

# XXXVIII IAH Congress

Groundwater Quality Sustainability  
Krakow, 12–17 September 2010

## Extended Abstracts

**Editors:**  
Andrzej Zuber  
Jarosław Kania  
Ewa Kmieciak



University  
of Silesia  
Press 2010



abstract id: **269**

topic: **6**  
**General hydrogeological problems**

**6.7**  
**Managing aquifer recharge**

title: **Extensive aquifer recharge through atmospheric chloride deposition on the land by means of groundwater from penetrating wells**

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

**Francisco Javier Alcalá**  
Experimental Station of Arid Zones, Science Research Council (CSIC), Spain,  
[fjalcala@eeza.csic.es](mailto:fjalcala@eeza.csic.es)

keywords: chloride deposition, recharge, aquifers, mixed samples

## INTRODUCTORY REMARKS

Aquifer recharge is the water arriving at the water table as a result of precipitation and occasionally surface water infiltration, including excess irrigation water and possible leakages. The transit from the soil root zone to the water table means a delay and also a smoothing out of precipitation irregularity. Most of rainfall infiltration is temporarily stored in the root zone and partly evaporated, although a fraction may penetrate below the root zone through soil discontinuities, thus avoiding evapotranspiration. When the water table is shallow groundwater may be up-taken by permanent or alternative phreatophytes or evaporated. Net recharge is then diffuse recharge arriving to the water table (total recharge) less groundwater evapotranspiration and the possible vadose zone lateral recharge. What follows refers mostly to diffuse rainfall recharge under Mediterranean climates, especially in areas with a remarkable topographical relief and relatively deep water table.

Aquifer recharge is essential to evaluate aquifer renewable water resources for water studies and management. However this is one of the most difficult issues in hydrogeology. In order to get reasonable results, as many different appropriate techniques as possible should be used. The most used ones for total diffuse recharge are those relying on soil water balance. In order to check the evaluations, the use of other independent methods is advisable, even if they are simple ones. The chloride mass balance method is one of them and the subject of this paper. It is not a novel method (Eriksson, 1960; Prych, 1998; Custodio, 2009) and is has been used widely, but some caution is needed. Commonly the results are long-term recharge values.

## ATMOSPHERIC CHLORIDE BALANCE IN THE SOIL

Precipitation is a source of chloride, a conservative and non complexed ion under most natural circumstances. It falls dissolved in rain water (wet deposition) and contained in dust (dry fall-out or dry deposition). The main chloride source is the sea, but there are also chlorinated volatile compounds in the air, and continental and lithologic sources. Deposition values are obtained by means of sampling stations operated along some time. Anthropogenic sources are a disturbance to be avoided.

In a given parcel and time interval, the water and chloride mass balances in the vadose zone column, assuming only rainfall input and that there is no significant lateral outflow from the vadose zone, is:

$$P = R + ES + \Delta S + E \quad \text{water balance} \quad (1)$$

$$A = R \cdot C_R + ES \cdot C_{ES} + \Delta SC + F \quad \text{chloride mass balance} \quad (2)$$

where:

P = water precipitation on the land

R = net diffuse recharge to the water table

ES = surface runoff from the area

$\Delta S$  = increase in root zone soil water

E = total evapotranspiration (vadose zone + water table), which is chloride-free water vapour

$A$  = atmospheric bulk chloride deposition

$C_R$  = average chloride concentration in recharge water

$C_{ES}$  = average chloride concentration in runoff

$\Delta SC$  = change (increase) of root zone soil chloride mass storage

$F$  = other sources of chloride

The long-term balances are obtained by adding the successive time intervals:

$$\begin{aligned}\sum P_i &= \sum R_i + \sum ES_i + \sum E_i ; \\ \sum A_i &= \sum (R_i \cdot C_{Ri}) + \sum (ES_i \cdot C_{ESi}) + \sum (F_i)\end{aligned}\quad (3)$$

in which the storage changes cancel out.

$\sum A_i \equiv \sum (P_i \cdot C_{Pi})$  in which  $C_{Pi}$  is the rain sample concentration (including dry deposition) for a precipitation  $P_i$  in a given sampling interval. In developed soils  $F$  can be safely neglected except when evaporites and recent unleached saline sediments are present.

If  $\bar{C}_R$  is the average chloride concentration at the water-table top, for a simple case and a series of  $n$  complete years, the average recharge value  $\bar{R}$  is:

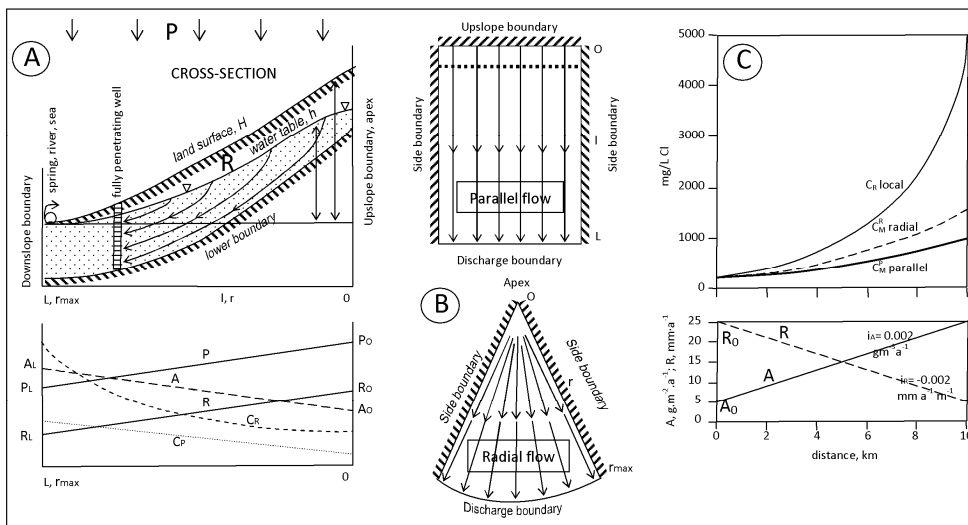
$$\bar{R} = \frac{1}{n} \left[ \sum A_i - \sum (ES_i \cdot C_{ESi}) \right] \frac{1}{\bar{C}_R}$$

whose estimation uncertainty can be evaluated by error propagation. A calculated negative value of  $\bar{R}$  may be due to errors in the estimation of  $\bar{A}$ ,  $\bar{ES}$ ,  $\bar{C}_{ES}$ , or non-representative  $\bar{C}_R$  values. For a permeable soil in flatland  $ES$  is small, provided the ground does not become water logged or frozen. When  $ES$  and  $ES \cdot C_{ES}$  are not negligible and are not considered,  $\bar{R}$  results too high. In thick unsaturated zones in dry climates –small recharge– the effect of past climate changes may still be moving down, so water entering the water table is not current recharge but recharge under past conditions.

### UPSLOPE RECHARGE CONTRIBUTION

Groundwater mixing is a common fact for springs, long-screened wells, and stream base-flow. Therefore, samples do not yield the local  $C_R$  value. The chloride content of these samples,  $C_M$ , corresponds to a weighed mixture of water recharged at other sites and altitudes. The  $C_M$  value can be used to yield lumped aquifer recharge rates over the aquifer catchment by assuming an exponential mixing model.

In the situation depicted in Figure 1A,  $H$  is land elevation, and  $h$  the water-table elevation, all of them above the discharge base, such as a major river, the coast, a large lake, or a highly pervious aquifer.  $P$  is the average precipitation and  $R$  the average recharge, with respective average chloride contents  $C_P$  and  $C_R$ , which vary with location. Steady state is assumed and runoff is taken as negligible, or its effect is previously discounted from rainfall contribution.



**Figure 1.** Behaviour of a sloping aquifer. A.– Cross-section and assumed evolution with altitude of P, R, A, C<sub>P</sub> and C<sub>R</sub>. B.– Parallel and radial flow aquifers along which recharge and chloride mass are integrated, C.– Results for linear variations of R and A along slope and the resulting differences between C<sub>M</sub><sup>P</sup> (parallel flow), C<sub>M</sub><sup>R</sup> (radial flow) and local recharge chloride concentration (after Custodio, 2009).

For parallel flow lines (Figure 1B), the water and mass (chloride) balances per unit width at distance l from the divide can be computed:

Flow per unit width at l (x is an intermediate distance dummy integration variable).

$$\text{Water balance } q_l = \int_0^l R(x)dx ; \text{ Mass balance } q_l^c = \int_0^l R(x)C_R(x)dx \quad (5)$$

For divergent flow lines (flow in a wedge-shaped aquifer) the same reasoning can be applied (Figure 1B), in which case r is the distance to the apex and ρ the dummy integration radius. Flows are total flows through the section, per unit angle (radians):

$$\text{Water balance } Q_r = \int_0^r R(\rho)d\rho ; \text{ Mass balance } Q_r^c = \int_0^r \rho R(\rho)C_R(\rho)d\rho \quad (6)$$

Then, the average chloride content C<sub>M</sub><sup>P</sup> for parallel flow at l and C<sub>M</sub><sup>R</sup> for radial flow at r are:

$$C_M^P = \frac{q_l^c}{q_l} = \frac{\int_0^l R(x)C_R(x)dx}{\int_0^l R(x)dx} \quad \text{and} \quad C_M^R = \frac{Q_r^c}{Q_r} = \frac{\int_0^r \rho R(\rho)C_R(\rho)d\rho}{\int_0^r \rho R(\rho)d\rho} \quad (7)$$

Chloride concentration in the top of the water table at distance l is C<sub>R</sub>(l)=A(l)/R(l) and at radius r is C<sub>R</sub>(r)=A(r)/R(r). They may be very different from C<sub>M</sub> measured at the same place (see Figure 1C).

Since  $C_R$  may vary remarkably and non linearly from top down, it is more convenient to refer it to the smoother variable  $A$ , being  $A \equiv R(l) \bullet C_R(l)$ , or  $A \equiv R(r) \bullet C_R(r)$ . Then equations [6] transform into:

$$C_M^P = \frac{\int_0^l A(x)dx}{\int_0^l R(x)dx} \text{ for parallel flow ; } C_M^R = \frac{\int_0^r \rho A(\rho)d\rho}{\int_0^r \rho R(\rho)d\rho} \text{ for radial flow} \quad (8)$$

If  $R$  and  $A$  vary linearly, with top-down slopes (negative for decreasing values), designed as  $i_R$  and  $i_A$ , respectively, the linear variations are:

$$R(x) = R_0 + i_R x \quad ; \quad R(\rho) = R_0 + i_R \rho \quad (9)$$

$$A(x) = A_0 + i_A x \quad ; \quad A(\rho) = A_0 + i_A \rho \quad (10)$$

where  $R_0$  and  $A_0$  are respectively the recharge rate and the atmospheric bulk chloride deposition at the upper boundary or apex. Results are:

$$\frac{1}{C_M^P} = \frac{2R_0/A_0 + (i_R/A_0)l}{2 + (i_A/A_0)l} \quad ; \quad \frac{1}{C_M^R} = \frac{3R_0/A_0 + 2(i_R/A_0)r}{3 + 2(i_A/A_0)r} \quad (11)$$

Plotting  $1/C_M$  versus  $l$  or  $r$  allows drawing a curve (about a straight when  $i_A$  is small). The coordinates of three points distributed along it can be used to solve for the unknowns.

In the cases in which  $A$  is almost constant ( $i_A \approx 0$ ):

$$\frac{1}{C_M^P} = \frac{R_0}{A} + \frac{i_R}{2A} l \quad ; \quad \frac{1}{C_M^R} = \frac{R_0}{A} + \frac{2 i_R}{3 A} r \quad (12)$$

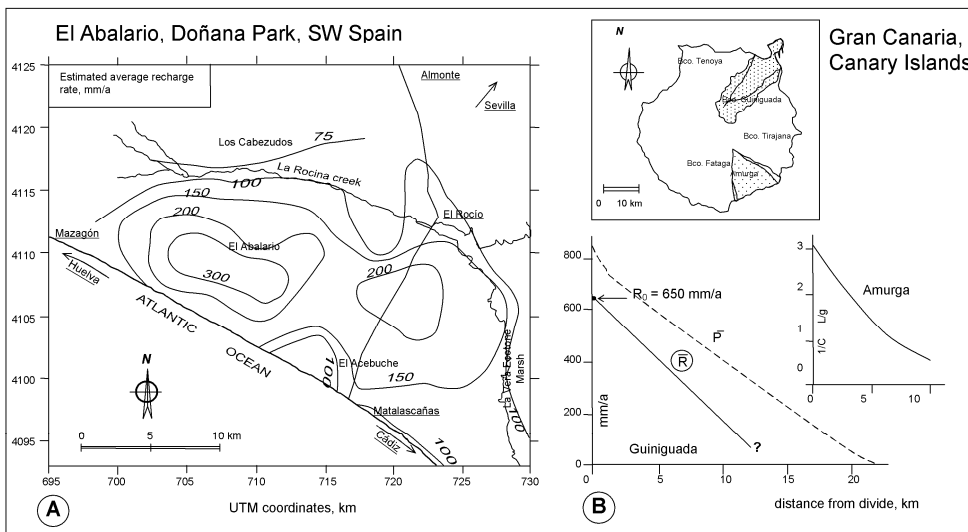
In a plot  $1/C_M$  vs.  $l$  or  $r$ , they are straight lines with intersects  $R_0/A$  and respective slopes  $\frac{i_R}{2A}$  and  $\frac{2 i_R}{3 A}$ .

### SIMPLE APPLICATION EXAMPLES

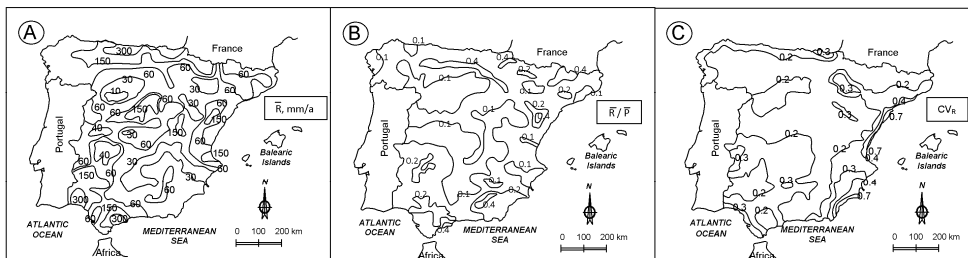
Several application to slopping and varied topography aquifers have been considered in Custodio (2009) and the method has been applied to the whole Spanish territory in the Iberian Peninsula (Alcala, 2006) and the estimation errors are been analysed and refined in two papers under review. Figure 2 shows the results from a well-recharge sandy area and variable rainfall and arid basins from a volcanic island. Figure 3 considers results for the Iberian Peninsula, with a rough estimation of uncertainty.

### ACKNOWLEDGEMENTS

The authors acknowledge the support received by the Geological Survey of Spain (IGME) and the Spanish Committee for Science and Technology (CICYT, HID-99-205), and currently through CICYT project REDESAC (CGL2009-12910-C03-01).



**Figure 2.** Two local examples of recharge estimation (mm/a) through atmospheric chloride mass balance. A.- The eolian sand covered area of El Abalarío, Doñana, SW Spain, B.- altitudinal variations of recharge in Gran Canaria volcanic island, for the Guinguada basin (wet to semi-arid) and Amurga massif (arid:  $\bar{R}$  is 10 mm/a,  $R_0=30$  mm/a (after Custodio, 2009).



**Figure 3.** Average recharge in Peninsular Spain after Alcalá (2006). A.- Average recharge in mm/a. B.- Ratio of average recharge to average precipitation. C.- Preliminary coefficient of variation (standard deviation/mean value, as a fraction) of recharge; upgraded data series treatment reduces the higher values by a factor about 2.

**REFERENCES**

Alcalá F.J., 2006: *Recarga a los acuíferos españoles mediante balance hidrogeoquímico [Recharge to Spanish aquifers through a hydrogeochemical balance]*. Doctoral thesis, Technical University of Catalonia (UPC). Barcelona. 2 Vols: 1-719.

Custodio E., 2009: *Estimation of aquifer recharge by means of atmospheric chloride deposition balance*. Contributions to Science, 5(2).

Eriksson E., 1960: *The yearly circulation of chloride and sulphur in nature; meteorological, geochemical and pedological implications, part II*. Tellus, 12: pp. 63-109.

Prych E. A., 1998: *Using chloride and chloride-36 as soil-water tracers to estimate deep percolation at selected locations on the U.S.* US Geological Survey Water Supply Paper 2481: pp. 1-67.



**International Association of Hydrogeologists**



**AGH University of Science and Technology**

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