Predicting the effects of sea spray deposition and evapoconcentration on shallow coastal groundwater salinity under various vegetation types

Pieter J. Stuyfzand[1,2]
[1]Faculty of Earth and Life Sciences, VU University, Amsterdam, Netherlands
[2]KWR Watercycle Research Institute, Nieuwegein, Netherlands

ABSTRACT

Shallow groundwater in coastal areas can be brackish purely due to sea spray deposition followed by evapoconcentration, thus without any sea water intrusion. But when and where?
A simple analytical model is presented, capable of predicting the mean chlorinity of shallow groundwater under various vegetation types in a sandy recharge area.

INTRODUCTION

Groundwater recharged by precipitation in temperate climates can become brackish when sea spray deposition and evapoconcentration (concentration rise by evapotranspiration losses) are high. For instance, the upper groundwater under pine forests close to the sea shore with frequent storms blowing inland may show Cl concentrations in the Netherlands as high as 1,100 mg/L (Stuyfzand 1993, Stuyfzand & Rambags 2011).
It is important to be able to predict the Cl concentration of rain fed groundwater for 4 reasons: (i) chloride, which is mainly (>95%) linked to sea spray inputs, determines also a very significant part of the concentrations in groundwater of Na, K, Mg, SO_4, Br, B, I, Li, Mo and Rb (Stuyfzand, 1993); (ii) climate change, sea level rise, coastal erosion or progradation (by e.g. beach nourishment) affect the quantity of sea spray deposition and vegetation composition, and thereby groundwater quality; (iii) Cl peaks in vertical logs of rain fed, coastal groundwater can be used to date shallow groundwater and to derive actual evapotranspiration rates via the chloride mass balance (Stuyfzand 1993 and 2014); and (iv) the observation of brackish groundwater in wells does not necessarily indicate salt water intrusion, so that an atmospheric origin needs to be excluded before panic is justified.

METHOD

The annual mean Cl concentration of rain-fed groundwater (Cl_G) in natural recharge areas is predicted by the following set of semi-empirical equations that were tested on a huge population of data (Stuyfzand 2010 and 2014):

$$Cl_G = f_E^{1.5}\, Cl_P \qquad (1)$$

$$\begin{array}{ll} \text{if } E/P < 0.95 & f_E = P / (P - E) \\ \text{if } 0.95 \leq E/P < 1 & f_E = 20\, E / P \\ \text{if } E/P \geq 1.00 & f_E = 20 \end{array} \qquad (2)$$

$$Cl_P = (Cl_M / 16{,}800)\, f_W\, \Sigma\, (v_W^{3.4}\, 550\, [X_{WIND}]^{-0.45}) / 365.25 + 0.1 \qquad (3)$$

where:
P = annual total of gross precipitation [mm/y]; E = annual total of evapotranspiration [mm/y]; Cl_P , Cl_M = chloride in bulk precipitation, coastal sea water [mg/L]; f_E =

evapoconcentration factor according to Eq.2; Σ = summation of daily values during calendar year under consideration; v_W = daily mean wind velocity measured at 10 m altitude [m/s]; X_{WIND} = daily mean distance of the Cl monitoring site to the beach high water line (HWL) as measured along each day's mean wind direction [m]; f_W = empirical correction factor to obtain the best overlap of the calculated or reconstructed Cl_P signal (based on wind data) with the measured Cl_P time series on site.

The above given approach requires the daily measurement of X_{WIND}, which can be automatized by using GIS or as follows, in case of a straight coastline (Fig.1):

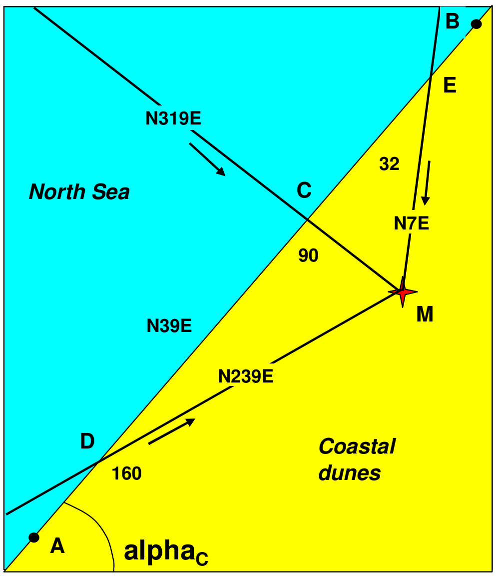
In case of offshore wind, thus if $(90 - \arctan(a_C)) < W_D < (180 + \arctan(a_C))$:

$$X_{WIND} = 200{,}000 \text{ [m]} \qquad (4)$$

In case of onshore wind:

$$X_{WIND} = \text{sqrt}\,[\{a_C\,(b_C - b_M)/(a_M - a_C) + b_C - Y_M\}^2 + \{(b_C - b_M)/(a_M - a_C) - X_M\}^2] \qquad (5)$$

Where: W_D = wind direction [e.g. west = 270]; $a_M = 90 - \tan(W_D)$; $b_M = Y_M - a_M X_M$; a_C = tan(alpha$_C$) = slope of straight line between A and B in Fig.1 [-].



Annual mean values for frequently occurring vegetation types are listed in Table 1. The factor f_W is 0.0015 for KNMI's meteorological station De Kooy (North Holland). This value yields the best fit of calculated with measured Cl data at De Kooy in the period 1978-1987 (both annual and monthly data).

FIG. 1. Spatial relations between the location of monitoring site M, a straight coastline (between A and B) and 3 wind directions with fetch over land from the HWL up to monitor point M, being EM (N7°E), CM (N319°E) and DM (N239°E) respectively. From Stuyfzand (2010).

The power factor 3.4 corresponds with observations by Monahan & O'Muircheartaigh (1980). The theory behind Eqs.1-5 is that wind velocity determines the amount of sea spray in the atmosphere (Monahan & O'Muircheartaigh, 1980), and the wind direction determines the amount of sea spray in the atmosphere that disappears by sedimentation, impaction etc., in between the HWL and monitoring point M (X_M,Y_M).
As we know from literature (Leeflang 1938; Stuyfzand 1993), a decreasing distance to the coastline leads to an exponential increase of sea spray deposition. That distance is shortest when the wind is blowing perpendicularly to the coastline, and increases when the wind angle deviates from that (Fig.1).

TABLE 1. Relations between gross precipitation (P), evapotranspiration (E), groundwater recharge (R) and evapoconcentration factor (fE), as function of 10 characteristic (dune) vegetation types. The values shown for E/P and f_E hold for P = 0.845 m/y.

VEGETATION		EVAP			Conc.
Type	Code	R = (p ln(P)-c)/1000			factor Evap
Prec (P) m/y =	0.845	p	c	E/P	fE = P/R
Bare	1	750.0	4330	0.143	0.725
Bare + some mosses/grasses	2	741.6	4338	0.219	0.660
Mosses	3	730.0	4360	0.338	0.560
Poor dry dune veg, mix of mosses+grasses+bare	4	720.0	4370	0.429	0.482
Dry shrubs (open), <50% mosses/grasses	5	710.0	4383	0.524	0.402
Rich dry dune veg, Heather, Dry deciduous	6	702.4	4398	0.603	0.335
Dense shrubs, Wet tall grasses, Oaks	7	641.6	3977	0.590	0.347
Wet dune slack, Deciduous forest (wet)	8	600.0	3750	0.653	0.294
Pines, dense dry	9	550.0	3500	0.755	0.207
Pines	9.5	504.3	3251	0.825	0.148
Pines, wet and dense	10	475.0	3100	0.880	0.101

Effects of evapoconcentration and interception deposition (= additional atmospheric, mainly dry deposition by vegetation compared to a bulk precipitation collector) are combined in the term $f_E^{1.5}$ of Eq.1.
Alternatives to using Eqs.3-5 are: (i) measuring the annual inland Cl gradient in bulk precipitation, or (ii) using the following approximation:

$$Cl_P = (Cl_M / 16{,}800)\ A\ [f_A\ X_{HWL}]^{-B} + 0.1 \qquad (6)$$

Where: X_{HWL} = shortest distance to the High Water Line of the sea [m]; f_A = correction factor for a longer distance to HWL when measured along the azimuth of the predominant wind direction, along which on average during a year the strongest winds blow (with velocity >5 Beaufort) and with which the highest amount of sea spray is deposited; A,B = constants depending on storm frequency and intensity during calendar year.

In the Western Netherlands near Haarlem for instance, the following values hold: f_A = 1.20 (with azimuth = N260E); A = 550, B = 0.45 during windy years like 1981, and A = 101.89, B = 0.3437 during calm years like 1938-1939 and 2010-2011 (Stuyfzand 2014). The strength of Eq.6 is, that in principle only one coastal rain monitoring station may suffice to establish the annual windiness.

RESULTS AND DISCUSSION

The model shows an excellent fit with annual mean data from 28 monitoring plots collected in the early 1980s in the Western Netherlands, with vegetation types ranging from very scanty (nearly bare) to full-grown pine stands, and with distances to the HWL of 0.2 – 100 km (Fig.2).
The advantage of using wind data is, that (i) they have been measured much more frequently and for a longer time than Cl measurements in bulk or wet-only precipitation, and (ii) climate models do generate information on changes in wind climate, but not on sea spray deposition.
Sometimes a correction factor (f_{LOC}) for location specific deviations from the normal inland Cl deposition gradient is needed, for instance due to an extremely high exposition to seawinds along the windward border of a forest ($f_{LOC} > 1$), or due to shielding from salty winds in the interior parts of a forest ($f_{LOC} < 1$).

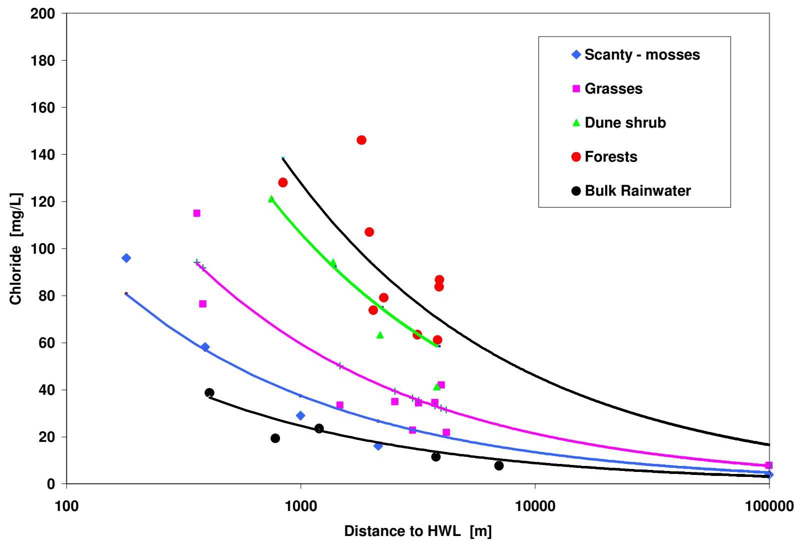


FIG. 2. Measured and with Eqs.1-5 calculated mean Cl concentrations of bulk precipitation and shallow dune groundwater under 4 vegetation types, as function of the distance of the monitoring plots to the North Sea high water line (HWL).
Data points = measured in the early 1980s in coastal dunes of the Western Netherlands and National Park Veluwe (~100 km inland); Curves = calculated relations.

CONCLUSION

The validated analytical model can be used to predict the effects of for instance coastal erosion by sea level rise, coastal extension by sand nourishment, climate change or vegetation changes. And also, they can strengthen the chloride mass balance approach in estimating evaporation losses.

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Contact Information: Pieter J. Stuyfzand, KWR Watercycle Research Institute, Water Systems Department, P.O. Box 1072, 3430 BB Nieuwegein, Netherlands, Phone: 0031-6-10945021, Fax: 0031-30-6061-165, Email: Pieter.stuyfzand @kwrwater.nl