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OPTIMUM WELL SAMPLING DISTANCE OF GROUNDWATER LEVELS IN TILL AND COVERSANDS, LEERINKBEEK CATCHMENT AREA, THE NETHERLANDS[1]

H. RYCKBORST[2] & A. LEUSINK[3]

ABSTRACT

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Spectral decomposition of groundwater-table profiles from the extremely wet year 1965 shows that the wavelength of 1710 m is the most significant for fluctuations in Pleistocene till and aeolian coversands in The Netherlands. Consequently, the optimum well sampling distance of groundwater levels in till and coversands is 855 m, whereas the average distance in the national groundwater network (12,000 wells) is 1600 m.

The distance of 855 m corresponds to half the average distance between soil classes, mapped on the 1:25,000 soil maps. The design of an optimum groundwater well network will thus benefit from 1:25,000/1:50,000 soil maps and land use maps.

INTRODUCTION

In the Leerinkbeek research catchment (52 km^2), in the Eastern Netherlands (Fig. 1), water levels in more than 190 groundwater-table wells were measured in Pleistocene till and aeolian coversands at bi-weekly intervals over a period of one decade. During that decade another 180 wells were in operation for shorter intervals (COLENBRANDER, 1979-c), bringing the total to about 380 wells. All this data served a national research effort to:

(1) locate the changing phreatic boundary; a number of wells were therefore installed outside the basin boundary (COLENBRANDER, 1970-a);

(2) compute the groundwater contribution to streamflow (COLENBRANDER, 1970-b);

(3) locate recharge-discharge areas and stretches where river waters infiltrate (DE RIDDER, 1970);

(4) outline agricultural areas with drainage problems and to compute the frequency of problem events (STOL, 1970; PAPE & EBBERS, 1970; COLENBRANDER, 1970-c);

(5) assess the conflicting uses of groundwater and the economic prospects of improvement (SNYDERS, 1970; VAN ELDIK, 1970; VISSER, 1970);

(6) determine the magnitude of the groundwater storage term in the water-balance equation (COLENBRANDER, 1970-d; MAKKINK & HEEMST 1970; BLOEMEN, 1970).

From the large amounts of available data, those for the period January 1965 to December 1965 were selected as network design data, since 1965 was an extraordinary wet year of a once-in-25 year-recurrence. Large groundwater-table fluctuations occurred, and fortunately the data for that year is of exceptionally good quality. Some 22 sets of groundwater levels were selected for that year at bi-weekly intervals. The reason for selecting a 1:25 year recurrence interval is based on the assumption that the research catchment project life will extend 15 years beyond the end of the International Hydrological Decade in view of significant investments in proven research equipment and in regard to the considerable number of scientific results produced.

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[2]Petro-Canada, P.O. Box 2844, CALGARY, Alberta T2P 2M7, Canada.
[3]Earth Sciences Institute, Free University, 1085 De Boelelaan, AMSTERDAM, The Netherlands.

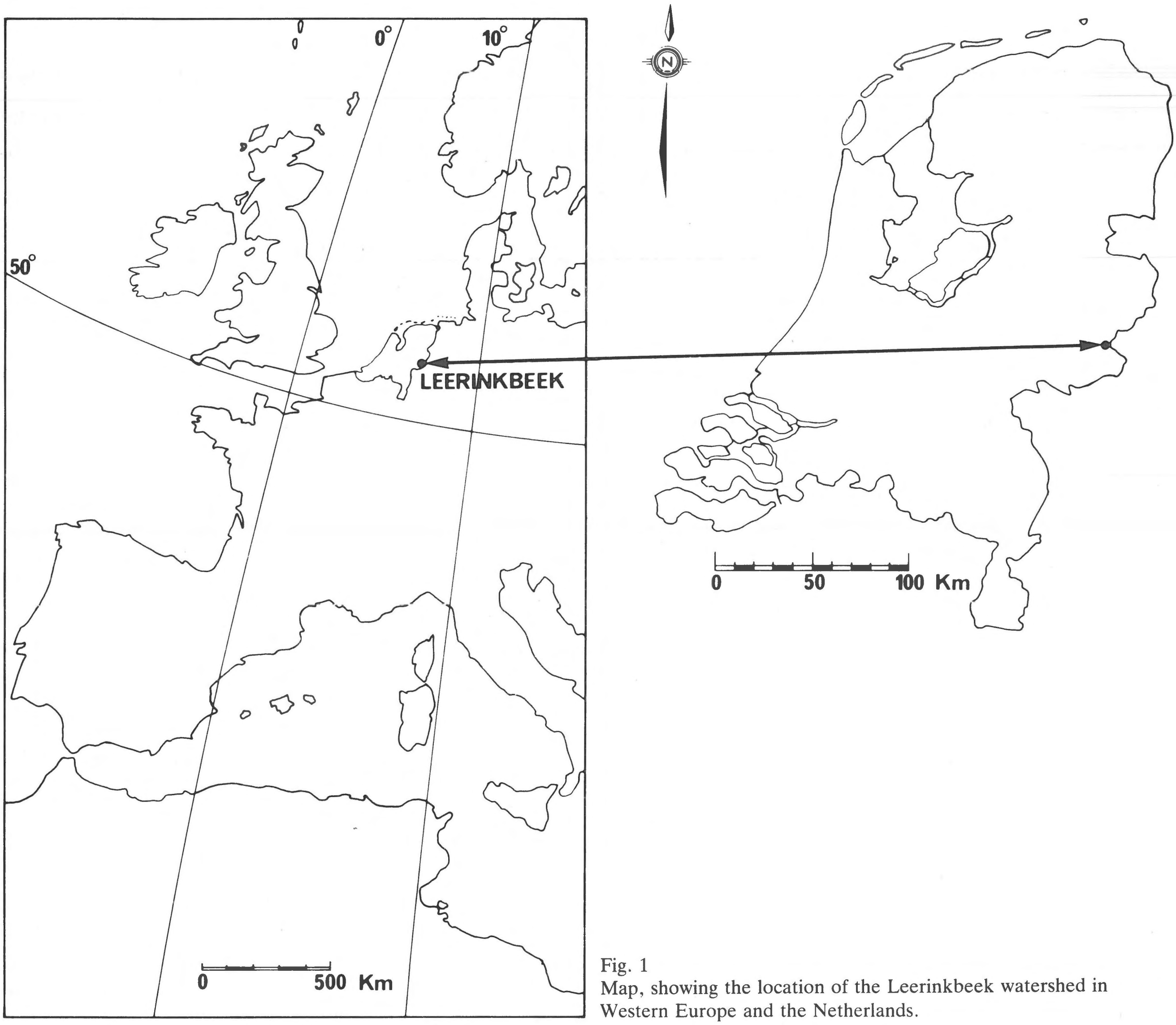

Fig. 1
Map, showing the location of the Leerinkbeek watershed in Western Europe and the Netherlands.

PROBLEM STATEMENT

Sometime during the International Hydrological Decade the number of groundwater wells, used for the bi-weekly mapping of the groundwater table in a 52 km^2 research catchment in The Netherlands, increased and was reduced by 50%, from 190 to 380 and back to 190 wells. This change in the number of wells is partly related to a changing number of research projects with evolving purposes. However, the changing number of wells brings up a question of how to obtain an objective yardstick to determine an optimum spacing between wells. The problem is defined as: what minimum well spacing is required to map a groundwater table of a given area with a pre-set accuracy (say 10%) for a given spatial resolution (say 300 m) and given sampling time interval (say bi-weekly) such that that water table is defined accurately during $((1-e^{-1})\,100)\%$ of the time in the wettest, most variable year of the design life span for the groundwater well network (say 25 years). The economics of a groundwater well network design puts bounds on such parameters as accuracy, spatial resolution, time sampling interval, project life span, pay-out, write-off and percentage of time during an extreme year when the pre-set accuracy cannot be attained. Practical aspects pose also limitations on a groundwater well network, e.g. road access, finding the wells back in the fields, and the search for well locations that do not interfere with farming operations, yet are sufficiently far away from roads, ditches or creeks.

THEORY

The optimum groundwater gauge spacing was computed from the 22 data sets, using power spectra based on BURG'S (1972) algorithm. The Burg method was applied because of its suitability to detect significant spatial periodicities (wavelengths) in short data sets. The main advantage of Burg's method is that it will not lead to misplaced spectral peaks. The Burg algorithm is known from detailed descriptions by BURG (1967, 1968, 1972), ULRYCH (1972), ULRYCH ET AL. (1973) and notably by DENHAM (1975): at the start of the procedure two N vectors $F = (f_1, f_2, \cdots, f_N)$ and $B = (b_1, b_2, \ldots, b_N)$ are both set equal to the complex data $X = (x_1, x_2, \cdots, x_N)$.

Next the k vector $C = (c_1, c_2, \cdots, c_k)$ is formed by setting $C_1 = 1$ and obtaining C_j ($j = 2$ to k) by applying the following three expressions recursively in the order given (an asterisk denotes a complex conjugation):

$$C_j = \left(-2\sum_{i=j}^{N} b^*_{i-j+1} f_i\right) \cdot \left(\sum_{i=j}^{N} (f^*_i\, f_i + b^*_{i-j+1}\, b_{i-J+1})\right)^{-1} \quad (1)$$

$$f_i^{new} = (f_i = C_j b_{i-j+1})^{old} \quad (2)$$

$$b_{i-j+1}{}^{new} = (b_{i-j+1} + C^*_j\, f_i)^{old} \quad (3)$$

The vectors F and B are forward and backward prediction errors and C represents the reflection coefficients. After $C = (1, c_2, \cdots, c_k)$ is obtained, the prediction error filter $G = (1, g_2, \cdots, g_k)$ is formed by recursion from $j=2$ to k:

$$(1, g_2, \ldots, g_j)^{new} = (1, g_2, \ldots, g_{j-1}, 0)^{old} + C_j\,(0, g^*_{j-1}, g^*_2, 1)^{old} \quad (4)$$

The unscaled power spectrum of the complex data X is then the reciprocal spectrum of G, i.e. the reciprocal squared moduli of the Fourier transform of G calculated at small intervals of frequency. Scaling is accomplished by multiplying the result by a running product of terms with index j:

$$\prod_{j=2}^{k} (1 - C^*_j\, C_j) \quad (5)$$

The value of this running product is the fractional power in the spatial series X which remains unaccounted for by the k term prediction error filter.

DATA PREPARATION

Of all available wells, 136 were selected for the drawing of bi-weekly groundwater level contour maps. The maps were reduced to a profile of 12 km length. The profile was taken perpendicular to the strike of the groundwater table in the direction of the long axis of the watershed which coincides with the line from the villages of Borculo to Zwilbroek. The reduction of maps to profiles was carried out as follows. The Leerinkbeek watershed was divided into 40 segments (Fig. 2),

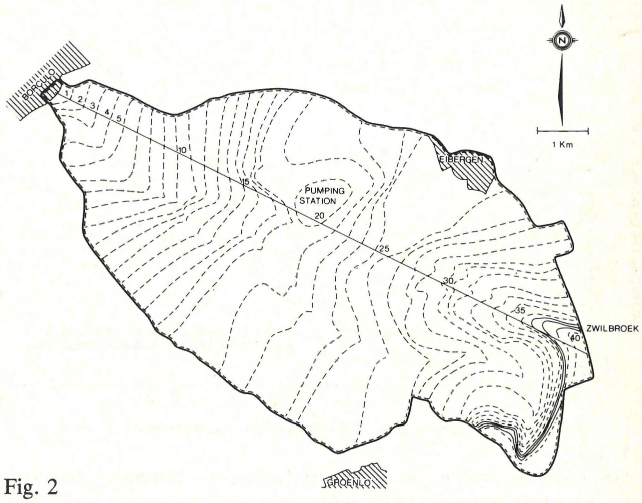

Fig. 2
Map of Leerinkbeek – Watershed, showing 40 segments parallel to groundwater contours. Each segment occupies 300 m on the profile from Zwilbroek – Borculo.

such that:

(1) the boundaries of each segment paralleled the groundwater contours;

(2) each segment occupied 300 m on the profile.

The profile was thus divided into 40 equal parts of 300 m. The groundwater-table levels for each segment were computed as the arithmetic average of all wells in that segment. From one end of the profile to the other end the levels ranged from 14.4 m above MSL for the downstream segment on a dry October 28, 1965, to 32.4 m above MSL for the upstream segment on a wet November 28, 1965. All contour maps and profiles show a cone of depression in the groundwater table near Eibergen (Fig. 3), which is caused by the production of drinking water from the underlying aquifers by the Eibergen pumping station. Although this constitutes interference with a natural groundwater situation, it represents man-made interference of a magnitude which occurs frequently in the heavily populated Netherlands. In other words, the basin remains a representative watershed and results can be extrapolated to areas of comparative geology.

ANALYSIS

A profile of the groundwater table represents, at a given instant in time, the resultant effects of water and gas flow in the soil. The flow is governed by the coupled mass transfer, heat flow and chemical transport equations. The flow is not a simple matter to predict since it has non-linear deterministic components as well as random components, both governed by the sets of coupled equations. Although the results of the flow processes are of a not very predictable nature, for many practical purposes, it is sufficient to know something about the statistical, or in this case, the spectral properties of the groundwater table. In spectral analysis, the profile of the

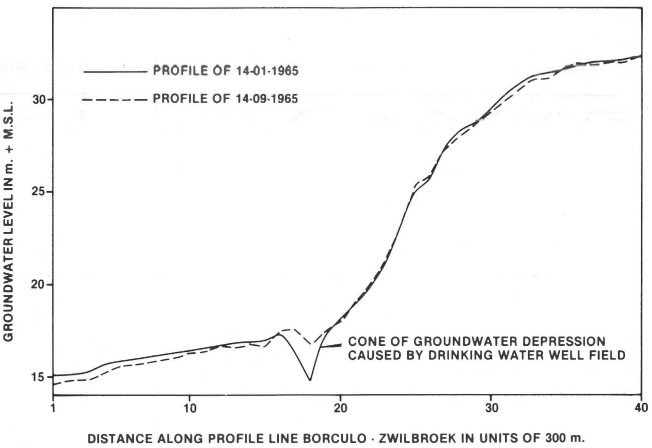

Fig. 3
Groundwater profiles along the line Zwilbroek – Borculo during a dry (14-01-1965) and wet (14-09-1965) interval.

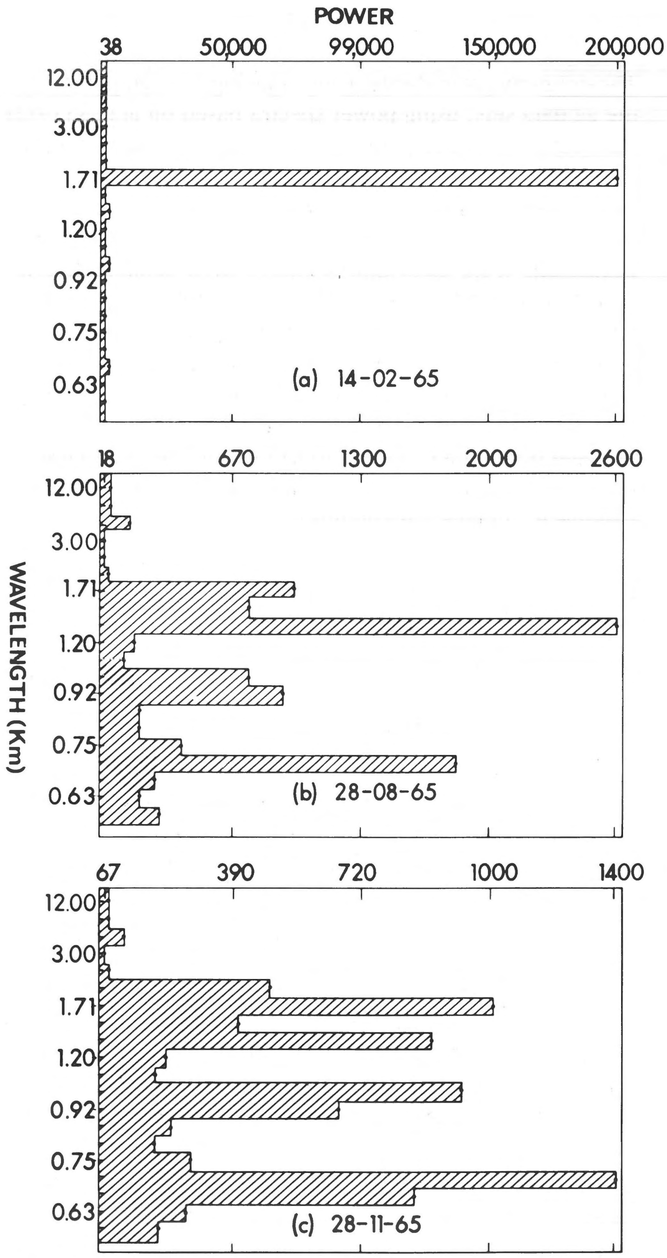

Fig. 4
Power spectra from 14-02-1965 (a), showing average wet conditions with a 1:25 year recurrence. Power spectra from 28-08-1965 (b), and 28-11-1965 (c), showing more extreme conditions in a 1:25 wet year.

groundwater table is considered as a waveform, represented by a large number of harmonics at a given instant in time. A number of spectral analysis methods are available. In this case, since the groundwater profiles are short (39 data points) the method of BURG (1972) was used to compute the spectra of bi-weekly profiles. The results of the computations are listed in table I. In that table an asterisk denotes the wavelength of the maximum power in the groundwater-table profile for each given date, whereas the plus signs indicate significant secondary wavelengths. The matrix in table I and Fig. 4a shows that the wavelength of 1.71 km is dominant. A harmonic has two degrees of freedom: amplitude and frequency. The wavelength of 1.71 km must be sampled twice and therefore the optimum gauge spacing in the Leerinkbeek basin would be 1.71/2 = 0.86 km for two thirds of the year. The optimum number of wells required in the basin (52 km^2) corresponds in this case to 70 groundwater wells. During the late summer and fall, a wavelength of 1.33 km appears to be significant (Fig. 4b). In that case the sampling distance is 0.67 km and 117 wells would be required. In some odd instance (Fig. 4c, November 28, 1965) 417 wells would be required, which is almost exactly the number of wells that has ever been installed in the basin over a period of two decades.

DISCUSSION

It is interesting to compare the results for the Leerinkbeek with the national groundwater network for the entire Netherlands. During 1965 the groundwater levels of 11,930 wells were measured (GROENEWOUD, 1965). Assuming that the Netherlands consist of 30,000 km^2, excluding lakes, waterways and highways, then the average well spacing in 1965 amounted to 1.6 km. The spacing of 1.6 km goes back to a design for a groundwater well network undertaken in 1951 when the older national T.N.O. groundwater well grid was supplemented by two C.O.L.N. networks: a bi-weekly and a quarterly network. The bi-weekly grid was designed such that the spatial resolution was 4.5-5.5 km, equivalent to one well per 20-30 km^2. For the quarterly grid, measurements are recorded on April 28, August 28, October 14 and December 14, but the spatial resolution amounted to 1.0-1.2 km; equivalent to one well per 1.0-1.5 km^2 (STOL, 1958). As the networks evolved over time, the national average well spacing became 1.6 km. This spacing compares reasonably well with the optimum spacing of 0.86 km computed for the Leerinkbeek watershed. Vice versa, the optimum number of wells in the Leerinkbeek,

Table I
Significant wavelengths denoted by * from a spectral analysis of groundwater contour maps, Leerinkbeek area, 1965. The crosses (+) define less significant wavelengths.

Sampling	Wavelengths (km)																
Date, 1965	3.00	2.40	2.00	1.71	1.50	1.33	1.20	1.09	1.00	0.92	0.86	0.80	0.75	0.71	0.67	0.63	0.60
14-01			*						+					+	+		
28-01				*					+						+		
14-02				*													
28-02				*													
14-03				*	+				+						+		
28-03				*					+								
14-04				*													
28-04				*					+						+		
14-05				+											*		
28-06				*		+			+								
14-07				*		+			+								
28-07				*											+		
14-08						+			+						*		
28-08				+		*			+					+			
14-09					+					*				+			
28-09						*				+							+
14-10				+		*				+					+		
28-10				+		+			+					+			*
14-11				*		+			+				+				
28-11				+		+			+					*			
14-12				*					+					+			
28-12				*	+	+			+					+			

extrapolated over the conterminous provinces (30,000 km^2) would require some 54,500 wells. It is doubtful, however, whether that much accuracy is generally required for a national network, nor is the geology of the Leerinkbeek representative for the entire Netherlands. It should also be emphasized that the implicit assumption in this report is, that by the selection of a 300 m sampling distance spatial changes over less than 600 m are excluded (Nyquist frequency).

It is noteworthy that the optimum spacing of 0.86 km was found to equal half the distance between the different soil classes which have been mapped on a scale of 1:25,000 in the catchment (SNYDERS, 1970) and the average distance between the different classes equals 1.7 km, twice the optimum spacing. The value of 1.7 km, was arrived at by excluding patches of soil with diameters <300 m. This same distance of 1.7 km has been also calculated from the 1964 land use map (SNYDERS, 1970). That is understandable since the land-use map categories, which show grassland, arable land and forest, depend to a great extent on the different soils. This leads to the conclusion that in the case of the Leerinkbeek, the design of a groundwater well network could be based on an optimum groundwater well spacing estimated from the 1:25,000 or 1:50,000 soils map.

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