Artificial recharge of a shallow hard rock aquifer as a climate change mitigation method: model solution from the Czech Republic

David Rozman^{1,2} · Zbyněk Hrkal^{1,2} · Miroslav Tesař³

Received: 3 October 2018 / Accepted: 10 November 2018 / Published online: 14 November 2018
© The Author(s) 2018, corrected publication 2018

Abstract

Drought has always been one of the crucial water management issues especially in a dry climate areas. Recently this matter is emerging also in the Czech Republic and in other parts of the temperate and continental climate zone. With progressing climate changes, we can expect that the current water management systems will often have to adapt to new conditions. This paper offers an evaluation of artificial recharge as a drought mitigation method in areas with crystalline bedrock. The core of the study is a pilot location model solution, which provided a tool to assess the efficiency of artificial recharge, operated in order to improve water budget of a shallow hard-rock aquifer. The results of simulations confirmed suitability of artificial recharge through infiltrations wells or ponds, which significantly enhanced water budget of the experimental catchment and improved its potential as a water resource.

Keywords Drought · Artificial recharge · Hard rock · Shallow aquifer · Modeling · Czech Republic

Introduction

The effect of climate change and long term drought on water resources is becoming an important water management issue for many regions worldwide, including Central Europe. Higher temperatures and changes in yearly temperature and precipitation patterns considerably affect local water supply systems. A statistically significant raise of surface evaporation has been recorded in Central Europe during last decades and because of the rising temperatures this trend is expected to continue in the future (Dezsi et al. 2018; Orth et al. 2016; Teuling et al. 2009; Seneviratne et al. 2006). According to Kašpárek (2007), the annual increase of evaporation in the area is approximately 5 mm. The same source is also presenting a record of local changes in seasonal distribution of rainfall, with a decrease in summer precipitation and increase in winter precipitation. In consequence a larger

portion of summer precipitation is absorbed by vegetation or evaporated and a deficit in aquifer cannot be compensated by increased precipitation in winter months.

A major part of Czech Republic is formed by crystalline bedrock, where groundwater occurs in shallow aquifer in permeable fissures and weathered zones. Similar hydrogeologic structures have been recognized as an interesting alternative groundwater resource by several researchers in different regions (Gustafson and Krásný 1994; Guihéneuf et al. 2014; Baiocchi et al. 2016). Shallow fissured aquifers may locally reach to depths of several tens of meters. Sufficient amount of precipitation and high hydraulic gradient caused by rough topography lead to dynamic circulation of groundwater. In mountainous regions in the Czech Republic the specific groundwater runoff reaches values between 8 and 15 l/s (Krásný et al. 2012). Such aquifer may provide an important local water resource. However, in comparison to deep sedimentary basin structures, shallow hard rock aquifers can be very vulnerable to drought, due to low accumulation capacity. Previous studies on Na Lizu site confirmed, that decrease in precipitation, which recharge shallow aquifer, leads to quick subsequent decrease of well yield in a given aquifer. According to the results of the hydraulic model, even a small drop in infiltration has a fundamental impact on transmissivity in shallow hard rock aquifers (Hrkal et al. 2007).

✉ David Rozman
david.rozman@vuv.cz

¹ Faculty of Science, Charles University, Albertov 6, Prague, Czech Republic

² T.G. Masaryk Water Research Institute, Podbabská 30, Prague, Czech Republic

³ Academy of Sciences, Hydrodynamic Institute, Podbabská 13, Prague, Czech Republic

Artificial recharge is one of the possible approaches to mitigate the effect of drought by slowing down runoff from catchments and directly replenishing groundwater resources (Ringleb et al. 2016; Benseddik et al. 2017). The source of infiltrating water can be surface water captured during heavy precipitation events to control floods. However a modern trend known especially from some arid and semiarid regions is infiltration of treated wastewater. Such approach substantially improves the effectiveness of water management in a given catchment. Experiences from Israel, Spain, USA, Australia, China, Iran, Jamaica, Morocco, South Africa and also from localities in Bohemian Massif in Czech Republic confirm, that process of attenuation in aquifers is capable to eliminate most of the casual pollutants in wastewater (Lallana and Krinner 2001; Ringleb et al. 2016; Rozman et al. 2013, 2017). The European Environment Agency reports an increasing trend in artificial recharge in a number of above mentioned countries (Lallana and Krinner 2001). Nevertheless, such technology of mitigation of drought in hard rock aquifers is practically unused in Czech Republic.

The modeling techniques proved to be a suitable tool for assessments, predictions of MAR (Managed Aquifer Recharge) and its operational schemes. Due to its flexibility, modeling assessment is often recommended to perform as a preliminary experiment (Maliva et al. 2015; Chitsazan and Movahedian 2015).

The purpose of our study is to provide expert outcomes about effectiveness of artificial recharge in a mountainous hard rock region and its application as one of the groundwater withdrawals mitigation methods. The results of the study may be used as a material for further investigation, which could gradually lead to legislation adjustments and wider implementation of this technology.

Methods and experimental catchment

The subject of our research was studied by application of numerical modeling tools BILAN and MODFLOW. The combination of both tools enabled us to perform an experimental simulation of surface and groundwater flow in the catchment Na Lizu.

The experimental catchment Na Lizu is situated in the Šumava Mountains in Southern Bohemia, about 120 km SW of the capital Prague (Fig. 1) The surface elevation ranges between 829 and 1071 m a.s.l. with mean elevation at 946 m a.s.l. It covers an area of 0.85 km².

The bedrock of the site consists of Proterozoic biotite paragneisses and migmatites, which are locally covered by Holocene deluvial and fluvial loams or loamy and pebbly deposits. The area has no distinctive tectonic structures. However, the bedrock is partly weathered and fissured to depth of several meters. The fissures and fractures are less

Fig. 1 Position of study area marked on the map of Central Europe (map source: Natural Earth)

abundant in greater depths and therefore also permeability is decreasing with depth.

The required data were acquired by the Czech Academy of Sciences, which runs monitoring system on the site (Fig. 2). The model area was defined as a catchment of the surface water closing profile, with discharge record. The available meteorological records come from the borders of the catchment. This enables us to define representative meteorological conditions for the area by interpolation of the selected data series. The temperature and precipitation measurement stations are located on open meadows (M) as well as in the spruce and beech forests (I, L), which provides good information about interception of precipitation by the vegetation. The arrangement of the stations also enables analyses of temperature and precipitation patterns dependent on elevation of the terrain. The only groundwater level measurement points are two 25 m deep boreholes. One is located in the upper part of the catchment (WI) and the second borehole is located close to the northeastern border in the lower part of the catchment (WD). For model calibration purposes several groundwater level control points were defined. The values at those points were derived from the available groundwater depth data and its proximity to the creek, where groundwater level corresponds to the surface.

The first step of the assessment was hydrological modeling in BILAN, which simulates water balance components in a catchment. The model was developed by T.G. Masaryk

Water Research Institute (Prague, Czech Republic) and was described in Tallaksen and van Lannen (2004). It has been further developed during the last decade and it has proven to be a reliable tool in local conditions (Vizina et al. 2015; Hanel et al. 2012; Horáček et al. 2008). The structure of the model is constructed by a system of equations describing basic principles of water balance. It simulates the process on the surface, in the soil aeration zone including the effect of vegetation and in the saturated zone. Air temperature is used as an indicator of energy conditions, which significantly affect the water balance components. The time resolution of the model is 1 day.

The input data includes daily series of precipitation, air temperature and relative air humidity. The required datasets were generated for the reference period from year 2009 to 2016. In mountainous regions, meteorological values vary significantly depending on elevation. Therefore data from several measurement stations were first statistically analyzed to find relations between them. The output of the statistical analysis was a factor, which was then used to correct the original data series and get new data series representative for the catchment.

The first step of preparation of air temperature data was calculation of the annual mean temperatures for stations M, L and I (Fig. 2). The annual mean values were then compared to elevations of the respective stations and linear regression equation was found. The equation was used to calculate annual mean air temperature for the catchment, by setting elevation at 946 m a.s.l. and subsequently a correction factor was computed by comparing this value to mean value from one of the measurement stations. Original daily data series were then corrected by the computed factor. This procedure enabled usage of all of the accessible data from different stations to gain new data series representative for the catchment. The approach is based on proportionality of the meteorological values and elevation. The same procedure was used also to generate catchment representative data series of relative humidity and precipitation.

The BILAN model simulates the amounts of water stored in the snow pack, in the soil and in the aquifer. The simulated flow of water is dependent on six free parameters:

- capacity of soil moisture storage
- snow melting factor
- parameter controlling outflow from direct runoff storage
- parameter controlling distribution of percolation into direct runoff and groundwater recharge under summer conditions
- parameter controlling distribution of percolation into direct runoff and groundwater recharge under snow melting conditions
- parameter controlling outflow from groundwater storage

Fig. 2 Delineation of the experimental catchment, its topography and input data measurement points

The parameters are calibrated using an optimization algorithm. The optimization process employs MAPE criterion to find the best fit between the observed and simulated runoff at the outlet from the catchment (Fig. 3) (BILAN 2015). The gained results are potential and actual evapotranspiration, soil infiltration and recharge of the aquifer.

The BILAN output was used as a crucial input for the MODFLOW hydraulic model. The MODFLOW tool was developed by McDonald and Harbaugh (1984) of the US Geological Survey and had been updated for several times (Harbaugh et al. 2000; Harbaugh 2005). It is a widely used international standard for hydraulic modeling of groundwater conditions (Yeh 2015; Singha et al. 2016).

The hard rock aquifers are characterized by fracture systems, in which groundwater flow has a discrete character to a certain extent. However, due to high degree of weathering and dense fissuring network, this study assumes aquifers as an equivalent porous medium. This approach is often applied in similar conditions (Jaunat et al. 2016; Hrkal et al. 2009; Carrera et al. 1990). The primary and secondary porosity and the hydraulic conductivity distribution are replaced by continuous porous medium having equivalent hydraulic properties (Cook 2003).

The geometry of the model is derived from a digital model of the terrain elevations in 10×10 m resolution and thickness of aquifers, which is estimated based on well log data from boreholes in the location. The assumed thickness of the shallow aquifer is gradually rising from 9 m in the

upper part, to 13 m in the lower part of the catchment. This aquifer is underlain by another 15 m thick layer, with lower permeability, which represents a transition to impermeable bedrock in greater depths. For steady state simulation of the current natural situation, the model was completed by definition of no flow boundary condition along the watershed a recharge boundary condition over the area and a line of drainage, which represents a creek. A well and a river boundary conditions were added in the shallow aquifer to simulate different pumping rates and artificial recharge.

The calibration was performed by parameter sensitivity analysis and PEST automatic calibration tool.

After calibration the model was used for simulation of several hypothetical conditions, including long term drought and artificial recharge in the upper part of the experimental catchment.

Results and discussion

The hydrologic model provided parameters of the experimental catchment (Table 1). For reference period 2010–2016 the mean annual rainfall reached 843 mm and mean annual air temperature 6.1°C . Mean snow cover period is 92 days/year and specific total runoff is 11.7 l/s/km^2 . According to the model 28% of precipitation is infiltrated and recharges the groundwater. In terms of this study, those are normal conditions. In year 2015, the wider area of Central Europe

Fig. 3 Comparison of measured and simulated values of runoff

Table 1 Annual mean values of the meteorological and hydrological parameters of the experimental catchment Na Lizu

Period	9/2010 to 1/2016	11/2014 to 1/2016
P (mm)—precipitation	843	534
T (°C)—air temperature	6.07	6.28
PET (mm)—potential evapotranspiration	508	515
ET (mm)—basin evapotranspiration	447	396
RC (mm)—recharge of groundwater	233	105
R (mm)—runoff observation	372	322
DR (mm)—direct runoff simulation	175	64
BF (mm)—baseflow simulation	243	190

including Czech Republic and Šumava Mts. experienced relatively severe drought (Orth et al. 2016). In the catchment Na Lizu, it was detected as temperature raise by 0.2 °C and a distinctive 37% loss of precipitation. The shallow aquifer was recharged by only 20% of precipitation. In contrary to 28% during whole reference period this is apparently a result of lower soil humidity and increased evapotranspiration. The amounts of recharge and baseflow during whole reference period are practically equal, which is characteristic for a balanced system. However, during year 2015 the amount of baseflow was much higher than recharge. Apparently in such situation the long term water reserves of the catchment were used. In terms of this study, the outputs of the hydrologic model for year 2015 define drought conditions.

After calibration of the MODFLOW model, the hydraulic conductivity was set as follows:

- for upper layer K_{xy} (in lateral directions) in a range between 9.3×10^{-6} and 1.0×10^{-5} m/s
 K_z (in vertical direction) 5.8×10^{-6} m/s
- for lower layer K_{xyz} (in all directions) in a range between 7.0×10^{-8} and 5.6×10^{-7} m/s

Normal conditions and drought

The basic results of hydraulic modeling in MODFLOW are groundwater levels for normal conditions presented in the Fig. 4. For normal conditions recharge was set according to the hydrologic model to 233 mm/year. The depth of the groundwater level reached in general from 10 m in the upper part of the catchment to 3 m in the lower part. For drought conditions recharge was set to 105 mm/year. Such conditions caused a significant fall of groundwater levels, with 2–5 m drawdown in major part of the catchment, but also as much as 22 m on the highest parts of the watershed.

Fig. 4 Contours of groundwater level for normal conditions and drawdown of groundwater level during drought

Managed aquifer recharge (MAR)

Managed aquifer recharge was simulated as infiltration through recharge ponds and through infiltration wells. Both means of managed recharge were assessed and compared to each other.

Hypothetic infiltration objects were set in the MODFLOW model as cells with river type boundary condition in the upper part of the catchment at elevation of 996 m a.s.l. Each recharge pond was defined as 10 m long, 3 m wide and 3 m deep basin, with 0.5 m thick gravel bed. The water level was set constantly to 1 m below surrounding terrain. The infiltration wells were defined as 9.5 m deep boreholes with 0.3 m in diameter. The water level was again set constantly to 1 m below surrounding terrain. For simulation with several objects, the distance between individual objects was approximately 40 m, according to estimated distance of direct influence for such objects. Distance of influence was estimated based on Kusakin equation calculation (Aravin and Numerov 1953):

$$R = 575 \text{ s} (K H)^{0.5} \quad (1)$$

where R = radius of influence (44 m), s = drawdown/water level raise (8.3 m), K = hydraulic conductivity (9×10^{-6} m/s), H = initial thickness (9.5 m).

As presented in the table (Table 2), infiltration wells have lower effectivity than infiltration ponds. For simple systems

Table 2 Achieved infiltration rates for different settings of infiltration objects in drought conditions

Recharge facility	Achieved infiltration rate (m ³ /day)	Recharge facility	Achieved infiltration rate (m ³ /day)
1 Well	52	1 Pond	72
2 Wells	89	2 Ponds	115
3 Wells	119	3 Ponds	149
4 Wells	150	4 Ponds	184

a single object has infiltration capacity from 52 to 72 m³/day. For systems with several objects the overall infiltration capacity is higher, but the effectivity of a single object in the system is decreasing with increasing number of objects, due to their interaction. Although the theoretical radius of influence, calculated based on groundwater hydraulic theories, is relatively short, the effect of managed aquifer recharge is much wider. The model simulated the raise of groundwater level due to MAR even in the lower parts of the catchment.

MAR can be affected by clogging, when conductance of the infiltration objects reduces over time, due to differed chemical, physical and biological process. This study is not taking into account this phenomenon. However, the issue of clogging associated with MAR is described in detail in a monograph by Martin (2013).

Further assessment of MAR in this study is based on simulation of two recharge ponds at 120 m distance and with very low interaction. This state results in infiltration rate 122 m³/day in normal conditions and 138 m³/day in drought conditions. Such setting in practice would probably represent a compromise solution with significant volume of infiltrated water and reasonable technical and financial demands of the system. A resulting extensive raise of groundwater level in the catchment is presented in next figures (Figs. 5, 6).

Managed aquifer recharge and groundwater extraction in drought

The impact of drought was demonstrated also by setting a hypothetical extraction well in the lower part of the catchment. In normal conditions its maximum yield reached 88 m³/day, while in drought conditions its maximum yield decreased to 24 m³/day. MAR in drought conditions enables maximum yield 55 m³/day. The effect of MAR in such situation is presented in Fig. 7.

According to the model results, a single extraction well enables to retrieve about 40% of the water, artificially recharged in the upper parts of the catchment. The excess of the infiltrated water can be perceived as a contribution to drought mitigation of a wider area. However, more sophisticated groundwater extraction in lower part of the catchment could enable more efficient retain of the infiltrated water.

Fig. 5 Groundwater level raise due to managed aquifer recharge in normal conditions **Fig. 6** Groundwater level raise due to managed aquifer recharge in drought conditions

Fig. 7 Groundwater level raise due to managed aquifer recharge during drought conditions and groundwater extraction

Although this study is based on model simulations, which provide a theoretical solution, it tends to assess MAR within realistic limits. The simulated infiltration rate in drought is $138 \text{ m}^3/\text{day}$ or 1.6 l/s . The nearby town Zdíkov is located about 3 km north of the experimental catchment and it has about 2000 residents (permanent inhabitants and tourists). According to average water consumption in Czech Republic (90 l/day/person) those people use about $180 \text{ m}^3/\text{day}$ or 2 l/s . Due to loss of water in the system, the production of wastewater is slightly lower and can be estimated to approximately the same rate as simulated infiltration rate. The town operates a conventional mechanical–biological wastewater treatment plant and its effluent could potentially be used as a source of the infiltrated water for a similar artificial recharge site.

Conclusions

The combination of hydrologic and hydraulic modeling provided the results to assess the impact of drought and its possible mitigation method in specific conditions of mountainous hard rock shallow aquifer.

The simulation of drought event, recorded in year 2015, resulted in a distinctive 37% loss of precipitation, raise of air temperature and consequently only 45% of recharge (compared to long term average). Simulation of drought showed

a significant drawdown of groundwater levels, especially in the areas close to the watershed but also in the vicinity of the draining creek.

Simulation of artificial recharge through infiltration wells and recharge ponds proved the efficiency of both techniques. The most appropriate tested mode of MAR for the site is two recharge ponds, with infiltration capacity $122 \text{ m}^3/\text{day}$ in normal conditions and $138 \text{ m}^3/\text{day}$ in drought conditions. Such artificial recharge generates an extensive raise of groundwater level in the catchment and enables higher yield of the extraction wells. A single extraction well in the lower part of the catchment retrieves about 40% of water artificially recharged in the upper part of the catchment. More sophisticated extraction scheme could enable more efficient retain of the infiltrated water.

The potential source for MAR in the experimental catchment is treated waste water from a nearby town Zdíkov, which could supply sufficient amount of water.

Although this study is based on realistic input data it provides rather generalized preliminary results. Any construction project on the pilot site should be supported by further detailed investigation (e.g. infiltration tests, assessment of the attenuation potential of the aquifer).

According to the results of this study, MAR is an interesting technique of drought mitigation also for vulnerable shallow hard rock aquifers in regions like Central Europe.

Acknowledgements The research leading to these results was financially supported by GA UK-Charles University Grant Agency.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Aravin VI, Numerov SN (1953) Theory of motion of liquids and gases in undeformable porous media. Gostekhizdat, Moscow, pp 616 (Russian)
- Baiocchi A, Lotti F, Piscopo V (2016) Occurrence and flow of groundwater in crystalline rocks of Sardinia and Calabria (Italy): an overview of current knowledge. *Acque Sotter Ital J Groundw* 5. <https://doi.org/10.7343/as-2016-195>
- Benseddik B, El Mrabet E, El Mansouri B, Chao J, Kili M (2017) Delineation of artificial recharge zones in Mnasra Aquifer (NW, Morocco). *Model Earth Syst Environ* 3:10. <https://doi.org/10.1007/s40808-017-0267-2>
- BILAN water balance model (2015) User manual. T.G. Masaryk Water Research Institute, Prague
- Carrera J, Heredia S, Vomvoris S, Hufschmied P (1990) Modeling of flow with a small fractured monzonitic gneiss block. In: *Hydrogeology of low permeability environments*. IAH Selected Papers 02, Heise, Hanover, Germany, pp 115–167

- Chitsazan M, Movahedian A (2015) Evaluation of artificial recharge on groundwater using MODFLOW model (case study: Gotvand Plain-Iran). *J Geosci Environ Prot* 3:122–132. <https://doi.org/10.4236/gep.2015.35014>
- Cook P (2003) A guide to regional groundwater flow in fractured rock aquifers. CSIRO, Dickson ACT, Australia, p 115
- Dezi S, Mîndrescu M, Petrea D, Rai PK, Hamann A, Nistor M-M (2018) High-resolution projections of evapotranspiration and water availability for Europe under climate change. *Int J Climatol* 38:3832–3841. <https://doi.org/10.1002/joc.5537>
- Guihéneuf N, Boissona A, Bour O, Dewandel B, Perrina J, Dausse A, Viossanges M, Chandra S, Ahmed S, Maréchal JC (2014) Groundwater flows in weathered crystalline rocks: Impact of piezometric variations and depth-dependent fracture connectivity. *J Hydrol* 511:320–334. <https://doi.org/10.1016/j.jhydrol.2014.01.061>
- Gustafson G, Krásný J (1994) Crystalline rock aquifers: their occurrence, use and importance. *Hydrogeol J* 2:64. <https://doi.org/10.1007/s100400050051>
- Hanel M, Vizina A, Máca P, Pavlásek J (2012) A multi-model assessment of climate change impact on hydrological regime in the Czech Republic. *J Hydrol Hydromech* 60(3):152–161. <https://doi.org/10.2478/v10098-012-0013-4>
- Harbaugh AW (2005) MODFLOW-2005, The U.S. Geological Survey modular ground-water model - the ground-water flow process. In: US Geological Survey Techniques and Methods. U.S. Geological Survey, Reston, Virginia, USA. <https://pubs.usgs.gov/tm/2005/tm6A16/PDF/TM6-A16front.pdf>
- Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, The US Geological Survey modular groundwater model—user guide to modularization concepts and the groundwater flow process. US Geological Survey Open-File Report 00-92. Reston, Virginia
- Horáček S, Kašpárek L, Novický O (2008) Estimation of climate change impact on water resources by using Bilan water balance model. *IOP Conf Ser: Earth Environ Sci* 4:012023. <https://doi.org/10.1088/1755-1307/4/1/012023>
- Hrkál Z, Kobl M, Nedvěďová E, Tesar M, Vilhelm Z (2007) Impact of global climate change on transmissivity of shallow hard-rock aquifers. In: Marszałek H, Chudy K (eds) 2007: Selected hydrogeological problems of the Bohemian massif and other hardrock terrains in Europe. *Acta Universitatis Wratislaviensis, Hydrogeologia* 07, pp 191–203
- Hrkál Z, Milický M, Tesar M (2009) Climate change in Central Europe and the sensitivity of the hard rock aquifer in the Bohemian Massif to decline of recharge: case study from the Bohemian Massif. *Environ Earth Sci* 59:703–713
- Jaunat J, Dupuy A, Huneau F et al (2016) Groundwater flow dynamics of weathered hard-rock aquifers under climate-change conditions: an illustrative example of numerical modeling through the equivalent porous media approach in the north-western Pyrenees (France). *Hydrogeol J* 24:1359. <https://doi.org/10.1007/s10040-016-1408-9>
- Kašpárek L (2007) Research and protection of hydrosphere—investigation of relations and process in aqueous component of the environment focused on anthropogenic effects, permanent exploitation of hydrosphere and its protection including legislative measures. MS, TG Masaryk Water Research Institute, Prague
- Krásný J, Císlarová M, Čurda S, Dátl J, Dvořák J, Grmela A, Hrkál Z, Kříž H, Marszałek H, Šantrůček J, Šilar J (2012) Groundwater in the Czech Republic—Regional hydrogeology of groundwaters and mineral waters. Czech Geological Survey, Prague, Czech Republic, ISBN 978-80-7075-797-0
- Lallana C, Krinner W (2001) Sustainable water use in Europe. Part 2: Demand Management. Environmental Issue Report No. 19
- Maliva RG, Herrmann R, Coulibaly K (2015) Advanced aquifer characterization for optimization of managed aquifer recharge. *Environ Earth Sci* 73:7759. <https://doi.org/10.1007/s12665-014-3167-z>
- Martin R (ed) (2013) Clogging issues associated with managed aquifer recharge methods. IAH Commission on Managing Aquifer Recharge, Australia. https://recharge.iah.org/files/2015/03/Clogging_Monograph.pdf. Accessed 16 May 2018
- McDonald MG, Harbaugh AW (1984) A modular three dimensional finite-difference ground-water flow model. US Geological Survey Open-File report, pp 83–528
- Orth R, Zscheischler J, Seneviratne SI (2016) Record dry summer in 2015 challenges precipitation projections in Central Europe. *Sci Rep* 6:28334. <https://doi.org/10.1038/srep28334>
- Ringleb J, Sallwey J, Stefan C (2016) Assessment of managed aquifer recharge through modeling—a review. *Water* 8:579. <https://doi.org/10.3390/w8120579>
- Rozman D, Hrkál Z, Eckhardt P, Novotná E, Vencelides Z (2013) Waste water recharge—case study of Řevničov site. *VTEI* 55:6 (ISSN 0322-8916)
- Rozman D, Hrkál Z, Váňa M, Vymazal J, Boukalová Z (2017) Occurrence of pharmaceuticals in wastewater and their interaction with shallow aquifers: a case study of Horní Beřkovice, Czech Republic. *Water* 9(3):218
- Seneviratne SI, Lüthi D, Litschi M, Schär C (2006) Land-atmosphere coupling and climate change in Europe. *Nature* 441(7108):205–209. <https://doi.org/10.1038/nature05095>. 443).
- Singha S, Verma MK, Singha S (2016) Application of GIS and MODFLOW to ground water hydrology—a review. *Int J Eng Res Appl* 6(1):36–42 (ISSN:248-9622)
- Tallaksen LM, van Lannen HAJ (2004) Hydrological Drought—process and estimation methods for streamflow and groundwater. Elsevier, Amsterdam
- Teuling AJ et al (2009) A regional perspective on trends in continental evaporation. *Geophys Res Lett* 36:L02404. <https://doi.org/10.1029/2008GL036584>
- Vizina A, Horáček S, Hanel M (2015) Recent developments of the BILAN model. *VTEI* 57:4–5 (ISSN 0322-8916)
- Yeh WWG (2015) Review: optimization methods for groundwater modeling and management. *Hydrogeol J* 23:1051. <https://doi.org/10.1007/s10040-015-1260-3>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.