Journal of Hydrology 552 (2017) 564–577

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Inferring near surface soil temperature time series from different land uses to quantify the variation of heat fluxes into a shallow aquifer in Austria

Hans Kupfersberger *, Gerhard Rock, Johannes C. Draxler

JR-AquaConSol GmbH, Steyrergasse 21, 8010 Graz, Austria

ARTICLE INFO

Article history:
Received 6 April 2017
Received in revised form 11 July 2017
Accepted 13 July 2017
Available online 17 July 2017
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Philip Brunner, Associate Editor

Keywords:
Groundwater temperature
Subsurface heat flux
Near surface soil temperatures
SoilTemp
Groundwater heat transport

ABSTRACT

Different land uses exert a strong spatially distributed and temporal varying signal of heat fluxes from the surface in or out of the ground. In this paper we show an approach to quantify the heat fluxes into a groundwater body differentiating between near surface soil temperatures under grass, forest, asphalt, agriculture and surface water bodies and heat fluxes from subsurface structures like heated basements or sewage pipes. Based on observed time series of near surface soil temperatures we establish individual parameters (e.g. shift, moving average) of a simple empirical function that relates air temperature to soil temperature. This procedure is useful since air temperature time series are readily available and the complex energy flux processes at the soil atmosphere interface do not need to be described in detail. To quantify the heat flux from heated subsurface structures that have lesser depths to the groundwater table the 1D heat conduction module SoilTemp is developed. Based on soil temperature time series observed at different depths in a research lysimeter heat conduction and heat storage capacity values are calibrated disregarding their dependence on the water content. With SoilTemp the strong interaction between time series of groundwater temperature and groundwater level, near surface soil temperatures and the basement temperatures in heated buildings could be evaluated showing the dynamic nature of thermal gradients. The heat fluxes from urban areas are calculated considering the land use patterns within a spatial unit by mixing the heat fluxes from basements with those under grass and asphalt. The heat fluxes from sewage pipes and of sewage leakage are shown to be negligible for evaluated pipe diameters and sewage discharges. The developed methodology will allow to parameterize the upper boundary of heat transport models and to differentiate between the heat fluxes from different surface usages and their dynamics into the subsurface.

1. Introduction

Groundwater temperatures vary as a result of subsurface heat conduction and storage parameter distribution and thermal gradients which develop from diverse heat sources and sinks. The shallow groundwater thermal regime is of interest due to different reasons. First, there is the use of groundwater for heating and cooling of surface structures (e.g. residential homes, business or commercial centers) and for the supply of warm water. In that context, the thermal use of groundwater provides an important contribution to the reduction of greenhouse gas emissions since it substitutes the use of fossil energy (Blum et al., 2010). Zhu et al. (2010) quantified the potential heat content in urban aquifers and available capacities for space heating and found out that by decreasing the 20 m thick urban aquifer's temperature by 2 °C, the amount of extractable geothermal energy beneath Cologne is 2.5 times the residential heating demand of the whole city.

However, the thermal use of groundwater in Austria is restricted due to other legitimate groundwater uses like the provision of good quality drinking water and ecosystem services. The Austrian regulation ÖWAV-Regelblatt 207 (ÖWAV, 2008), which guides the thermal use of groundwater and of the subsurface for heating and cooling, specifies that at the location of reinjection the resulting groundwater temperature (i.e. after mixing of the ambient and the thermally altered groundwater) may neither exceed 20 °C nor fall below 5 °C. Additionally, the thermal modification of the groundwater between extraction and injection may not surpass 6 K. Hähnlein et al. (2010) provided a comprehensive

* Corresponding author.
E-mail addresses: hans.kupfersberger@jr-aquaconsol.at (H. Kupfersberger), gerhard.rock@jr-aquaconsol.at (G. Rock), johannes.draxler@jr-aquaconsol.at (J.C. Draxler).

http://dx.doi.org/10.1016/j.jhydrol.2017.07.030
0022-1694/

overview of the current international legal status for the use of shallow geothermal energy revealing that most countries have no legally binding regulations or even guidelines. Thus, it becomes clear that to optimize the use of the geothermal potential of an entire aquifer under legal constraints and to locally adjust the positioning and the operational mode of groundwater heat pumps an appropriate management tool is needed that is capable of addressing the temporal and spatial variation of the relevant involved parameters and drivers.

Numerical models have been applied on that background for some time. Some of the models have been set up to investigate the impact of urban structures on groundwater temperature (also referred to as the suburban urban heat island effect). Ferguson and Woodbury (2004) concluded that additional reasons to heat losses from buildings for increases in subsurface temperature, such as changes in surface cover or climate change, may be responsible for some of the observed increase in groundwater temperatures. Other numerical heat transport models have been applied to investigate different operational schemes and to maximize the heat extraction rate from groundwater heat pumps (e.g. Fujii et al., 2005). Yang et al. (2010) provided a review of ground source heat pump systems and the typical simulation models.

In more recent modeling studies Händel et al. (2013) described on a regional scale the impact of future scenarios for heating and cooling purposes of large groundwater heat pumps on groundwater temperature changes. Epting et al. (2013) built a 3D groundwater flow and heat transport model of the shallow groundwater body underneath the city of Basel accounting for the effects of heated buildings and river-groundwater interaction on groundwater temperatures.

No matter the scope or the scale of the numerical heat transport model, in order to create a reliable prognosis tool it is of utmost importance to represent the heat fluxes across the aquifer boundaries in appropriate spatio-temporal detail. Benz et al. (2015) investigated the spatial resolution and annual quantity of anthropogenic heat fluxes into urban aquifers. They distinguished between 6 different sources of heat fluxes (i.e. groundwater surface temperature, buildings, sewage systems, sewage leakage, subway system and district heating network) and computed the heat fluxes based on estimated ground surface temperatures under different land uses for the cities of Cologne and Karlsruhe. In the heat transport model set up by Epting et al. (2013) the authors differentiated between open space, sealed surfaces, water covered and buildings as land uses.

In this work we present an approach to quantify the spatial and temporal variation of the subsurface heat input signals discriminating between land uses of grass, agriculture, forest, sealed surfaces (asphalt) and surface water bodies based on measurements of air temperature. Moreover, we account for the influence of heat sources below the ground (e.g. heated basements) on subsurface heat fluxes by the 1D vertical heat conduction model SoilTemp and show the dynamic nature of thermal gradients. We also use this model to represent heat fluxes from a mixture of different land surfaces in urban areas.

2. Method

2.1. Definition of empirical function

The variation of soil temperature with depth can be described by a sinusoidal function (e.g. Wu and Nofzinger, 1999) exploiting the average soil temperature and the annual amplitude of the surface soil temperature. This representation can be linked to the 1-D vertical differential equation of heat transport; however, the availability of soil temperature data is still required. Since this is highly unlikely on the regional scale and for different land uses we develop a methodology that is based on modelling the relationships between air temperature time series measured at 2 m above ground and soil temperature time series measured 5 cm below ground under grass, forest and asphalt. The simple idea behind this approach is to relate the near surface soil temperature to its main driver, the air temperature, for which extensive data is available. The measured soil temperatures at 5 cm depth are the results of all physical processes at the soil atmosphere interface (e.g. radiation, reflection, wind) so that further aspects of these processes do not need to be considered.

In Eq. (1) the calculation of the soil temperature at 5 cm depth is shown for positive air temperatures and in Eq. (2) for negative air temperatures. In general, the observed air temperatures are modified by (i) adding a constant value to achieve a shift, and/or by (ii) multiplying with a constant value to achieve an attenuation or an exaggeration and/or by (iii) computing a moving average over a window with varying length.

$$T_{B5cm,i} = \frac{1}{(2n+1)} \times \sum_{-n}^{n} T_{L,i-n} \times b_{pT} + a, T_{L,i} \geqslant 0 \quad (1)$$

$$T_{B5cm,i} = \frac{1}{(2n+1)} \times \sum_{-n}^{n} T_{L,i-n} \times b_{nT} + a, T_{L,i} < 0 \quad (2)$$

with

T_{B5cm}: computed soil temperature at 5 cm depth [°C]
T_L: observed air temperature (200 cm above ground) [°C]
i: current time step
(2n + 1): number of days for which a moving average is computed; n is an integer number
a: shift of observed air temperature [°C] (same value for positive and negative air temperatures)
b_{pT}: attenuation or exaggeration of positive air temperatures [−]
b_{nT}: attenuation of negative air temperatures [−]

For the different land uses the parameters of the equations are individually fitted by comparison to corresponding measured soil temperatures (see results section). To quantify the goodness of fit between the two time series the Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) value is calculated for each land use category. A NSE value of 1 indicates a perfect fit. Based on verification of the fitted parameters with independent data sets (see Chapter 4.1), we assume that the fitted parameters are valid for all areas of that land use class.

2.2. 1-D model SoilTemp

Anthropogenic heat fluxes into the groundwater body from additional heat sources, e.g. across basement from buildings, from sewage pipe or district heat networks, take place at varying depths below the surface. In general, if the exact locations of the different objects in the unsaturated zone are known they could be accordingly implemented in a heat transport model. However, in a regional context such a procedure would lead to very complex computational meshes which in turn might cause numerical instabilities and long computational times. Instead, we propose an alternative way forward, which is based on a further development of the "Multi-Layer-Model" presented by Händel et al. (2013).

In the "Multi-Layer-Model" vertical heat transport processes (namely conduction, convection, and heat storage) within the unsaturated zone are calculated (Händel et al., 2013). The model divides the unsaturated zone into layers of the same thickness, with the number of layers depending on the depth to the