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Analiza shranjevanja toplote v vodonosnikih - možnost uporabe v Sloveniji

The Analysis of Thermal Energy Storage in Aquifers - the Possibility of Application in Slovenia

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Že nekaj desetletij se pojavljajo težnje po učinkovitejši rabi energije. K temu so pripeljale ugotovitve o razpoložljivih količinah fosilnih goriv in pa naraščajoča ekološka osveščenost ljudi. Zanemarljive pri tem niso bile niti nenehno rastoče cene goriv. Ker se v prihodnosti pričakuje še povečana raba energije, se raziskujejo možnosti za povečano izrabo obnovljivih virov in kakovostnejše izrabe energije. Kakovost rabe se večinoma povečuje s shranjevanjem energije (predvsem termalne) v različnih hranilnikih. To velja predvsem za odpadno toploto, ki jo pridobimo pri določenih tehnoloških postopkih in jo večinoma zavržemo. To toploto je mogoče koristno izkoristiti v ogrevalnih sistemih z nizkimi temperaturami. Enako velja za toploto, odvzeto s kondenzatorjev klimatizacijskih naprav.

Ena od rešitev je shranjevanje te energije v sezonskih hranilnikih, med katere spada tudi vodonosnik. Ker so ti precej obsežni, je vanje mogoče shraniti velike količine energije.

Namen prispevka je raziskati pregled metod za analiziranje shranjevanja toplote v vodonosnikih, predstavitev teh hranilnikov v svetu z osnovnim matematičnim popisom dogajanja v vodonosniku ter možnost za uporabo v Sloveniji.

(Ključne besede: hranilniki toplote, vodonosniki, prenos toplote, prenos snovi)

Tendencies towards rational energy use have been appearing for the last decades due to the fact of limited quantities of fossil fuels and increased ecological awareness. Also the rising prices of all fuels should be taken into account. Since energy consumption will increase in the future, the possibility of using renewable energy resources and rational energy use are investigated. The quality of energy exploitation can be increased by storing thermal energy in different types of storage. This is especially important for waste heat from industrial processes, which is usually thrown away. This heat can be efficiently used in low-temperature heating systems. The same holds true for heat from condensing units of air-conditioning systems.

One of the solutions is thermal energy storage in seasonal storage, where aquifers are one of the possibilities. Since they are very large, the amount of heat that can be stored is very high.

The paper gives a review of thermal energy storage methods in aquifers, describes such storage in the world with a basic mathematical description of the processes in aquifers, and presents the possibilities of use in Slovenia.

(Keywords: thermal storage, aquifers, heat transfer, mass transfer)

1 SPLOŠNO O HRANILNIKIH TOPLOTE

Namen hranilnikov je shranjevanje energije takrat, ko je ne potrebujemo, hkrati pa morajo omogočati odvzem energije, ko jo potrebujemo [1].

Tak primer je toplotna energija, ki jo pridobivamo poleti. Proizvodnja je v tem letnem času lahko precej večja od porabe. V tem primeru toploto shranimo in jo v ogrevalni sezoni ponovno odvzamemo. Enako velja tudi za toploto, ki jo odvajamo s kondenzatorjev hladilnih naprav. Brez prevelikega

1 GENERAL ABOUT THERMAL STORAGE

Thermal storage is used for storing energy at the time when it is available and must be able to release energy when it is needed [1].

An example of this is energy that is stored during the summer. The production of heat at this time is much larger than its utilization. In this case energy is stored and extracted during the heating season. The same principle is used with heat from condensers of cooling devices. Without additional truda in vlaganja energije lahko v zimskih mesecih shranjujemo hlad. Proizvodnja hladu v poletnih mesecih je namreč izredno draga. Tako hranilniki termalne energije omogočajo izboljšanje izkoristka sistema, s tem pa precejšnje zmanjšanje stroškov ogrevanja in hlajenja.

Dolgotrajni hranilniki toplote so namenjeni sezonskemu shranjevanju termalne energije. Ločimo zemeljske, vodne in kombinirane dolgotrajne hranilnike toplote. Pri vračanju toplote si pri nižjih temperaturah pomagamo z uporabo toplotnih črpalk.

2 VODONOSNIKI

Podzemno vodo opredeljujemo kot vodo, ki se pojavlja pod površjem, ne glede na to, ali imamo opraviti z vodo v tleh, naplavinah ali kamninah. Pojav podzemne vode v odvisnosti od geoloških razmer opredelimo s hidrogeološko analizo in modelom. Tako kakor pri vsakem modelu tudi tukaj izhajamo iz nekaterih zasnov, ki pomagajo natančneje opisati in opredeliti dejanske razmere, ki vladajo v naravi. Tako je v središču zanimanja za podzemno vodo in njeno izkoriščanje model vodonosnika in njegov shematski profil.

Vodonosnik razdelimo na dva dela, ki ju med seboj ločuje gladina podzemne vode. Zgornji del vodonosnika pomeni nezasičeno območje. V tem predelu voda, ki prodira skozi tla, teče navpično navzdol skozi z vodo neprežete pore proti gladini podzemne vode. Pod slednjo leži zasičeno območje, v katerem so vse pore prežete z vodo. V tem predelu je tok vode pod vplivom gradienta in ga praviloma poenostavimo kot vodoravni. Zasičeno območje v spodnjem delu omejuje slabo prepustna podlaga vodonosnika [2].

Gladina podzemne vode lahko prosto niha, v kakšni meri niha, je odvisno od intenzivnosti napajanja in od hidrogeoloških lastnosti vodonosnika. Takšen tip vodonosnika imenujemo odprt vodonosnik. Poleg tega poznamo še zaprt tip vodonosnika, v katerem gladina podzemne vode ne niha prosto, ker je zgornji del vodonosnika neprepustna plast. V takšnem vodonosniku se spreminja le hidrostatični tlak. Če takšen vodonosnik prevrtamo z vrtino, se voda praviloma prelije na površino in opraviti imamo z arteškim vodnjakom. Seveda med obema tipoma vodonosnika obstajajo tudi prehodi, tako poznamo polodprt in polzaprt vodonosnik [2].

V hidrogeologiji označujemo kot vodonosnike praviloma tiste kamnine ali naplavine, ki so dovolj prepustni, da je iz njih mogoče izkoriščati podzemno vodo pod gospodarnimi pogoji. Dosedanje izkušnje kažejo, da se v Sloveniji podzemno vodo v večjih količinah izkorišča v rudninah, kjer so koeficienti hidravlične prevodnosti večji od 10^{-6} m/s, v zadnjem času pa tudi pri hidravličnih prevodnostih, večjih od 10^{-7} m/s. Takšna definicija je seveda nekoliko nenatančna in odvisna od trenutnih potreb po oskrbi z

energy, cold can be stored during winter, while the production of cold in the summer time is very expensive. In this way thermal energy storage can reduce costs for heating and cooling.

Long-term thermal storage is used for seasonal thermal storage, enabling the storage of waste heat and its use in the cold season. There are earth, water and combined long-term thermal storage. Heat pumps can be used at lower heat temperatures.

2 AQUIFERS

Groundwater is defined as water stored beneath the surface, either in the soil, sediments or rocks. The appearance of groundwater in relation to geological conditions is defined on the basis of hydrogeological analyisis and model. As in every model, some conceptual schemes are used as the starting point to enable a more precise description and determination of the actual conditions occurring in nature. In this way the aquifer model and its schematic profile become the centre of interest for groundwater and its exploitation.

The aquifer is divided into two parts, separated by groundwater table. The upper part of the aquifer is the unsaturated zone. In this zone, water that is infiltrated through the soil penetrates vertically through unsaturated pores down towards the water table. Beneath the water table lies the saturated zone where all pores are filled with water. In this zone, water flow is influenced by the gradient and is as a rule simply defined as horizontal. The lower part of the saturated zone is confined by a low-permeable aquifer bedrock [2].

Aquifers where the groundwater level can change freely, depending on the intensity of recharge and on the hydrogeological properties of the aquifer, are called unconfined aquifers. On the other hand, there is the confined type of aquifer, where the groundwater table cannot change freely, because the upper part of the aquifer is overlain by an impermeable layer. In such an aquifer, only the hydrostatic pressure changes. If such aquifer is penetrated by a well, the water flows to the surface, and this is an artesian aquifer. Of course there are also intermediate stages between the two aquifer types, known as semi-unconfined and semi-confined aquifers [2].

Hydrogeology defines as aquifers generally those rocks or sediments which are permeable enough to enable an economical exploitation of groundwater. Experience so far shows that in Slovenia groundwater is exploited in larger quantities in cases where permeability exceeds 10^{-6} m/s, and recently also when permeability is greater than 10^{-7} m/s. Such definition is of course somewhat inaccurate and depends on momentary demands of water supply or other groundwater uses. For vodo ali kakšni drugi uporabi podzemne vode. Glede na hidrogeološke lastnosti rudnine se je zato v praksi uveljavila tudi razdelitev, ki je odvisna od koeficienta hidravlične prevodnosti *K*. Kamnine ali naplavine, katerih koeficient hidravlične prevodnosti *K* je večji od 10^{-6} m/s uvrščamo v vodonosnike. Rudnine, v katerih še zasledimo podzemno vodo, imenujemo akviklude, zanje so značilne hidravlične prevodnosti med 10^{-6} in 10^{-12} m/s. Za kamnine ali naplavine, ki jih lahko s praktičnega vidika štejemo za neprepustne pa uporabljamo izraz akvifob, njihov koeficient hidravlične prevodnosti *K* je manjši od 10^{-12} m/s.

V kamninah in naplavinah je voda v porah povezanih med seboj, ki lahko glede na geometrijsko obliko zavzamejo različne oblike. Tako v naplavinah zasledimo medzrnsko poroznost, ki jo povzroči stik med zrni. V kamninah zasledimo razpoklinsko poroznost, ki nastane zaradi razpok. Tretji tip poroznosti je kanalska poroznost, ki jo predstavljajo kanali različnih izmer. Značilni vodonosniki s kanalsko poroznostjo so kraški vodonosniki, v katerih pogosto zasledimo kanale večmetrskih izmer. V rudnini lahko obstaja tudi kombinacija vseh tipov poroznosti. Tako poznamo vodonosnike z dvojno poroznostjo, ali pa celo s trojno poroznostjo.

3 MATEMATIČNI POPIS SHRANJEVANJA TOPLOTE V VODONOSNIKIH

Prenos toplote in snovi v vodonosniku je kombinacija prevoda, konvekcije in difuzije [3]. Splošno lahko to popišemo s teorijo potencialov. Zaradi zapletene narave fizikalnega pojava je treba uporabiti nekaj poenostavitev, kakor je predpostavka laminarnega toka podzemne vode. Nadalje predpostavimo nespremenljivo gostoto in viskoznost podzemne vode pri obravnavanih temperaturah.

3.1 Difuzija snovi

Matematični opis toka podzemne vode temelji na Darcyjevem zakonu. Ta popisuje linearno odvisnost med specifičnim pretokom *q* in gradientom hidravličnega potenciala grad *h*.

this reason, the division based on the coefficient of hydraulic conductivity *K* with regard to hydrogeological properties of the geological medium is also widely used. Rocks or sediments that have a coefficient of hydraulic conductivity *K* greater than 10^{-6} are classified as aquifers. Geological media where groundwater still occurs are called aquicludes and have conductivities between 10^{-6} and 10^{-12} m/s. Rocks and sediments which are practically impermeable are called aquifobes and their coefficient of hydraulic conductivity *K* is smaller than 10^{-12} m/s.

Water in rocks and sediments is found in interconnected pores that can take different forms with regard to geometry. Thus sediments have intergranular porosity, resulting from the contact between grains, interstitial porosity is found in rocks, due to the presence of interstices. The third type is channel porosity, represented by channels of different dimensions. Channel porosity is typical of karst aquifers where underground rivers flow in several metre wide channels. A geological medium can also have a combination of all types of porosity, e. g. there are aquifers with double or even triple porosity.

3 MATHEMATICAL DESCRIPTION OF HEAT STORAGE IN AQUIFERS

Heat- and mass- transport in aquifers is a combination of conduction, diffusion and convection processes [3]. In general, these processes can be described by the theory of potentials. The complex nature of physical phenomena requires some simplification, e.g. assuming fluid flow as laminar for groundwater flow calculations. Also density and viscosity of groundwater is assumed constant within the temperature range found in shallow underground.

3.1 Mass diffusion

Mathematical description of groundwater flow is based on Darcy's law. It describes a linear correlation between the specific flow *q* and the gradient in hydraulic potential grad *h*.

$$q=\frac{Q}{A}=-K\cdot grad\ \mathrm{h} \qquad (1).$$

Darcyjev zakon je primeren le za popis poroznih teles in laminarnega toka. Na mikroskopski skali je tok posamezne molekule v porah vodonosnika turbulenten, vendar pa na makro skali še vedno lahko govorimo o laminarnem toku. Ker je hidravlična prevodnost *K* nespremenljiva in le statistična vrednost popisa makroskopskega toka, velja le za majhna Reynoldsova števila (Re<10).

Darcy's law is only valid for porous media and laminar flow. In microscopic scale the individual water molecules have varying velocity due to variations in pore space leading to turbulence. The turbulent flow of the individual water molecules is leveled out in large volumes, and the flow can be considered as laminar. Hence Darcy's law with the constant *K* is a statistical description of macroscopic flow and is valid for small Reynolds numbers values (Re<10).

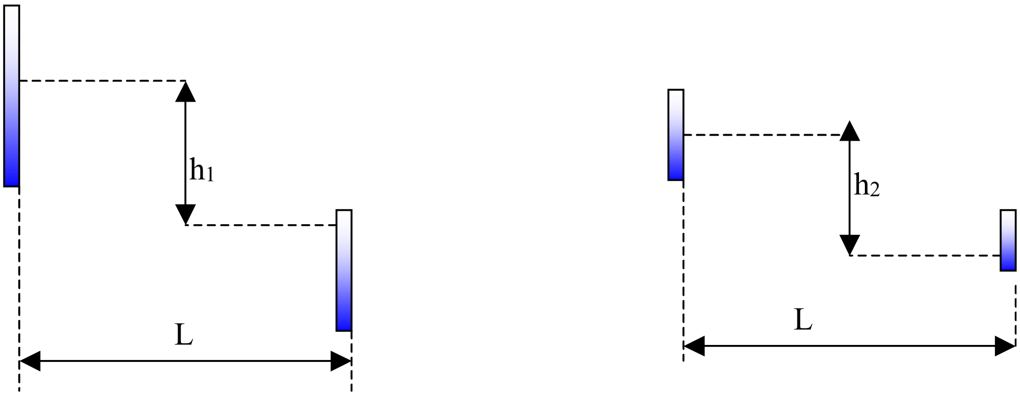
Za enorazsežen tok se zakon lahko poenostavi v obliko:

For one-dimensional flow the law can be simplified into:

$$q = \frac{Q}{A} = k\frac{h}{l} \qquad (2).$$

Pretok podzemne vode *Q* med dvema točkama je sorazmeren spremembi višine med točkama *h*, razdalje med točkama *l* in hidravlične prevodnosti snovi *K*, skozi katero teče tok. Hidravlična prevodnost je definirana s prepustnostjo snovi, hitrostjo tekočine in gravitacijsko silo. Slednji dve komponenti imata manjši vpliv, zato ju lahko poenostavimo s prepustnostjo.

The flow *Q* between two points is proportional to height *h*, distance *l* and hydraulic conductivity *K* of the medium through which the flow flows. Hydraulic permeability is defined with permeability of mass, flow velocity and gravity force. The last two components have smaller influence and can be approximated with permeability.



Sl. 1. *Prikaz definicije Darcyjevega zakona*
Fig. 1. *Presentation of the Darcy law definition*

Oba para vrtin na sliki1 sta enako oddaljena drug od drugega *l*, vendar imata različno hidravlično višino *h*. Zakon tako pravi, da bo tok večji tam, kjer je večja razlika potencialov.

Both wells have the same difference between them *l* but different hydraulic height *h*. The law says that the flow will be larger at higher height potential.

3.2 Zakon o ohranitvi snovi

3.2 Mass conservation law

Naslednji zakon, kateremu je podrejen sistem, je zakon o ohranitvi snovi. Ne glede na časovni korak *dt* je sprememba mase dm_{vol} v vodonosniku enaka razliki mase, ki vstopi, in mase, ki izstopi iz opazovane prostornine:

Furthermore groundwater flow is governed by the law of mass conservation, which is in hydrogeology also called the principle of continuity. Irrespective of the time interval *dt*, the mass change dm_{vol} within the aquifer equals the difference of the masses entering and leaving the observed volume.

$$\frac{m_{in}}{dt} - \frac{m_{out}}{dt} = \frac{dm_{vol}}{dt} \qquad (3).$$

Če postavimo telo v kartezični koordinatni sistem, in zaradi predpostavke o nespremenljivi gostoti tekočine, maso nadomestimo s specifičnim pretokom, dobimo:

Using the geometry of Cartesian co-ordinates and substituting mass flow by changes of the specific flow dq follows:

$$\frac{dq_x}{dx} + \frac{dq_y}{dy} + \frac{dq_z}{dz} = S_s\frac{dh}{dt} \qquad (4).$$

Z vstavitvijo Darcyjevega zakona v enačbo (4), ter dodanim členom vira oziroma ponora tekočine Q_w, dobimo diferencialno enačbo, ki opisuje trirazsežen tok v anizotropnem vodonosniku:

Inserting Darcy's law into equation (4) and adding a source/sink-term Q_w results in a partial differential equation describing a three-dimensional, transient flow in an anisotropic aquifer:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) - Q_w = S_s\frac{\partial h}{\partial t} \qquad (5).$$

Pri praktičnih izračunih splošno enačbo toka podzemne vode (5) po navadi glede na uporabo poenostavimo. Tako na desni strani zanemarimo časovno odvisnost shranjevanja energije in dobimo Laplaceovo enačbo. Nadalje lahko v večini primerov predpostavimo izotropni vodonosnik (K_x=K_y=K_z) ali pa zanemarimo navpični tok.

This general equation for groundwater flow often can be simplified for practical application. Thus for steady flow the right, time-dependent storage term can be neglected and the Laplace equation results. Furthermore, the assumption of an isotropic aquifer (K_x=K_y=K_z) is possible in most cases, or the omission of vertical flow.

3.3 Prevod toplote

3.3 Conductive heat transfer

Analogno hidravličnemu toku popišemo tudi toplotni tok $\dot{Q}_t$. Ta teče, kadar obstaja temperaturni gradient:

Analogous to the hydraulic transport equation a heat flow $\dot{Q}_t$ develops when a temperature gradient exists:

$$j = \frac{\dot{Q}_t}{A} = -\lambda \;\; grad \text{ T} \qquad (6).$$

Ko uporabimo zakon o ohranitvi energije za opazovano prostornino, lahko izračunamo spremembo temperature (dT) v kartezičnem koordinatnem sistemu:

Applying the law of energy conservation for a body of given volume, a temperature change (dT) can be calculated in Cartesian co-ordinates:

$$\frac{dj_x}{dx} + \frac{dj_y}{dy} + \frac{dj_z}{dz} = c\rho \frac{dT}{dt} \qquad (7).$$

Združitev enačb (6) in (7) da Fourierjevo diferencialno enačbo prenosa toplote, v splošnem to pomeni prevod toplote skozi anizotropno sredstvo:

The combination of Eq. (6) and (7) results in Fourier's differential equation of heat transport, which in general describes the transient conductive heat transport in anisotropic media:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) = c\rho \frac{\partial T}{\partial t} \qquad (8).$$

3.4 Konvektivni prenos toplote

3.4 Convective heat transfer

Konvektivni prenos toplote je vedno povezan s prenosom snovi v kapljeviti ali plinasti fazi. Pri tem je bistvena razlika med naravno in prisilno konvekcijo. Pri naravni temperaturi gradient povzroči razliko gostot, kar ima za posledico gibanje tekočine z željo po uravnovešenju stanja. Pri prisilni konvekciji je gibanje tekočine posledica različnih potencialov tlaka oziroma hidravličnih višin, zaradi tega pride še do prenosa toplote. Če tako vzamemo enako tekočino kakor v zgornji enačbi, ima enačba konvektivnega prenosa toplote naslednjo obliko:

Convective heat transport is always combined with mass transport in fluid or gaseous phase. A distinction can be made between free convection and forced convection. In free convection, temperature gradients cause differences in density. Mass transport tries to equilibrate and thus heat transport occurs. Forced convection is due to pressure differences like differences in hydraulic head leading to groundwater flow and consecutive heat transport. Assuming a flowing fluid has now thermal conductivity, a pure convection heat transport equation has the form:

$$\rho c Q_x \left(\frac{\partial T}{\partial x}\right) + \rho c Q_y \left(\frac{\partial T}{\partial y}\right) + \rho c Q_z \left(\frac{\partial T}{\partial z}\right) = c\rho \frac{\partial T}{\partial t} \qquad (9).$$

Prenos toplote s sevanjem iz Zemljine notranjosti lahko zanemarimo. Do prevoda toplote prihaja v kameninah vodonosnika, s konvekcijo pa se toplota prenaša v podzemni vodi. Trdna in tekoča faza vodonosnika predstavljata dva popolnoma različna sistema prenosa toplote. Pri izračunih predpostavimo, da je tekočina v temperaturnem ravnovesju s kamnino.

Tako ima enačba trenutnega toplotnega toka v poroznih sistemih s tokom tekočine prevodni in konvektivni del:

Convective heat transport in the ground through radiation can be neglected. Conductive heat transport mainly takes place in rock- and soil-matrix, and convective heat transport in groundwater. Solid and liquid phase hence constitute different systems with matching transport equations for each.

Thus the transient heat flow equation for a porous system with fluid flow consists of a conductive and a convective term:

$$\left(\rho_w \phi c_w + \rho_g (1-\phi) c_g\right) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial tT}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) - \rho_w c_w q_x \frac{\partial T}{\partial x} - \rho_w c_w q_y \frac{\partial T}{\partial y} - \rho_w c_w q_z \frac{\partial T}{\partial z} - \dot{Q}_t \quad (10).$$

4 PROBLEMATIKA VODONOSNIKOV

Shranjevanje toplote v vodonosnikih je tehnološko zelo podobno izkoriščanju pitne vode, izkoriščanju nafte in ogljikovodikov ter termalne energije iz geoloških sestavov, zaradi tega so pri izvedbah projektov shranjevanja toplote v vodonosnikih uporabljene izkušnje s teh področij geotehnike in drugih geoznanosti.

Shranjevanje toplote v vodonosnikih temelji na nalivanju tople vode v vodonosnik in na kasnejšem črpanju te vode iz vodonosnika. Kljub temu, da sta s hidravličnega vidika postopka črpanja in nalivanja v vodonosnik podobna, pa se pri praktični izvedbi zaradi naravnih danosti vodonosnikov pojavljajo številni problemi.

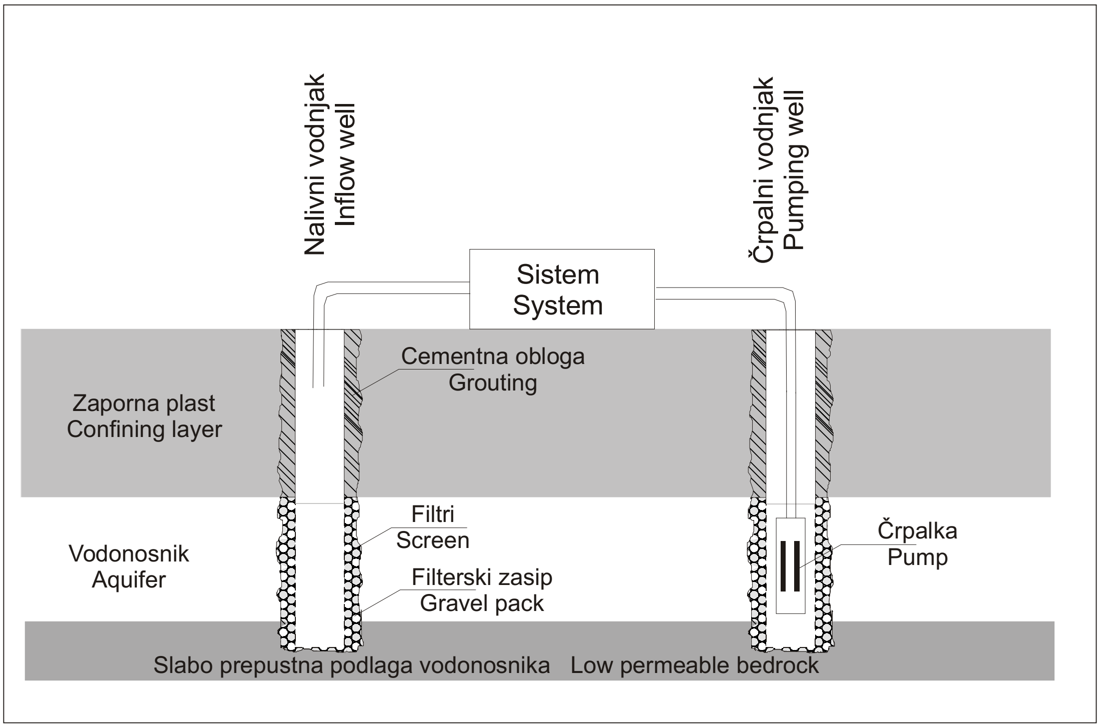
Sistem shranjevanja toplote v vodonosnikih praviloma sestoji iz vrste nalivnih in črpalnih vodnjakov. Po konstrukciji so si nalivni in črpalni vodnjaki podobni. To so lahko vodnjaki različnih premerov, bodisi izkopani, bodisi izvrtani. Konstrukcija vodnjaka sestoji iz trdnih cevi, filtrov in usedalnika. Med zunanjim robom konstrukcije vodnjaka in kamnino ali naplavino je izveden filtrski zasip. Vodnjaki so lahko izvedeni tudi brez filtrskega zasipa, vendar je učinkovito delovanje takšnih vodnjakov krajše od tistih s filtrskim zasipom. Filtri praviloma segajo v celotni zasičeni del vodonosnika, če pa je zasičeni del vodonosnika zajet le deloma, se pojavijo večje tlačne izgube, vodnjak se hitreje postara. V črpalnih vodnjakih je črpalka praviloma vstavljena v tisti del vodnjaka, kjer ni filtrov.

4 PROBLEMS OF AQUIFERS

The storing of heat in aquifers is technologically very similar to the exploitation of drinking water and the extraction of oil, gasses and thermal energy from geological structures, therefore experience from these fields of geotechnics and other geosciences is used in carrying out of such projects.

The storing of heat in aquifers is based on the inflow of warm water into the aquifer and its later withdrawal from the aquifer. Although the processes of pouring and extracting of water are similar from the hydraulic point of view, numerous problems occur in practice because of aquifers' natural properties.

The system of heat storage in aquifers usually consists of a battery of injection and pumping wells. Their construction is similar; they can have different diameters and are either dug or bored. The construction of the well is made of solid pipes, filters and a sediment trap. A gravel pack is placed between the outer edge of the well's construction and the rock or sediment. Wells can also be constructed without the gravel pack, yet such wells have a more short-term effective performance. Filters usually reach into the entire saturated part of the aquifer. Only partial penetration of the saturated zone leads to larger pressure losses and the well ages more rapidly. In pumping wells, the pump is normally installed into the part of the well where there are no filters.



Sl. 2. *Skladiščenje toplote v vodonosniku*
Fig. 2. *Heat storage in aquifer*

Pri shranjevanju toplote v vodonosnik se pojavljajo številni problemi. Do teh problemov pride zaradi mašenja filtrov v vodnjakih. Ta pojav je opazen predvsem v nalivalnih vodnjakih, v manjši meri pa tudi v črpalnih vodnjakih. V praksi ugotavljamo, da je zmogljivost črpalnih vodnjakov do trikrat večja od zmogljivosti nalivalnih vodnjakov. Zaradi mašenja filtrov pride do povečanja tlačnih izgub vodnjaka, s časom se zmanjša izdatnost vodnjaka in tudi zmogljivost celotnega sistema.

Pojave mašenja filtrov vodnjakov razdelimo v naslednje skupine:

a) Kemično mašenje je posledica spremenjenih fizikalno-kemijskih razmer v vodonosniku. Voda, ki jo v vodonosnik vbrizgavamo s površja, je po fizikalno kemijskih karakteristikah drugačna od tiste v vodonosniku. Razlikuje se tako po temperaturi, pH, elektropotencialu in po količini raztopljenih snovi. Ko pride v stik s hladno vodo iz vodonosnika se fizikalno-kemijske razmere na hitro spremenijo, zaradi tega imamo opraviti z obarjanjem mineralov [4], ki se odlagajo na filtre in na filtrski zasip nalivnega vodnjaka. Povišana temperatura vbrizgane vode pa ima tudi določeno prednost, zaradi boljše topnosti mineralov je njihovo odlaganje na filtre vodnjaka počasnejše.

b) Mehansko mašenje filtrov je posledica različno velikih delcev, ki se odlagajo na filtrih vodnjakov. Zamašitve zaradi delcev v vodnjaku so lahko posledica vnosa nečiste vode s površine ali pa posledica konstrukcijskih napak. Zamašitve z delci s površine se pojavljajo predvsem pri nalivnih vodnjakih. Trdni delci prodrejo v filter ali pa celo v filtrski zasip. Pri koloidih pride do kosmičenja. Konstrukcijske napake so lahko posledica slabe izdelave filtrskega zasipa ali pa napačne in nezadostne aktivacije vrtine.

c) Bakterijsko mašenje je posledica delovanja bakterij, ki so v vodonosnik vnesene z vbrizgom ali pa celo nekaterih združb, katerih življenjsko okolje je v vodonosnikih. Problemi z bakterijami se pojavljajo predvsem pri sistemih z nizkimi temperaturami.

d) Kombinirano mašenje je lahko posledica kombinacije vseh treh zgoraj naštetih pojavov. Zaradi spremembe kemijskih razmer v vodonosniku pride do naselitve specifičnih kultur bakterij, ki jih sicer v vodonosniku ne bi zasledili. Delovanje bakterij v vrtinah je v veliki meri odvisno od fizikalno-kemijskih razmer. Od bakterij, ki jih opazimo v vodnjakih, najbolj škodljivo vplivajo na konstrukcije vodnjakov železove bakterije in sulfat reducirajoče bakterije. Zaradi sprememb kemijskih razmer se lahko tudi poveča ali zmanjša gibljivost drobnih delcev v vodonosniku.

Mašenje je z nekaterimi tehničnimi postopki mogoče zmanjšati, ali pa tudi kratkotrajno odpraviti.

In storing heat into the aquifer, several problems can occur, linked mainly to the inflow of water into the aquifer. These problems are caused by the fouling, i.e. the clogging of well filters. Fouling occurs primarily in injection wells, and to a lesser extent also in pumping wells. The capacity of pumping wells is in practice up to three times greater than the capacity of inflow wells. Filter fouling causes increased pressure losses, which with time leads to a decrease in well yield and also to a smaller capacity of the entire system.

Filter fouling processes are divided into the following groups:

a) Chemical fouling. The fouling of filters which is a consequence of changes in physical and chemical conditions in the aquifer is called chemical fouling. Water that is injected into the aquifer from the surface has different physical and chemical characteristics than the water in the aquifer. It has a different temperature, pH, electropotential and a different quantity of dissolved matter. When it comes into contact with water from the aquifer, physical and chemical conditions change rapidly, leading to the precipitation of minerals (4) that are then deposited on filters and on the gravel pack of the inflow well. On the other hand, higher temperature of injected water causes better solubility of minerals and slows down their depositing on well filters.

b) Mechanical fouling. Mechanical fouling is caused by particles of different sizes. Fouling due to particles in the well can be the consequence of inflow of dirty water from the surface or the consequence of construction faults. Fouling with particles from the surface occurs mainly in inflow wells. Solid particles penetrate into the filter or even into the gravel pack. Colloids cause flaking. Construction faults can be the consequence of bad gravel pack or improper and insufficient well activation.

c) Bacterial fouling. Bacterial fouling is caused by the activity of bacteria, introduced into the aquifer with injected water, or even by bacteria that have aquifers as their natural habitat. Problems with bacteria occur mainly with low-temperature systems.

d) Combined fouling. Combined fouling is another possibility. It can be a consequence of all of the above mentioned processes. Because of the changes in chemical conditions, the aquifer becomes populated with specific cultures of bacteria that are not usual for this environment. The activity of bacteria in wells is to a large extent dependent on physical and chemical conditions. Among bacteria that are found in wells, iron bacteria and sulphate-reducing bacteria have the most damaging effect on well construction. Changes in chemical conditions can even lead to the mobility of fine particles in the aquifer.

Fouling processes can be reduced or eliminated for a short period of time with some

Takšni postopki so predvsem čiščenja nalivalnih vodnjakov. Tako poznamo mehanska batiranja vodnjakov, kislinske in klorne obdelave ter obdelave s podhlajenimi inertnimi plini. Vendar pa so ti postopki praviloma zelo dragi in zahtevni, ob nepazljivosti in nenatančni izvedbi pa so lahko tudi neučinkoviti. Tako je pri zmanjšanju izdatnosti vodnjaka pogosto ekonomsko bolj upravičeno izdelati nov vodnjak, še zlasti v primerih, ko vodnjaki ne dosegajo večjih globin. Upočasnitev mašenja lahko dosežemo tudi z ustrezno pripravo vbrizgane vode na površini, toda tudi ti postopki so pogosto pri svoji učinkovitosti omejeni, predvsem zaradi slabega poznavanja interakcij med vbrizgano vodo in vodo iz vodonosnika. Vsi ti postopki so omejeni tudi zaradi tega, ker imamo pri skladiščenju toplote v vodonosnikih opraviti z odprtim obtokom.

Zaradi spremenjenih fizikalno-kemijskih razmer so zelo izpostavljeni tudi materiali, iz katerih so izdelani filtri. Korozija filtrov vodnjakov v podzemni vodi je stalen pojav, v vodi s povišano temperaturo pa je korozija še hitrejša. Korozija se pojavi zaradi različnih energijskih nivojev kovin, ki sestavljajo konstrukcijo vodnjaka in zaradi delovanja vode kot elektrolita. Poznamo štiri tipe korozije vodnjaških konstrukcij:

- zvezno enakomerno tanjšanje elementa; zaradi te korozije pride do zmanjšanja nosilnosti elementov,
- točkovna korozija; ta vrsta korzije se pojavlja v heterogenih kovinah, zaradi česar je korozija na nekaterih mestih mnogo večja kakor na preostali površini,
- medkristalna korozija, ki nastane v sami kovinski zlitini med posameznimi zrni; pojavlja se predvsem v aluminijevih zlitinah z deležem bakra in pri nerjavnih jeklih z deležem ogljika,
- elektrokemična korozija; nastane na stiku dveh kovin z različnim potencialom.

Na korozijo imajo vpliv številni dejavniki. Naj jih opišemo le nekaj:

- *Temperatura*
  Zaradi povišane temperature se obseg korozije poveča predvsem v zaprtih termodinamičnih sistemih, v katerih kisik iz sistema ne more uiti.
- *pH vode*
  Kovine kot so Al, Zn, Pb so močno izpostavljene koroziji kislih in bazičnih raztopin. V nevtralnih raztopinah na površinah teh kovin nastanejo hidroksidi, ki pa ob spremembi pH v kislih ali bazičnih področjih razpadejo. Nasprotno pa nekatere kovine kot so Fe, Mg in Ni v bazičnih in kislih okoljih naredijo zaščitni sloj.
- *Hitrost tekočine*
  Hitrost tekočine ima precejšen vpliv na tip korozije. Tako je pri majhni hitrosti in laminarnem toku opazno le zvezno tanjšanje elementov, pojavlja pa se tudi točkovna korozija. S pojavom turbulentnega toka pride predvsem do nastanka točkovne korozije. Pri nadaljnji povečani hitrosti toka pride do odnašanja snovi, kar še pospeši korozijo. V primeru zelo velikih hitrosti

technical processes. The cleaning of inflow well is the most common solution: mechanical surging of wells, acid and chlorine treatment and treatment with cooled inert gasses. Yet, these procedures are often very expensive and demanding, and may also be ineffective if not carried out properly. In case of well yield drop it is therefore often more economical to build a new well, especially when the well is not very deep. Fouling can also be slowed down with adequate conditioning of injected water on the surface. Also these procedures have a limited efficiency, mainly because of insufficient knowledge of interactions between injected water and water from the aquifer. All these procedures are limited also because heat storage in aquifers is an open circuit.

Changes in physical and chemical conditions also have a negative impact on the materials from which filters are made. The corrosion of filters in groundwater wells is a permanent problem, and the process of corrosion is even faster in the water with higher temperatures. Corrosion is caused by different energy levels of metals of which the well is constructed and because of the water functioning as electrolyte. There are four groups of well construction corrosion:

- continuous proportionate thinning of the element; this corrosion causes decreased bearing strength of the element,
- point corrosion; it occurs in heterogeneous metals and causes some places to corrode far more than the rest of the surface,
- intercrystalline corrosion, which occurs in the metal alloy between individual grains; it is mostly found in aluminium alloys with copper content and in stainless steel with carbon content,
- electrochemical corrosion; it takes place at the contact of two metals with different potentials.

Corrosion is influenced by several factors:

- *Temperature*
  Because of higher temperature, the scope of corrosion is increased above all in closed thermodynamic systems where oxygen cannot exit the system.
- *pH of water*
  Metals such as Al, Zn, Pb are very prone to the corrosion in acid and basic solutions. In neutral solutions, hydroxides are formed on the surface of these metals. They decompose in acid or basic environment. On the other hand, some metals, i.e. Fe, Mg and Ni, form a protective layer in basic and acid environments.
- *Flow rate*
  Flow rate has considerable effect on the type of corrosion. Small velocity and laminar flow only cause a continuing thinning of elements, and point corrosion can also take place. Turbulent flow mainly causes point corrosion. Further increase of flow rate can wash away material, leading to increased corrosion. Very high flow rates can lead

lahko ob stenah nastajajo področja nizkega tlaka in s tem pride do nastajanja mehurčkov. Ti v področjih višjega tlaka implodirajo, kar povzroči kavitacijo.

- *Raztopljene soli*
  V splošnem se z naraščajočo koncentracijo soli povečuje učinek korozije do največje vrednosti, ko se korozija ustali.
- *Raztopljen kisik*
  Raztopljen kisik je dejavnik, ki najbolj vpliva na nastanek korozje. Raziskave so pokazale, da je stopnja korozije sorazmerna deležu kisika v vodi, do 5,5 mg/l. Pri višjih parcialnih tlakih kisika korozija ni več tako intenzivna, saj rabi rja kot zaščitni sloj.
- *Raztopljen ogljikov dioksid (CO_2)*
  Sistem CO_2-H_2O v veliki meri vpliva na pH raztopin. Stopnja korozivnosti se povečuje z večanjem parcialnega tlaka CO_2. Podobno kakor pri kisiku se intenziteta korozivnosti pri določeni vrednosti parcialnega tlaka CO_2 ne povečuje več.
- *Vodikov sulfid*
  Voda, ki vsebuje H_2S, je vedno problematična. Deluje korozivno na železove in kislinsko neodporne zlitine. Pri oksidaciji vode, v kateri je raztopljen H_2S, se zaradi nastanka H_2SO_4 pojavi korozija tudi pri kislinsko odpornih materialih.

Zaradi posledic, ki so nastale pri delovanju prvih sistemov uskladiščenja toplote v vodonosnikih, so bile izdelane smernice za izbiro gradiv. Tako se za izdelavo vrtin priporoča uporaba nerjavnih jekel in nerjavnih zlitin. Ta so bolje odporna proti fizikalno-kemijskim razmeram v vodonosnikih. Zaradi razmer v vodonosnikih pride predvsem do poškodbe zaščitnega sloja gradiv, kar se zgodi zaradi točkovne korozije in kloridov v vodonosnikih.

Poleg tehničnih problemov, ki se pojavljajo pri vbrizgu tople vode v vodonosnik, se, morda še nekoliko bolj izrazito, pojavljajo tudi problemi, ki se navezujejo na onesnaževanje vodonosnikov, saj so vodonosniki praviloma najpomembnejši vir čiste pitne vode. V Sloveniji skoraj vso pitno vodo (95%) pridobivamo iz podzemnih vodnih teles, zaradi česar je velik del države (22%) prekrit z že sprejetimi ali pa predlaganimi vodovarstvenimi pasovi, ki poleg posegov, ki so namenjeni javni vodooskrbi, ne dopuščajo nikakršnih posegov v vodonosnik. Poleg zaščitenih območij vodnih virov in uredb o njihovi določitvi, ki so dopustne v napajalnem zaledju vodnih virov, se je v zadnjem desetletju močno poostrila tudi zakonodaja, ki varuje podzemno vodo kot naravno dobrino, ne glede na to, ali je podzemno vodno telo, v katerem se pojavlja voda, zajeto za javno vodooskrbo ali ne. Na ta način je možnost uporabe vodonosnikov za shranjevanje toplote precej okrnjena. Morebitna izvedba shranjevanja toplote v vodonosnike bi terjala celovito in zahtevno analizo vplivov na kakovost in količino podzemne vode v podzemnem vodnem telesu, v katerega bi shranjevali toploto.

to low-pressure areas along the walls and the formation of bubbles. These bubbles implode in areas with higher pressure, causing cavitation.

- *Dissolved salts*
  Higher salt concentration generally increases the effect of corrosion to a maximum value, when corrosion stops.
- *Dissolved oxygen*
  Dissolved oxygen is the factor which has the most influence upon corrosion. Research showed that the degree of corrosion is proportional to the content of oxygen in water up to 5,5 mg/l. At higher partial pressures of oxygen, corrosion is not so intensive any more, since rust acts as a protective layer.
- *Dissolved carbon dioxide (CO_2)*
  The CO_2-H_2O system has considerable influence on the pH value of solutions. The degree of corrosion increases with the rise in partial pressure of CO_2, similarly as is the case with oxygen, where the intensity of corrosion no longer increases above a certain value of partial pressure of CO_2.
- *Hydrogen sulphide*
  Water with H_2S content is always problematic. It has a corrosive effect upon iron alloys and alloys that are not resistant to acids. Water containing dissolved H_2S is corrosive also for acid-resistant materials because of the H_2SO_4, formed during oxidation.

Because of the consequences observed in the operation of the first heat storage systems in aquifers, guidelines for the selection of materials were set. Therefore the use of stainless steels and alloys is recommended in the construction of wells. These materials are better resistant to the physical and chemical conditions in aquifers, which mainly cause damage to the protective layer of materials due to point corrosion at the presence of chlorides in aquifers.

Beside technical problems that are encountered at the injection of warm water into aquifers, problems linked to the pollution of aquifers are perhaps even more pronounced, since aquifers are as a rule the most important source of pure drinking water. Almost all drinking water in Slovenia (95%) is gained from underground water bodies, therefore a great part of the country (22%) is covered with already defined or proposed groundwater protection zones that allow no intrusions into the aquifer. In addition to protection zones and ordinances which define them and the activities that are allowed in water resource recharge areas, the strictness of legislation protecting groundwater as a natural resource has been intensified over the last decade, irrespective of the fact whether a groundwater body is exploited for public water supply or not. The possibility of aquifer exploitation for heat storage has been substantially reduced in this way. A project of heat storage in aquifers would demand a comprehensive and complex analysis of impacts upon the quality and quantity of water in the groundwater body intended for heat storage.

5 ŠVICARSKI PRIMER

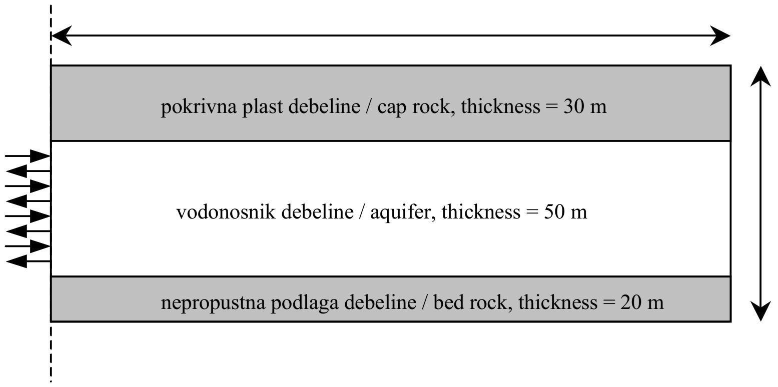
Švicarski laboratorij za geologijo je izvedel simuliranje shranjevanja toplote in nato črpanje te iz vodonosnika prek ene vrtine [5]. Namen je bil primerjava izkoristka vračanja toplote za potrebe ogrevanja.

Simuliranje je bilo izvedeno s programskim paketom FEFLOW, ki temelji na metodi končnih elementov. Modeliran je bil zaprt vodonosnik, v katerem je bil simuliran razvoj temperaturnega polja in tokovi podzemne vode. Simuliranje je bilo dvorazsežno in osnosimetrično, vodonosnik pa je bil razdeljen na trikotne elemente.

5 EXAMPLE FROM SWITZERLAND

Swiss Laboratory for Geology made a simulation of thermal energy storage in an aquifer with one well [5] with the aim to compare the heating efficiency.

The simulation was done by the FEFLOW software, based on the finite element method. Classical aquifer was used where temperature fields and flows of the underground water have been analyzed. The simulation was two-dimensional and axis-symmetrical, and the aquifer was divided into riangular elements.



Sl. 3. *Prikaz zaprtega vodonosnika za dvorazsežen dimenzionalen osnosimetrični model. Mreža je sestavljena iz 50000 trikotnih elementov, katerih stranice so dolge približno 60 cm.*
Fig. 3. *Presentation of the classical aquifer for two dimensional axis-symmetrical model. The net consists of 50000 triangular elements with 60-cm length.*

Preglednica 1. *Prikaz predpostavljenih termohidravličnih parametrov*
Table 1. *The presentation of thermohydraulic parameters*

hidravlični parametri hydraulic parameters		vodonosnik aquifer	podlaga in pokrov bedrock and cap rock
vodoravna hidravlična prevodnost horizontal hydraulic conductivity	K_h m/s	10^{-3} - 10^{-5}	10^{-8}
razmerje hidravličnih prevodnosti hydraulic conductivity anisotropy	$\kappa=K_v/K_h$	1 - 0,1	0,1
poroznost porosity	ϕ	0,2	0,2
stisljivost compressibility	S_o m^{-1}	10^{-4}	10^{-4}
toplotni parametri thermal parameters			
toplotna prevodnost thermal conductivity	λ_s W/mK	3	3
toplotna prevodnost thermal conductivity	λ_l W/mK	0,65	
toplotna prevodnost thermal conductivity	λ_a W/mK	$\Phi\lambda_l+(1-\Phi)\lambda_s=2{,}53$	
prostorninska toplotna prevodnost volumetric heat capacity	$(\rho c)_s$ J/m^3K	$2{,}52\cdot10^6$	
prostorninska toplotna prevodnost volumetric heat capacity	$(\rho c)_l$ J/m^3K	$4{,}2\cdot10^6$	
prostorninska toplotna prevodnost volumetric heat capacity	$(\rho c)_a$ J/m^3K	$\Phi(\rho c)_l+(1-\Phi)(\rho c)_s=2{,}856\cdot10^6$	
toplotna vzdolžna razpršilnost thermal longitudinal dispersivity	α_l m	5	5
toplotna prečna razpršilnost thermal transverse dispersivity	α_t m	0,5	0,5
začetna temperatura vodonosnika t_0=15 °c reference temperature t_0=15°c			

Predpostavljen je bil vodoraven vodonosnik stalne debeline. Skalnata podlaga in zgornja plast sta prav tako predpostavljeni kot vodoravni. Pri simuliranju je bila uporabljena vrtina s premeri od 0,4 do 1m, odvisno od debeline vodonosnika in vbrizganega toka.

Najmanjša temperatura povratka iz ogrevalnega sistema T_{min}=30 °C. Temperatura polnjenja vodonosnika je nespremenljiva. Pretok vode pri polnjenju Q_{in} in praznjenju Q_{out} je nespremenljiv, velja še $Q_{in} = Q_{out}$. Trajanje polnjenja in praznjenja je enak, in sicer 180 dni, brez dodatnega časa shranjevanja. Izkoristek je definiran kot:

A horizontal aquifer with a constant height was used. Rock basement and upper layer are also horizontal. The diameter of the well is 0.4 to 1 m, depending on aquifer depth and injected flow.

Minimal temperature of backflow from the heating system is T_{min}=30ºC. Temperature of filling the aquifer is constant. Water flow at filling Q_{in} and extracting Q_{out} is constant, it is valid also: $Q_{in} = Q_{out}$. Time for filling and emptying is the same: 180 days without additional time for storing. The efficiency is defined as:

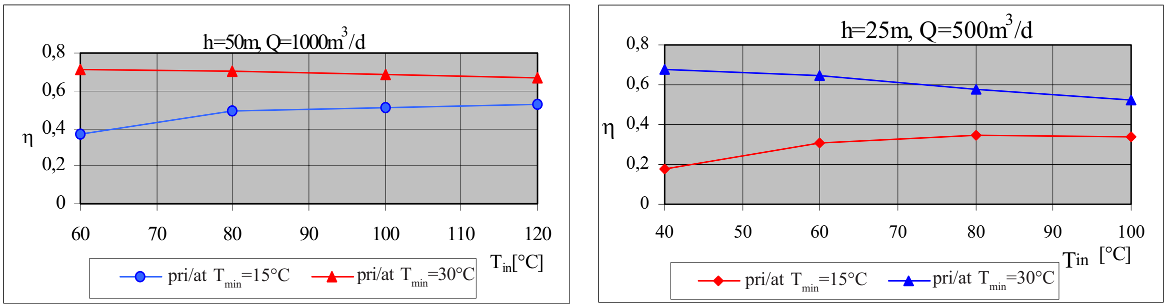
$$\eta = \frac{\text{celotna izčrpana energija pri } T \geq T_{mn}}{\text{celotna shranjena energija}} = \frac{\int_0^{t_{out}} (\rho c)_l Q_{out} (T_{out}(t) - T_{\min}) dt}{\int_0^{t_{in}} (\rho c)_l Q_{in} (T_{in} - T_0) dt} \qquad (11).$$

Za spremenljivki sta bila vzeta debelina vodonosnika *h* v m in pretok vode pri polnjenju Q_{in} v m^3/d. Rezultati so za drugi krog, to je drugo leto obratovanja sistema.

Pomemben dejavnik je temperatura vode pri polnjenju. Za majhne sisteme (Q_{in}<100m^3/d) in nizko temperaturo polnjenja (T_{in}<60 °C) je izkoristek precej majhen (manj ko 30 %). Drug pomemben dejavnik je naravna konvekcija skozi površino ter podlago vodonosnika. Za določeno debelino vodonosnika obstaja optimalen pretok, tako da preprečimo prevelike izgube. Hidravlična prevodnost K_h, manjša od 10^{-4}m, zmanjša naravno konvekcijo in zato tudi vpliv debeline vodonosnika na izkoristek.

Depth of aquifer *h* and water flow at injection Q_{in} were taken as variables. The results presented are for the second cycle, which is for the second year of system operation.

The minimum return temperature for the user is an important factor of the thermal efficiency of aquifer thermal energy storage. Small systems (Q_{in}<100m^3/d) and low temperature stock (T_{in}<60ºC) present therefore weak thermal recovery rates (less than 30%). Natural convection is another important and unfavorable factor. For a given injection flow rate Q_{in} an optimum aquifer thickness exists, allowing to avoid buoyancy phenomena and excessive conductive losses through the bedrock and cap rock. Aquifer hydraulic conductivity K_h smaller than 10^{-4} m/s reduces the natural convection cells appearance, and, consequently the importance of aquifer thickness as a factor of efficiency.



Sl. 4. *Izkoristek sistema kot funkcija temperature vode pri polnjenju T_{in}, T_{min}=30 °C in T_{min}=15 °C*
Fig. 4. *System efficiency as a function of water temperature at injecting T_{in}, T_{min} = 30 ℃, T_{min} = 15 ℃*

Preglednica 2. *Izkoristek sistema v odvisnosti od vodoravne hidravlične prevodnosti K_h*
Table 2. *System efficiency as a function of hydraulic conductivity K_h (second cycle T_{min}=30 ℃)*

η	Q_{in}=100m^3/d					Q_{in}=500m^3/d					Q_{in}=1000m^3/d			
K_h	10^{-3}	5. 10^{-4}	10^{-4}	5. 10^{-5}	10^{-5}	10^{-3}	5. 10^{-4}	10^{-4}	5. 10^{-5}	10^{-5}	10^{-3}	5. 10^{-4}	10^{-4}	10^{-5}
h=5			26,0		29,2			32,3						
h=10	12,6	17,6	29,1		31,2			37,5					40,1	
h=25			15,8	24,6	34,7	5,7	13,3	35,0	41,1	44,0	14,7	23,6	43,1	
h=50			8,7		33,4	1,1	2,7	20,2	32,5	43,9			47,6	
h=100								17,3		42,			21,4	46,1

h [m], K_h [m/s], η [%]

6 MOŽNOST UPORABE VODONOSNIKOV KOT HRANILNIKOV TOPLOTE V SLOVENIJI

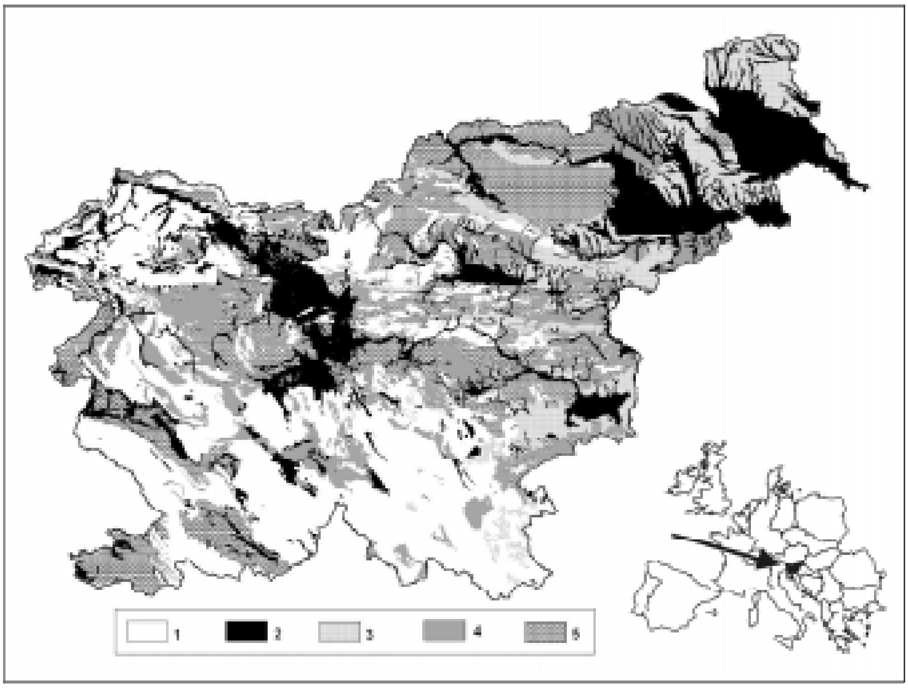
Slovenija je navkljub majhni površini geološko zelo pestra. Prevladujejo kamnine iz srednje zemeljske dobe, navzoče pa so tudi kamnine iz številnih drugih geoloških dob. Za slovensko ozemlje je značilna pestra tektonska dejavnost. Kamnine so prepredene s številnimi prelomi in narivi, zaradi časov so kamnine zelo poškodovane, v njih se pojavljajo številne razpoke, ki pomembno vplivajo na njihove hidrogeološke lastnosti. Tudi na porazdelitev naplavin močno vplivajo tektonske razmere.

Glede na različne tipe poroznosti lahko Slovenijo razdelimo na več hidrogeoloških enot. Takšna razdelitev je dokaj groba, vendar pa v grobem poda hidrogeološke lastnosti slovenskega ozemlja. Medzrnski vodonosniki ležijo predvsem v nižinskih predelih in v dolinah velikih rek. Pokrivajo 22 odstotkov površine države. Medzrnske vodonosnike najdemo v Prekmurju, na Dravskem in Ptujskem polju, v Ljubljanski kotlini in Ljubljanskem barju, Krško-Brežiški kotlini ter v Celjski kotlini. V medzrnskih vodonosnikih praviloma ležе največja in najizdatnejša črpališča pitne vode.

6 THE POSSIBILITY OF USING AQUIFERS AS THERMAL STORAGE IN SLOVENIA

Despite its small area, Slovenia is geologically very diverse. Mesozoic rocks prevail, and there are also rocks from numerous other geological periods. Intensive tectonic activity is typical of the Slovenian territory. The rocks are cut with faults and thrusts, therefore they are damaged to a large extent, and numerous joints have an important influence on their hydrogeological properties. Tectonic conditions also have a strong impact on the distribution of sediments.

With regard to different types of porosity, Slovenia can be divided into several hydrogeological units. Such division is rather inexact, yet it can roughly define the hydrogeological properties of the Slovenian territory. Intergranular aquifers lie mainly in lowlands and in the valleys of big rivers. They cover 22% of the country’s surface. Intergranular aquifers are found in Prekmurje, in the Dravsko and Ptujsko Polje, in the Ljubljana basin and in the Ljubljansko Barje, in the Krško-Brežice basin and in the Celje basin. Intergranular aquifers generally provide the biggest and richest drinking water reservoirs.



Sl. 5. *Pregledna hidrogeološka karta Slovenije (1 – kraški vodonosniki; 2 – medzrnski vodonosniki; 3 – vodonosniki z dvojno poroznostjo; 4 – razpoklinski vodonosniki; 5 – slabo prepustne kamnine)*
Fig. 5. *Hydrogeological map of Slovenia (1 - karst aquifers; 2 - intergranular aquifers; 3 - aquifers with double porosity; 4 - interstitial aquifers; 5 - rocks with low permeability)*

Slovenija je znana po številnih kraških pojavih. Kraški vodonosniki prekrivajo največjo površino Slovenije, njihov delež znaša 32 odstotkov. To so predvsem apnenci, ki jih najdemo na območju Alp in Dinarskega krasa v južni Sloveniji. Kamnine, v katerih se pojavljajo le razpoke, ki pa so lahko zaradi različnih pojavov

Slovenia is known for numerous karst phenomena. Karst aquifers cover the largest part of Slovenia, their share amounting to 32%. These are mostly limestones in the alpine region and in the Dinaric karst in southern Slovenia. Rocks with interstices that can also be somewhat dilated, are tudi nekoliko razširjene, so uvrščene v kategorijo razpoklinskih vodonosnikov, pri tem gre predvsem za različne vrste dolomitov. Ti vodonosniki prekrivajo 15% površine Slovenije. Z dvojno poroznostjo so opredeljeni predvsem peščenjaki terciarne starosti. V teh kamninah se pojavljata tako medzrnska kakor tudi razpoklinska poroznost. Te kamnine pokrivajo 11 odstotkov površine. Kot posebno kategorijo lahko izločimo slabo prepustne kamnine. To so tiste kamnine, pri katerih le stežka govorimo o njihovem potencialu za izkoriščanje podzemne vode, pokrivajo pa le dobro petino države. Sem sodijo različne vrste glinavcev, laporovcev in nekatere magmatske ter metamorfne kamnine.

Za shranjevanje energije so primerni le vodonosniki z majhno hitrostjo podzemne vode. Pomembno pa je tudi, da so v bližini večjih središč, kjer je mogoče to energijo tudi dokaj poceni prenesti do uporabnikov. Na kratko si oglejmo nekaj vodonosnikov. v katerih bi bilo mogoče uskladiščiti energijo. Osnovne lastnosti teh vodonosnikov so zbrane v preglednici 3.

Velenjska kadunja je mlada pliocenska tektonska udorina, ki jo zapolnjujejo rečne in potočne naplavine, predvsem gline in peski. Za tisti del vodonosnika, ki ga tvorijo peščene naplavine, so značilne srednje hidravlične prevodnosti, podzemna voda pa ima nizek gradient.

Krško-Brežiško polje je obsežna kotanja, ki je zasuta s kvartarnimi naplavinami, ki se navzdol nadaljujejo v pliocenske naplavine. Skupna debelina teh sedimentov na nekaterih delih presega 200 m. V zgornjem delu imamo opraviti z dokaj visokimi hidravličnimi prevodnostmi, v spodnjem pliocenskem delu pa se te hidravlične prevodnosti močno zmanjšajo, zaradi česar se močno upočasni tudi tok podzemne vode.

Kamniško-Mengeško polje je tektonska udorina, zapolnjena z mladimi kvartarnimi naplavinami, ki so po svojem izvoru predvsem ledeniškega nastanka. Debelina kvartarnih naplavin se od Kamnika proti Domžalam veča in doseže debelino več ko 70 m. Zaradi strmo nagnjene predkvartarne podlage so tudi hidravlični gradienti razmeroma visoki.

Na območju Prekmurskega in Murskega polja imamo opraviti z obsežnim vodonosnikom kvartarne starosti, ki se navzdol nadaljuje v pliocenske, nekoliko slabše prepustne naplavine. V kvartarnem delu vodonosnika imamo opraviti z relativno hitrim tokom podzemne vode, v pliocenskem vodonosniku, pa je tok podzemne vode počasnejši in zaradi tega primernejši za skladiščenje toplote.

Gričevje Goričkega je sestavljeno iz pleistocenskih in pliocenskih rečnih naplavin v katerih je razmerje med peščeno - prodnato in glinasto - meljasto frakcijo 1 : 2. Za te peske in prode so značilne dobre do srednje hidravlične prevodnosti. Glede na geološko sestavo, ki tone v smeri severozahod – jugovzhod, te naplavine v Moravskih toplicah segajo že do globine 1000 m. V tej globini pa se pojavlja podzemna voda s temperaturo prek 60 °C. Ti peski na

classified as interstitial aquifers, and are mainly different types of dolomites. These aquifers cover 15% of Slovenia. Aquifers with double porosity are mainly found in sandstones of Tertiary age. These rocks have intergranular as well interstitial porosity and have an 11% share. Rocks with low permeability are classified as a separate category. These are rocks that can hardly be considered to have any groundwater exploitation potential, and they cover only a good fifth of the country. Different types of clays, marls and some volcanic and metamorphic rocks belong into this group.

Only aquifers with slow groundwater flow are suitable for heat storage. It is also very important that they are in the vicinity of larger centres where the energy can also be relatively cheaply transported to consumers. The following is a short list of some aquifers where energy could be stored. The basic properties of these aquifers are summarized in Table 1.

The Velenje valley is a young Pleistocene tectonic depression filled with fluvial deposits, mainly clays and sands. The sandy part of the aquifer has medium porosity, while groundwater has a low gradient.

The Krško-Brežice field is an extensive basin, filled with Quaternary sediments that are downwards followed by Pliocene sediments. Total thickness of these deposits exceeds 200 m in some parts. The upper zone has relatively high permeability which is reduced to a large extent in the lower, Pliocene part, causing also the groundwater flow to slow down.

The Kamnik-Mengeš field is a tectonic depression filled with young Quaternary sediments of mostly alluvial origin. The thickness of Quaternary sediments increases from Kamnik towards Domžale and reaches more than 70 m. Because of the steep Pre-Quaternary bedrock also hydraulic gradients are relatively high.

The Prekmurje and Mura field has an extensive aquifer of Quaternary age that is downwards followed by Pliocene sediments of somewhat lower permeability. Groundwater flow is relatively fast in the Quaternary part of the aquifer and slower in the Pliocene aquifer, which is consequently more suitable for heat storage.

The hills of Goričko are composed of Pleistocene and Pliocene fluvial deposits with a 1:2 ratio between sand-gravel and clay-silt fractions. High to medium porosities are typical of sand and gravel. Because of the geological structure that declines in the NW-SE direction, these sediments reach already a depth of 1000 m in Moravske toplice. At this depth groundwater temperature is over 60^0C. The thickness of the saturated zone in these sands in Goričko is sufficient for storing energy, however it has to be

Goričkem sicer nudijo dovolj debelo omočeno plast, ki omogoča skladiščenje energije.

Ljubljansko barje je mlada tektonska udorina, v kateri se dobro prepustne plasti izmenjujejo s slabše prepustni. Opraviti imamo z dvema obsežnima vodonosnikoma. V zgornjem delu imamo opraviti z odprtim vodonosnikom, v spodnjem delu pa z obsežnim zaprtim vodonosnikom, ki bi bil primeren za skladiščenje energije.

pointed out that there is no source of surplus industrial heat in this area.

The Ljubljansko barje is a young tectonic depression in which layers with high porosity alternate with those with lower porosity. There are two large aquifers: an open aquifer in the upper part and a closed aquifer in the lower part, which would be suitable for energy storage.

Preglednica 3. *Ocenjeni parametri nekaterih vodonosnikov v Sloveniji, ki so primerni za skladiščenje toplote*
Table 1. *Estimated parameters of some aquifers in Slovenia that are suitable for heat storage*

lokacija in sestava location and composition	globina do depth up to	debelina thickness	hidravlična prevodnost porosity	gradient	poroznost porosity	hitrost flow rate
	m	m	m/s			m/dan m/day
Pomurje						
kvartarni prodi (odprt) quaternary gravels (open)	3 do 5	5 do 50	10^{-4} -10^{-6}	$1*10^{-3}$	0,25	3,5e-02
pliocenski peski (zaprt) pliocene sands (closed)	8 – 55	50 – 200	10^{-6}	$1*10^{-3}$	0,2	4,3e-04
Goričko						
pliocenski peski (zaprt) pliocene sands (closed)	0 - 50	50 – 200	10^{-6}	$1*10^{-3}$	0,2	4,3E-04
Velenje						
pliocenski peski (zaprt) pliocene sands (closed)	100	10	10^{-6}	$<1*10^{-3}$	0,2	4,3E-04
Krško						
pliokvartarni zaglinjeni prodi (zaprt) plio-quaternary clayey gravels (closed)	50	5	10^{-6}	$0,5 - 1*10^{-3}$	0,15	2,8E-04
Kamnik - Mengeš						
kvartarni prodi (odprt) quaternary gravels (open)	5 - 20	10 - 50	10^{-4}	$0,5 – 1*10^{-2}$	0,25	1,7E-01
Lj. barje						
kvartarni prodi in peski (zaprt) quaternary gravels and sands (closed)	50	15	10^{-4}	$<1*10^{-3}$	0,2	4,3E-04

V Sloveniji so glede na hidrogeološke lastnosti številni vodonosniki primerni za skladiščenje toplote, vendar pa so to praviloma tudi vodonosniki, ki pomenijo pomemben vir pitne vode. Zaradi tega je pri nadaljnjih raziskavah izkoriščanja vodonosnikov za potrebe uskladiščenja toplote v Sloveniji veliko pozornosti treba posvetiti morebitnim vplivom na kakovost in količino podzemne vode.

Skladiščenje toplote v vodonosnike je smiselno tam, kjer obstaja vir odvečne industrijske toplote. Za vsako možno lokacijo je treba pripraviti podrobne hidrogeološke in tehnološke osnove, s katerimi se oceni bistvene parametre podzemnega skladiščenja toplote, ki so v zvezi z naravnimi pogoji skladiščenja (hitrost razširjanja toplote v vodonosniku), s tehnološkimi pogoji skladiščenja (razporeditev nalivalnih in črpalnih vodnjakov in

With regard to hydrogeological properties, several aquifers in Slovenia are suitable for heat storage, yet these are as a rule also the aquifers providing an important drinking water resource. Because of this fact, further investigations of aquifer exploitation for heat storage will have to pay much attention to possible impacts upon the quality and quantity of groundwater.

The storing of heat in aquifers is reasonable where there is a resource of excessive industrial heat. For each potential location, detailed hydrogeological and technological bases have to be prepared in order to estimate essential parameters of underground heat storage that are in connection with natural storage conditions (how fast heat spreads in the aquifer), with technological conditions of storage (the distribution of injection and pumping wells and their njihova konstrukcija, interakcija tople vode s podzemno vodo v vrtinah) ter z zakonodajnimi pogoji, povezanimi s toplotnim onesnaževanjem v vodonosnikih in vplivi na vire pitne vode.

7 SKLEP

Možnost za uporabo vodonosnikov kot hranilnikov toplote se v svetu izraziteje raziskuje zadnjih petindvajset let. Po posameznih državah gredo raziskave v različne smeri, pač glede na to, kaj je lokalno pomembno. Na Japonskem iščejo rešitev v smeri le ene vrtine, medtem ko primer iz Kanade kaže rezultate raziskave o uporabi še dodatne odpadne vrtine. Posamezne države imajo različno geološko sestavo. Povsem različni sta Nizozemska in Švica. Prvo skoraj v celoti pokrivajo medzrnski vodonosniki, medtem ko so ti v Švici, katere primer je prikazan v prispevku, le v ledeniških dolinah in na redkih ravninskih delih.

Za popis shranjevanja termalne energije v vodonosniku je potrebno zelo natančno poznavanje geoloških razmer. Poznati moramo hitrosti in pretoke podzemne vode. Ti se lahko po globini zelo razlikujejo, kar dodatno oteži računalniška simuliranja. Spregledati ne smemo niti naravnega vzgona. Zaradi tega je treba namestiti odvzem tople vode na manjši globini kakor je izvedeno vbrizganje.

V Sloveniji delujočega sistema, kjer bi iz vodonosnika črpali in nato vračali vodo, še ni. Izvedenih je le nekaj primerov z vkopanimi cevmi. Glede na to, da večino vodonosnikov v Sloveniji uporabljamo za črpanje pitne vode, je shranjevanje toplote v njih dokaj tvegano, ker vsako vbrizganje v vodonosnik pomeni nevarnost onesnaženja.

construction, the interaction of warm water with groundwater in wells) and with legislative conditions pertaining to the heat pollution of aquifers and influences on drinking water resources.

7 CONCLUSION

The possibility of aquifer utilization has been investigated in the world for the last 25 years. In different countries the research is directed towards different objectives, depending on the specific conditions in each country. The solution in Japan is directed towards one well only, whereas the example form Canada shows the utilization of one pumping well and one refuse well. Netherlands and Swiss are different. The first is almost entirely covered by intergranular aquifers whereas in Swiss aquifers are usually in glacial valleys and rare flat areas.

For the description of thermal energy storage in aquifers, a detailed knowledge of the aquifer's structure is necessary, together with the speed and flows of underground water. Those can vary considerably with the depth, presenting difficulties at computer simulations. Natural convection cannot be neglected. This is the reason why the pumping of warm water has to be performed at smaller depths than the injection of cold water.

Systems that would pump warm water from the earth and inject cold water back are not known in Slovenia. The fact that most aquifers in Slovenia are used for drinking water, makes thermal energy storage in aquifers very risky.

8 SIMBOLI
8 SYMBOLS

koordinate kartezičnega koordinatnega sistema	x,y,z		coordinates of the Cartesian system
specifičen tok	q	m/s	specific flow
prostorninski tok	Q	m^3/s	volumetric flow
površina	A	m^2	area
hidravlična prevodnost	K	m/s	hydraulic conductivity
hidravlična višina	h	h	hydraulic height
gostota toplotnega toka	j	$\mathrm{W/m}^2$	heat flux density
toplotni tok	$\dot{Q}_t$	W	heat flux
toplotna prevodnost	λ	W/mK	thermal conductivity
temperatura	T	K	temperature
čas	t	s	time
specifična toplota tekočine	c_w	J/kgK	specific heat of fluid
specifična toplota kamenine	c_g	J/kgK	specific heat of rock
gostota tekočine	ρ_w	$\mathrm{kg/m}^3$	fluid density
gostota kamnine	ρ_g	$\mathrm{kg/m}^3$	rock density
poroznost	ϕ	%	porosity
stisljivost	S_o	m^{-1}	compressibility
polmer	r	m	radius
transmisivnost vodonosnika	τ_a	m^2/d	transmisivity of aquifer
hitrost tekočine	$\vec{v}$	m/s	fluid velocity

komponente hitrosti tekočine	u,v,w	m/s	components of fluid velocity
gravitacijski pospešek	g	m/s^2	gravitational acceleration

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