The impact of vertical water flow in boreholes on monitoring operations

Emilio CUSTODIO [(1)*]

Influence sur le monitorage des flux verticaux d'eau dans les forages

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Abstract

Long-screened or open observation boreholes are commonly used groundwater monitoring devices to measure groundwater heads and to get groundwater samples by means of different sampling methods. The long penetration into the aquifers may produce short circuiting of layers of different heads, even inside what is generally considered a single aquifer. Vertical head differences may be due to natural hydrodynamic circumstances or to groundwater abstraction. These head differences affect measured groundwater head values and, what is more important, may alter temperature, salinity and water quality vertical distribution along the borehole, compared with the actual stratification inside the aquifer. This is important for monitoring coastal aquifers but also for obtaining representative water samples to study the hydrochemical behaviour or contamination processes. Under a series of circumstances groundwater contamination may not show up or some layers may appear as polluted when they are not. A series of point boreholes or a bundle of nested, isolated point observation tubes inside a large diametre borehole are the solution, but this is expensive and not problem free due to failures in seals, groutings, and tube joint waterproofing and continuity. Two situations of a screen affected by vertical flow inside the borehole are considered to deduce the mixing process, the shape of the concentration profile and the parametres that control the seriousness of the affection. Vertical flows produce a change in the observed characteristic at the screen or permeable section entrance, if differences are large enough, and then it tends towards the groundwater value in the aquifer layer against the screen. Electrical conductivity and temperature logs help to identify small vertical flows. A simplified example is given.

Résumé étendu

Les puits d'observation ouverts ou crépinés sur une grande longueur sont fréquemment utilisés comme dispositifs de surveillance des nappes pour mesurer la pression hydraulique et pour prélever des échantillons d'eau souterraine par différentes méthodes d'échantillonnage. La pénétration sur une grande longueur dans les aquifères peut produire des court-circuits entre des couches de pressions différentes, même à l'intérieur de ce que l'on considère généralement comme un aquifère simple. Ces différences verticales de pression peuvent être dues à des phénomènes hydrodynamiques naturels ou à un prélèvement d'eau souterraine. Elles affectent les valeurs mesurées de la pression de la nappe et, ce qui est plus grave, elles peuvent modifier la distribution verticale de la température, la salinité et la qualité des eaux le long du forage, par rapport à la stratification existant au sein de l'aquifère. Ceci est important pour surveiller les aquifères littoraux mais aussi pour obtenir des échantillons représentatifs d'eau dans le but d'étudier le comportement hydrochimique ou les processus de contamination. Il se peut que la contamination de l'eau souterraine ne soit pas visible suite à une série de phénomènes ou alors des couches peuvent apparaître comme étant polluées alors qu'elles ne le sont pas. La solution consiste en une série de forages ponctuels ou en un ensemble de tubes d'observation, séparés, insérés à l'intérieur d'un forage de grand diamètre, mais ceci est coûteux et n'est pas exempt de problèmes dus à des carences concernant les joints étanches, la cimentation, et l'étanchéité des raccords de tuyaux ainsi que la continuité.

Nous examinons deux cas de crépines affectées par un flux vertical à l'intérieur du forage pour déduire le processus de mélange, la forme du profil de concentration et les paramètres qui déterminent la gravité de ce désordre. Les flux verticaux produisent une transformation dans les constantes observées à l'entrée de la crépine ou de la partie perméable, si les différences sont suffisamment importantes. La valeur tend alors vers la valeur de l'eau souterraine dans la couche aquifère touchant la crépine. Les diagraphies de conductivité électrique et de température apportent une aide dans la détermination des

(1) Departement of Ground Engineering/International Centre for Groundwater Hydrology, Polytechnic University of Catalonia, Gran Capità s/n. Ed. D-2, 08034 Barcelona, Spain.

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faibles flux verticaux. Un exemple simplifié est donné.

Lorsque l'on est en présence d'un flux vertical le long d'un forage orienté vers la partie à faible potentiel hydraulique, examinons une crépine intermédiaire. Cette crépine reçoit par une extrémité de l'eau, provenant d'autres parties du forage. Le flux d'eau sortant est modifié par cet apport des autres sections. L'eau apportée se mélange à l'eau entrante. Dans le cas où le rabattement dans la crépine examinée est assez grand pour produire un flux entrant radial et que l'effet du flux horizontal dans l'aquifère peut être négligé, la fraction d'eau venant d'autres crépines et arrivant dans le flux le long de la crépine, f, est de :

$$f = \frac{c - ç}{c_o - ç} = \frac{1}{1 + B\,\lambda/Q_o}$$

c = concentration de l'eau à une distance z de l'entrée de la crépine
c_o = concentration dans l'eau arrivant verticalement à l'entrée de la crépine
ç = concentration de l'eau dans l'aquifère en face de la crépine
Q_o = flux d'eau s'écoulant verticalement à l'entrée de la crépine
B = valeur caractéristique adimensionnelle, $B = 2\pi k\, \Delta h\, [ln\,(R/r)]^{-1}$
k = perméabilité de l'aquifère
Δh = rabattement dans la crépine = charge dans des conditions non perturbées moins charge normale dans l'hypothèse où le régime permanent est atteint
R = rayon d'influence du rabattement
r = rayon efficace de la crépine
λ = longueur de la crépine

Concentration signifie concentration réelle d'un soluté, salinité, conductivité électrique ou température.

La concentration de l'eau dans la crépine est un peu modifiée si on considère que dans l'aquifère | c-ç | / ç est en-dessous d'une valeur prédéterminée ϵ, par exemple : 0.01. Cela signifie que pour z = λ, la longueur de la crépine est :

$$f\,|\,(c_o / ç) - 1\,| = \frac{|\,(c_o / ç) - 1\,|}{1 + B\lambda / Q_o} < \epsilon$$

L'eau s'écoulant verticalement dans le forage est un peu modifiée par la présence d'une crépine si | c_o-ç | / c_o est en-dessous d'une valeur prédéterminée, ϵ, par exemple : 0.01. Cela signifie que pour z = λ

$$(1 - f)\,\frac{|c_o - ç|}{c_o} = \frac{|1 - (ç/c_o)\,|}{1 + \frac{1}{1 + B\,\lambda/Q_o}} < \epsilon$$

Si le flux vertical est faible, le flux horizontal à travers la crépine est un peu modifié et l'eau se mélange à l'intérieur de celle-ci. La perturbation de l'écoulement est faible

si $A = \pi r\,(v_o - V)\,/\,(2\lambda g) << 1$

v_o = vitesse d'écoulement vertical à l'entrée de la crépine = $Qo/\,(\pi\, r2)$
V = vitesse d'écoulement vertical à la sortie de la crépine
r = rayon de la crépine
q = vitesse d'écoulement horizontal dans la crépine.

Dans le mélange d'eau, la fraction d'eau arrivant verticalement dans la crépine est de :

$$f = \frac{c - ç}{c_o - ç} = \left(\frac{1 - x + (C/A)}{1 + (C/A)}\right)^{1/A}$$

dans laquelle $x = z\,/\,\lambda$; $C = \pi\, r\, V\,/\,(q/\lambda)$, les autres symboles ayant été déjà définis.

L'importance de la modification de la concentration à l'intérieur de la crépine par rapport à l'eau de l'aquifère ou l'eau du courant vertical, peut être dérivée à partir de la formule ci-dessus en remplaçant par la nouvelle valeur de f.

Introduction

A common erroneous assumption is that observation wells show groundwater level values and yield samples accurately representing the penetrated local aquifers. This assumption neglects that groundwater flow is essentially tridimensional, especially in thick aquifers, in sloping layers and near springs, wells and major aquifer heterogeneities. Away from these features, groundwater flow is very close to horizontal and thus head changes along a vertical line are small and can be assumed negligible for areal studies of groundwater head, although not necessarily for groundwater chemistry and temperature. The piezometers may be long-screened boreholes or wells, and even uncased bores if the rock is consolidated, with the precaution of isolating other penetrated aquifers. But in other circumstances groundwater heads may vary conspicuously along a vertical line, as shown in figures 1 and 2. A long-screened or open borehole will show a groundwater head which is between the extreme values. In many cases this is a poor information or even may lead to wrong interpretations (fig. 3) of hydraulic gradients and groundwater flow. In that case to get the right information several point or short-screened piezometers at different depths and isolated from the formations above and below are needed. They can be installed in separated boreholes or as a bundle of nested tubes inside a simple borehole of enough diametre. This last solution may be cheaper but is more difficult to install and failures are not rare. Flows through poor seals, failed groutings, tightless tube joints and casing breakdowns may alter the point character of the observation device. Things become more complex for representative groundwater sampling, as will be shown later on.

Groundwater heads and vertical flows

The existence of vertical head gradients along a vertical line in an aquifer is easily shown by the head differences measured by means of point boreholes at different depths if groundwater density does not change.

Salinity and large temperature changes along the borehole make head differences along a vertical line not directly convertible into vertical gradients. Let us consider a water column of variable water density, δ, and two points A and B at depths z_A and z_B, $z_A < z_B$. If water pressure at point A is P_A, in a hydrostatic system (no vertical flows) the pressure at point B should be:

$$P_B^* = P_A + \int_{z_A}^{z_B} g\,\delta(z)\,dz$$

in which $\delta(z)$ is water density as a function of depth and g is the acceleration of gravity. Be P_B the true pressure at point B as measured by means of a point piezometer. Then if:

$P_B > P_B^*$ there is an upward vertical head potential gradient and upward vertical flow

$P_B = P_B^*$ the system is hydrostatic (no vertical flow)

$P_B < P_B^*$ there is a downward vertical head potential gradient and downward vertical flow

Inside the aquifer, vertical flows are controlled by vertical pressure and density changes. According to the generalized Darcy's law applied to a heterogeneous fluid moving in the vertical direction (de Marsily, 1986):

$$q = \frac{k_o}{\mu}\frac{\partial}{\partial z}(P - \rho g z)$$

or

$$q = \frac{k_o}{\mu}\left[\frac{\partial P}{\partial z} + -\rho g - gz\frac{\partial \rho}{\partial z}\right]$$

q = specific vertical flow (positive upwards) $[LT^{-1}]$
k_o = intrinsic permeability $[L^2]$
μ = water viscosity $[ML^{-1}T^{-1}]$
P = water pressure $[ML^{-1}T^{-2}]$
z = downward directed vertical coordinate [L]
δ = water density $[ML^{-3}]$
g = acceleration of gravity $[LT^{-2}]$

According with physical tables fresh water density changes by -0.25 $kg.m^{-3}C^{-1}$ in the range of 10 to 30 C, which comprises common groundwater temperatures for shallow aquifers. This means a head increase of 0.025 m when 100 m of water column in the borehole increases its temperature by 1°C. For the same range of temperature the effect of salinity is about 714 $kg.m^{-3}$ when salinity is given in weight fraction of marine salts in the solution. This produces a 2.5 m head decrease when a 100 m fresh water column is substituted by a saltwater column with the salinity of sea water (0,035 weight fraction of salts) at the same temperature, as shown by the classical Ghyben-Herzberg law (Custodio and Bruggeman, 1986). In this case small temperature changes have a relative minor influence when compared with salinity changes.

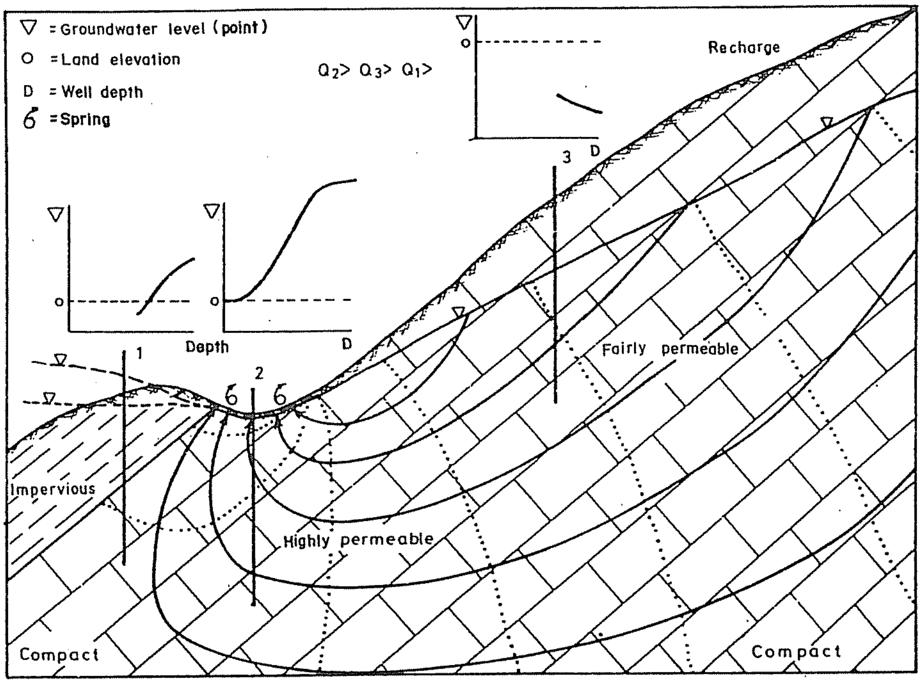

Fig. 1. – A common situation producing vertical flow components in a carbonate aquifer discharging into a ravine through springs. Idealized from Les Comes spring area in the Carme-Capellades aquifer, near Barcelona. Far from the springs there are downward vertical flow components. Surface pollution affects only the upper layers of the aquifers but may show up in deep long-screened monitoring boreholes. Near the springs there are upward vertical flow components. The polluted upper layer in the aquifer will never show up in the deep boreholes, and will appear diluted in the springs. The vertical groundwater level axis represents about 4 m.

Fig. 1. – Situation classique d'une nappe de formations carbonatées comportant des flux verticaux de décharge vers un thalweg. Idéalisée depuis l'aire de sources de Les Comes, dans la nappe de Carme-Capellades, près de Barcelona. Loin des sources, les composantes du flux sont verticales descendantes. La pollution superficielle affecte seulement la partie supérieure de la nappe, mais peut aussi apparaître dans les sondages de monitorage profonds crépinés sur toute leur longueur. Près des sources les composantes verticales du flux sont ascendantes. La pollution de la partie supérieure de la nappe n'apparaîtra jamais dans les sondages profonds, mais on la trouvera diluée dans les sources. L'axe vertical des niveaux de l'eau souterraine représente près de 4 m.

The existence of vertical flows means that between screens or inside low permeability sections salinity is constant, as well as temperature if velocity is high enough to avoid heat exchange with the walls; otherwise temperature tends to that corresponding to the geothermal gradient.

In a hydrostatic system with salinity (density) increasing downwards, consider two short screens at depths z_1 and z_2 ($z_1 < z_2$; $z_2 - z_1 = l$). If P_1 is the pressure at point z_1, at point z_2 it should be:

$$P_2 = P_1 + \int_{z_1}^{z_2} \gamma(z)dz$$

If $\gamma(z)$ varies linearly with depth,

$$\gamma(z) = \frac{\gamma_2 + \gamma_1}{l} z$$

$$P_2 = P_1 + \frac{\gamma_1 + \gamma_2}{z} l$$

$$P_z = P_0 + \gamma_1 z + \frac{\gamma_2 - \gamma_1}{l}\frac{z^2}{2}$$

The only stable vertical distribution of salinity between the screens is a also a lineal variation. The lineal salinity profile has to be maintained by salt diffusion from z_1 to z_2. Any other monotonical distribution would change P_z and vertical flows will develop, but some

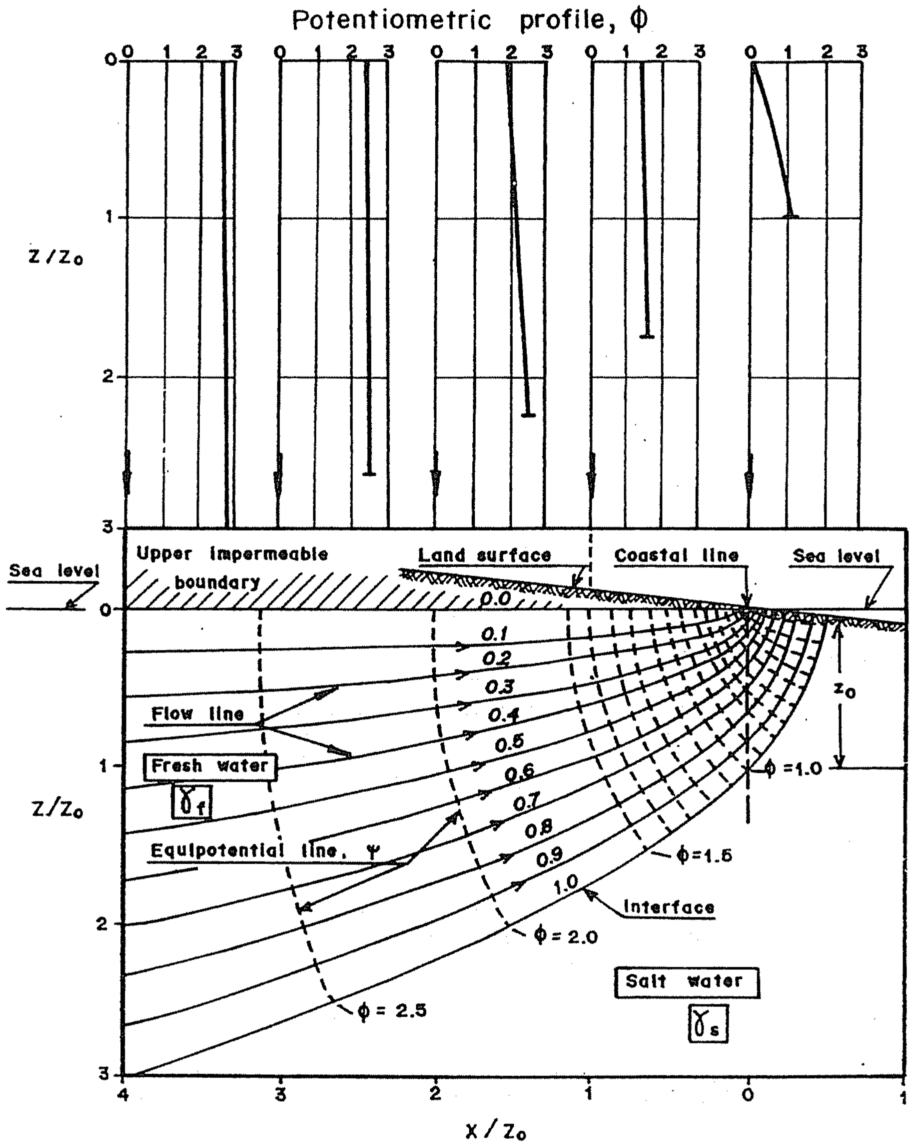

Fig. 2. – Flow net of a homogeneous sharp-interface coastal aquifer with stationary saltwater showing how vertical flow components develop in the freshwater body. Flow net from Glover (1959). ϕ is the potential; the freshwater head is $h = \phi\ z_o/\alpha$, z_o = interface depth along the coast; $\alpha = (\gamma_s - \gamma_d)/\gamma_d$; γ = specific weight; f = freshwater; s = saltwater.

Fig. 2. – Dans cette figure on utilise le réseau de flux d'une nappe côtière homogène à interface brusque sur l'eau salée stationnaire, pour montrer comment il se produit des composantes verticales du flux d'eau souterraine dans le corps d'eau douce. Réseau de flux depuis Glover (1959). ϕ est le potentiel ; le niveau piézométrique d'eau souterraine est $h = \phi\ z_o/\alpha$, z_o = profondeur de l'interface au long de la côte ; $\alpha = (\gamma_s - \gamma_d)/\gamma_d$; γ = poids spécifique ; f = eau douce; s = eau salée.

step-like distribution will be able to produce the $P2$ value. But this distribution cannot be steady and will slowly evolve towards the lineal one through diffusion.

Any transient change of $P1$ or $P2$ breaks the hydrostatic equilibrium and them the tube is partially or fully invaded by water from one of the ends (z_1 or z_2). This produces a new unsteady vertical salinity distribution.

The result is that between screens transient salinity distributions may happen. They are difficult to interpret if the full history of density and head changes is not known. Things are more easy when vertical flows are always found.

Quantifying vertical flows not only needs knowing changes of P with depth but of δ as well. Multipiezometer installations give a few points of this functions. Values of P may be interpolated with some caution. In situ density values are not directly measurable and water samples may change temperature during abstraction. Furthermore density changes in the aquifer are more frequent and faster than those of pressure. Good temperature logs can be obtained from cased boreholes. Salinity logs have to be derived from point measures in the boreholes. These salinity and temperature values are needed to deduce the vertical density function.

Since point piezometres are very expensive - especially in thick or deep aquifers, and furthermore only supply point values, a long-screened borehole may seem a good and simple device to know salinity stratification but, as it will be discussed later, this may not be the case due to changes in the vertical distribution of water inside the borehole due to vertical flows. If there are various screens, sections between screens contain may water from the upper or lower screen, more or less adapted to the external temperature, but with salinity not corresponding to the depth inside the aquifer.

Representative groundwater samples and temperature logs

Water inside the unscreened tube of a monitoring borehole equilibrates thermally with the temperature of the geological formations outside, provided vertical flow between the tube and the bore walls is prevented by good isolation and there is no cement still releasing the heat of hardening. In this case, and after changes due to drilling, water abstraction or injection have faded out, the transient vertical temperature distribution inside the tube generally corresponds to that of the formations penetrated, if there is no vertical cross-flow inside the tube.

For constant salinity, the increase of temperature with depth decreases slightly the water density. This is an unstable situation but mixing by free convection is generally not triggered in small diametre boreholes for small vertical thermal gradients if there is no gas bubbling. When salinity increases with depth stability is favored by compensating or overcompensating for the thermal density decrease effect.

Small vertical head gradients exist in many cases due to the flow pattern or created by pumping effects. They induce vertical flows between screens or open sections inside the borehole. Water moves from high head sections (inflow) to low head ones (outflow). Almost unnoticeable head differences of a few centimetres may be enough to disturb quality stratification inside the borehole after a long rest period.

In some actual situations head differences between screen sections may attain several metres, naturally or due to groundwater abstraction. The section receiving water may be deeply invaded and long pumping times may be required to obtain native water from this aquifer layer. Direct sampling of it by means of thief samplers, even with previous bailing, or by means of a small discharge pump, will produce modified samples. In extreme situations whole subaquifers may have their quality and temperature permanently changed. Thus, the cheaper, long screened or open observation boreholes are a mixed blessing and often a source of erroneous observations (Everett, 1980), even in variable fluid density coastal aquifers (Kohout, 1980; Custodio and Bruggeman, 1986).

Other important causes of disturbance are faulty seals, leaky tube joints and tube cracks. Generally a very small quantity of water enters or leaves through them, affecting negligibly groundwater heads, but long time spans between samplings allow for important volumes of water to penetrate or leave the borehole, thus changing water vertical physical and chemical composition inside low permeability or cased sections. This affects diversely water inside the screens or open sections, as will be discussed later on. The process is well known and clearly observed when performing tracer tests inside boreholes (Baonza *et al.*, 1970; Custodio and Llamas, 1983). The water inflow or outflow may be so slow that normal duration of tracer tests is not enough to show them but still they are important in altering water quality vertical distribution since exposure is much longer than a normal test duration. This is especially

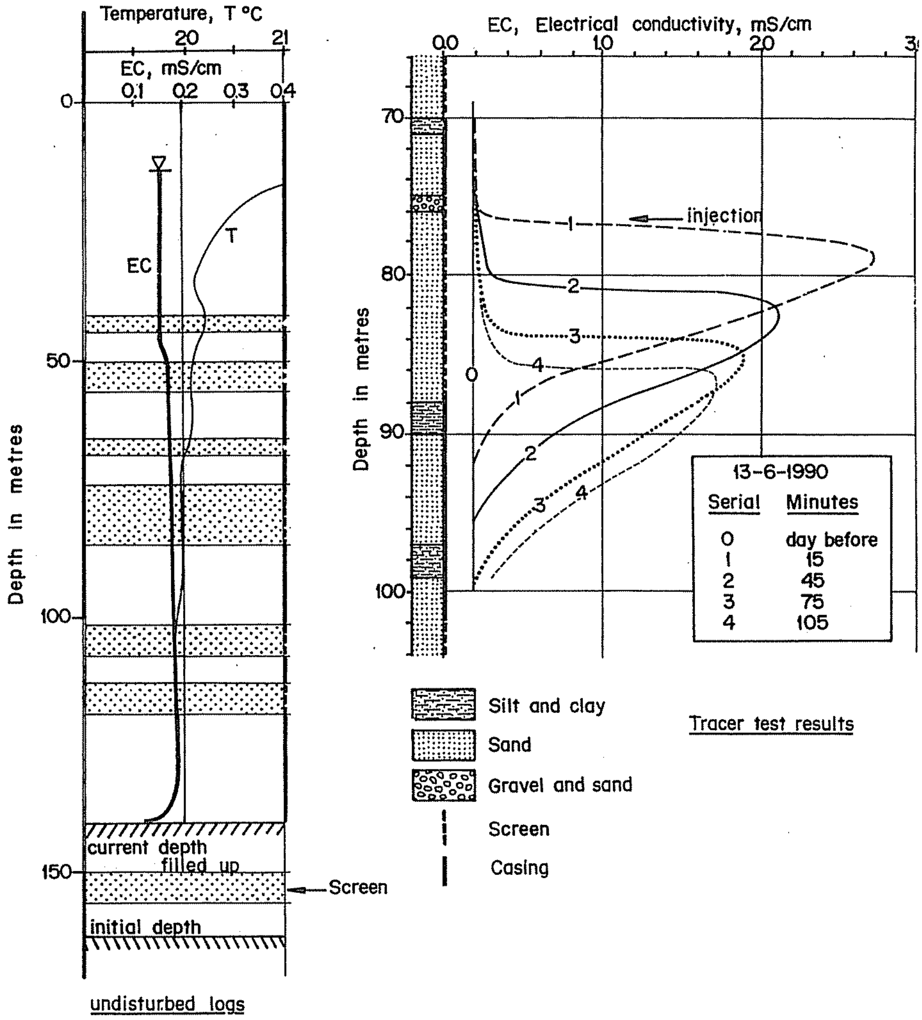

Fig. 3. – Step-like salinity (electrical conductivity, EC) and temperature (T) logs of a deep multiscreened observation borehole in Matalascañas (Doñana area coast, Huelva) and results of a saline water tracer test to measure the downward vertical flow inside the well (Custodio, 1993). The pointed stripes and the dashed sections indicate the screen locations. Vertical downward velocity in the tested depth is 8 m/hour. Relatively warm shallow water moves down into the cooler, deeper layers, which are recharged at higher altitude under forest cover.

Fig. 3. – Diagraphies de salinité (conductivité électrique, EC) et de température (T) d'un sondage de monitorage équipé de crépines multiples à Matalascañas (côte de Doñana, Huelva), et résultats d'un essai de traçage destiné à mesurer le flux d'eau vertical à l'intérieur du sondage (Custodio, 1993). Les bandes pointillées et les sections en tireté montrent la position des crépines. La vitesse verticale descendante est de 8 m/h à la profondeur essayée. De l'eau relativement chaude à faible profondeur descend vers les nappes plus froides profondes, rechargées dans des aires plus élevées et plus forestées.

true for cased sections between screens. Inside the screen the groundwater flow through them may partly or fully erase the effect.

Monitoring coastal aquifers and the apparent shape of the saltwater-freshwater mixing zone

Monitoring of the mixing zone between freshwater and saltwater in a coastal aquifer is important to know aquifer changes. This helps management decisions. It seems that long-screened boreholes are good devices to carry out this monitoring, and in some cases they are, but distorted pictures are obtained (Custodio and Bruggeman, 1986; Falkland and Custodio, 1992; Cotecchia, 1977) and even unrealistic vertical displacements show up, especially in double porosity aquifers such as karsts (Monkhouse and Fleet, 1975; Kohout, 1980), in which water fluctuations in the fis-

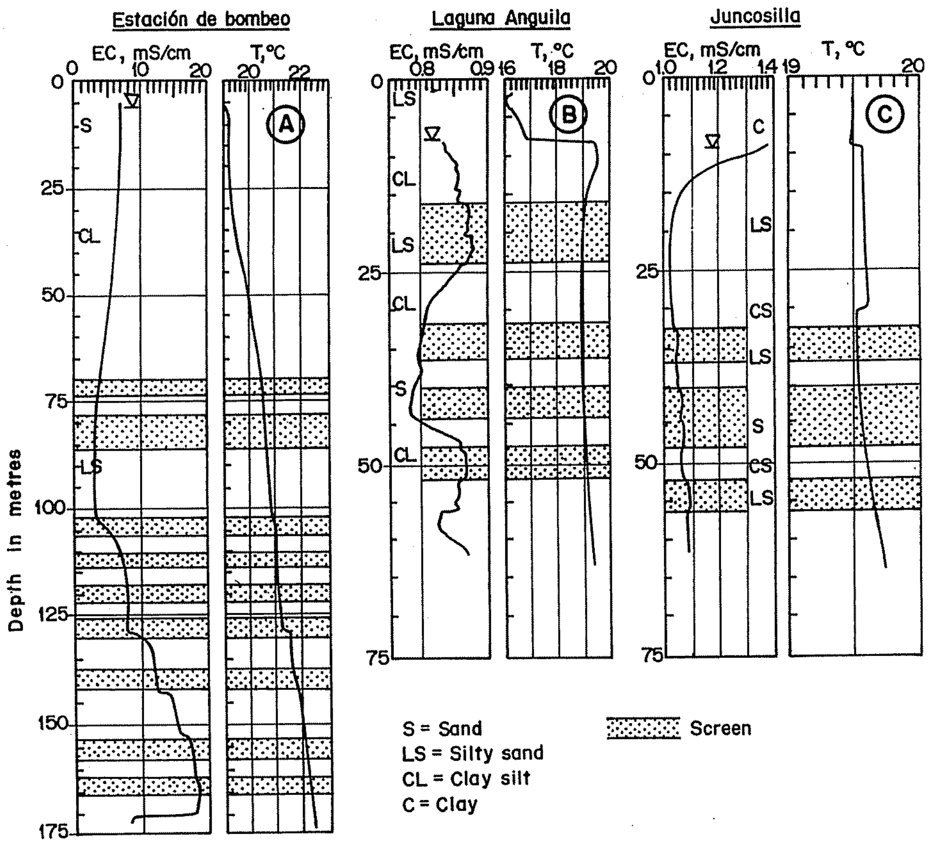

Fig. 4. – Step-like salinity (electrical conductivity) and temperature logs in recently drilled, multiscreened deep observation boreholes in the Doñana (Lower Guadalquivir) area marshes and northern territory (courtesy of CGS and CHG), penetrating unconsolidated clays, silt and sand with gravel layers. The pointed stripes correspond to the screen positions. Figure A corresponds to a borehole penetrating saline water soaked sediments. Figure B and C correspond to hard freshwater. EC = electrical conductivity; T = temperature.

Fig. 4. – Diagraphies de salinité (conductivité électrique) et de température avec des échelons. Sondages d'observation profonds récents équipés de crépines dans la région des marais du territoire nord de Doñana (Bas Guadalquivir) (par courtoisie de CGS et de CHG). Ces sondages pénètrent des argiles, limons et sables non consolidés, avec niveaux de graviers. Les bandes pointillées correspondent à la position des crépines. La figure A correspond à un sondage qui pénètre des sédiments imprégnés d'eau salée. Les figures B et C correspondent à des eaux douces mais dures. EC = conductivité électrique ; T = température.

sures are faster and wider than in the blocks, where the bulk of the groundwater storage occurs.

Inside the mixing zone the salinity increase with depth may produce stability against small head changes, but not if they are large. But even with small head changes, in heterogeneous aquifers there is some vertical flow between permeable layers linked by the borehole. This produces a step-like shape of salinity as well as of temperature logs, as has been consistently observed in several areas of Catalonia, Mallorca and Doñana (Southern Spain) ; see figure 4. Multiscreened observation boreholes in unconsolidated formations present sudden electrical conductivity (EC) changes at the screen lower ends. In consolidated rocks things are more complex since permeable lengths do not always coincide with screens or uncased sections, but salinity and temperature changes help in locating them.

Significant vertical flows inside the borehole reduce or cancel the vertical temperature gradient between the inflow and outflow sections. Step-like changes may be produced if there are intermediate yielding sections. Small vertical flows only decrease the thermal vertical gradient since heat is exchanged with the exterior, assuming steady state. This means that time since last disturbance of water inside the borehole (pumping, water injection, sampling) is long enough and circumstances controling vertical flows do not change. At the boundaries of the vertical flow section fast temperature changes may appear. Upward flow may produce relatively high temperatures at shallow depths.

More complex situations may be found, as that shown in figure 5, in the Aguadulce area, Campo de Dalías (Domínguez and Custodio, 1993). There is a heavily exploited, highly permeable salinized dolostone deep aquifer with low head and relatively cool water recharged in the nearby high Gador coastal range. Along the borehole there is a downward flow of fresh and relatively warm water from the less permeable, locally recharged upper layers under the warmer coastal plain. At the same time there is an upward flow of saline and warmer water from deep carbonate formations. These contributions from above and below mix with water flowing through the main aquifer.

Effect of vertical flow inside a screen section yielding water

Consider a borehole that penetrates high head deep aquifers and two separated deep screens in them, as shown in figure 6. Groundwater penetrates into the borehole through the two screens, and it flows upwards towards a non shown shallower low head screen or a pump. Calculations refer to the intermediate screen, subjected to a given head drawdown, Δh, with respect to the undisturbed head of the corresponding aquifer. After the Thiem formula for pumping wells:

$$\Delta h = \frac{\Delta Q}{2\pi k\lambda} \ln \frac{R}{r} \qquad [1]$$

Δh = head drawdown [L]

ΔQ = flow contributed by the screen [L^3T^{-1}]

k = aquifer permeability [LT^{-1}]

λ = screen length (assumed equal to aquifer layer thickness) [L]

R = radius of influence [L]

r = effective screen radius (taking into account gravel packs or skin effects)

Then

$$\Delta Q = \frac{2\pi k \Delta h\ \lambda}{\ln (R/r)} = \mathrm{B}\ .\ \lambda\ ;\ B \equiv \frac{2\pi k \Delta h}{\ln (R/r)} [L^2 T^{-1}] \quad [2]$$

Assuming a homogeneously distributed inflow into the bore through the screen, the vertical flow increase in a screen lenght dz is:

$$dQ = \frac{\Delta Q}{\lambda} dz = \mathrm{B} dz$$

Be: Q = vertical flow inside the screen at elevation z

Q_o = upward flow arriving from the lower screen at $z = 0$

c_o = concentration or temperature arriving from the lower screen

ç = constant concentration or temperature of water entering the screen under consideration from the aquifer

z = lengh of screen measured in the flow direction (from 0 to λ)

The solute mass or heat balance in a screen section of heigth dz is:

Vertical mass inflow + contribution through the screen = vertical mass outflow

$$\mathrm{Q.c} + \text{ç}\mathrm{dQ} = (\mathrm{Q} + \mathrm{dQ})(\mathrm{c} + \mathrm{dc})$$

considering that there is good mixing inside any screen section.

Neglecting second order differentials and considering that

$$Q = Q_o \quad \text{at} \quad z = 0 \quad \text{and} \quad Q = Q_o + Bz$$

the fraction of water from the lower screen in the upward flow, f, is:

$$f \equiv \frac{c - \text{ç}}{c_o - \text{ç}} = \frac{1}{1 + (Bz/Q_o)} \quad [3]$$

An example is included in figure 6. When the upward flowing water enters the screen there is a sudden change of concentration or temperature, and then smoothly evolves towards the aquifer characteristics. The evolution is interrupted when the screen finishes. The sudden change position indicates if vertical flow is upwards or downwards. In the unscreened – or low permeability sections – there is no vertical change of concentration, or of temperature if heat exchange by conduction through the walls is negligible. This is a reasonable assumption in quasi steady-state situations.

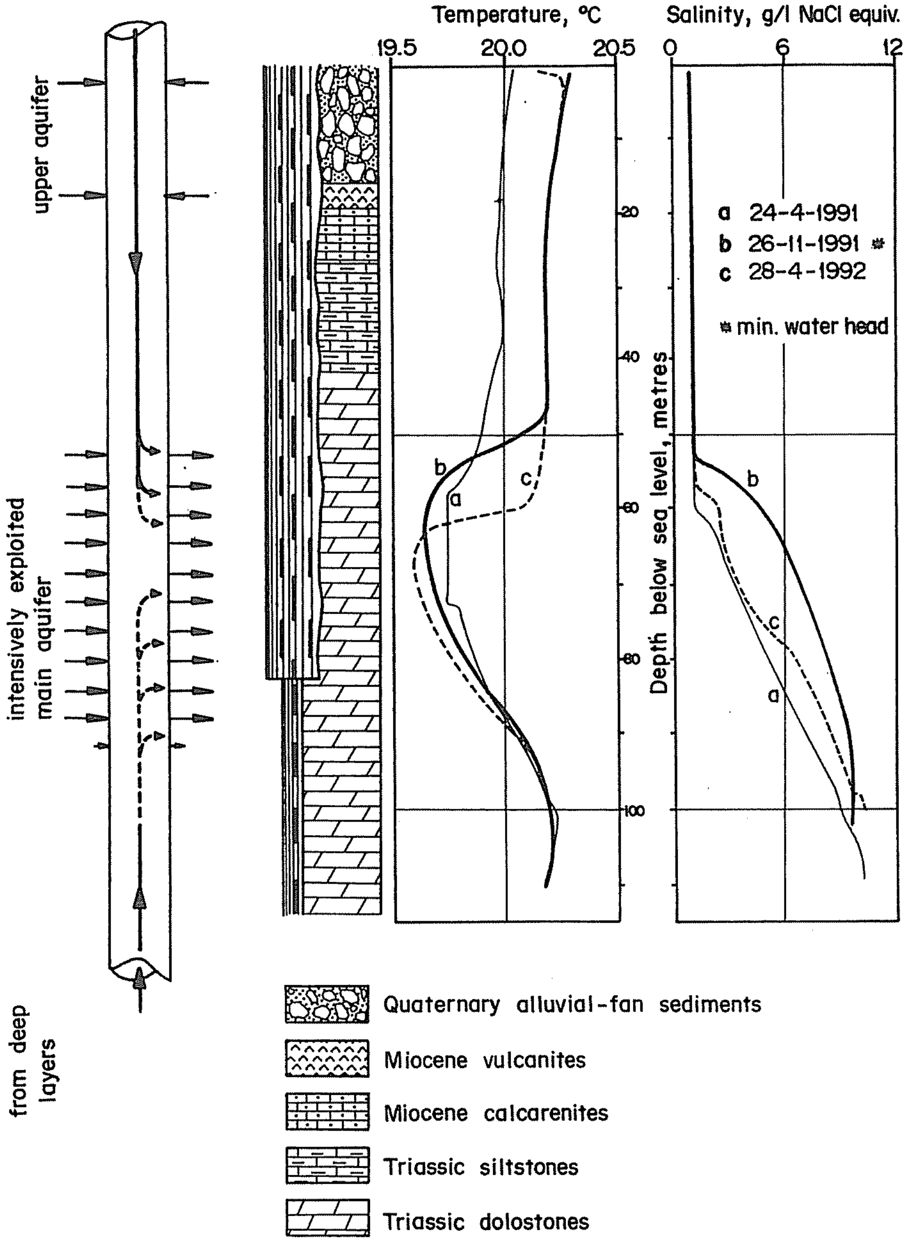

Fig. 5. – Salinity and temperature logs of observation well 224 RM in Aguadulce (Campo de Dalías, Almería) indicating well characteristics and lithology (Domínguez and Custodio, 1993). The results of the log depend on the relative head differences between the highly permeable, main carbonate aquifer (60 to 80 m deep) and the upper (less permeable, freshwater, relatively warm) and lower (less permeable, saline, warmer) aquifers. The main aquifer is recharged along the high and cooler Gador coastal range. The arrows indicate the assumed flow inside the well.

Fig. 5. – Diagraphies de salinité et de température du puits de monitorage 224 RM à Aguadulce (Campo de Dalías, Almería), montrant également les caractéristiques du puits et la lithologie (Domínguez et Custodio, 1993). Les résultats de la diagraphie dépendent des différences relatives de charge entre la nappe carbonatée principale (à une profondeur de 60 à 80 m) et les nappes supérieure (moins perméable, eau douce, relativement chaude) et inférieure (moins perméable, saline, plus chaude). La nappe principale est rechargée au long de la chaîne littorale de Gador, de grande altitude et froide. Les flèches montrent les circulations d'eau dans le puits.

The water concentration inside the screen is little changed with respect that in the aquifer if $|c - \text{ç}|/\text{ç}$ is less than a small value ∊, eg. 0.01. This means that for $z = \lambda$, length of the screen:

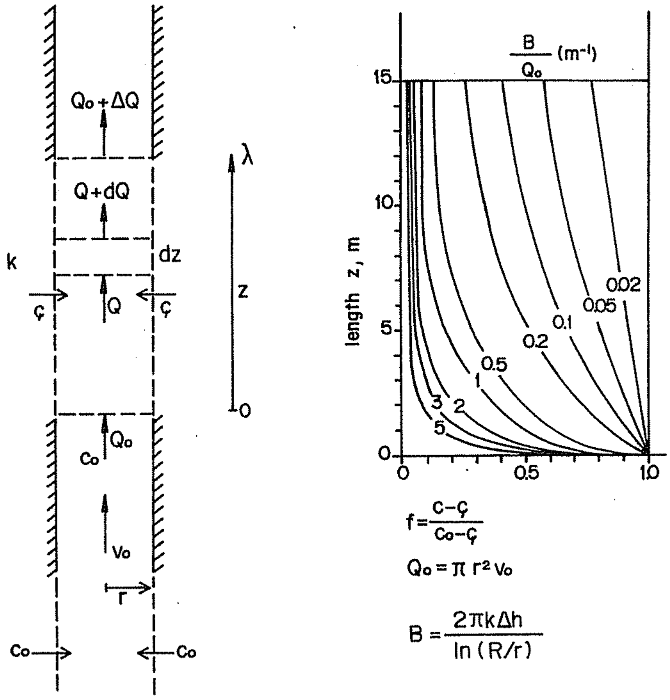

Fig. 6. – Flow sketch of a multiscreened borehole subjected to large drawdown from above, creating a dominantly radial flow in the lower screens, and results of calculations. The application to a sandy aquifer with a moderate head difference, for k = 1m/d; Δh = 0.5 m; R = 10 m; r = 0.05 m; v_o = 10 m/d, gives B/Qo = 0.755 (formule [2]).

Fig. 6. – Schéma de flux dans sondage multicrépiné soumis à un fort rabattement à sa partie supérieure. On crée ainsi un flux radial dominant dans les crépines inférieures. Les résultats de calcul sont pour une nappe sableuse présentant une différence de niveau piézométrique modérée. Pour k = 1m/j ; Δh = 0.5 m ; R = 10 m ; r = 0.05 m ; v_o = 10 m/j, on obtient B/Qo = 0.755 (formule [2]).

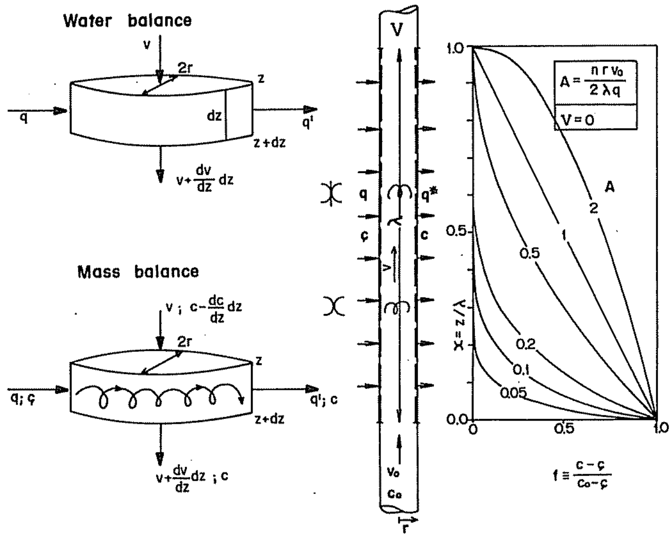

Fig. 7. – Balance sketches inside a screen section subjected to flow from the aquifer and vertical flow inside the borehole, and resulting shape of the salinity or temperature log. The application is to a screen in a sandy aquifer, in which there is no vertical outflow velocity (V = 0), for k = 1 m/d, hydraulic gradient 0.005; flow concentration factor in the bore α = 2 (then q = 0.01 m/d); r = 0.05 m; v_o = 1 m/d; λ = 10 m gives A = 0.78. This produces a close to lineal concentration variation along the screen.

Fig. 7. – Schémas des bilans d'eau et de masse dans une section de crépine qui reçoit le flux de la nappe et le flux vertical provenant par l'intérieur du sondage, montrant la forme de la diagraphie de salinité (ou de température) ; application à une nappe sableuse équipée d'une crépine ne présentant pas de flux à son extrémité supérieure (vitesse nulle ; V = 0) à l'extrémité de laquelle le flux vertical est nul (V = 0). Pour k = 1m/j, gradient hydraulique 0.005 ; facteur de concentration du flux dans le sondage = 2 (ainsi q = 0.01 m/j) ; r = 0.05 m ; v_o = 1 m/j ; λ = 10 m, on trouve A = 0.78, et une variation presque linéaire de la concentration au long de la crépine.

$$\frac{|c-\text{ç}|}{\text{ç}} = f|(c_o/\text{ç})-1| = \frac{|(c_o/\text{ç})-1|}{1+(B\lambda/Q_o)} \le \epsilon \quad [4]$$

The vertically flowing water in the borehole is little changed by the presence of a screen if $|c_o - c|/co$ is less than a small value, ϵ, eg. 0.01. This means that for $z = \lambda$:

$$\frac{|co-\text{ç}|}{c_o} = (1-f)\ |(1-(\text{ç}/c_o))| = \frac{|1-(\text{ç}/c_o)|}{1+\frac{1}{1+(B\lambda/Q_o)}} \le \epsilon \quad [5]$$

This simplified calculation assumes that flow through the screen (entering and leaving it) is negligible in comparison with radial inflow. This happens when large head changes relative to natural flow gradients occur. Otherwise horizontal flow from the aquifer through the screen has to be considered, as shown below.

Effect of natural flow in changing vertical flow characteristics inside a screen or open section

Let us assume a screen or open section of length λ [L] and radius r [L], subjected to natural flow (specific discharge) in the aquifer q [LT^{-1}] measured at the inner face of the screen. The vertical water velocity inside the bore is v [LT^{-1}], and z [L] the vertical distance directed upflow. The q values can be linked with flow velocity (Darcy velocity) in the aquifer by means of a flow concentration coefficient that corrects for the local permeability changes (Baonza *et al.*, 1970; Custodio and Llamas, 1983).

Let us consider the water balance in a differential length of screen, dz (fig. 7), assuming that vertical flow changes does not affect the horizontal inflow from the aquifer:

$$\text{inflow} = 2rqdz + \pi r^2 v$$

$$\text{outflow} = 2rq'dz + \pi r^2 \left(v + \frac{dv}{dz}dz\right)$$

$$\text{Balance: } q' = q - \frac{\pi r}{2}\frac{dv}{dz}$$

q' is the horizontal flow leaving the screen

For sake of simplicity let us assume a linear variation of v along the screen, from $v = vo$ at $z = 0$ (inflow end) to $v = V$ at $z = \lambda$ (outflow end)

$$v = (v_o - V)\left(1 - \frac{z}{\lambda}\right) + V \ ; \frac{dv}{dz} = -\frac{v_o - V}{\lambda}$$

Then:

$$q' = q + \frac{\pi r(v_o - V)}{2\lambda} = q\,(1 + A)\ ; A \equiv \frac{\pi r(v_o - V)}{2\lambda q} \quad [6]$$

The horizontal flow is little disturbed when $|A| << 1$.

Let us now consider the mass balance in a differential length of screen, dz, under the preceeding assumptions. The aquifer inflow has concentration ç and the water concentration inside the volume is c:

$$\text{mass inflow} = 2rq\text{ç}dz + \pi r^2\, v\,(c - \frac{dc}{dz}dz)$$

$$\text{mass outflow} = 2rq'cdz + \pi r^2\,(v + \frac{dv}{dz}dz)\,c$$

It is assumed that all inflow is perfectly mixed in the volume and all outflow are at the concentration of the mixture.

Be:

$q^* = q'$ if the water balance is taken into account
$q^* = q$ if the water balance is not taken into account, which is equivalent to vertical mass transport without water flow.

The mass balance is:

$$q\,\text{ç} - q^*\,c = \frac{\pi r}{2}\left[c\frac{dv}{dz} + v\frac{dc}{dz}\right]$$

For a lineal variation of v along the screen:

$$q\,\text{ç} - q^*\,c = \frac{\pi r}{2}\left[-\frac{c(v_o - V)}{\lambda} + \left[(v_o - V)(1-\frac{z}{\lambda}) + V\right]\frac{dc}{dz}\right]$$

If $q^* = q' = q\,(1 + A)$, after some algebraic manipulation:

$$\frac{dc}{dz} = \frac{\text{ç} - c}{A(\lambda - z) + C\lambda} \quad \text{with } C \equiv \frac{\pi r V}{2q\lambda}$$

If $q^* = q$

$$\frac{dc}{dz} = \frac{\text{ç} - c\,(1 - A)}{A(\lambda - z) + C\lambda}$$

Then:

$$\frac{dc}{dz} = \frac{\text{ç} - c\,(1 - \alpha A)}{A(\lambda - z) + C\lambda}$$

$\alpha = 0$ for $q^* = q'$

$\alpha = 1$ for $q^* = q$

Since $c = c_o$ (concentration of vertical flow at the inflow end of the screen), for $z = \lambda$, when $v_o - V > 0$, the following elemental solution is obtained:

$$\frac{\text{ç} - c\,(1 - \alpha A)}{\text{ç} - c_o(1 - \alpha A)} = \left(\frac{1 - (z/\lambda) + (C/A)}{1 + (C/A)}\right)^{\frac{1-\alpha A}{A}} \quad [7]$$

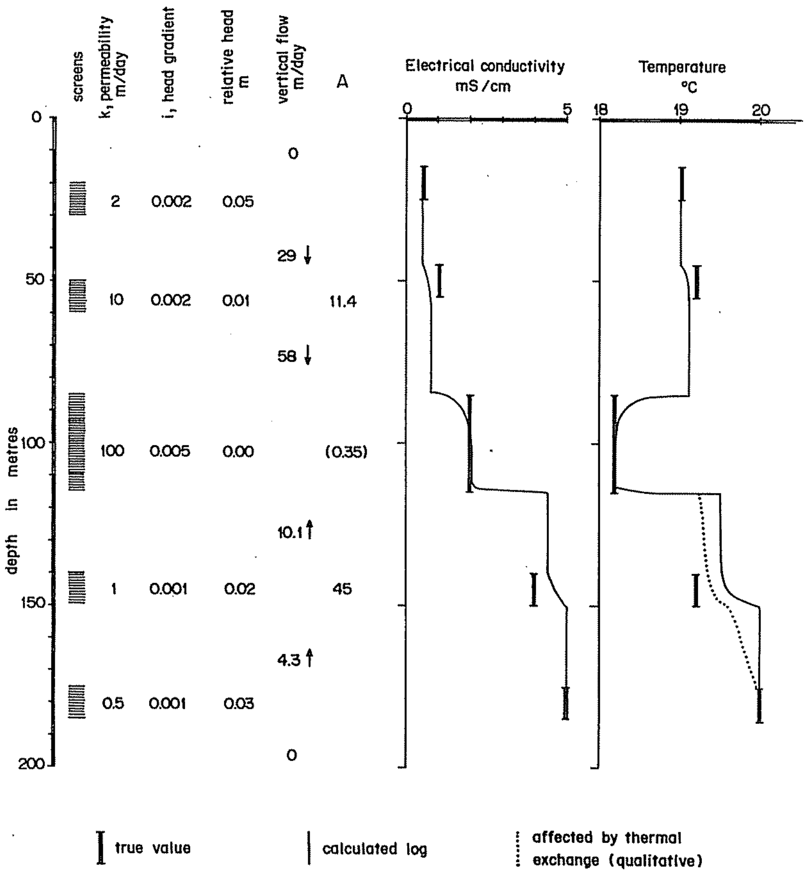

Fig. 8. – Simplified example of a hypothetical five screen observation borehole. The central screen corresponds to a highly permeable and thick aquifer which has low head due to intensive exploitation by means of wells. The figure show the depth of the screens, the permeability, the head gradient, the relative head respect the central screen, the calculated vertical flow velocity and the A value, as defined in [6]. The q value is taken as 2 ki. Along the central screen there is a no vertical flow point. The expected electrical conductivity and temperature logs are given.

Fig. 8. – Exemple simplifié d'un puits d'observation hypothétique avec cinq crépines. La crépine centrale correspond à une nappe épaisse et très perméable, laquelle a un bas niveau piézométrique à cause de l'exploitation par des puits. La figure montre la profondeur des crépines, la perméabilité, le gradient hydraulique, le niveau piézométrique relatif à la crépine centrale, la vitesse verticale du flux vertical et la valeur de A, depuis la définition dans [6]. La valeur de q est 2 ki. Au long de la crépine centrale existe un point de vitesse verticale nulle. On montre les profils de conductivité électrique et de température.

For $z = 0$; $c = c_o$
For $z = \lambda$; $c = M(c_o - \frac{\text{ç}}{1 - \alpha A}) + \frac{\text{ç}}{1 - \alpha A}$;

$$M \equiv \left(\frac{C/A}{1 + (C/A)}\right)^{\frac{1-\alpha A}{A}}$$

and for $\alpha = 0$; $c = (\frac{C/A}{1 + (C/A)})^{1/A}(c_o - \text{ç}) + \text{ç}$

When $V = 0$ (no vertical flow at the outflow end of the screen), is $c = 0$. Then:

$$c = \frac{\text{ç}}{1 - \alpha A} - \left(\frac{\text{ç}}{1 - \alpha A} - c_o\right)(1 - \frac{z}{\lambda})^{\frac{1-\alpha A}{A}}$$

$$c = \frac{\text{ç}}{1 - \alpha A} \quad \text{for } z = \lambda$$

and for $\alpha = 0$
$c = \text{ç} - (\text{ç} - c_o)\,(1 - \frac{z}{\lambda})^{1/A}$; $c = \text{ç}$ for $z = \lambda$

The degree of mixing is given by $f \equiv \frac{c - \text{ç}}{c_o - \text{ç}}$ (fraction of vertically inflowing water to the screen) and the position along the screen is $x = z/\lambda$. Simple algebraical manipulation leads to:

$$f = \frac{\text{ç}\alpha A + [c_o(1 - \alpha A) - \text{ç}]\left(\frac{1 - x + (C/A)}{1 + (C/A)}\right)^{\frac{1-\alpha A}{A}}}{(c_o - \text{ç})\,(1 - \alpha A)} \quad [8]$$

and for $\alpha = 0$; $f = \left(\frac{1 - x + (C/A)}{1 + (C/A)}\right)^{1/A}$

The slope is given by:

$$\frac{df}{dx} = \frac{c_o(1 - \alpha A) - \text{ç}}{(co - \text{ç})\,(1 - \alpha A)}\,\frac{1 - \alpha A}{A + C}\left(\frac{1 - x + (C/A)}{1 + (C/A)}\right)^{\frac{1}{A} - \alpha - 1}$$

For $\alpha = 0$

$$\frac{df}{dx} = -\frac{1}{A + C}\left(\frac{1 - x + (C/A)}{1 + (C/A)}\right)^{\frac{1}{A} - 1}$$

This means that at $z = 0 \quad (x = 0)$

$$\frac{df}{dz} = -\frac{1}{A+C} \quad \text{if } \alpha = 0.$$

The dimensionless parameter A depends on the screen slimness (r/λ) and the ratio of vertical flows to aquifer flow $(v_o/q;\ v/q)$ flows, and should be << 1 in order to have a close-to-natural flow pattern. See figure 7 for an example. A jump is produced at the screen entrance end and the concentration or temperature slowly tends to the value in the aquifer facing the screen under consideration. There is no change in the borehole outside the screen.

The importance of the concentration change inside the screen with respect aquifer water or vertical flow water can be derived from the formulae of the previous section by substituting in them the new value of f.

Simplified example

In order to provide an example of the possible vertical changes of electrical conductivity and temperature in the figure 8 a hypothetical aquifer is presented with five aquifer layers separated by aquitards. Each aquifer layer is fitted with a screen. The central layer is much more permeable and has a higher flow than the others and its head is decreased due to abstractions by means of wells. The example tries to mimic the assumed circumstances of the borehole of figure 5. Figure 8 shows the depth of the screens, the permeability (k), the head gradient (i) and the relative head refered to the central screen (Δh). It is assumed a borehole radius of r = 0.1 m and an influence radius of 100 m. Vertical flows can be easily obtained [1] [2] and the corresponding velocities as well as the A values [6]. The q values are calculated by the formula q = 2ki in which the value 2 means that the borehole behaves as an uncased bore with undisturbed walls. Only at the central screen is the horizontal flow dominant [7] [8]; in the others radial flow is dominant [3] [4]. The central screen receives water from both ends and therefore there is some point with no vertical flow, which can be placed according to the velocities. The electrical conductivity and temperature logs can be calculated. The results show sudden changes at both ends of the central screen and that the true water characteristics are found in the central part of it. Obviously water in front of the upper and lower screen is the same as in the corresponding aquifer, but not in the other two, in which a mixture of water exists always, and the composition changes gradually along the screen.

Conclusions

Long uncased or screened sections, or multiscreened observation boreholes may produce vertical flows inside the bore as a consequence of intersecting layers with different water heads, both natural or induced by groundwater abstraction. Those vertical flows change water quality and temperature distribution along the borehole with respect to water in the aquifer, and salinity and temperature logs may be often distorted. Long-screened boreholes may not produce reliable values of the depth to the interface and mixing zone thickness in coastal aquifers. Conditions can be found to know if the disturbance is serious or not. Often heterogeneities and screen sections show up as sudden changes of salinity or temperature, that tend to the aquifer natural value. The sudden change shows up in the screen end through which the vertical flow along the borehole enters.

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