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Evaluation Of The Impact Of Groundwater Abstraction Around Well Field Using Time Series. The Case Study Of The Kruidhaars Well Field In Assen (Drenthe Province, The Netherlands)

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Abstract
The Kruidhaars Well Field is located between Sleen and Oosterhesselen villages, in the south-eastern part of Drenthe province in the Netherlands. The well field comprises one of the thirteen for groundwater abstraction sites of the water supply company N.V.Waterleidingmaatschappij Drenthe '(WMD).
The Kruidhaars well field was put into operation in September 1987 and operated below the licenced annual abstraction rate of 2 Mm3. Maximum annual abstraction rates in the order of 1.6 Mm3 were reached in 1990. The abstractions are taken from the mainly unconfined coarse sandy Pleistocene aquifer with well screen settings in the range from 40 to 85 m below land surface. To assess the effects of the Kruidhaars pumping station, a pumping test and groundwater modelling have been carried out before the station became operational (KIWA, 1984). The WMD decided that the predictions of drawdowns by the KIWA model had to be verified using later collected data. To compare the monitored impact of groundwater abstractions at the Kruidhaars pumping station with the predictions made on the basis of the regional groundwater flow model (KIWA,1984), a statistical approach based on time series analyses techniques has been used. The study led to the conclusion that the KIWA model structurally underestimated the impact (in terms of draw-downs) of the well field. Predicted drawdowns were about 15 to 25% below drawdowns later observed and analyzed by statistical techniques. Possibly, the underestimation can be related to assumptions made for the conceptual model including an over- estimation of the effect of the surface water courses. On the other hand, the predicted drawdowns with the KIWA model were mainly for (dry) spring-summer conditions, whereas the observed drawdowns concern all-season groundwater behaviour.
Key Words: *Groundwater, Abstraction, Impact, Assessment, Kruidhaars, Well Field, Time series*

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I. Introducton

Literature is tremendously rich on the subject of time series analysis starting with the pioneering works such as Matalas, 1967; Box and Jenkins, 1976; Bloomfield, 1976; Anderson, 1979; Vandaele, 1983; Chatfield, 1991, etc.). Details on the statistical fundamentals underlying the theory of time series analysis is considered beyond the scope of this paper.

The evaluation of groundwater abstraction around well fields is a critical component in sustainable water management, particularly in areas subjected to significant hydrological changes such as the Kruidhaars Well Field in Assen, Netherlands. Groundwater abstraction raises important issues regarding the sustainability of water resources, ecological balance, and hydrological dynamics. This literature review synthesizes various studies focused on time series analysis and its implications for groundwater level monitoring, driven by the necessity of robust data for effective resource management.

Time series modeling has become an essential tool for understanding groundwater dynamics as it provides a systematic approach to analyzing groundwater levels over extended periods. The study by Zaadnoordijk et al. demonstrates the efficacy of automated time series models in assessing piezometer data across the Netherlands, which offers a foundation for predicting groundwater levels with reduced computational overhead compared to traditional hydrological modeling approaches (Zaadnoordijk et al., 2018). Similar frameworks are employed by Marchant and Bloomfield, who highlight the necessity for long-term series data to effectively model groundwater drought conditions, addressing observed inadequacies during events like the

European drought of 2015 (Marchant & Bloomfield, 2018). They emphasize that specific hydrological data must be accessible for timely assessments.

Advancements in data-driven methodologies, such as those explored by Li et al., provide substantial insights into groundwater storage changes across various geographic scales, integrating satellite data with traditional groundwater datasets using GRACE (Gravity Recovery and Climate Experiment) (Li et al., 2019). These findings underscore the importance of incorporating remote sensing data alongside in situ measurements to enhance the understanding of hydrological responses to abstraction activities.

The use of advanced machine learning techniques in time series analysis offers an innovative approach to predicting groundwater levels, as evidenced by studies discussing the application of artificial neural networks (ANN) and other machine learning models (Yoon et al., 2019; (Bowes et al., 2019). For instance, Bowes et al. successfully forecast groundwater table variations in flood-prone areas using recurrent neural networks, indicating how complex temporal patterns can inform management strategies under fluctuating water availability (Bowes et al., 2019).

Moreover, it is crucial to consider the role of external factors influencing groundwater levels. Factors such as precipitation variability, which may not be uniformly distributed, significantly impact on the hydrological cycle and, thus, groundwater sustainability. Yang et al. emphasize that ARIMA and SARIMA models can effectively capture these dynamics, particularly regarding non-stationarity and seasonal behaviors (Yang et al., 2015). This understanding aligns with the findings by Brakkee et al., which illustrate the effects of drought conditions on groundwater levels in the Netherlands, emphasizing a need for detailed temporal modeling in times of water scarcity (Brakkee et al., 2022).

To develop a comprehensive strategy for groundwater abstraction in areas like the Kruidhaars Well Field, it is paramount to integrate these findings into localized management plans. By utilizing a combination of historical hydrograph data and advanced statistical approaches, researchers can enhance the predictive power of groundwater models (Butler et al., 2021; Mohanasundaram et al., 2019). For example, the application of synthetic time series data, as explored by Pulla et al., can serve to fill gaps in existing datasets, offering a more robust framework for effectively predicting future groundwater conditions (Pulla et al., 2024).

Overall, the effective evaluation of groundwater abstraction at the Kruidhaars Well Field necessitates a multifaceted approach that combines long-term time series analysis, machine learning methods, and satellite data assimilation. These combined strategies offer a promising avenue for enhancing groundwater sustainability amidst increasing hydrological pressures. This study, however, is limited to long-term time series analysis.

The Kruidhaars Well Field is located between the villages of Sleen and Oosterhesselen, in the South-Eastern part of Drenthe province in The Netherlands . The Kruidhaars Well Field was put into operation in September 1987 under a licensed annual abstraction rate of 2Mm3 (million cubic meters). However, in the period from September 1987 up to 1990, the actual annual abstraction only rose to about 1.6 Mm3.

From 1990 onwards, the abstractions remained more or less constant. It was therefore paramount to compare the monitored impact of groundwater abstractions at the Kruidhaars Well Field, expressed in terms of drawdowns of groundwater levels, with the predictions made on the basis of a regional groundwater flow model (KIWA,1984). This model was prepared before the start of the pumping activities. To accomplish this goal, a statistical approach based on time series techniques was to be used. This implied the analysis of groundwater levels, abstraction rate, and precipitation excess rate adopting a step-wise approach: graphical, univariate and bivariate analyses were to be performed.

II. Methodology

Depressed groundwater levels are one of the main effects of groundwater abstractions in an aquifer system. To formulate a methodology to analyse this effect, one has to realise that groundwater levels are in fact a time-dependent function of various natural and man-induced hydrological stresses. Among the natural processes are the effects of recharge by precipitation, and the man-induced stresses include abstraction, water drainage, artificial recharge, changes in land uses, irrigation, etc. The evaluation of the impact of abstractions will have to be done by establishing the relationship between all the stresses in an area and the groundwater levels.

Through the application of time series analysis techniques, the relationships between stresses and groundwater levels can be established. In view of the fact that several stresses influence the behaviour of the groundwater levels, it may not be an easy task to single out the effects of each of the individual stresses. The task becomes complicated when, for example, more than one well field influences the groundwater levels, or for the case that no groundwater level records are available before pumping started.

Fortunately, in the study area only the effect ofthe Kruidhaars well field has to be considered and the groundwater levels prior to the start of the abstractions have been recorded. Therefore, a relatively simple methodology has been selected, which is also presented in the following diagram (Figure 1).

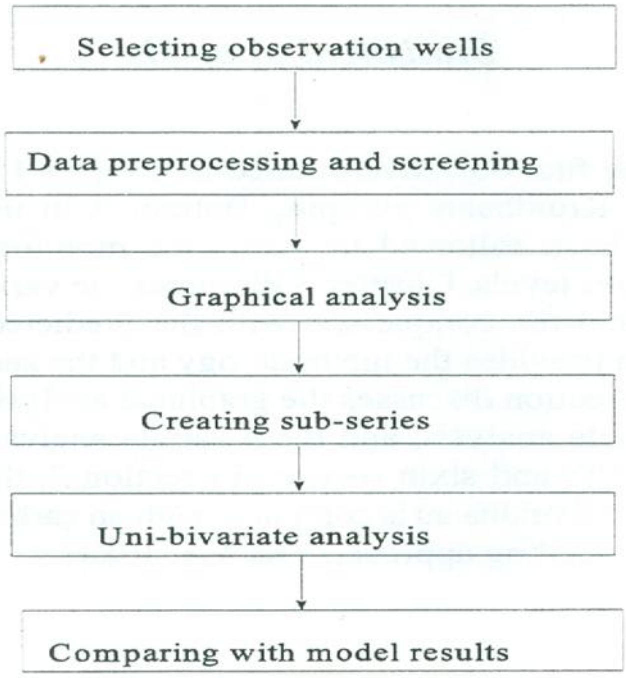

Figure 1: Schematisation of the methodology

Selecting observation wells

In order to carry out the study as schematised in the diagram above, a set of observation wells was to be selected. In line with the objective of the study, this task was to be based on a number of criteria comprising the land use around the observation well, the distance between the observation well and the production well field, the availability of time series and the sampling frequency. The spatial distribution of the selected wells was to be done in such a way that conclusions drawn from data collected at these wells could be generalised for the entire study area.

Data pre-processing and screening

Data pre-processing was to include the aggregation of groundwater level data by combining bi-weekly measurements into monthly records. The conversion of bi-weekly groundwater level data to monthly data would enable easy further processing and handy comparison with both recharge and abstraction data which are given monthly. Besides, it has been shown that monthly time series of groundwater levels provide the same information as the bi-weekly series (Zhou Y., 1992).

Upon completion of this task, classical data screening techniques using the code DATSCR (Dahmen and Hall,1990) were to be applied to the selected time series in order to check their consistency and homogeneity.

Graphical analysis

In the graphical analysis, the groundwater level time series were to be compared visually with the natural recharge and the abstraction rate of the Kruidhaars Well Field.

Levels, recharge and abstraction rate would be presented in one plot to facilitate comparison. It would be assumed that recharge, and the abstraction at Kruidhaars, are the main hydrological stresses that affect groundwater levels in the study area.

Nevertheless, some effect because of changes in drainage basis could also be present.

Throughout the graphical analysis, it had to be kept in mind that its results would form the basis for the univariate and bivariate analyses.

Creating sub-series

For the univariate time series analysis of groundwater levels, natural recharge and abstraction rate, sub-series would also be analyzed. To find out the possible effects of the changes in abstraction rate on groundwater levels, sub-series of groundwater levels had to be made corresponding with periods of a typical abstraction rate at the Kruidhaars Well Field. These periods of typical abstraction rate (including the zero rate before pumping started) were to be based on historical pumping records and the graphical analysis of these records. To establish the effects of natural recharge on groundwater levels, sub-series for the recharge would also be created.

Univariate analysis

In the univariate analysis, groundwater levels, natural recharge or abstraction rate are analyzed individually. Complete time series and sub-series were to be analyzed. For the time series in the Kruidhaars study area, the univariate analyses would comprise a trend and periodicity analyses. This statistical part of the analysis would be done by the univariate interpretation options of the computer code FREQ (Zhou, 1992). Step trends and linear trends in groundwater levels were to be correlated with changes in abstraction rate which are also indicated by trends. By considering the step trend magnitudes and equation constants for linear step trends, the impact of the abstraction rate (1.6 Mm3/year) on groundwater levels was to be established.

Bivariate analysis

The combined analysis of two hydrological variables is the aim of bivariate analysis. For the Kruidhaars area, the analysis would concern the setting up of a cross-correlation between the following two variables:

(1) Two sets of groundwater level time series measured at the same point but taken at different screens in the well. This analysis was to be done graphically in this study, but for additional confirmation could also be done through bivariate analyses.

(2) Two sets of groundwater level time series recorded at different observation points.

(3) Either the abstraction rate or natural recharge as one hydrological variable versus the groundwater level at an observation well as the other variable. This was to be done for the confirmation of the cause-effect relationship between these variables.

The bivariate cross-correlation analysis was to be performed using the statistical code SPSS. As mentioned above, bivariate analysis may confirm the relationship between variables such as groundwater levels and abstraction rate. In case of necessity, the technique would also be used in the Kruidhaars area, to determine the quantitative effects of changes in abstraction rates on groundwater levels. Especially, when the effect of abstraction on groundwater levels can't be separated from the effects of natural recharge, bivariate analysis is useful. The cross correlation between the groundwater levels inside and outside the influence sphere of the Kruidhaars well Field before pumping started would then be used to make the required corrections for the effect of natural recharge after pumping commenced.

Comparison with model results

The statistically detected impact of changes in abstraction rate at the Kruidhaars Well Field on the groundwater levels was to be compared with the KIWA model results. To compare the results, the model-computed groundwater drawdowns would be considered at the locations of the selected observation wells, and they would further be adapted to compensate for the difference in model-used and actual pumping rates at the Kruidhaars production wells. The comparison itself was to be done by tabular analysis of the differences between statistically calculated drawdowns and the model-calculated drawdowns.

III. Results And Discussion

Selection of the observation wells

For the time series analysis of the groundwater levels, a large amount of data from several observation wells and from various screen depths is available. Six observation wells, and their related historical groundwater level records were selected for a complete analysis (Table 1). The selection was made based on geohydrological and land-use criteria, and on the aim of the study. It is very important to underline that

for this study, the selected wells are inside the influence zone of the Kruidhaars Well Field, which has an estimated radius of about 2000 m. (KIWA, 1984). The well WP09, however, is located near the boundary of the influence zone. Furthermore, the wells are situated on 2 more or less perpendicular section lines, in an East-West and North South direction (Figure 2). The groundwater levels for the deeper screens, tapping the coarse sandy Pleistocene aquifer have mainly, but not exclusively, been used for the groundwater time series analyses.

Table 1: Selected observation wells

Observation well and selected sereen	Top-bottom of serene (m+NAP)	Measuring point (m+NAP)	Distance to the production well (m)	Coordinates
WP01 (3)	-77.20, -79.20	15.37	55	248720,531550
WP04 (4)	-47.54, -49.54	14.13	70	248540,531360
WP06 (4)	-48.34, -50.34	13.22	550	248720,530855
WP07 (4)	-50.53, -52.53	13.89	800	2487750,531750
WP05 (4)	-40.65 -42.65	12.88	1500	248810,530010
WP09 (4)	-43.01, -45.06	15.55	2075	246580,530930

Data pre-processing and screening

A set of raw data concerning monthly rainfall, potential evaporation, natural recharge, cumulative abstraction rate, and groundwater levels recorded on a bi-weekly basis have been collected from the WMD database. In this database, tdata were checked visually for obvious errors such as wrongly labeled observation screens, typing errors, etc. Data have also been imported into the spreadsheet, and the reliability of those data has also been checked using classical data screening techniques. Classical data screening included tabular comparison and preliminary plotting of time series for identification and correction of missing values, possible sources of error and any strange values and patterns. To re-check raw data reliability, emphasize on consistency and homogeneity, and to generate general statistics, the software code for data screening DATSCR has been used (Dahmen and Hall,1990).

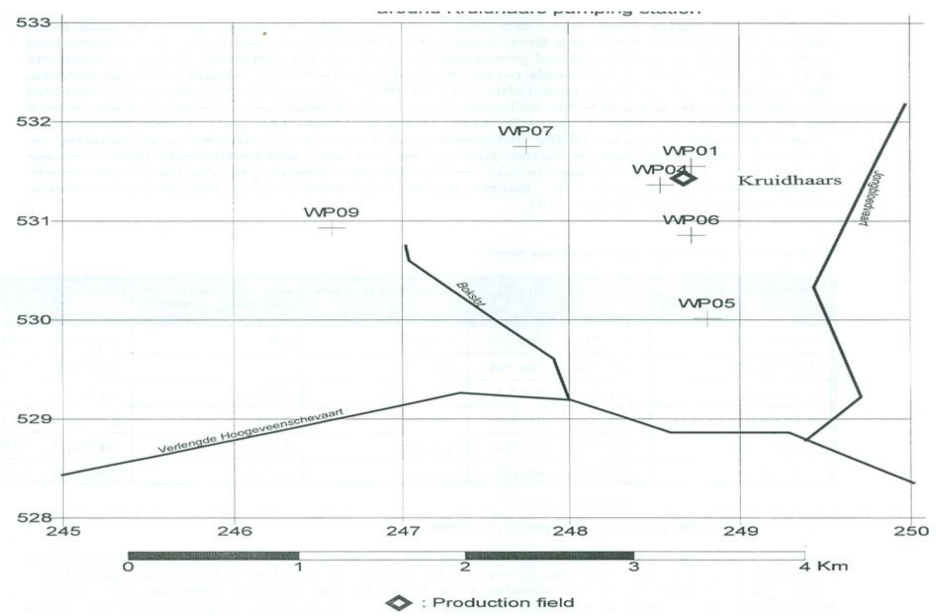

Figure 2: Location of selected observation wells around Kruidhaars Well Field

Natural recharge

To set up the series of natural recharge data, to be discussed in this section, rainfall and evaporation data from the meteorological station in Eelde have been taken. Following the methodology outlined above, data were screened and tested for completeness, consistency, etc. It was generally found that data were complete and consistent. The checked rainfall and evaporation data were combined to yield information on the natural recharge of the area. To complete the analysis, a rough indication on the magnitude of the natural recharge Re, has been obtained from:

Re=P-CtEp

whereby P is the precipitation rate in mm/month, Ep, is the reference-crop evaporation in mm/month, and Ct an evapotranspiration factor depending on the vegetational cover in the area. The reference-crop evaporation has been computed using the Makkink method for open water. An evapotranspiration factor of 0.8 has been assumed. This factor correlates with evapotranspiration from grassland which is the main "crop" around the Kruidhaars Well Field.

Abstraction rate

For the time series analysis, the monthly cumulative data for the abstraction rate of the Kruidhaars Well Field were considered. With the spreadsheet, the data were screened and tested for completeness, consistency, etc. It was generally found that data was complete and consistent. The monthly abstraction rate data were then derived from the raw cumulative monthly abstraction rates. This operation was also easily performed with the spreadsheet. The computed monthly abstraction rates have then been checked with DATSCR, basically for data consistency. The consistency of the data was found to be in order: the abstraction data were judged to be fit for further time series analysis.

Groundwater levels.

With the spreadsheet, the groundwater level data have been checked for completeness, etc. The tabular comparison of bi-weekly groundwater levels as well as the bi-weekly preliminary graphical plots of time series do not show large gaps.

Only two "strange" values have been observed and adjusted respectively at well WP04 and well WP05. To standardize the time basis of all the parameters to be analyzed, all groundwater level data have been converted from bi-weekly to monthly values through an averaging process. Upon completion of this task, all data have been checked with the DATSCR code. The data series was found to be consistent and homogeneous.

Summary

To conclude the data screening section, Table 2 gives the basic characteristics for the time series of selected groundwater levels, natural recharge and abstraction rates. The table shows that the maximum groundwater levels range from 12.4 to 13.7 m + NAP, whereas the minimum values range from 11.4 to 12.3 m + NAP. The differences between maximum and minimum groundwater levels refer respectively to the highest levels before the Kruidhaars Well Field was put into operation, and the lowest levels while being in full operation. The difference between these extremes in groundwater levels then range from 0.8 m to 1.6 m around the Kruidhaars Well Field.

Table 2: Basic statistics of selected time series

Data (source)	Minimum (m)	Maximum (m)	Mean (m)	STD (m)
WP01 (3)	11.5	13.1	12.4	0.4
WP04 (4)	11.5	13.0	12.4	0.3
WP06 (4)	11.4	12.7	12.3	0.2
WP07 (4)	12.1	13.1	12.7	0.3
WP05 (4)	11.6	12.4	12.0	0.2
WP09 (4)	12.3	13.7	12.9	0.3
Abstraction (m3/month)	0.0	193850.0	71122.3	60843.7
Recharge (mm/month)	-69.9	155.8	32.5	45.7

Graphical analysis

With the spreadsheet, plots of the recorded monthly abstraction rate, natural recharge, and computed monthly groundwater levels have been made. In detail, the following partial conclusions may be drawn from both the plots of the individual time series and the combination of the plots, set against the same time scale.

Natural recharge

Figure 3 shows the time series of natural recharge for the period from September 1983 up to May 1996. The plot suggests that:

Natural recharge rates range between about-70 mm/month for the summer period reflects the high evapotranspiration rate during this period exceeding the precipitation rate, whereas the positive value during the winter reflects the lack of evapotranspiration during the cold season.

It does not seem to be clearly identifiable long term trend in the whole series of natural recharge data.

The major periodic fluctuation in natural recharge is annual. However, a long term fluctuation could also be observed. In particular, the long term fluctuation for the period from about September 1986 to September 1994 can be observed showing a minimum around September 1990. The left part of this fluctuation corresponds to a period (September 1986 to September 1990) during which conditions became drier.

An extremely dry period with little recharge can be noticed from August 1995 till May 1996.

Abstraction rates

Figure 4 shows the development of the abstraction rate at the Kruidhaars Well Field for the period from September 1983 up to May 1996. The abstraction rate time series shows clearly several "steps" which allows the allows the splitting up of the series into 3 sub-series as follows:

The period before the start of the pumping activities in Kruidhaars are characterized by zero pumping rates.

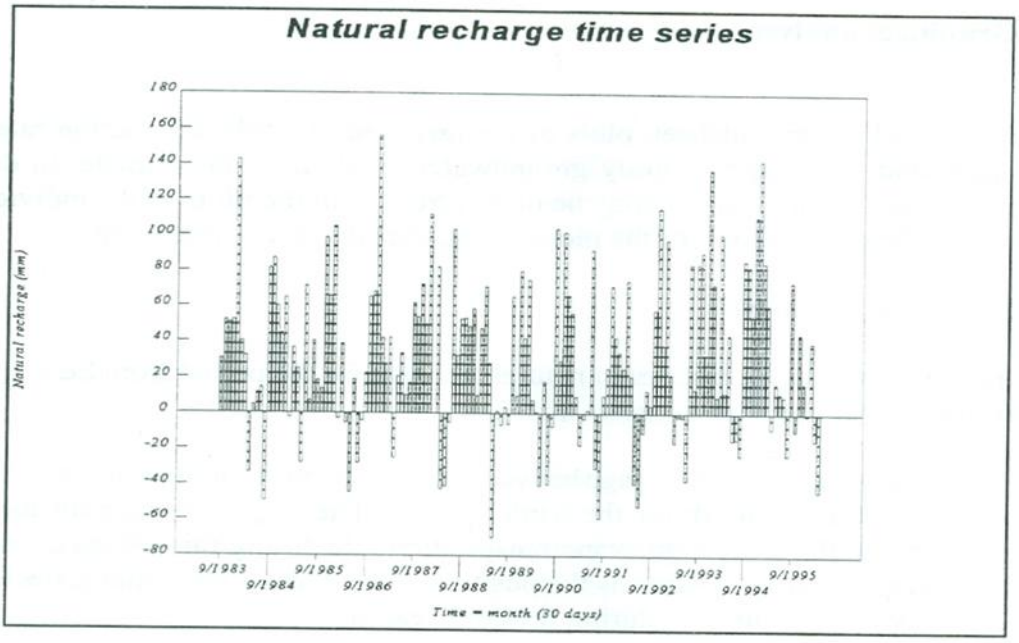

Figure 3: Natural recharge time series

The period from September 1987 up to around September 1990 shows an average rate of abstraction of about 60,000m3/month (0.72 Mm3/year);

The period from September 1990 up to April 1996 has an average abstraction rate of about 134, 000 m3/month (1.61 Mm3/year). In detail, however, this period may be split up into two sub-periods with the last sub-period beginning in September 1994. This last sub-period has a somewhat lower mean abstraction rate of about 120, 000m3/month (1.44Mn3/year).

Groundwater lever time series

In the plots of the groundwater lever series, one can find that a high correlation exists between the groundwater level time series recorded at different screens of the same observation well. All the wells present this high correlation. This indeed may be seen as the result of high vertical hydraulic conductivity in the aquifer system. Therefore, the levels at only deep screens, monitoring the coarse sandy Pleistocene aquifer, will be further interpreted by time series analysis techniques. Figure 5 shows an example of such a series: the time series of observation well WP01.

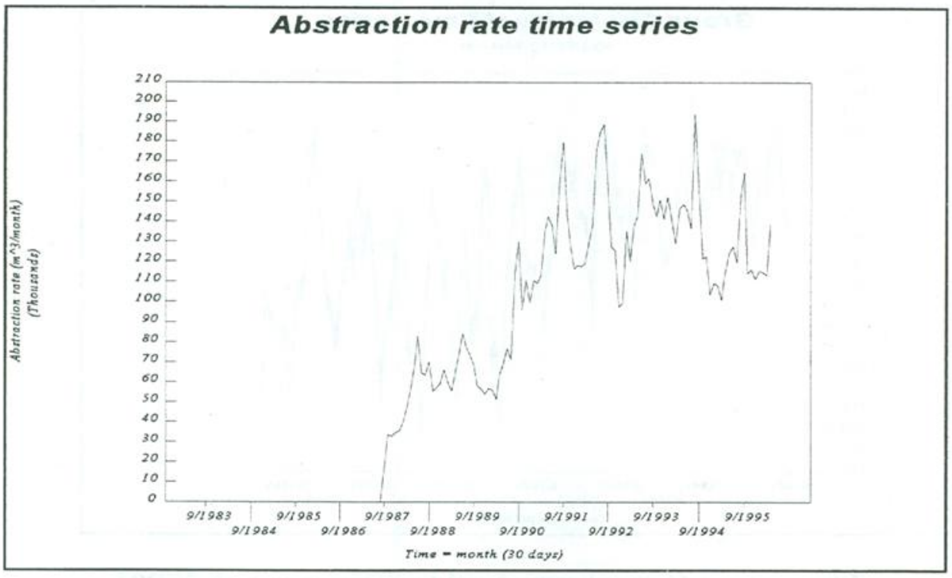

Figure 4: Abstraction rate time series at Kruidhaars

The general patterns of groundwater level time series reveal that at most of the wells, the following features can be observed:

The groundwater levels over the entire period range between 11 m and 14 m + NAP in the influence area of the Kruidhaars Well Field.

As expected, the general pattern of groundwater level time is related to the distance from the Kruidhaars well field. The wells closest to the production wells show clear step trends (WP01, WP04), with the main trends occurring around 1987 and 1990. The step trends do not clearly appear in well WP05 (1500m away from the Kruidhaars production wells) and in well WP09 (at 2075 m);

The groundwater level plots show that the main fluctuation is the annual fluctuation. At the same time a fluctuation with a much larger periodicity, in the order of 6 to 7 years, seems to be present, it is difficult to distinguish between the step trend pattern and this long term fluctuation.

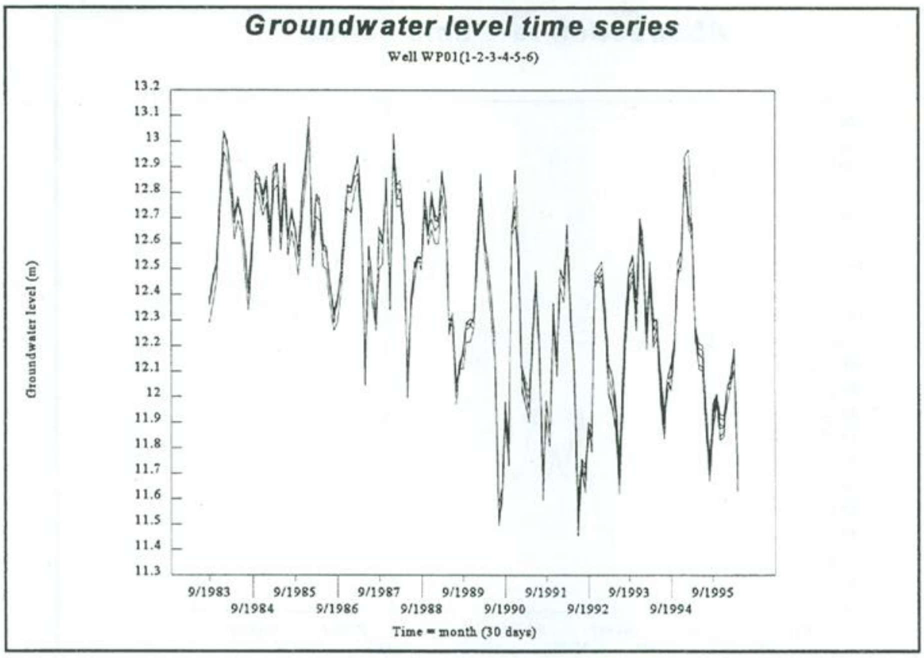

Figure 5: Groundwater level time series in well WP01

Recharge-abstraction rate-groundwater lever relationships

The inter-relationship between recharge, abstraction rate at the Kruidhaars Well Field, and groundwater levels may be found by jointly considering the time series plots for these parameters. The combined plots suggest that:

The low natural recharge in the summer periods correlates with a higher abstraction rate, and the high recharge rate in winter correlates with a lower abstraction at Kruidhaars;

The effect of natural recharge on the aquifer system is indeed clearly shown by the perfect correlation between natural recharge and the groundwater level time series. A high natural recharge yields high groundwater levels and vice versa. This relationship can be established for the seasonal changes in recharge rate and for the longer term fluctuations (periodicity 6-7 years) in recharge.

A comparable correlation is also found between abstraction rate and the time series plots of groundwater levels. Basically, this correlation concerns the relatively higher abstraction rate in the summer (see above) which leads to lower groundwater levels, and the lower abstraction in the leading to higher levels. The higher abstraction rate in the summer corresponds indeed with the lowest groundwater levels in the observation wells closest to the well field. Although this effect of abstraction is noticeable, it is also clear that the individual effects of recharge and abstraction are, in places, indeed difficult to distinguish graphically.

In addition to (seasonal) fluctuations, the abstractions also seem to have trend-like effects on groundwater levels. The aquifer response to abrupt changes in abstraction rate can be identified by the trends shown in the groundwater level time series. Most likely the observed step trends in the nearest observation wells (WP01, WP04, WP07) might be correlated with the changes in the abstraction rate the Kruidhaars Well Field. The sequential estimation of the groundwater level components in then of primary importance for the quantification of the abstraction impacts on the groundwater levels.

Creation of Sub-series

To relate groundwater level variations to the changes in abstraction rate, nearly the whole time series under study can be considered. This means that the period from September 1983 to August 1995 has been taken. In view of the extremely dry period starting in August 1995, the data from this month up to August 1996 have been left out. The considered time series consists of a total number of measurements (n), equal to 144. The series are divided, in full hydrological years, into 3 sub-series correlating with the main phases of typical abstractions. The times series are divided into the following sub-series:

Sub-series A: September 1983- August 1987

There are no pumping activities in the area. Population size: n=48

Sub-series B: September 1987-August 1990

This period corresponds to the beginning of pumping characterized by an average abstraction rate of 6.01, 104 m3/month (0.72 Mm3/year). Population size: n=36

Sub-series C: September 1990-August 1995

This period corresponds to an average abstraction rate of 13.46104 *m3/month (1.61 Mm3/year). Population size: n=60

Univariate time series analysis

Univariate time series analyses are applied to evaluate the statistical characteristics of respectively natural recharge, abstraction rate, and groundwater levels. These analyses from the core of the assessments to establish the impact of the groundwater abstraction on groundwater levels around the Kruidhaars Well Field.

Based on the time series for periods A, B and C, the univariate analyses have been carried out. For the recharge, the whole series A-B-C has been analyzed, as well as the sub-series A.B.C, and A, B and C separately. Since we have two step trends in the series (related to the two increases in abstraction rate), the time series of the abstraction rate can't be analyzed as a whole series by FREQ. With FREQ only one step trend can be analyzed at one time. Therefore, for this parameter only the sub-series A-B, B-C and (A), B and C separately have been analyzed. The same applies to the series of groundwater levels. Also, for this parameter, only the sub-series A-B, B-C, and C separately have been considered.

Natural recharge

Trend detection

Except for period B (September 1987- August 1990) which exhibits a linear trend, the natural recharge series does not show a statistically significant trend. The absence of trends is true for the whole series A-B-C and for the remaining sub-series A-B, B-C and, A and C.

As has been indicated above, the natural recharge exhibits a linear negative trend (figures 6 and 7). This is the result and the confirmation of the long dry period which had also been detected in the graphical analysis. The trend for this period has been detected because of the splitting-up of time series into sub-series.

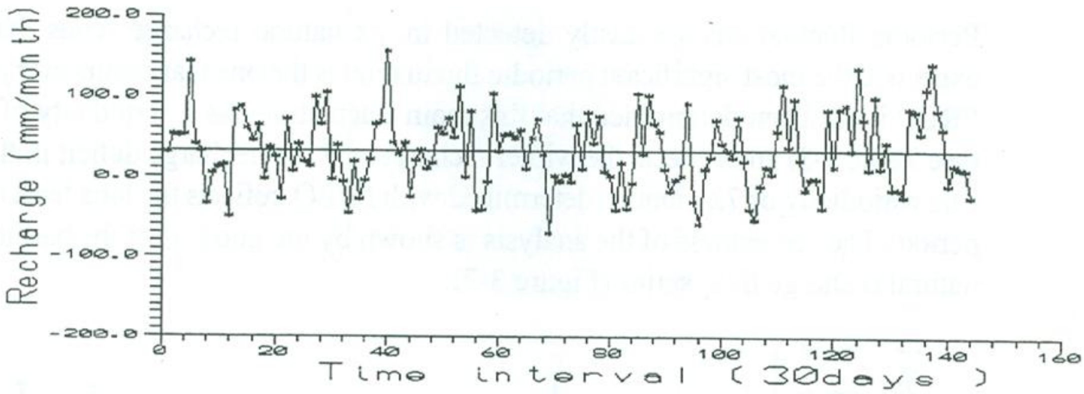

Figure 6: Natural recharge time series (A-B-C)

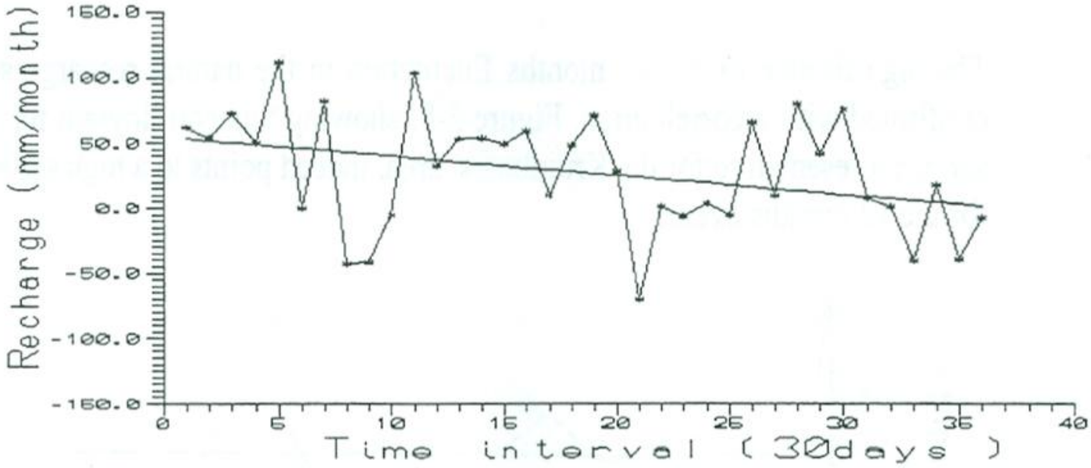

Figure 7: Natural recharge time series and fitted trend (sub-series B)

Periodic fluctuations

Periodic fluctuations are easily detected in the natural recharge series. Naturally, as expected, the most significant periodic fluctuation is the one that occurs every year. With FREQ it has been determined that this main fluctuation has a periodicity of 12 months and reflects the winter recharge and the recharge deficit in the summer (Table 3). The periodicity of 72 months, determined with FREQ reflects the long term dry and wet periods. The correctness of the analysis is shown by the good fit the harmonics to the natural recharge time series (figure 8).

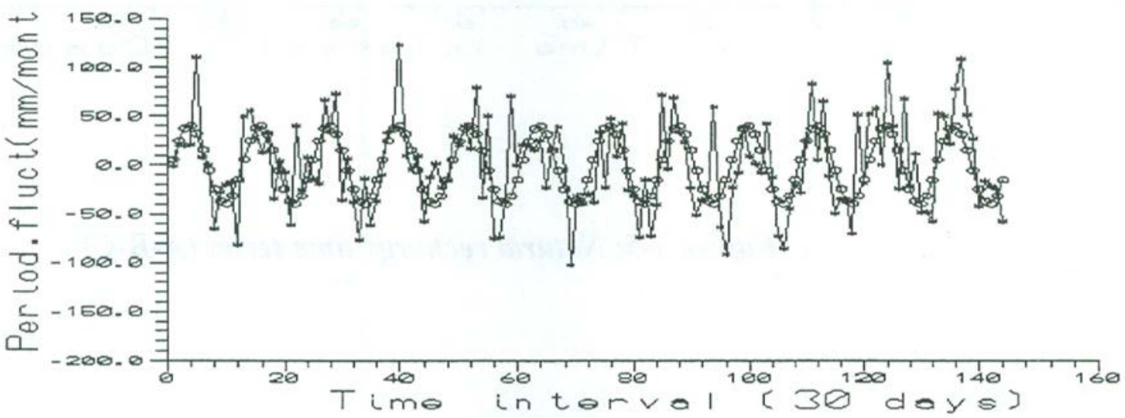

Figure 8: Fit of harmonics to natural recharge time series

The significance of the 12 months fluctuation in the natural recharge series can be confirmed with a correlogram. Figure 9, showing this correlogram for the recharge series representative for the Kruidhaars area, indeed points to a high serial correlation for the 12 months events.

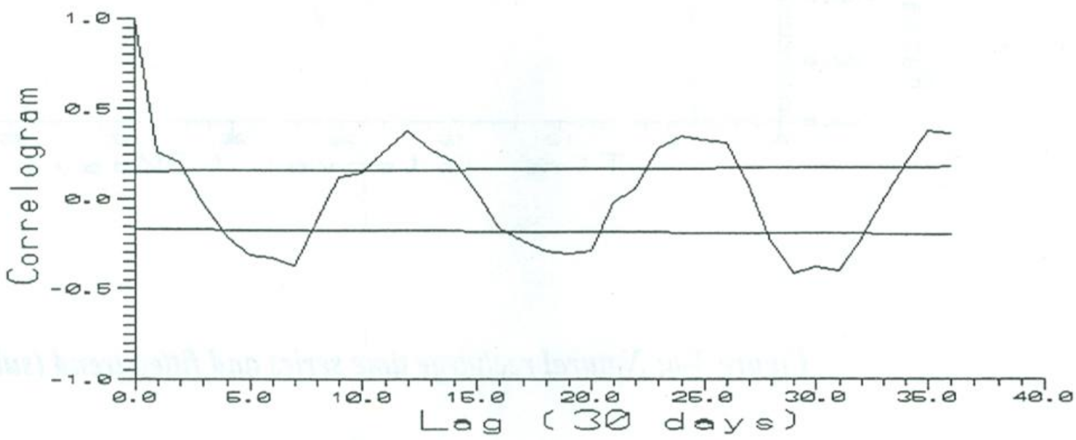

Figure 9: Correlogram of the recharge time series

Tableau 3: Example of results for univariate analysis for recharge series

Recharge (mm/month)	**Sub series A-B-C**
Mean of series	32.47
Standard deviation	45.85
Type of trend	Not applicable
Means of sub series, or constant B_0 of linear trend equation	Not applicable
Means difference or slope B_1 of linear trend equation	Not applicable
Periodicity of 10 most significant harmonics	12, 3, 2.3, 9, 4.4, 5, 8, 2.6, 72, 21
Number of substracted harmonics	1
Geohydrological explanation	Long term stationarity of recharge

Abstraction rate

Trend detection

The time series of abstraction rate shows trends (figures 10-13). For sub-serie A-B covering the period from September 1983 up to August, FREQ could fit a step trend with a magnitude of 6.01104* m3/month (0.72 Mm3/year) (figure 10). In line with the graphical analyses, the time of the step trend coincides with the start of the abstractions in September 1987.

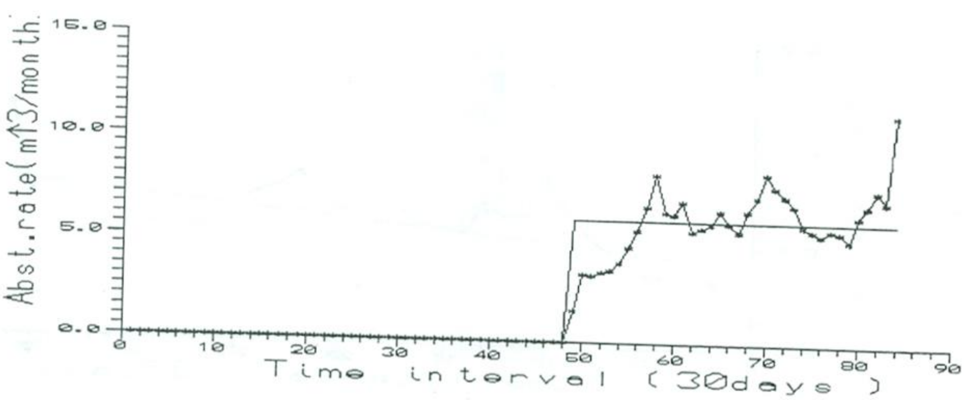

Figure 10: Abstraction rate time series and fitted trend (sub-series A-B)

For the abstraction rates represented by sub-series B-C, which run from September 1987 up to August 1995, FREQ confirmed the step around September 1990, with a trend magnitude of 7.45104 * m3/ month (0.9 Mm3/year, figure 11). In this sub-series, the step trend marks the increase in abstraction rate around September 1990, from an average monthly rate of 6.01* m3/month (0.72 Mm3/year) up to 13.46104* m3/month (1.62 Mm3/year).

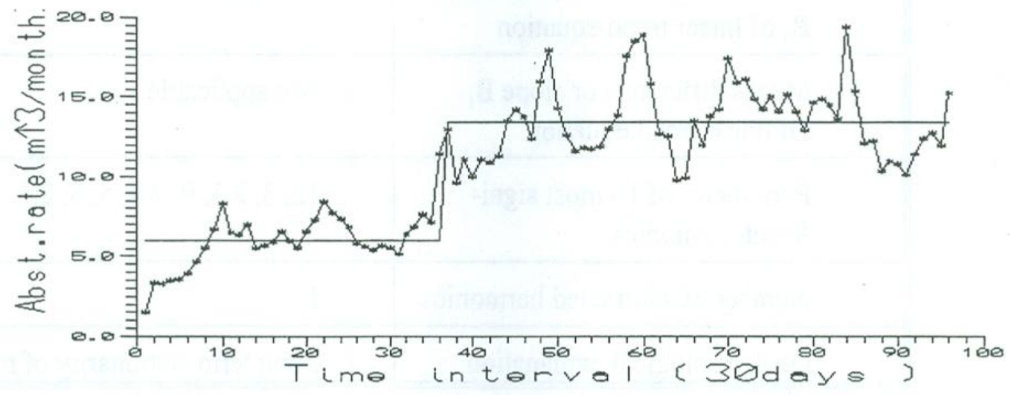

Figure 11: Abstraction rate time series and fitted trend (sub-series B-C)

Trend detections have also been carried out for the individual sub-series B and C of the abstraction data. Since the start and end of these series area based on step trends, only linear trends have been considered. For the sub-series B, FREQ detected a linear trend with a positive slope (see figure 12). This trend is due to the gradual increase in abstraction during this relatively dry period.

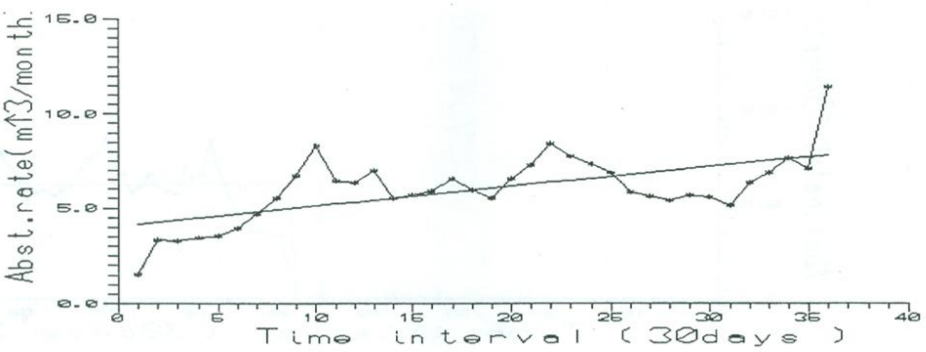

Figure 12: Abstraction rate time series and fitted trend (sub-series B)

For the sub-series C no linear trend, i.e. no significant change in the mean value of the monthly abstraction rate has been detected. The absence of a significant trend is indicated by the virtually horizontal line in figure 13 .

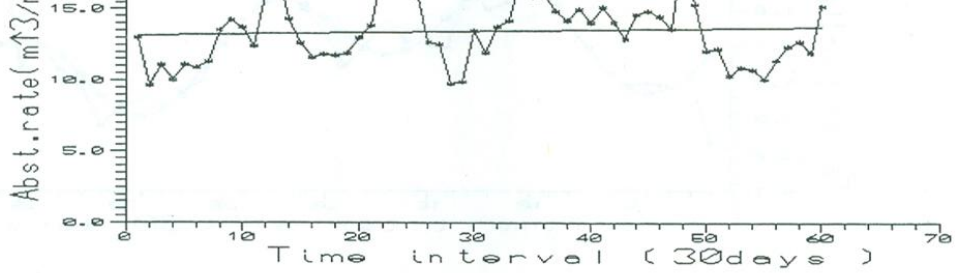

Figure 13: Abstraction rate time series with no trend (sub-series C)

The trend detections for the sub-series A-B and B-C can be compared with the detections for the individual series A, B and C. It can be observed that the sum of the step trend magnitudes for the sub-series A-B and B-C, which is 13.46104 * m3/month (1.62 Mm3/year), is equal to the difference in mean value for the individual sub-series A and C. In view of the computation procedure for the (step) trend magnitude (based on mean values), this result could be expected. In other words, the latter determined difference also provides a check on the trend detection using the sub-series A-B and B-C.

Periodic fluctuations

Periodic fluctuations may not be that easy to detect in abstraction series. With FREQ, the analysis for sub-series A-B and B-C, and for B and C individually gave similar results, especially for the short fluctuations. For the analysis of the longer fluctuations, only the sub-series B-C, from September 1987 up to August 1995, will be discussed. The sub-series A-B has only abstractions during the second part of series. Naturally, the most important fluctuations detected with FREQ for the sub-series B-C is the one with a periodicity of 12 months. Long term fluctuations with periodicities of 48 months (4 years) and 96 months (8 years) were also detected. The quality of the analysis of the fluctuations (harmonics) is confirmed by the harmonic model, as fitted to the trend-free series of abstraction rates (figure 14 and 15). The 12 monthly fluctuations are in line with the graphical analysis, and point to the increased abstractions during summer periods. The 4 and 8 yearly periodicities may be ascribed to the long term fluctuations in abstraction rate, correlating with series of above or below average rainfall during summer seasons.

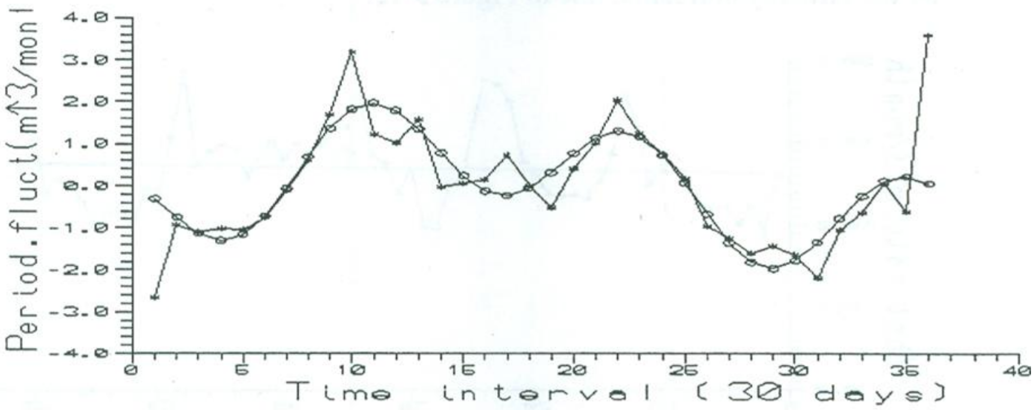

Figure 14: Fit of harmonics to abstraction rate time series (sub-series B)

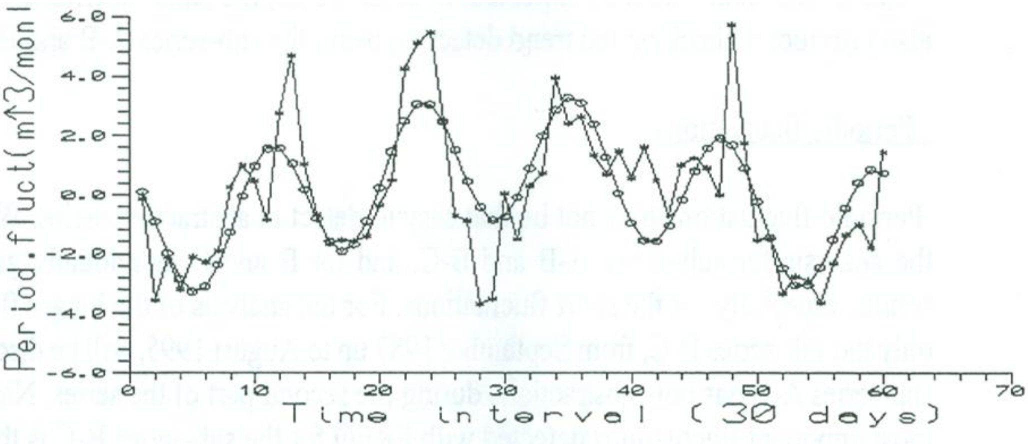

Figure 15: Fit of harmonics to abstraction rate time series (sub-series C)

The abstraction rates show a negative correlation with the groundwater level time series. A negative correlation means that with an increase in abstraction rate, the groundwater level decreases. In absolute values, the correlation coefficients between abstractions and groundwater levels decrease from 0.607 for the observation well closest to the well field (WP01) to a very poor correlation of 0.17 for the farthest away well (WP09). A zero lag time has been considered for analysis. The explanation for this decrease in correlation coefficient is the decreasing influence of the abstraction rate on the groundwater level time series.

For the abstraction rate time series of the Kruidhaars Well Field, an analysis of the stochastic part has also been carried with FREQ. The stochastic components for all the analyzed series were fitted with an AR(1) model which refers to an autoregressive model of order 1. To carry out the analysis, the trends and fluctuations were first subtracted from the original series. After the fit with the AR(1) model, it appeared that the residuals are random and independent. This confirms that the analysis of the abstraction rates has been carried out adequately.

Groundwater levels

Trend detection

Steps trends have been identified and quantified in groundwater level time series in most of the observation wells in the influence area of the Kruidhaars Well Field. FREQ clearly detected step trends in WP01, WP04, WP06, WP07. In wells WP05 and WP09 no step trends were identified. The analysis was carried out for sub-series A-B and B-C. for the sub-series A-B and B-C. For the sub series A-B, covering the period from September 1983 up to August 1990, the detailed analyses for the individual wells can be summarized as follows:

Observation well WP01

A step trend with a magnitude of 0.21 m has been detected in well WP01, nearby Kruidhaars Well Field. The well is 50m from the station. The occurrence of this step trend can be correlated with the start of the pumping activities in September 1987.

Observation well WP04

For well WP04, at 70 m distance from the Kruidhaars well field, a step trend of 0.18 m has been found. The reason for this step trend is the same as for well WP01, that is the start of groundwater abstractions at Kruidhaars.

Observation wells WP06 and WP07

These two wells which are located much farther away from the Kruidhaars pumping station (at 550 to 800 m distance) have shown step trends of almost the same magnitude: 0.11 m and 0.10 m. Also, for these wells, the step trend can be associated with the start of the pumping activities at Kruidhaars.

For the sub-series B-C from September 1987 to August 1995, a step trend could be detected around September 1990 only for the wells WP01 and WP04, located close to the Kruidhaars pumping station. The step trend magnitude for WP01 is 0.27 m and for WP04 the magnitude is 0.21 m. For wells WP06 and WP07, no step trend has been detected, which may come as a surprise in view of the significant increase in abstraction rate at Kruidhaars around September 1990. The linear upward trend detected for well WP07 for sub-series C (figure 16) could give an explanation. The rise in groundwater levels during the period September 1990 to August 1995, because of wetter climatic conditions and a slight reduction in abstractions from 1993 onwards, balance the effect of increased pumping on the groundwater levels. Therefore, a step trend has not been detected.

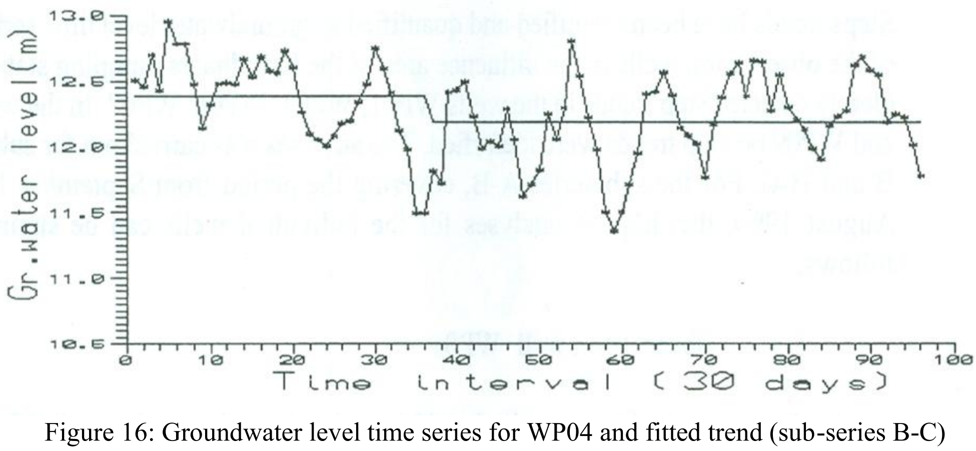

Figure 16: Groundwater level time series for WP04 and fitted trend (sub-series B-C)

Linear trends have been identified and quantified for the groundwater level time series in observation wells around the Kruidhaars Well Field. FREQ detected and supplied the equation for linear trends for A-B-C and the individual series. A, B and C. Most telling are the linear trends have been detected for the period A from September 1983 to August 1987. For all the wells linear downward trends A from September 1983 to August 1990. For wells WP04, WP05, WP07 and WP09 linear upward trends were detected for sub-series C, indicating the advance of wetter conditions and some reduction in abstraction rate at Kruidhaars.

Periodic fluctuations

Periodic fluctuations in the groundwater levels have been identified and analyzed with FREQ. For all the sub-series analyzed, A-B, B-C, and the individual series A, B and C, the main fluctuation was the one with a periodicity of 12 months. For the sub-series A-B from September 1983 to August 1990, the long term fluctuations had periodicities around 42 months (3.5 years) and 48 months (7years). For the period B-C, from September 1987 up to August 1995, FREQ detected a main long term fluctuation with a periodicity of 96 months (8years). We may conclude that during the observations, the long term fluctuation seems to change, to some extent from a relatively short to a longer periodicity. This could be related to the natural recharge fluctuations, to the lengths of sub-series analyzed, or to the introduction of the abstractions at Kruidhaars (figure 17).

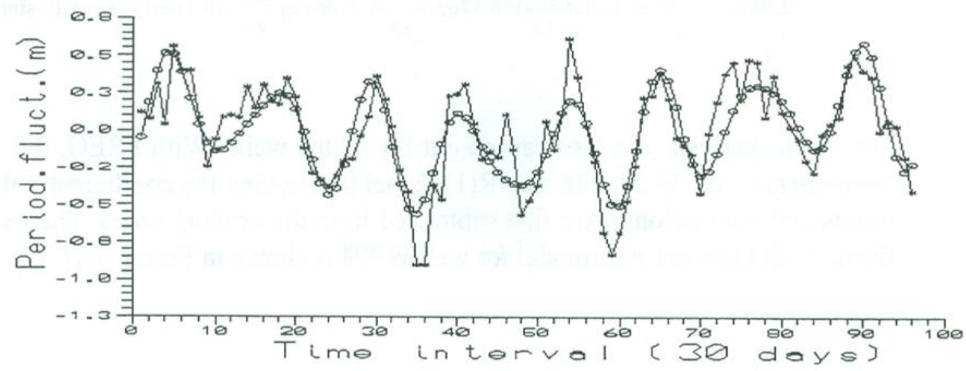

Figure 17: Fit of harmonics to water level time series of WP04 (sub-series B-C)

The correctness of the analysis of the periodic fluctuations is confirmed by the harmonic model simulating the trend free series of the groundwater levels in well WP04. To construct the model, a cumulative periodogram can be made (figure 18). With this periodogram, it has been determined that the first 3 periodicities are sufficient to define the harmonic model.

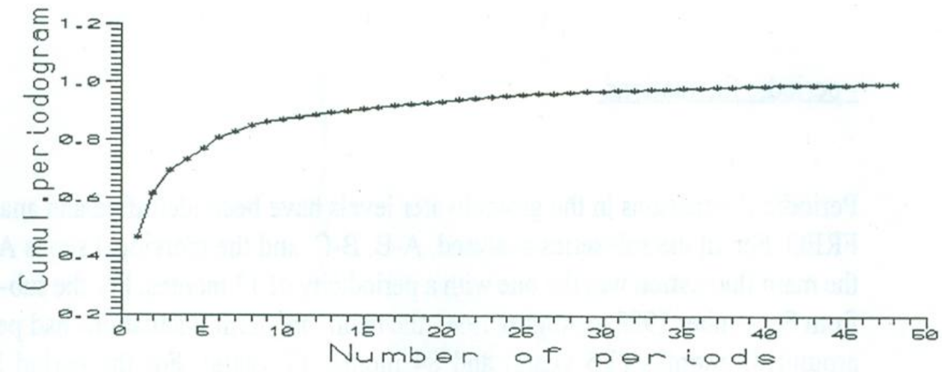

Figure 18: Cumulative periodogram of water levels in WP04 (sub-series B-C)

Using a Fourier model equation and the result of the FREQ analysis, the harmonic model can be computed and presented as:

$$h_t = 2.95\cos(2\pi t/12)+0.12\sin(2\pi t/12)+0.17\cos(2\pi t/96)-0.06\sin(2\pi t/96)-0.1\cos(2\pi t/9)+0.08\sin(2\pi t/9)$$

Stochastic analysis was also carried out for all the wells. With FREQ, the stochastic components were fitted with an AR(1) model (autoregressive coefficient = 0.38). The trends and fluctuations were first subtracted from the original series. The result of the fitting with stochastic model for well WP04 is shown in figure 19.

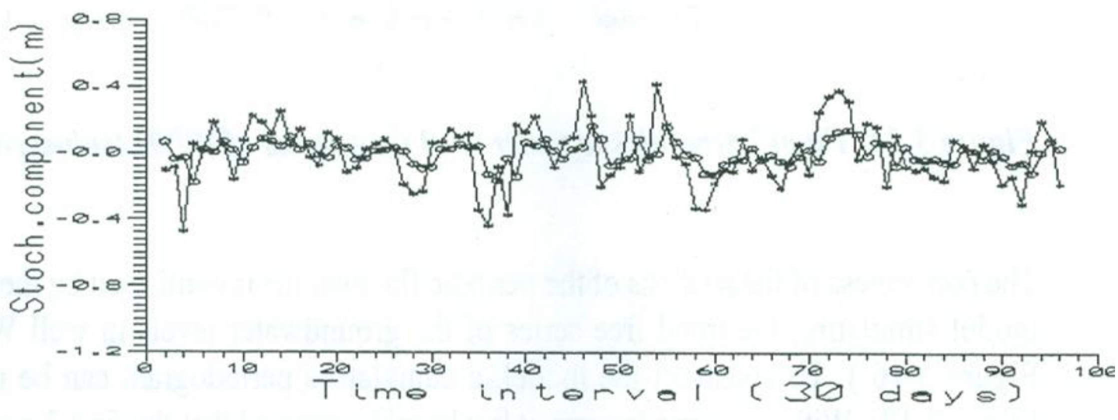

Figure 19: Fit of stochastic model AR (1) for well WP04 (sub-series B-C)

After fitting with the AR(1) model, the residuals between the trend and harmonic-free time series and the stochastic model have been calculated. The results are shown again for observation well WP04 in figure 20. The figure shows that the residuals appear to be rather random, varying between -0.4 and + 0.4 m, whereas zero seems to be the mean value of the series.

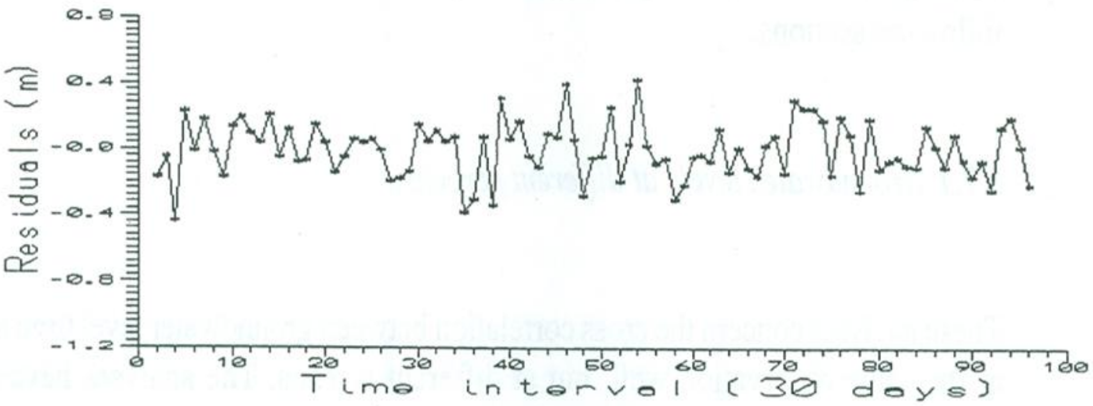

Figure 20: Residuals of time series for well WP04 (sub-series B-C)

The randomness and independence of the residuals have been checked by autocorrelation. This was shown by correlograms which indicated that there are no correlations left between the measurements. On the correlogram for well WP04 (figure 21), this is shown by the fact that the fluctuations of the residual series are between the limits of -0.2 and +0.2m. This lack of correlation proves that the trend and the periodic fluctuations have been successfully removed, and that the stochastic components have been correctly analyzed.

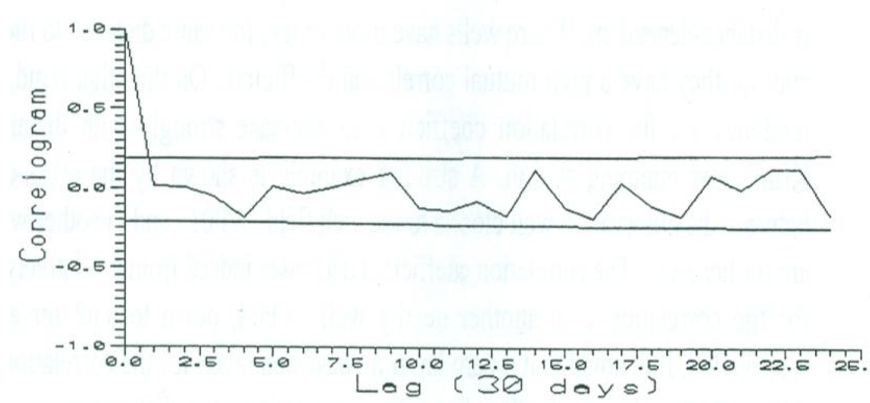

Figure 21: Correlogram of residuals in well WP04 (period B-C)

Bivariate Analyses

The main task that been carried out in the bivariate analyses been the setting up of cross correlations for various parameters. Cross-correlations have been performed to evaluate the degree of relationship between natural recharge, abstraction and groundwater levels. The results will be summarized in the following sections.

Groundwater levels at different screens

These analyses concern the cross correlation between groundwater level time series taken at the same observation well, but at different screens. The analyses have been done graphically. It has been found that there exists an extremely high correlation between these groundwater level time series. The graphical plots of the groundwater level time series recorded at different screens of the same well have unique and similar curves. Therefore, it was not considered necessary to complete the statistical cross correlation analysis.

Groundwater levels at different wells.

These interpretations relate to the comparison of groundwater levels recorded at the different wells around the Kruidhaars Well Field . The diagonal of the cross-correlation matrix shows that the magnitude of the correlation coefficient is distance-dependent. Where wells are the same distance to the pumping station, they have a high mutual correlation coefficient. On the other hand, there is a tendency for the correlation coefficient to decrease strongly with distance to the Kruidhaars Well Field. A striking example is shown by the cross-correlation between the observation well closest to the well field, WP01, and the other wells which are further away. The correlation coefficient decreases indeed from a relatively high 0.94 for the correlation with another nearby well, WP04, down to 0.62 for a faraway well: WP09. It is noted that a zero lag time has been taken for the correlation analysis. Although the choice of other lag times may reduce the differences in correlation coefficient to some extent, the results of the cross correlations between wells indicate that the impact of the abstractions on the groundwater levels is significant (table 4). Similarly, the analysis suggests that the aquifer system itself and the recharge in the investigation area are rather constant in composition and rate.

Table 4: Cross-correlation between groundwater levels

	WP01	WP04	WP06	WP07	WP05	WP09
WP01	1					
WP04	0.94	1				
WP06	0.85	0.9	1			
WP07	0.79	0.87	0.95	1		
WP05	0.74	0.83	0.93	0.98	1	
WP09	0.62	0.74	0.83	0.92	0.93	1

Recharge, abstraction and groundwater levels

The cause-effect relationship between natural recharge and groundwater levels, and abstraction rate and groundwater level time series has also been established by cross correlation. Natural recharge or abstraction rates served as input variables and groundwater level time series as output. Table 5 shows the results. One can observe with respect to the natural recharge and groundwater levels, that the magnitude of the correlation coefficient increases with increasing distance from the Kruidhaars Well Field: from 0.468 for the nearby well WP01 to 0.604 for the farther away well WP05. It is noted that a zero lag time was selected for analysis. Checking for other lag times showed that, except for well WP09 (see below), the use of a zero lag time gave the best results.

The explanation for increase in correlation coefficient with distance from the Kruidhaars Well Field is the increasing influence of recharge on the groundwater level time series and the decrease of the effect of abstractions. However, the groundwater level time series recorded in the farthest away observation well, WP09, has shown an unexpectedly poor correlation (0.42 at lag 0 and 0.556 at lag 2) with the natural recharge time series. This may be interpreted as the result of the different land uses in the area and a certain delay in the recharge process (time lag of 30 days) due to the relatively thicker unsaturated zone at the well location.

Table 5: Cross-correlation recharge, abstraction and groundwater levels

Wells	Recharge (A-B-C)-groundwater levels (A-B-C)		Recharge (-B-C)-groundwater levels (A-B)		Abstraction (B-C) groundwater (B-C)	Distance to the well field (m)
	Maximum coefficient	Delay (lag)	Maximum coefficient	Delay (lag)	coefficient	
WP01	0.468	0	0.568	0	-0.607	50
WP04	0.507	0	0.589	0	-0.536	70
WP06	0.576	0	0.632	0	-0.343	550
WP07	0.584	0	0.618	0	-0.261	800
WP05	0.604	0	0.634	0	-0.2	1500
WP09	0.556	2	0.603	2	-0.17	2075

The abstraction rates show a negative correlation with the groundwater level time series. A negative correlation means that with an increase in abstraction rate, the groundwater level decreases. In absolute values, the correlation coefficients between abstractions and groundwater levels decrease from 0.607 for the observation well closest to the well field (WP01) to a very poor correlation of 0.17 for the farthest away well (WP09). A zero lag time has been considered for analysis. The explanation for this decrease in correlation coefficient is the decreasing influence of the abstraction rate on the groundwater level time series.

Comparison with model results

The main goal of the time series analyses, including the graphical analysis as well as the univariate and bivariate analysis, concerns the assessment of the impact of the Kruidhaars Well Field on groundwater levels. The analyses have resulted in the determination of the total drawdown on groundwater levels induced by the pumping activities. Except for well WP09, the drawdown has been determined for the groundwater observation wells located in the influence area of the production well field. At these sites, the drawdown has been compared with the drawdown computed with the KIWA groundwater model, before the abstractions were put into place.

The computations of the drawdowns have been undertaken as follows. In the Kruidhaars area, the groundwater levels in the observation wells are mainly influenced by recharge and abstractions at the well field. The univariate analysis has shown that in periods A and C, the mean long term recharge rates were rather similar at respectively 33 and 35 mm/month. In period B, the mean recharge was at a lower level, at about 27 mm/month. For a first rough assessment of the drawdown, we have assumed that the long term recharge for A and C is equal. The above means that the difference in the long term mean in groundwater levels for the period A and C can, as a first estimate, be considered as the effect of the abstraction at Kruidhaars on the groundwater levels.

The actual computation of the impact of abstractions on the groundwater levels has been done by subtracting the long term mean groundwater levels for period C from those for period A. This computation has been based on the results of the univariate analysis. In fact, the same result would also be obtained by adding the computed step trend magnitudes for the combined periods A-B and B-C (wells WP01 and WP04).

Table 6 presents the total computed drawdowns of the groundwater levels as a result of the abstraction activities at the Kruidhaars Well Field. The results shown reveal that the drawdowns of the groundwater levels are distance dependent with respect to the Kruidhaars Well Field. The drawdowns vary from 0.48 m in the nearest well (WP01) to only 0.04 m in a far away well (WP05). In the farthest away observation well (WP09), the decline is even 0 m. Thus, the closer the observation well is to the pumping station, the larger the drawdown of the groundwater levels.

A better estimate of the groundwater level declines has been obtained by considering the small differences in mean recharge rate for the periods A and C. The increase from 33 to 35 mm/month, i.e. 2 mm/month would have resulted in an increase in groundwater levels, which means that the actual declines determined above are estimated on the low side. The computation of the effect of changes in recharge has been based on estimates for period B, which showed a significant downward trend in the magnitude of this parameter. For this period, time series for the observation wells were developed, free of the effect of abstractions. To complete this task, a correlation was set up for the pre-pumping period between a well inside the influence area and a well not influenced by the pumping station. In view of the poor correlation coefficients found in the bivariate analysis, the uninfluenced well selected was WP09. The agricultural well L13 was less suitable for the task, since only 3-monthly data are available for this well, and linear trends were detected for period A. This was not the case for the other these wells which that the hydrological conditions may be rather different at L13 as compared with the conditions at the other wells.

Table 6: Drawdown of groundwater levels

Observation well	Initial estimate of groundwater declines due to pumping activities (m)	Declines corrected for effect of change in recharge (m)	Distance to production field (m)
WP01	0.48	0.50	50
WP04	0.39	0.41	70
WP06	0.15	0.17	550
WP07	0.08	0.10	800
WP05	0.04	0.06	1500
WP09	0	-	2075

With the correlations for WP09 established, the abstraction free series could be computed for period B for the wells inside the influence area. For period B the abstraction free declines in groundwater levels were computed to range between 0.36 and 0.42 m. These would be the effects of the decline in recharge rate for this period. Since the univariate analysis, the decline in recharge rate can be computed as amounting to 53 mm/month. Based on an average groundwater level decline of 0.39 m, the rate of decline (change) in groundwater level per unit change in recharge rate could be computed as 0.0075 m. For the 2 mm difference in recharge rate for the periods A and C, 33 and 35 mm, the groundwater levels would have risen an average 0.015 m. This is indeed very low value, which changes the initial results only slightly. The decline now ranges from 0.5 m in well WP01 to about 0.06 m in well WP05.

IV. Conclusion

The prediction of impact of abstraction at the Kruidhaars Well Field on the groundwater levels was done through a modeling approach (KIWA, 1984). The drawdowns predicted from modelling were based on the calculation for the spring-summer situation which has been assumed to be representative of the average yearly situation. A pumping rate of 2 Mm3/year has been considered, and the resistance of the covering layer has taken as 2000 days (summer situation). The quoted abstraction rate for the model was somewhat more than the mean amount pumped during the period from September 1990 up to August 1995 (period C) when a constant high abstraction rate was maintained: 1.6 Mm3/year. Table 7 compares the predicted and observed groundwater level declines, also recalculating the observed levels for the case when an abstraction rate of 2 Mm3/year would have been maintained.

Table 7: Comparison between predicted and observed groundwater levels

Wells	Groundwater decline computed by time series techniqiues for 1.6 million meter cubic per year (m)	Groundwater decline computed by time series techniqiues for 2.0 million meter cubic per year (m)	Groundwater decline computed by the KIWA model	Difference between observed and predicted levels
WP01	0.50	0.63	0.45-0.55	0.08-0.18
WP04	0.41	0.51	0.40	0.11
WP06	0.17	0.21	0.21	0.0
WP07	0.10	0.13	0.08	0.05
WP05	0.06	0.08	0.03-0.04	0.04-0.05
WP09	-	-	-	-

The table shows that in general there was a structural under-estimation of the impact by the KIWA model. The predicted drawdowns were about 15% to 25% below drawdowns estimated by the time series techniques and based on the observed data. Even higher percentages seem to be indicated for the far away wells WP07 and WP05. The similarity in drawdown for well WP06 could be explained by the fact that this well might be placed near an open water course where the impact of pumping is strongly reduced. Possibly, the general under-estimation of the KIWA model can be assigned to assumptions made for its conceptual set up. For example, the effect of surface water courses could have been over-estimated.

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