XXXVIII
IAH Congress

Groundwater Quality Sustainability
Krakow, 12–17 September 2010

Extended Abstracts

Editors:
Andrzej Zuber
Jarosław Kania
Ewa Kmiecik

University of Silesia Press 2010

abstract id: **266**

topic: **1**
Groundwater quality sustainability

1.6
Groundwater monitoring

title: **Groundwater flow and recharge in the Doñana aquifer system (Huelva, SW Spain) from temperature profiles in boreholes**

author(s): **Emilio Custodio**
Technical University of Catalonia, Spain, emilio.custodio@upc.edu

keywords: groundwater, flow, recharge, temperature, Doñana

INTRODUCTION

Ground average temperature depends on long–term, local average ground surface temperature and the geothermal vertical gradient. This is not only influenced by deep heat sources and the thermal properties of water–containing materials but also by groundwater flow rate, due to the large heat capacity of water. The influence of downward vertical recharge from the surface (or upward vertical discharge from the depth) is here considered as a 1–D problem between two constant temperature boundaries, one in the ground surface (the average of seasonal and diurnal variation) and the other in depth. This is the Bredehoeft and Papadopulos (1965) steady state problem, that now is considered here under non–steady conditions when there is a sustained sudden change in surface (or in depth) temperature (Custodio et al., 1996). This is applied to the Doñana area, in southwestern Iberian Peninsula, between the Guadalquivir and the Tinto–Odiel rivers marshes.

A recent morphological and hydrogeological description of the Doñana areas can be found in Custodio et al. (2009). It is the largest seminatural area of Western Europe and holds a 3000 km^2 aquifer system. The territory was unhabited due to the very poor eolian sand soil cover, the marshes and a large number of lagoons and wetlands. There is a very long, almost untouched coastal area only developed for shell–fish capturing, except for two recent, localized, large tourist resorts. The area was promoted for irrigated agriculture in the 1970s using local deep groundwater from a coarse layer below thick fluvio–marine sand formations. It also holds a large protected area as national and natural parks.

Groundwater studies are available since the late 1960s and especially from the late 1970s. In the 1980's a dedicated groundwater monitoring network, with point piezometres open at different depths. Detailed numerical modelling has been carried out. Studies included a temperature borehole logging survey.

HEAT TRANSPORT IN A SATURATED POROUS MEDIUM

The heat balance in a water–saturated porous medium can be given as:

$$-\mathrm{div}J_D - \mathrm{div}J_A + F = \frac{\partial}{\partial t}(c_g^v\theta) \qquad (1)$$

where:

J_D = conductive heat flow = –K grad θ	$[EL^{-2}T^{-1}]$
J_A = advective heat flow = $\rho_w c_w \theta$	$[EL^{-2}T^{-1}]$
F = heat source term (negative if it is a sink)	$[EL^{-3}T^{-1}]$
t = time	[T]
c^v_g = ground volumetric heat capacity = $(1–m)\ \rho_g c_g + m\rho_w c_w$	$[EL^{-3}K^{-1}]$
θ = temperature (assumed the same for ground and water)	[K]

for the following parametres:

K = ground thermal conductivity	$[EL^{-1}T^{-1}K^{-1}]$
k = hydraulic conductivity (permeability)	$[LT^{-1}]$

q = groundwater flow = –k grad h (Darcy's law)	$[LT^{-1}]$
h = groundwater head (for a homogeneous fluid)	[L]
ρ_w = water density (assumed homogeneous)	$[ML^{-3}]$
c_w = water specific heat (assumed homogeneous)	$[EM^{-1}K^{-1}]$
ρ_s = solid density	$[ML^{-3}]$
c_s = solid heat capacity	$[EM^{-1}K^{-1}]$
m = volumetric porosity	[––]

E=energy; L=length; T=time; K=temperature; M=mass $[E=M^2K^{-2}]$; –=dimensionless.

It is assumed a saturated ground (the vadose zone is thin); otherwise k, c_g and h will depend on saturation, which is a fraction of porosity (m).

Ground thermal conductivity depend on solid properties and groundwater flow. Then it is a combination of solid thermal conductivity (Fourier's law) and the thermal effect of water diffusion and dispersion (Fick's law), and increases with water flow. In the application q is assumed constant; then K will be considered constant but with a value higher than the mere thermal condutive one.

1–D SOLUTION FOR TWO BOUNDARY CONSTANT TEMPERATURES AND SURFICIAL WARMING

For the vertical (1–D) heat transport through the ground between the surface –with an average long–term temperature θ_o– and a deep constant temperature due to a relatively fastly renovating aquifer –with an average long–term temperature θ_f– when there is vertical flow in between –in what is considered a relative aquitard–, through a saturated medium (the vadose zone is assumed of negligible thickness), Bredehoeft and Papadopoulos (1965) found a well known solution, that has been used to determine steady state recharge rates by applying different plots (Cartwright, 1975).

The substitution of natural vegetation for pasture land and agricultural plots, or for suburban areas, is often accompanied by soil warming. Be Δt_o this increase, the current average value over previous average temperature. At depth z_f the ground temperature is kept constant, θ_f. If there is a vertical recharge q, assumed constant, with no heat source (F=0), the 1–D solution of the vertical heat transport in the ground (Custodio et al., 1996), for a coordinate system z (downwards from the soil surface, z=0 down to $z=z_f$) and θ (temperature) along time t from the moment the $\Delta\theta_o$ change is introduced (t=0) is:

$$\theta(z,t) = \theta_o + \Delta\theta_o \frac{\exp(\beta z/z_f) - e^{\beta}}{1-e^{\beta}} + \theta_f \frac{1-\exp(\beta z/z_f)}{1-e^{\beta}} - \\ -\Delta\theta_o \exp(\beta z/z_f) \sum_{n=1}^{\infty}\left[\frac{n\pi}{\lambda_n}\left(\exp(-a\lambda_n t)\,\sin\frac{n\pi z}{z_f}\right)\right] \tag{2}$$

being: $\beta = q\dfrac{\rho_w c_w}{K} z_f$ [dimensionless]

$\lambda_n=(n\pi)^2+\beta^2/4$ [dimensionless]

$$a=\frac{K}{\rho_g c_g z_f^2}$$ [T^{-1}] ; $\rho_g=(1-m)/\rho_s+m\rho_w$ (bulk density)

When $\Delta\theta_o=0$, no change in the soil surface temperature, the solution of Bredehoeft and Papadopulos (1965) for the steady state (t=∞) effect of recharge in the ground temperature is obtained:

$$\theta(z)=\theta_o\frac{\exp(\beta z/z_f)-e^{\beta}}{1-e^{\beta}}+\theta_f\frac{1-\exp(\beta z/zf)}{1-e^{\beta}} \quad (3)$$

DATA AND PARAMETERS

Temperature logs of point piezometric boreholes are available from the 1990's. They were carried out with a potable device with sensitivity 0.1°C and measurements every 1 m, down to 150 m in the deepest boreholes.

Thermal properties of local ground materials are not available. Then, values from the literature (e.g. Matthess, 1982) have been used, considering possible dynamic effects of water transport on the thermal conductivity in the stratified sands between the surface and the deep gravel and coarse sand layers, the preferentially exploited aquifer layers. See Table 1.

Table 1. Adopted values for parametres based on Matthess (1982), and other published values, for the local stratified fluvio–marine medium–fine silica sands.

Total porosity (measured)	m = 0.35	—
Dynamic thermal conductivity	K = 2.8	$W\ m^{-1}\ K^{-1}$
Water head capacity	c_w = 4000	$J\ kg^{-1}\ K^{-1}$
Water density	ρ_w = 1000	$kg\ m^{-3}$
Solid head capacity	c_s = 800	$J\ kg^{-1}\ K^{-1}$
Solid density	ρ_s = 2300	$kg\ m^{-3}$
Ground bulk density (calculated)	ρ_g = 1800	$kg\ m^{-3}$
Ground volumetric capacity (calculated)	$C_g = 2.96 \times 10^6$	$J\ kg^{-1}\ K^{-1}$
Ground thermal diffusivity (calculated)	$a_g = 0.946 \times 10^{-6}$	$m^2\ s^{-1}$

Near the coastal area, the sand (a relative aquitard with respect the bottom coarse layer) has a thickness of z_f=50 to 100 m and recharge is 150 to 200 mm/a (Custodio et al., 2009).

With Table 1 values and for z_f=100 m, q=200 mm/a, results are β=0.227 and $\ln(\beta/z_f)$=0.0010, which means a small vertical thermal disturbance with respect the linear thermal gradient for steady temperature.

The annual temperature oscillation in depth, the most penetrating one, is less than 0.1ºC –the temperature probe sensibility– at about 15 m, which is almost no affected by local recharge rate under present circumstances (Custodio et al., 1996).

RESULTS AND DISCUSSION

For a constant recharge, q, with a sudden temperature increase $\Delta\theta_o$ after t=0 the water front penetrates q/m per unit time. The thermal front is delayed due to heat exchange with the ground to attain thermal equilibrium; the penetration is q $\rho_w c_w / c_g^v$. The thermal front is smoothed out due to thermal conductivity, the more the greater is the front age; if t is the front age, the 68% of temperature values (±σ) is inside $\Delta z = \pm(2\ a_g\ t)^{1/2}$.

The piston flow vertical rates of propagation are:

- for recharge water v=q/m=2,86q
- for the sustained surface thermal change v'=q $\rho_w c_w / c_g^v$ =1,38q.

The Δz values are:

t, years	1	3	10	30	100	(300)
±Δz, m	7.8	13.5	25	43	78	(135)

When β is small (the thermal profiles are close to linear) $\Delta\theta_o$=1°C, Figure 1 shows the thermal perturbation penetration (in this case θ_o=18°C, θ_f=21°C, z_f=100 m) versus recharge rate for $\Delta\theta_o$=1°C and v/v'=2. This penetration is a slow one.

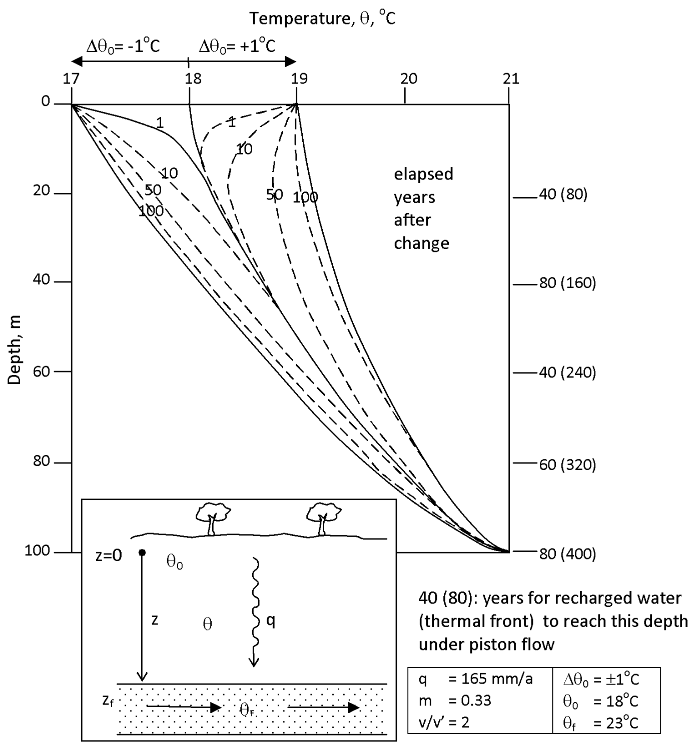

Figure 1. Calculated temperature logs for a sudden surface change $\Delta\theta_o$ of ±1°C from a previous average steady state value of θ_o=18°C in the ground surface and θf=21°C.

In the area of Doñana being considered the main land use perturbations correspond to rather well defined activities, such as introduction of large eucalyptus tree plantations in the 1940s and irrigated areas, colonization and tourist resorts in the 1970s, or respectively about 50 and 20 years with respect the date of the temperature logs (1995). This is indicated in Figure 2.

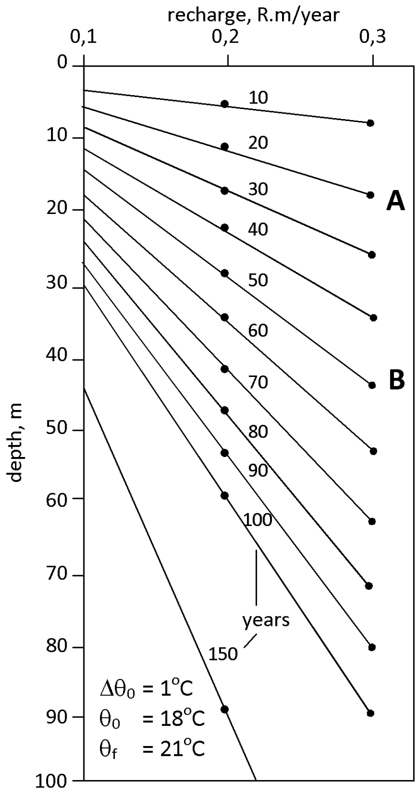

Figure 2. Calculated penetration of a sudden surface temperature change moving at half the recharge water penetration rate, for $\Delta\theta_o$=1°C, θ_o=18°C, θ_f=21°C, z_f=100 m, considering recharge rate and elapsed time. A=irrigation project; B=eucalyptus plantations.

The actual $\Delta\theta_o$ is not known since it depends on difficult–to–quantify influences of forestation, irrigation (mostly in winter with warm groundwater or cool water stored in large basins, depending on the area and variable along time) and urbanization.

CONCLUSIONS

Land use changes may be accompanied by sustained average temperature changes in the ground surface. They slowly propagate downwards when recharge is mostly vertical due to preferential groundwater flow in depth. Penetration is the compound of heat dynamic conduction and advection. The result is that temperature logs may differ from the expected vertical gradient, even considering the recharge effect. Even if actual temperature change is poorly known, the penetration of the disturbance points to the magnitude of recharge.

ACKNOWLEDGEMENTS

The closed form solution here used was obtained with the help of Dr. R. Juanes, of the University of A Coruña. Temperature logs were carried out by the Groundwater Group of the Ground Engineering Department, Technical University of Catalonia (UPC), Barcelona, with the help of the Geological and Mining Institute of Spain and the Guadalquivir River Authority. This is part of CICYT research project REDESAC (CGL2009–12910–C03–01).

REFERENCES

Bredehoeft J. D., Papadopulos I. S., 1965: *Rates of vertical groundwater movement estimated from the Earth's termal profile.* Water Resources Research, 15: pp. 1616–1622.

Cartwright K., 1975: *Measurement of fluid velocity using temperature profiles: experimental verification*. J. Hydrology, 43: pp. 185–194.

Custodio E., Manzano M., Iglesias M., 1996: *Análisis térmico preliminary de los acuíferos de Doñana [Preliminary thermal analysis of the Doñana aquifers]*. IV SIAGA, Almería, II: pp. 57–87.

Custodio E., Manzano M., Montes C., 2009: *Las aguas subterráneas en Doñana: aspectos ecológicos y sociales [Groundwater in Doñana: Ecological and socials aspects].* Agencia Andaluza del Agua. Sevilla: pp. 1–243.

Matthess M., 1983: *Evaluation of vertical groundwater fluxes and thermal properties of aquifers based on transient temperature–depth profiles.* Water Resources Research, 28(7): pp. 2021–2026.

International Association of Hydrogeologists

AGH University of Science and Technology

2-vol. set + CD
ISSN 0208-6336
ISBN 978-83-226-1979-0