groundwater resources not only in terms of groundwater quantity but also groundwater quality. For example after the dry period of 2003–2005 a significant increase of nitrate concentrations was observed at many public pumping wells of Switzerland (OFEV 2009). In this study we present a simple approach to reproduce recent nitrate concentration trends and recharge rates and to estimate future trends under different climatic conditions. The aquifer of Wohlenschwil (canton of Aargau, Switzerland), where land use change are known since 1997, is taken as a case study site. ...

#### **45. Impact of the uncertainty in river water levels on modeled groundwater residence times**

Riverbank filtration is a widely used method to produce drinking water. In Switzerland for instance, it accounts for 25% of the total drinking water supply. The residence time of the bank filtrate in the aquifer plays a key role in the purification process and therefore, modeling the travel times and groundwater flow paths in river-groundwater systems is important. The conceptual representation of the river boundary condition and the assigned river water levels are critical in this process. In past modeling studies, the assignment of river water levels has been accomplished using different methods, for instance by extracting data from a one or two dimensional hydraulic model (Derx et al. 2010; Doppler et al. 2007) or by interpolating measured water levels to the nodes in between measurement points (Lautz & Siegel 2006). These water level data are usually considered to be accurate and the calibrated model is used to extract quantitative information on parameters like residence time. However, there may be a considerable amount of uncertainty in the river water level information. Depending on the method used to derive water level data at specific points and depending on the interpolation approach to each boundary node, a different river water level distribution is likely to result due to the errors and assumptions within each method. This uncertainty would then impact the modeled groundwater flow paths, flow velocities and residence times. ...

#### **46. GEOBEST - A contribution to the long term development of deep geothermal energy in Switzerland**

The Swiss Seismological Service (SED) is implementing the GeoBest project on behalf of the Swiss Federal Office for Energy (SFOE) to provide cantonal and federal authorities with guidelines on how to handle seismic hazard in the framework of the environmental risk assessment. Within GEOBEST, selected pilot projects in Switzerland will be supported in the necessary seismic monitoring of natural and induced seismicity. GeoBest supports the pilot project in the first two years, that are most critical with respect to the financial risk, by providing seismological instrumentation from the GeoBest instrument pool and partial financial support for the installation and operation of the seismic monitoring network. In return the pilot projects grant SED access to project data needed for seismic hazard assessment and the development of best practice guidelines. ...

#### **47. Karst system characterization (KARSYS): a methodology for approaching the hydrogeology of karst systems in Switzerland (Swisskarst Project, NRP61)**

Karst hydrological systems are characterized by a highly heterogeneous structure including quick- and slow flow components (conduit network, phreatic and epikarstic storage). This induces an important hydrodynamic variability and complex flow dynamics. Furthermore, regional characteristics of karst aquifers in Switzerland are poorly documented and a synthetic overview of karstic resource does not exist yet. This situation is not satisfactory and the management of karst water resources is far from being optimal. In the framework of the SWISSKARST Project, the Swiss Institute of Speleology and Karstology (SISKA) developed a methodology for approaching karst systems in their geometries and behaviours at the scale of Switzerland: This methodology has been called KARSYS for KARst SYStem Characterization. This approach combines several general characteristics of karst media with regional aspects leading to a pragmatic 3D conceptual model of a karst system. This model depicts systems boundaries, catchment areas, the aquifer basement, the location and extension of groundwater bodies and their boundaries in high water stage. Results of this approach are presented as Identification Cards for each main karst system, including hydrogeological karst maps (based on a new mapping methodology), 3D views, a basic data-base and a series of attachments (typically literature). Details on ID cards are presented in a separate

paper (Demary *et al.* (2011)). Another part of the SWISSKARST project is dedicated to the development of a pragmatic hydrological modelling tool for the simulation of karst spring discharge from precipitation data. This part is presented in a separate paper (Weber *et al.* (2011)). Application of this applied methodology cover a wide range of water uses and land uses as water supply, management (tunnel, dam,...), renewable energies (evaluation of power production potential or geothermic), natural hazards prediction,... KARSYS was applied to the whole Vaud canton (2 822km<sup>2</sup>) in 2010 and is now extended to the Bern and Fribourg cantons demonstrating that the KARSYS method is applicable and provides much of meaningful information. Results can be viewed on the evolutionary SWISSKARST website: [www.swisskarst.ch](http://www.swisskarst.ch).

#### **48. Multi-disciplinary study for the exploration of deep low enthalpy geothermal reservoirs, Neuchâtel, Switzerland**

The authorities of the canton of Neuchâtel, in the Western part of Switzerland, is willing to develop geothermal energy for district heating in the two main cities of the canton: Neuchâtel, located along the Lake of Neuchâtel, and La Chaux-de-Fonds situated in a high valley of the Jura Massif. The geology of both areas is linked to the Jura Range and present complex structures, where the landscape is composed of anticlines associated with overthrust faults, which are overcut by strike-slip fault and secondary faulting events. The rock formations go from the Trias, which forms the detachment layer, up to the Quaternary rock. Bedrocks are mainly composed of limestones and marls, which can reach a thickness of several hundreds meters. The three main deep aquifers investigated in this area, from the shallowest ( $\leq 400$  m below surface) to deepest ( $< 2000$  m), are the Malm, the Dogger and the Muschelkalk. The estimated temperatures, based on previous studies, should range between 20 to 65 °C, which are function of depth, elevation and groundwater velocity. The expected low temperature is mainly due to the presence of karstic systems, which drains the heat towards the low elevation of the basin. The present study is based on gravimetry surveys, 3D geological models and 3D gravimetry models to best characterize the underground structures and to find areas where the rock properties would be favourable to geothermal exploitation. ...

#### **49. Using high resolution lysimeter data to quantified current and future recharge rates and evaluating the uncertainty**

Groundwater recharge is the key parameter for sustainable water resources management. However, quantifying its spatial and temporal distribution is difficult, because infiltration is affected by soil types and the presence of vegetation. Different soil types have a profound influence on how precipitation relates to groundwater recharge. The task is further complicated through climate change: The effect of climate change on groundwater recharge is still poorly understood. Numerical models are an important tool in quantifying groundwater recharge. Typically, water flow and transport is simulated in 1-D models. Unfortunately, these models require a high number of parameters, which are difficult to measure. For example, water retention curves that describe the relation between saturation, matrix potential and hydraulic conductivity are required, yet their measurement in the laboratory is expensive and time-consuming. Pedotransfer functions are an alternative to direct measurements, but their reliability is highly questionable. Alternatively, the required parameters are calibrated to fit a set of available observations. However, in many cases only a few observations with low spatial and temporal resolution are available. Therefore, the unknown model parameters cannot be calibrated uniquely, resulting in large uncertainties associated with prediction. In this project a large amount of high quality data through the lysimeter facility AGROSCOPE in Reckenholz is available to calibrate 1D soil column models. Data from 3 types of soils found in Switzerland are at our disposition. Data measured include deep drainage, evapotranspiration, as well as soil moisture and matrix potential at different depths. ...

#### **50. Prospects of Deep Geothermal Energy in Switzerland**

Deep geothermal energy resources and utilization come in two main categories: hydrothermal and petrothermal. While the first is restricted to specific subsurface conditions and does not exist everywhere, the second is ubiquitous (in principle). The utilization is mainly for direct uses like district heating, for power generation or for both ("co-generation"). The rather arbitrary delimitation between shallow and deep is at 400 m depth. ...The goal here is to find and develop ample thermal water in deep aquifers for space heating and/or co-generation. ...

### **51. Deep geothermal systems – advantages and limitations of using natural Permeability**

The concept of hydrothermal systems in the sense of non-volcanic resources is based on the conceptual model of deep regional aquifers. In contrast, an Enhanced Geothermal System (EGS) is defined by improvement of the natural resource (ENGINE, 2009) usually either by hydraulic or chemical stimulation. In Switzerland, major regional aquifers have been distinguished in the Molasse basin in earlier studies: the Upper Malm, the Upper Muschelkalk and the upper crystalline basement. The Upper Marine Molasse and the Dogger are considered regional aquifers in northern and western Switzerland, respectively (e.g. Müller et al., 2001, Pasquier et al., 1999), but are usually too shallow for significant power production. One of the most productive examples worldwide for heat and electric power is the Upper Malm aquifer in the German Molasse basin. The permeable reef facies in the area of Munich, however, reveals also variable productivity depending on its degree of fracturation. The productivity can be naturally enhanced, when exploiting fracture zones within the aquifer, as most recently targeted in the Taufkirchen project, and it can be limited in undeformed areas or re-filled fractures. Thus, an expected hydrothermal project can turn into an EGS project such as the case of Mauerstetten. Analyzing recent hydrothermal projects and older wells in Switzerland, we come to the conclusion that the degree of fracturation is crucial for both hydrothermal and EGS projects and that our concept of regional aquifers lacks of confirmation by productive wells. ...

### **52. Swisskarst project (NRP61): Identification cards as tools for a sustainable management of karst systems.**

SWISSKARST project aims at setting up a specific approach and a series of tools for improving the sustainable management of karst groundwater systems. The KARSYS methodology (Karst system characterization methodology) provides a framework for producing geologically and hydraulically meaningful conceptual models of karst systems (see Malard et al., this volume). The present paper focuses more on the way to present these results in a systematic and applicable way and introduces the idea of ID cards for karst systems. Identification Cards intend synthesizing the main karst system characteristics. They have to be at once concise and enough complete. They must address questions from cantons, communities, water-supply associations or any further water-user of a karst area. For this reason, some aspects of the ID Cards are being adjusted to the respective demands and priorities of users. Furthermore, ID Cards consider the following potential user conflicts and interactions: drinking water supply, hydropower production, artificial snow, irrigation, geothermic, natural hazard management. ...

### **53. Quasi-operational estimation of water resources anomalies during the dry and wet spells of 2011**

During the last few years numerous research initiatives concerning climate impacts on water resources have been going on. Hydrological models have been applied to estimate current and future spatial and temporal availability of water resources in different areas of Switzerland and the European Alps. In parallel large efforts have been allocated to the development and operational application of hydrological ensemble prediction systems, with focus on floods. WSL has been active in all these fields and is now testing opportunities of combining the outcomes of climate impacts studies with operational forecasting. The goal is to establish a system for the early detection of anomalies in the temporal and spatial availability of water resources in Switzerland. To this end the FOEN CCHydro Project water resources climatology for the control period 1980-2009 and probabilistic scenarios (10 members) for two 30-years periods in the future (2021-2050 and 2070-2099) have been created. From the NRP61 project DROUGHT-CH tools are in preparation for the assimilation of snow water equivalent information for improving the prediction of water resources availability with lead times of up to 1 month. First simulation re-forecast experiments for the basins Thur and Alpine Rhine have been realized. In the presentation we will focus on the forecasts of the summer 2003 drought and the 1999 flood. Finally, the experience obtained since 2007 with the operational implementation of the hydrological model PREVAH for probabilistic flood forecasts has been transferred to an early prototype focusing on the estimation of water resources anomalies. ...

## Fachartikel H2Karst

### 54. Assessing water origin in a karst system using Radon, CO<sub>2</sub> and supersaturation - Proc. H2Karst, 9th Conference on Limestone Hydrogeology, Besançon

The Alpeau project aims at strengthening the protective role of forest soils with an eye to the sustainable management of groundwater resources and their quality. In karstic areas, it is important to discriminate between water originating from the soil reservoir, the epikarst (interface between soil and karst), the low permeability volume (the rock volume between the epikarst and the system outlet) and the freshly infiltrated rainwater. To do so, the Gorges de l'Areuse test site (Swiss Jura Mountains) was investigated by a combined monitoring of radon, CO<sub>2</sub> and TDGP (total dissolved gas pressure). These gases, produced in large quantities in the soil and dissolved in rainwater, were used as natural tracers. Electrical conductivity (EC), temperature, turbidity, TOC (total organic carbon), nitrogen isotopic composition and dissolved ions were also part of the survey program. The same origin of both radon and CO<sub>2</sub>, their different behaviour in the system, and their temporal variations at the outlet allowed to put forward the following premises: (i) high radon and CO<sub>2</sub> concentrations are typical for water originating from the forest soil, (ii) low radon and high CO<sub>2</sub> levels for the epikarst, (iii) low radon and CO<sub>2</sub> concentrations along with high EC values are representative of the saturated zone, (iv) whereas freshly infiltrated water shows low levels of EC, radon and CO<sub>2</sub>. The radon and CO<sub>2</sub> signals are likely to show periodic oscillation features. Soil radon concentrations are affected by various seasonal and daily changes, such as precipitations, atmospheric pressure and temperature, leading to complex time series. In order to obtain manageable data, these components needed to be removed. A Fourier transform was therefore applied on this set of measurements. This investigation allowed to get insight into the travel time, the storage location and the quality of water in a karstic and forested watershed.

### 55. Inverse modeling of karstic networks using a pseudogenetic technique

When modeling flow and transport in karst systems, previous studies have shown the necessity of accounting for the conduits. In a previous work (BORGHI, RENARD *et al.* submitted 2011), a technique has been developed to stochastically model the conduits with a pseudo-genetic method. It relies on the following principle: the conduit system develops by speleogenesis in an original heterogeneous fractured geological media. However, the method we proposed did not account for observations on the state variables of the system, such as spring hydrographs and tracer tests if any. In this paper, we show a preliminary work, which includes these data in an inverse problem framework. The stochastic pseudo-genetic algorithm is used to generate the ensemble of prior models. The inversion is performed on tracer test response combined with head data and spring hydrographs. The posterior ensemble is composed of the accepted resulting simulations within a certain tolerance threshold.

### 56. Vulnerability of karst aquifers to fecal bacteria: Validation of a numerical indicator of microbial contamination

The main objective of this study was to use field experiments with fecal indicators to verify the vulnerability of a karst spring to pathogens, as determined by using a numerical modeling approach. The groundwater modeling was based on linear storage models that can be used to simulate karst water flow. The vulnerability of the karst groundwater is estimated using such models to calculate criteria that influence the likelihood of spring water being affected by microbial contamination. Specifically, the temporal variation in the vulnerability, depending on rainfall events and overall recharge conditions, can be assessed and quantified using the dynamic vulnerability index *DVI*. *DVI* corresponds to the ratio of conduit to diffuse flow contributions to spring discharge. To evaluate model performance with respect to predicted vulnerability, samples from a spring were analyzed for *Escherichia coli*, enterococci, *Clostridium perfringens*, and heterotrophic plate count bacteria during and after several rainfall events. *DVI* was shown to be an indication of the risk of fecal contamination of spring water with sufficient accuracy to be used in drinking water management.

**57. Stochastic modeling of the transport of chlorinated solvents in a karst system: a case study in the Jura**

In the Jura, industries have used chlorinated solvents in high quantities for various applications. These compounds have been placed into waste disposal and constitute a threat for groundwater contamination in the karst system. The behavior of the chlorinated solvents is complex and difficult to predict because of their chemical and physical properties. These types of contaminations have been subject of various studies especially in porous aquifer. However, only a few studies deal with this type of contamination in karst systems. In this work, we present some preliminary results related to the case of a waste disposal in the Canton of Neuchatel. Existing and newly acquired field data (geology, continuous monitoring, tracer tests) have been used to develop a conceptual model of the transfer of the contaminants from the waste disposal to the various potential outlets. Based on these data, several assumptions have been formalized (flow along a main fault, capture in dry karst conduits, density driven flow following the geological structure). The main part of the work presented here consists in the modeling of the geometry of the system. The aim is to test how the chlorinated solvents may have escaped from the waste disposal and whether they can potentially reach a drinking water production well.

**58. Identification Cards of karst systems as tools for a sustainable management of karst systems.**

Results of the KARSYS approach are presented as Identification Cards (ID Cards) for each main karst system, including maps, 3D views, a basic data-base and a series of attachments (typically literature). Identification Cards intend synthesizing the main karst system characteristics. They have to be at once concise and enough complete. They must address questions from cantons, communities, water-supply agencies or any further water-users of a karst area. For this reason, some aspects of the ID Cards are being adjusted to the respective demands and priorities of users. Furthermore, ID Cards consider the following potential user conflicts and interactions: drinking water supply, hydropower production, artificial snow, irrigation, geothermic. The KARSYS documentation approach of karst systems is an important step towards a better understanding of karst hydrogeology at a regional scale. It is a necessary step for a sustainable management of karst groundwater and it represents a necessary base for any further step including modelling of water quantity, quality, or the assessment of global change on karst systems.

**59. Karst-ALEA-Method : a risk assessment method of karst for tunnel projects: Application To the Tunnel of Flims (GR, Switzerland)**

The KarstALEA method aims at assessing karst-related risk. It has been developed for underground engineering. From the assessment of karst related hazards, it suggests adequate investigation methods and mitigation plans for each construction phase. Many recent tunnel constructions have shown that uncertainties related to karst processes are a major issue, since they may lead to economic, social, security-related and environmental problems. In most cases problems are related to an inappropriate or a complete missing of karst risk assessment. Recent studies on the geometry of large cave systems show that the development of karst conduits is not random but predictable. This improved our understanding of the development of underground karst structures in time and space, and significantly improved the design and interpretation of hydrogeological investigations. Essentially, it is now possible to quantify the probability of karst occurrences inside a karstic rock mass and to delineate zones of different risk levels.

**60. UnderGroundPositioning System (UGPS): a new tool for localizing underground flowpaths in karst regions**

In 2006 the Swiss Institute of Speleology and Karstology (SISKA) heard about a new technology developed in medical Sciences for tracking the position of a small transmitter within the intestine. In 2009 an upscaled prototype demonstrated that the technique is efficient for applications in karst, with a range of 200 meters through limestone and a precision better than 2% on the positioning. The potential for applications being larger than karst hydrogeology, it was decided to create a company for the development of the technology. InfraSurvey was thus created in March 2010. The web-site of InfraSurvey presents the method and some first case-studies ([www.infrasurvey.ch](http://www.infrasurvey.ch)), including the positioning of a cave stream in Creta at the depth of 190m below ground. The prototype was quite big in size (a volume of about 20 liters). In 2011 a small size receiver (5cm in diameter and 40cm long) has been produced. The measurement technology is still

being improved and an application range of 400m is expected to be reached soon. The precision should also be improved to 0.5%. The coupling to laser-scanners makes it possible to build the 3D geometry of the underground passage. This technique can be used not only in large karst conduits, but in smaller pipes or in drillholes. UGPS is now already available for localizing quickly and precisely underground flow paths where human can enter down to depth of at least 200 meters. It is thus already a very effective tool for characterizing karst conduits networks. On-going improvements of the technique will make it possible in a few years to couple this positioning system to diving robots and to map unknown underground flowpaths directly from the surface. We will thus soon enter a new age of tracing experiments!

#### **61. Well hydrograph analysis for the estimation of hydraulic parameters and conduit network geometry of karst aquifers**

This paper presents analytical formulae for the characterisation of karst aquifers based on well hydrograph analysis. A combined analytical-numerical study has been undertaken to develop a systematic method for the quantitative analysis of well hydrographs. The analysis of numerically simulated well hydrographs provides an insight into the hydraulic behavior of karst hydrogeological systems. The well hydrograph analytical techniques presented here facilitate the determination of

hydraulic parameters and block size at specific locations within a catchment. The combination of the spring and well hydrograph analytical techniques provides a powerful tool for the characterization of the structure and hydraulic behaviour of karst systems. The proposed investigation method provides useful information for water resource assessment, flood prediction, vulnerability assessment, contamination risk assessment, geotechnical and speleological studies.

#### **62. Simulation of karstic networks using high order discrete Markov processes**

The shape of karstic networks, highly influential on flow and transport processes, is intrinsically uncertain. In this context, stochastic methods are an interesting avenue for karstic aquifers characterization. We propose to use a high-order discrete Markov process to generate a network of one-dimensional conduits in a 3D geological space. The networks produced have the same spatial properties than a given fully-known proxy network in terms of shape of conduits, fractal dimension and distribution of conduits orientations. Moreover, the resulting networks are conditioned to known points of recharge (inlets) and discharge (outlets). Proxy cases come from speleological exploration.

#### **63. Microbiological spring water quality monitoring across Switzerland**

The use of groundwater as a drinking water resource requires knowledge of its microbiological status and quality. In contrast to conventional microbiological groundwater monitoring, the present study is not limited to fecal indicator bacteria but covers the whole spectrum of microorganisms, including bacterial pathogens, viruses and protozoa. Samples collected at karst sites of the National Groundwater Monitoring NAQUA revealed the presence of diverse types of fecal microorganisms, whose occurrence could be linked to specific hydrogeological situations. The findings represent a snapshot of the microbiological status at the monitoring sites and provide a national overview of the types and occurrence of microorganisms in Swiss groundwater. In addition to fecal contamination, the overall microbial load in groundwater was assessed using cell density measurements which yielded typical ranges for this ecological parameter. The study highlights the enhanced vulnerability of karst groundwater to microbiological contamination, as well as its relationship with the microbial biocenosis, i.e. the interplay of allochthonous and autochthonous microbial components. On the basis of this data pool, it is possible to propose a microbiological classification of karst aquifers.

#### **64. Contaminant attenuation in karst aquifers – a paradigm shift**

Significant advances have been made in the characterisation of transport and storage in karst aquifers over recent decades. This improved understanding permits further integration of the behaviour of individual contaminants and their specific transport, enabling comparisons to be made. This has been particularly challenging as it is necessary to consider different flow components encountered in karst aquifers, including fast conduit flow and storage in less permeable rock volumes. Comparative tracing experiments using contaminant surrogates have proved to be an appropriate method for estimating the specific attenuation of selected substances at the field scale. Several attenuation processes may be involved and could be identified.

Examples from Swiss karst aquifers highlight the *in-situ* effectiveness of such attenuation processes, some of which can be described using first-order kinetics. It could be shown that solute and colloid tracers are able to interact with aquifer material despite the dominance of preferential and conduit flow components. Consequently, if reactive and/or non-persistent contaminants are involved, the arrival at karst springs is determined by contaminant-specific properties and hydrochemical characteristics rather than by the intrinsic vulnerability of the aquifer. This demands more refined conceptual transport models and also represents a paradigm shift in the assessment of karst groundwater vulnerability and contaminant attenuation.

#### **65. KARSYS, un concept de caractérisation des systèmes karstiques pour une gestion durable des ressources en eau**

Karst groundwater represents about 80% of Swiss groundwater reserves and about 50% of groundwater resources. In Switzerland karst hydrological systems are however badly documented and waters are still moderately used. Climate change, growing water needs for drinking water, agriculture, hydropower generation or geothermal reinforcement greatly increase the pressure on these aquifers. In order to improve their sustainable management the Swiss Institute of Speleology and Karstology (SISKA) is developing a specific method for approaching karst systems in Switzerland as part of the 61th National Research Program. KARSYS (Karst System Characterisation) is being developed in order to provide, as efficiently as possible, a 3D conceptual model of karst hydrological systems, for management and general purposes. This approach is based on a geological model, which is iteratively improved in order to characterize karst groundwater bodies, catchment boundaries, confined and unconfined areas as well as the position of the main underground flowpaths. This method is being applied to all major Swiss springs (~200 systems with  $Q > 50$  L/s) and will provide a consistent basic documentation including maps and 3D views. In some cases the method has also provided a sketch of high water situations, which is a significant understanding concerning natural hazard (floods and landslides). We believe that the KARSYS method is an efficient approach for any karst system. First results are already available on the [www.swisskarst.ch](http://www.swisskarst.ch) website.

#### **66. Swisskarst project (NRP61): Towards a pragmatic simulation of karstic spring discharge with conceptual semi-distributed model. The Flims case study (Eastern Swiss Alps)**

A hydrological semi-distributed model for simulating karst springs discharge is presented and applied to the Flims case study. This model used for flood prediction and management in river basins has been adapted to karst flow and springs. The model takes into account snowmelt, glacier melt, soil infiltration, evapotranspiration as well as flood routing in surface rivers, sinkholes, and fast and slow flow in underground reservoirs. The Flims karst system is composed of three springs at three different levels: Lag Tiert, Tunnel spring and Pulté spring. In 2002, this system was disturbed by the drilling of a highway tunnel. The model was able to simulate discharge of the three springs as well as the level of the Cauma lake fed by the Pulté spring with encouraging results. They show that the previous model developed between 2006 and 2009 was coherent. This new model has the advantage to simulate natural processes from soil infiltration to outflow at the system springs. It is therefore possible to understand the influence of every process on the spring discharge.

#### **67. Subsurface dissolution of evaporitic rocks**

Subsurface dissolution (subrosion) of evaporites such as halite and gypsum can lead to extensive land subsidence. Affected areas were surveyed at six separate locations in northwestern Switzerland. Diameters of the affected surface areas range from 100m to 1,500m, and corresponding subsidence rates were as much as 100mm/year. Based on a geometric model, three sites were outlined where land subsidence can likely be attributed to salt solution mining. The effects of increased hydrostatic gradient resulting from both groundwater withdrawal and fluid density contrasts were evaluated in more detail for the remaining sites with a series of 2D density-coupled solute transport simulations along an approximately 1000m long and 150m deep 2D cross section. Simulation results indicate that the upconing process of saline groundwater into the main aquifer occurs under different distributions of subsurface parameters and hydraulic boundary conditions. The simulations also revealed that the most sensitive factor for the dissolution rate is the structure or dip of the halite formation, with an increase of dissolution rate with increasing dip. As a result of the increased density of the brine, an independent flow dynamic develops that follows the direction of the dip.

## Fachartikel GQ'10

### 68. The artificial sweetener acesulfame as marker of domestic wastewater in groundwater

To assess sources and magnitude of possible groundwater contamination, chemical markers have proved to be useful. A chemical that is used in everyday life, the artificial sweetener acesulfame, may be ideally suited for detection of traces of domestic wastewater in natural waters. The compound was found ubiquitously in wastewater, surface waters, and groundwater from Switzerland. Acesulfame was not eliminated in wastewater treatment plants (WWTPs), and was quite persistent in lakes, where concentrations increased with population in the catchment area and decreased with water throughflow. Highest concentrations in groundwater were observed in areas with significant infiltration of river water, where the infiltrating water received considerable discharges from WWTPs. Given the currently achieved detection limit of approx. 0.01 µg/L, the presence of ≥0.05% wastewater can be traced in groundwater.

### 69. Perfluorinated chemicals in Swiss groundwater – results of the National Groundwater Monitoring NAQUA

Perfluorinated chemicals (PFC) are the subject of increasing public concern. Due to their hydro- and oleo-phobic properties, they are used in diverse industrial processes, and occur in several consumer products. The thermal and chemical stability of certain PFC has resulted in their global distribution in the environment. In a pilot study of the Swiss National Groundwater Monitoring NAQUA, PFC were detected at 21 of 49 sampled NAQUA monitoring sites. Except for one monitoring site, concentrations were below 100 ng/L, in most cases even below 10 ng/L. The highest concentrations were generally recorded for Perfluorooctanesulfonate (PFOS). All monitoring sites at which PFC were detected are situated in unconsolidated aquifers along rivers. The discharge of treated or untreated wastewater into rivers and streams and the subsequent infiltration of these waters into groundwater appear to be the major source of PFC in Swiss groundwater.

### 70. Drinking water production close to contaminant sites: a case study from the region of Basel, Switzerland

Production of drinking water in urban areas is challenged by different kinds of groundwater contamination. It is especially difficult to evaluate the origin of the contamination when former waste disposal sites and other sources of pollution are present. The presented site is characterized by a complex geological setting and changes in hydraulic boundary conditions over time. In order to take the appropriate measures to understand the transport processes of the contaminants, combined and adapted investigation methods were applied. They include drilling of observation wells, the chemical analysis of solid matter and groundwater as well as the construction of a 3-D groundwater flow model. Only the combination of all these methods made it possible to understand the observed distribution of contaminants. Results suggest that the actual contamination in the aquifer is due both to remobilization of contaminants and changing hydraulic boundary conditions affecting the flow direction of the contaminant plumes.

### 71. Modelling nitrate dynamics in the well catchment Baltenswil (Zurich, Switzerland)

Nitrate dynamics are investigated for the catchment of the drinking water pumping well Baltenswil (Zurich, Switzerland). Land use in the well catchment is mainly agriculture and forestry. Nitrate input into the subsurface is estimated based on yearly maps of crop rotation on the agricultural plots within the catchment, and on the results from lysimeter studies on nitrate mobilization for similar soils and climatic conditions and crop rotation. Calibration of the saturated part of the flow model is performed using long-term series of head data in wells and piezometers. Transient flow and transport modelling was performed using the software MIKE SHE for the period between 1994 and 2009 and compared with measured head and nitrate data. The results point to the importance of nitrate input and groundwater recharge rate for the complex nitrate transport system.

## **72. Modern groundwater management: measures undertaken at the source – pilot project nitrate reduction in Klettgau SH**

Nitrogen loss of soils into groundwater bodies is a common threat to drinking water resources in areas of high agricultural activities. Here we present a case study from the northern part of Switzerland, where a series of soil cultivation measures were applied in order to remediate one specific groundwater well. The water of this well could no longer be used due to elevated nitrate concentrations. The impact of the project on nitrate concentration in the well was predicted by a series of groundwater model simulations. Continuing monitoring both of groundwater quality and of soil layers by suction lysimeters allowed continual improvement and control of the success of the measures. After four years, the water from the well can again be used as drinking water. The observed gradient of nitrogen decrease in the groundwater can now be used to refine the groundwater models.

## **73. Assessing groundwater travel times and biogeochemical processes during riverbank filtration under the aspect of river restoration**

The largest Swiss groundwater reservoirs are located in gravel aquifers of flood plains with channelized rivers. Although the number of river restoration projects is increasing, the effects of river restoration on riverbank filtration and groundwater quality are still under debate. For detailed research on biogeochemical processes during river water infiltration, field data of nutrients or pollutants and advective groundwater travel times to observation and production wells are crucial parameters. We present results of a study on bank filtration at a field site in northeast Switzerland, which is located at a channelized and restored section of the peri-alpine losing River Thur. We analyse time series of electrical conductivity in the river and riparian groundwater wells to quantify mean residence times by means of non-parametric deconvolution and relate the calculated travel times with biogeochemical processes occurring during riverbank filtration.

## **74. Spatial characterization of hydraulic conductivity in alluvial gravel-and-sand aquifers: a comparison of methods**

For groundwater transport modelling on a scale of 10–100 m, detailed information about the spatial distribution of hydraulic conductivity is of great importance. At a test site (10 × 20 m) in the alluvial gravel-and-sand aquifer of the perialpine Thur valley (Switzerland), four different methods were applied on different scales. The comparison of the results showed that *multilevel slug tests* give the most reliable results at the required scale. For their analysis, a plausible value of the anisotropy ratio ( $K_{\text{vertical}}/K_{\text{horizontal}}$ ) is needed. For alpine and perialpine aquifers, a range of 0.1–0.2 can be expected. *Flowmeter logs* are recommended, if the relative distribution of hydraulic conductivity is of primary importance. *Sieve analyses* should be used, if an accuracy of a factor of 3 is acceptable. *Pumping test* results indicate the upper boundary of the natural spectrum of hydraulic conductivity at the scale of the test site.

## **75. Denitrification hot spot and hot moments in a restored riparian system**

Water samples were collected along hydrological connectivity in different functional process zones (FPZs) (*sensu* Thorp *et al.*, 2006) of a restored riparian zone of the River Thur, Switzerland. Denitrification was determined by the stable N and O isotope ratios of nitrate ( $\text{NO}_3^-$ ) and the abundance of functional denitrification genes, and related to organic carbon (OC) concentrations and discharge. The results showed that substantial losses of  $\text{NO}_3^-$  and an enrichment of  $^{15}\text{N}$  and  $^{18}\text{O}$  in the residual  $\text{NO}_3^-$  pool occurred post-flooding in a FPZ where the abundance of denitrification genes was increased and the vegetation cover was dominated by willow, a pioneer plant exhibiting high belowground C-dynamics. During flooding, dissolution of plant-derived OC occurred and fuelled post-flood denitrification activity in the groundwater. Thus, the interplay of FPZ configuration, subsurface hydrology, and flow regime of the river help direct the formation of denitrification hot spots and moments in a restored riparian system.

#### **76. Towards developing conceptual models for reactive contaminant transport in karst**

Conceptual models for reactive contaminant transport in karst groundwater must consider the reaction processes of specific contaminants in addition to the variable and complex flow regime. Due to insufficient information about the *in situ* relevance of attenuation processes, such concepts are in an early stage. A comparative tracing approach in conjunction with laboratory batch experiments allowed estimates to be made of attenuation *in situ* and on a process-scale. Examples for solute and colloid tracing experiments in the vadose and saturated zones of Swiss karst aquifers are presented and the consideration of specific mechanisms, such as biodegradation, kinetic sorption and colloid exclusion, are discussed. Such experiments may provide the basis for the development of coherent conceptual models of specific contaminant types in karst systems, while considering the effectiveness of the processes involved in different recharge and flow components.

#### **77. Particle density distribution measurements to control water quality of karst springs**

Karst springs are often very vulnerable to microbial contamination after rain events. Beside microorganisms, typically discharge, turbidity, the spectral absorption coefficient at 254 nm (SAK) and the number of particles increase rapidly, with a long tailing after a rain event. Measuring these parameters would allow an increase of the security of the management system for drinking water. However, small water suppliers often do not have enough means to acquire measurement systems which measure all these parameters. Often, it is also not necessary to measure all parameters because they are redundant, or, depending on the karst system, weak proxy variables for microbial contamination. To support such water suppliers, we developed a mobile measurement system which can be installed for a certain period in the karst spring. After the measurement period, suggestions can be made to water suppliers on which parameter is most sensitive and thus should be measured to decide when the water quality declines. For a case study, we installed the mobile measurement system in a karst spring in the Canton Basel-Landschaft, Switzerland.

#### **78. Estimating the vulnerability of karst springs to microbial contamination based on numerical flow modeling**

An approach is presented to develop an indicator for the vulnerability of karst springs to faecal contamination. The indicator is expressed as the Dynamic Vulnerability Index (DVI) and determined by the ratio of conduit to diffuse flow contributions to spring discharge. DVI is calculated based on a numerical model simulating karst water flow. The performance of DVI to estimate the risk of faecal spring water contamination was tested at a karst spring in northwest Switzerland. Five recharge events were sampled at the spring, and analysed for faecal indicators (FI). The comparison of DVI with FI showed that maximum DVI values correlate with maximum FI levels by trend in this study. In addition, DVI was capable of giving an early warning of elevated FI levels in four of the five analysed events. It is concluded that DVI holds promise for the assessment of microbial pollution risks of karst springs.

#### **79. Thermal groundwater use in urban areas - Spatiotemporal scales and concepts**

Over the last few decades, the use of the urban subsurface and urban groundwater resources has increased significantly. The application of groundwater for process and cooling purposes in particular may result in considerable pressure on urban aquifers. Additionally, the extension of subsurface infrastructures and the diffuse heat input of heated buildings have resulted in elevated groundwater temperatures in many urban areas. Therefore, for the sustainable development of urban subsurface resources, adequate management approaches are required. This includes the development of tools that will facilitate investigation of groundwater and heat flow processes at relevant spatiotemporal scales. An approach is presented where data from high resolution depth-oriented temperature monitoring are incorporated into 3-D numerical models that facilitate the simulation of groundwater flow and thermal regimes. The results form the basis for the development of concepts for the use of the urban subsurface for specific aquifer regions and future use scenarios.

#### **80. Risk analysis for riverine groundwater extraction**

Natural filtration in aquifers can improve the quality of groundwater relative to infiltrating surface water. During high discharge events, the microbial load of the groundwater can be several orders of magnitude higher than under normal flow conditions. The risk of contamination of groundwater extraction wells through infiltrating river water has been assessed by: (1) considering hydraulic gradients between the river and the groundwater, as well as the behaviour of quality parameters, such as turbidity, electrical conductivity and spectral absorbance coefficient; (2) principal component analysis to identify areas, time periods and parameters sensitive to infiltrating river. The results illustrate the major processes influencing the groundwater body in the study area, thus enabling a real-time assessment of potential sources of contamination.