Journal of Hydrology 260 (2002) 102–117

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Predicting average annual groundwater levels from climatic variables: an empirical model

Zhuoheng Chen*, Stephen E. Grasby, Kirk G. Osadetz

Geological Survey of Canada, 3303-33rd Street NW, Calgary, Alberta, Canada T2L 2A7

Received 25 January 2001; revised 1 November 2001; accepted 29 November 2001

Abstract

On the basis of one-dimensional theoretical water flow model, we demonstrate that the groundwater level variation follows a pattern similar to recharge fluctuation, with a time delay that depends on the characteristics of aquifer, recharge pattern as well as the distance between the recharge and observation locations. On the basis of a water budget model and the groundwater flow model, we propose an empirical model that links climatic variables to groundwater level. The empirical model is tested using a partial data set from historical records of water levels from more than 80 wells in a monitoring network for the carbonate rock aquifer, southern Manitoba, Canada. The testing results show that the predicted groundwater levels are very close to the observed ones in most cases. The overall average correlation coefficient between the predicted and observed water levels is 0.92. This proposed empirical statistical model could be used to predict variations in groundwater level in response to different climate scenarios in a climate change impact assessment. Crown Copyright © 2002 Published by Elsevier Science B.V. All rights reserved.

Keywords: Flow and budget models; Carbonate aquifer; Southern Manitoba; Impact assessment; Recharge; Climate change

1. Introduction

Groundwater has been, and will continue to be, an important water supply for industrial, agricultural and residential use on the Canadian prairies due to inadequate supplies of surface water (Maathuis and Thorleifson, 2000). Trends of increasing annual average air temperature and decreasing precipitation in the Canadian prairies in the last four to five decades (Gan, 1998) and possibility of global warming (Showstack, 2001) raise concerns about maintaining a sustainable supply of groundwater for this region. Changes in any key climatic variables could significantly alter recharge rates for major aquifer systems and thus affect the sustainable yield of ground water in the region. In order to predict the impacts of future climate change on groundwater levels in the prairies, it is essential to obtain quantitative information on the response of groundwater levels to climate variability. Here we examine the impact of climate change on the carbonate rock aquifer in southern Manitoba, one of the largest fresh water aquifers in the region. A deterministic approach for predicting groundwater level involves the development of a detailed model of the aquifer system, including estimation of key hydraulic properties and recharge rates, which are typically difficult to obtain and quantify (e.g. hydraulic conductivity, storage coefficients, etc.). For the carbonate rock aquifer, the recharge system is complicated and the recharge rate is essentially unknown. As well, the hydrological properties, and their spatial variation, of the aquifer are less known. Due to these limitations,

* Corresponding author. Tel.: +1-403-292-7115; fax: +1-403-292-7159.

E-mail address: ess-cal-zchen@x1.nrcan.gc.ca (Z. Chen).

PII: S0022-1694(01)00606-0

and a restricted time framework, a deterministic approach was deemed unsuitable.

In the Canadian prairie provinces, groundwater monitoring networks are common and observations of key climatic variables are also available from major meteorological observation stations. Analysis of groundwater level variation and climate data collected from this region shows an empirical relationship between the groundwater levels and climatic variables. The lack of adequate information on hydrological parameters and groundwater recharge of the aquifer, and the apparent empirical relationship motivated us to examine an alternative approach that allows a more rapid and less expensive assessment of aquifers with limited data under given climate change scenarios.

The proposed statistical approach is a simplification and combination of a water flow model and a water budget model based on the analysis of historical water well records and climatic data. Groundwater level variation reflects a dynamic equilibrium between recharge and discharge, resulting in changes in groundwater storage (Freeze and Cheery, 1979). The one-dimensional water flow model shows that there is a correlation between variations in groundwater level and aquifer recharge. The water budget model indicates that water recharge is a function of climatic variables. In this paper, we discuss a statistical model which relates climatic variables to groundwater level on the basis of the water flow and budget models.

In the following sections, we start with a discussion of the one-dimensional theoretical water flow model and its implications for the relationship between recharge and water level variation, and a discussion of the water budget model relating climatic variables to the recharge rate. A linear empirical model linking the climatic variables with groundwater variation is then presented. This is followed by an examination of the characteristics of the available climatic data from the Winnipeg meteorological station and water level data from the monitoring network of the carbonate rock aquifer in southern Manitoba, Canada. As an application of the model, we use part of the observed data to test its capability of predicting groundwater level using climatic variables.

2. Method description

The prediction of groundwater levels using climatic variables involves two hydrological systems, i.e. a groundwater flow system and a water budget system. We first examine the water flow system and its key control for the prediction of variation in groundwater level. This is followed by an analysis of the budget system and its relation to the flow system. Finally, an empirical model based on the relation between these two systems is presented.

2.1. Water flow model

Groundwater level variation reflects a dynamic equilibrium between recharge and discharge, which results in changes in groundwater storage. From a water balance equation, the inflow Q_{in} to a groundwater aquifer equals the outflow Q_{out} from the aquifer, plus the change of water storage ΔS in the system (Freeze and Cheery, 1979):

$$Q_{\mathrm{in}} - Q_{\mathrm{out}} = \Delta S \tag{1}$$

Eq. (1) can be converted to a water flow equation. In a homogeneous aquifer, a simple one-dimensional continuity equation of the above expression is written as

$$K\frac{\partial^2 h}{\partial x^2} = S_{\mathrm{c}}\frac{\partial h}{\partial t} \tag{2}$$

where h is the water head, S_{c} is the aquifer storage coefficient and K is the aquifer hydraulic conductivity. By applying Laplace transformation, an analytical solution of Eq. (2) can be written as (Mathematical handbook, 1979, p.737–738).

$$h(x,t) = h_0 erfc\left(\gamma\frac{x}{\sqrt{t}}\right) \tag{3}$$

with

$$\begin{cases} h|_{t=0} = 0, & 0 < x < \infty \\ h|_{x=0} = h_0, & t > 0 \end{cases}$$

and

$$\gamma = \sqrt{\frac{S_{\mathrm{c}}}{2K}}$$

Eq. (3) represents temporal–spatial groundwater response to a stable water head at the recharge area.

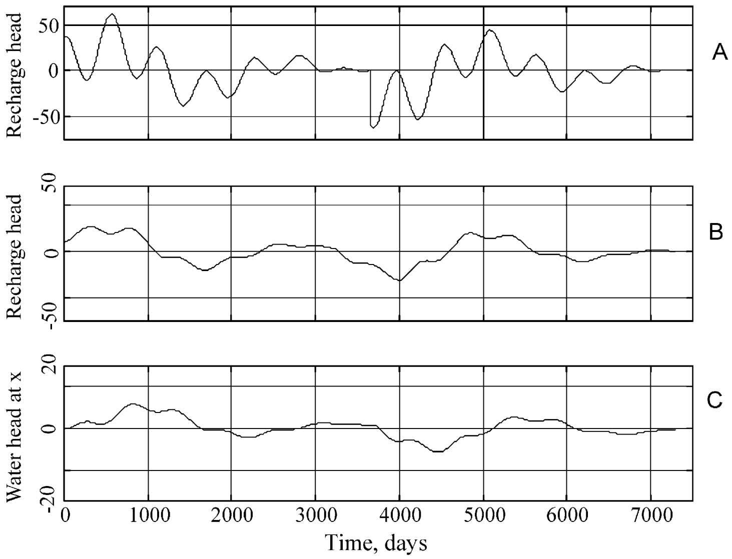

Fig. 1. Groundwater level variation in response to recharge fluctuation. (A) relative water recharge fluctuation measured as water head; (B) low-pass filtered water recharge heads; (C) water level responses in the same aquifer at a distance of 50 km and assuming $K = 200$ m/day, and $S_c = 1.0 \times 10^{-4}$.

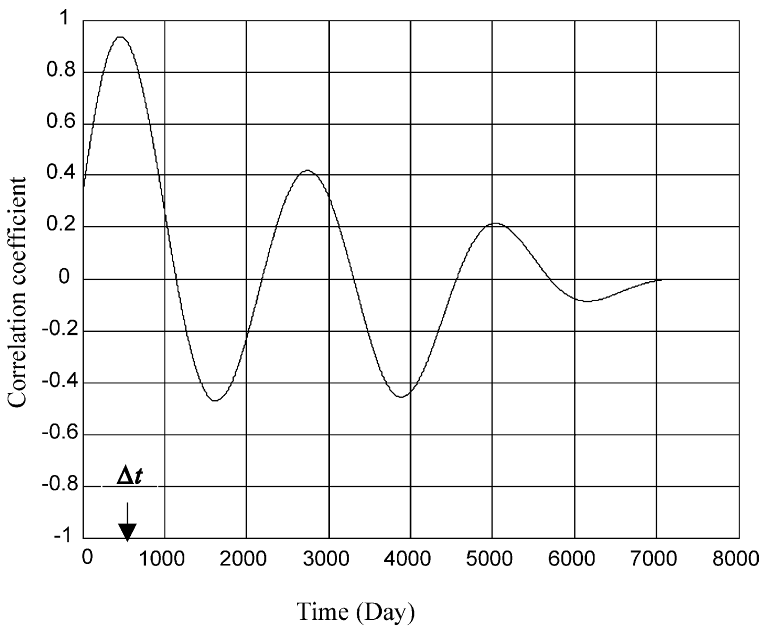

Fig. 2. Apparent time delay Δt determination. Δt is defined as a time shift between recharge and water lever time series and estimated as the time shift at which these two time series display a maximum correlation.

If we regard the water flow system as a dynamic system, consisting of input, system transfer and system output, then the complementary error function in Eq. (3) represents the system response.

Let $g(x,t)$ denote the system response function, i.e.

$$g(x,t) = erfc\left(\gamma \frac{x}{\sqrt{t}}\right) \tag{4}$$

Treating recharge $R(t)$ as a water head in the recharging area ($x = 0$), that is $R(t) = h(x_0, t)$, the variation in the water head at location x and time t, in response to variation in water recharge, $R(t)$, can be expressed as a convolution of the system response function with water recharge at past times:

$$H(x,t) = \int_0^t R(t)g(x, \tau - t)\,\mathrm{d}t \tag{5}$$

To examine the relationship between water recharge and water level variation, an artificial discrete water recharge time series, consisting of daily heads for 20 years with two major frequency components ($T_1 = 600$ and $T_2 = 2500$ days), was generated using a simple equation of $R(t) = \alpha\cos(t/T_1) + \beta\sin(t/T_2)$. Fig. 1 shows the original water recharge time series (A), a low-pass filtered water recharge (applied a moving average in this case) (B) and the corresponding water level variation calculated by using Eq. (5) (C), assuming system parameters $K = 200$ m/day, $S_c = 1.0 \times 10^{-4}$ and $x = 50$ km. It appears that the corresponding water head variation at distance x from the recharge area has a similar fluctuation pattern. However, three major differences were observed when comparing the recharge and water level response: (1) the aquifer heads at location x show a certain period of time delay (a time lag) in response to changes in recharge as indicated by a maximum correlation coefficient between the filtered water recharge (Fig. 1(B)) and groundwater level curve (Fig. 1(C)). The maximum correlation equals 0.95 with time delay of 400 days (Fig. 2); (2) the water head fluctuation is dominated by the low frequency component, i.e. the system transfer acts as a low-pass filter (comparing Fig. 1(A) and (C)); this phenomenon is explained as a buffering effect in the unsaturated zone of the recharge area by Gehrels (1999), and (3) the magnitude of the water level fluctuation at point x is smaller in comparison to the recharge head fluctuation. From Eq. (5), it appears that if we know the hydrological characteristics of the aquifer and its responses to the water recharge fluctuation, we can estimate the groundwater recharge by deconvolution. On the other hand, if we know the recharge rate and aquifer response, we can estimate certain hydrological properties of the aquifer.

2.2. Water budget model

From Eq. (5), it appears that recharge rate is one of the major factors affecting the natural groundwater level variations. From water balance principles, we know that only part of precipitation becomes groundwater recharge. The recharge can be approximated as a function of precipitation and temperature using the following equation (Freeze and Cheery, 1979):

$$R = P - Q_o - \mathrm{ET} \tag{6}$$

where R denotes recharge, P is precipitation, and Q_o represents outflow, which is the part of precipitation lost, and ET represents evapotranspiration which is a function of air temperature. We consider a simple linear relationship between evapotranspiration and air temperature (i.e. Singh, 1992):

$$\mathrm{ET} = \lambda_0 + \lambda_1 T \tag{7}$$

where λ_0 and λ_1 are constants and T is temperature. Replacing Eq. (7) in Eq. (6) and manipulating the equation, water recharge can be written as a linear function of precipitation and temperature:

$$R = C_1 + P - \lambda T \tag{8}$$

where C_1 is a constant which incorporates the effects of outflow and part of evapotranspiration effect.

2.3. Proposed statistical model

It is obvious that available water flow models for the prediction of water levels in an aquifer require knowledge of the characteristics of the aquifer, such as aquifer hydraulic conductivity, storage coefficients and their spatial variations, as well as the recharge rate. From the water budget model we have observations on precipitation and air temperature. However, without knowing the outflow and evapotranspiration, the recharge rate cannot be estimated. The lack of adequate information on hydrological parameters and recharge rate of the aquifer motivated us to examine an alternative approach. An empirical model using statistical methods is, therefore, considered in this study.

From Fig. 1, as a first order of approximation, it is reasonable to assume that annual ground water head H at location x and at time t is proportional to the annual water recharge $R(t)$ with a time delay Δt. We then have

$$H(x, t, \Delta t) = C_2 + \alpha R(t - \Delta t) \tag{9}$$

Using the water flow model, we have shown that the water level response to the recharge fluctuation is dominated by a low frequency component (Fig. 1). However, as it will be seen in the data analysis, groundwater level responses to precipitation are different from well to well in a shallow aquifer, likely due to the differences in permeability characteristics of the overlying sediments, suggesting a complicated recharge system. For some locations, the recharge may come from both, local and regional sources; whereas the others might be restricted to a regional resource. For those locations where the low frequency component is dominant, we assume that only regional recharge is available; whereas for the locations with mixed frequency components, we consider additional local recharge for the system. Since recharge rates are unknown, we consider precipitation to be comprized of three components, i.e. a long-term component P_l, a short term fluctuation P_s and seasonal variations P_{sv}, which can be written as

$$P = P_l + P_s + P_{sv} \tag{10}$$

After replacing Eqs. (8) and (10) in Eq. (9) and manipulating the equation, we can write the water level at location x and time t as

$$H(x, t, \Delta t) = C + \alpha_1 P_l(t - \Delta t) + \alpha_2 P_s(t - \Delta t) + \alpha_3 P_{sv}(t - \Delta t) + \beta T(t - \Delta t) \tag{11}$$

where C, α_i, and β are coefficients to be determined. This empirical model describes water level at location x and time t as a function of precipitation and temperature with a time delay Δt, directly relating groundwater level to climatic variables. The coefficients in Eq. (11) are estimated by minimizing the difference between the observed and the predicted water levels for each well. The three components of precipitation can be separated from a frequency analysis of the annual precipitation time series. The spatial variation of the water levels at a given time due to aquifer heterogeneity and the distance between recharge and observation is characterized by the spatial variation of the coefficients in Eq. (11). If water withdrawal (re-injection) data are available, the annual average variation of groundwater level due to the withdrawal and re-injection can be characterized by an additional term in Eq. (11). This portion of groundwater variation could be reasonably assumed to be proportional to the total quantity of annual withdrawal (re-injection) (Singh, 1992, p. 295).

As we discussed before, it is clear that the time delay is a function of aquifer hydraulic conductivity and storage, recharge head characteristics, as well as the distances between recharge area and observation. Because of the heterogeneity of aquifers and the fact that observation wells are located at different distances from the recharge area, the time lag will vary from well to well and has to be estimated individually. It is difficult to estimate the actual time delay because the water level responses at x and time t is a convolution of the system response function in Eq. (4) and water recharge at past times (Eq. (5)). We, therefore, define an apparent time delay as the time difference between the precipitation and its apparent corresponding water level, which is approximated by the time difference when the two time series reach a maximum correlation (Fig. 2):

$$\Delta t = \tau, \qquad \text{if } r_{xy}(\tau) = \max(r_{xy}(1), \ldots, r_{xy}(n)) \tag{12}$$

where

$$r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \sigma_y}$$

and

$$C_{xy}(k) = \frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x})(y_{t+k} - \bar{y})$$

where $r_{xy}(k)$ is the cross correlation coefficient with time lag k, $C_{xy}(k)$ is the cross-correlogram, and σ_x and σ_y are the standard deviations of the time series.

3. Application example

As an application example, the upper carbonate aquifer in southern Manitoba is chosen for two reasons. First, there is an excellent database consisting

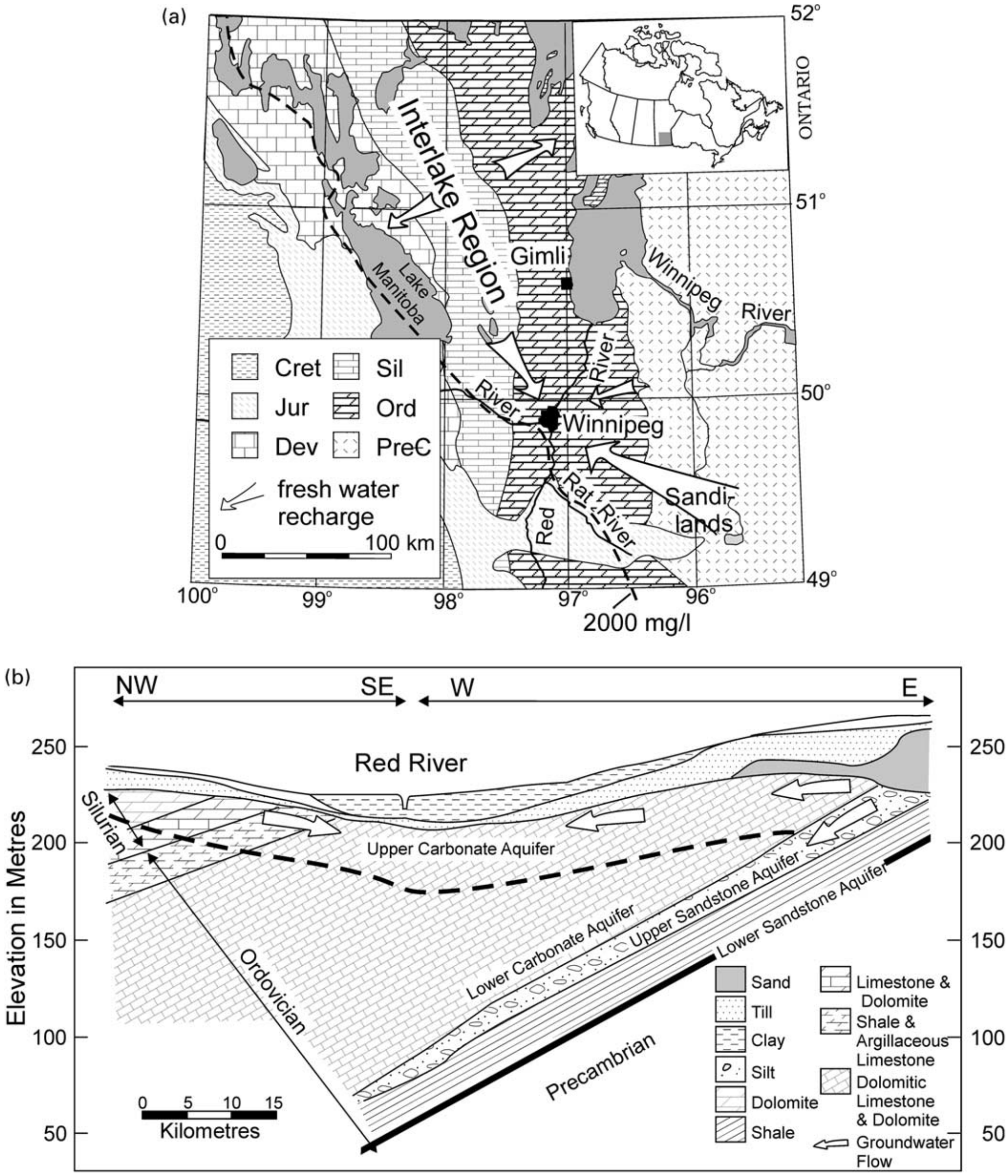

Fig. 3. Regional geological map (A) and geological cross section (B), southern Manitoba, Canada (after Betcher et al., 1995).

of a monitoring well network and long-term meteorological observation records for this region. These data allow us to test the empirical relationship established in the model using historical records. Second, groundwater supply has been a very important part of the water resource for industry, agriculture and residential use in this region. Any significant change in the climatic variables could alter the recharge system, and thus the sustainable supply of groundwater. There is a need, in the light of climate change adaptation strategy planning, for development of a method that can accurately predict the groundwater levels for climate change impact assessment.

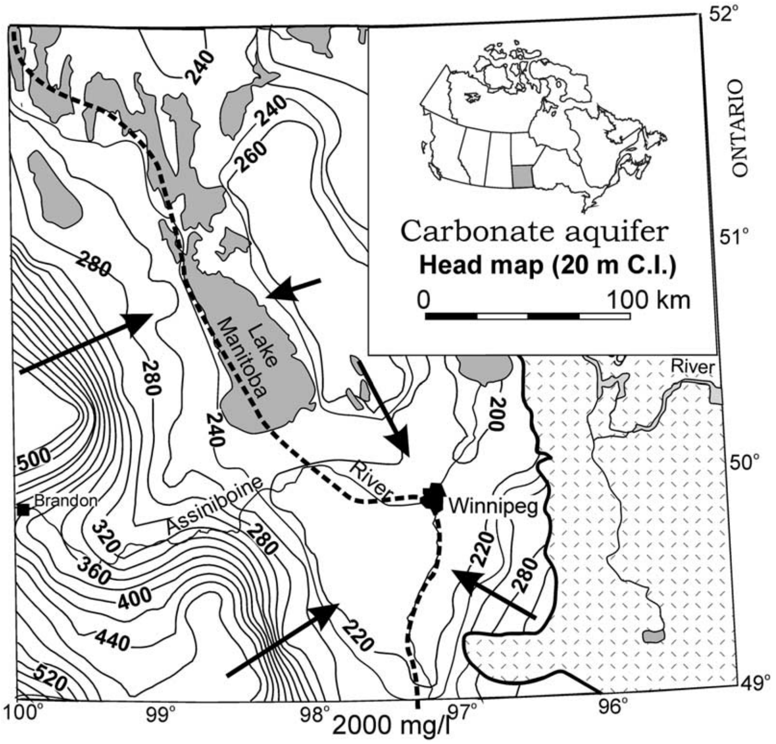

Fig. 4. Regional water head map, southern Manitoba, Canada.

3.1. Regional hydrogeological setting

The carbonate rock aquifer occurs along the eastern edge of the Williston Basin in southern Manitoba, and is formed by a series of gently west dipping Middle Ordovician to Middle Devonian carbonates with minor shales and evaporites (Betcher et al., 1995; McCabe, 1971). The aquifer crops out in the Manitoba lowlands, along a NW–SE trending zone lying to the east and north of the Manitoba Escarpment, which marks the transition to overlying argillaceous Mesozoic and Cenozoic sediments(Fig. 3(A) and (B)). Within the study area (from Winnipeg east to the Sandilands) the aquifer is dominantly Ordovician carbonates.

In the Manitoba lowlands the Carbonate Rock aquifer is generally considered a single hydrostratigraphic unit, although thin extensive argillaceous units do act as inter- or intra-formational aquitards (Fig. 3(B)). Fractures, joints and bedding planes form primary pathways for water movement in most of the aquifer, with dissolution processes having enhanced the permeability of these fractures in some areas. In particular, the upper few metres of the bedrock surface are often found to be extensively fractured. This zone forms the 'upper' carbonate aquifer. Fracturing in the upper carbonate aquifer appears to be a function of depth from surface and is not restricted to a particular stratigraphic unit (Render, 1970). Pleistocene glaciation covered extensive portions of the outcrop belt of the carbonate rock aquifer in the southern Manitoba lowlands with till. Within the Red River Valley, up to 20 m of glaciolacustrine sediments, predominantly clay, overlie 1–20 m of till. With some local exceptions (Day, 1977; Pach, 1994), these glaciolacustrine sediments form an effective cap, sealing the top of the Carbonate Rock aquifer through much of the outcrop belt. However, downward leakage through the clay has been estimated to account for up to 10% of recharge to the aquifer (Day, 1977). In contrast, highlands in the Interlake region (north of Winnipeg), and the Sandilands area (southeast of Winnipeg) are primarily underlain by silty tills and sands with bulk permeabilities greater than the

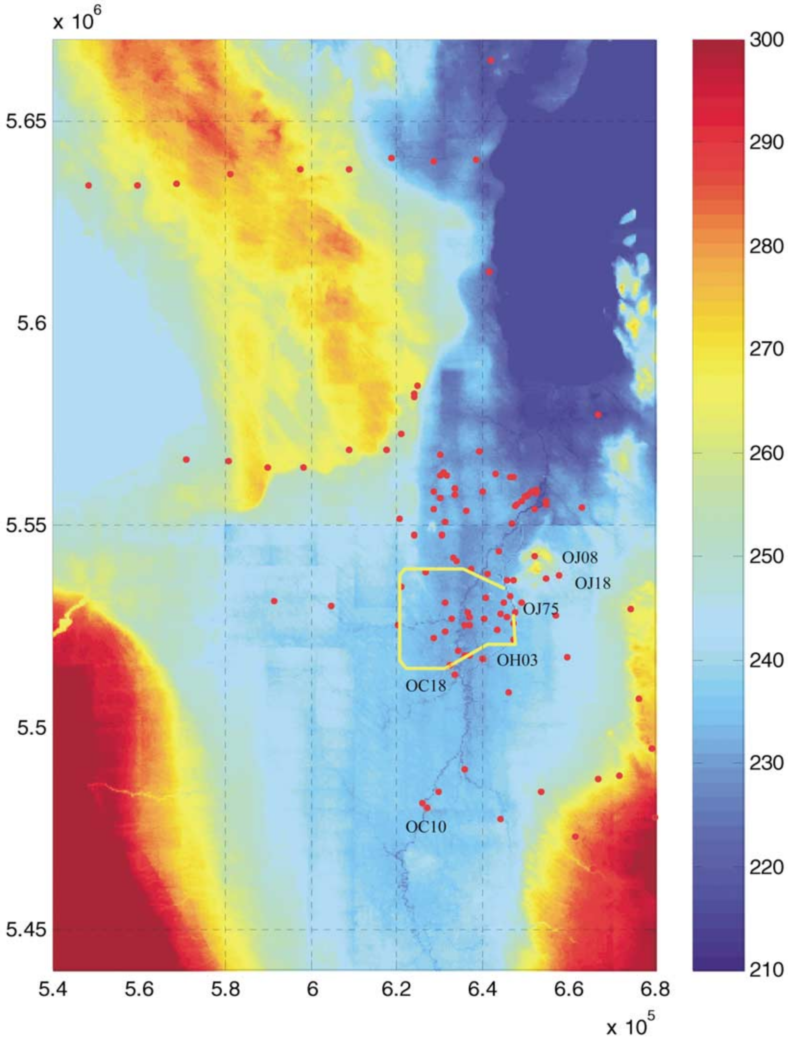

Fig. 5. Monitoring well locations (red dots), in the upper carbonate aquifer, southern Manitoba, are overlain on a digital elevation map. The elevation is indicated by the colour bar (right) in meters. The yellow polygon indicates the Winnipeg city area.

lacustrine clays. Regional head maps for the aquifer, geochemical and stable isotope data (Grasby and Betcher, per. comm.), and infiltration rate studies, all indicate that the Interlake region and Sandilands area are fresh water recharge zones for the aquifer.

The regional head map for the carbonate rock aquifer, illustrated in Fig. 4, indicates two dominant flow systems. Northeast directed flow of saline waters out of the Williston Basin, and NW and south directed intermediate-scale flow systems related to recharge in the Sandilands and Interlake region, respectively. The major topographic lows in the province, defined by the Rat, Red, Assiniboine, and Saskatchewan rivers, and lakes Manitoba and Winnipegosis, define a roughly N–S hydrologic divide separating these flow systems. This is readily observed by how closely the fresh/saline water boundary (taken as the 2000 mg/l isocon) parallels the course of the river systems (Grasby and Betcher, per. comm.). The slightly higher head on the east side of the Red River provides an effective pressure barrier that

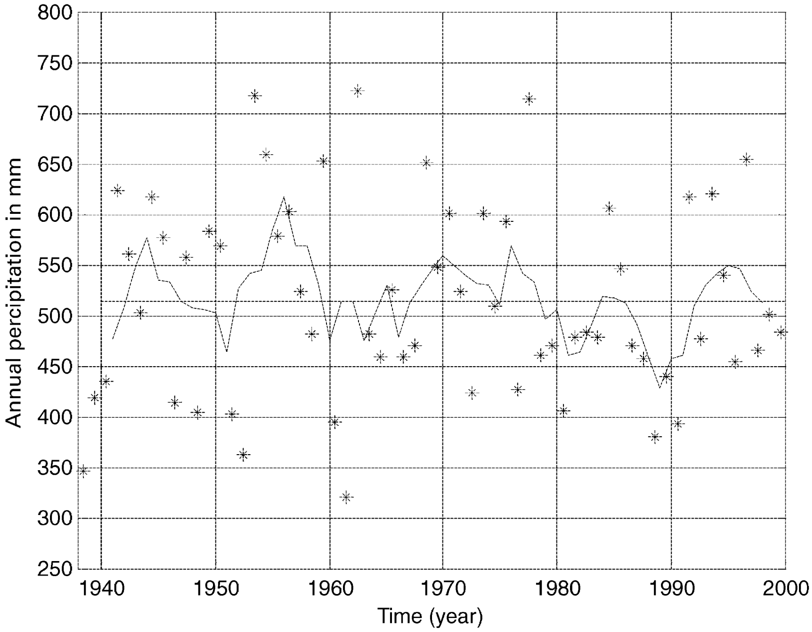

Fig. 6. Annual precipitation at Winnipeg Airport for period 1938–1999. Dash line: average for period 1938–1999, solid line: five year moving average, and star: annual precipitation.

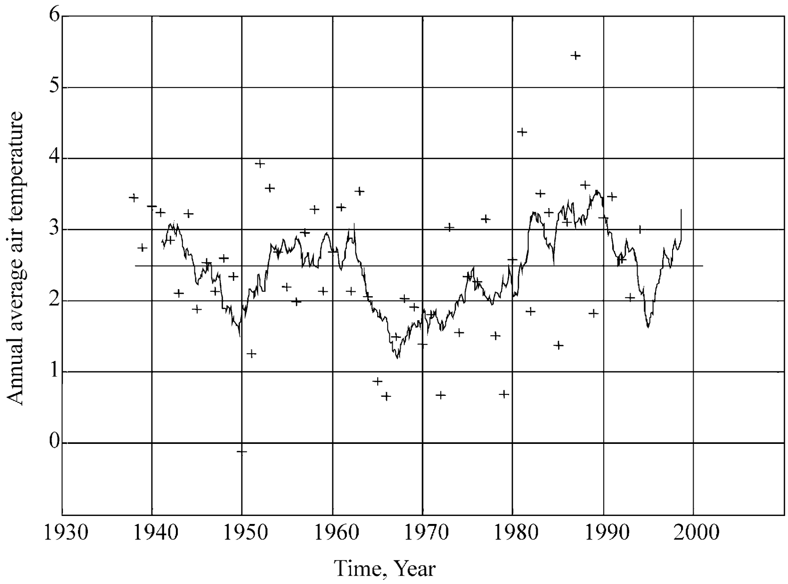

Fig. 7. Annual temperature at Winnipeg Airport for period 1938–2000. Thin solid line: average for period 1938–2000, solid line: five year moving average, and star: annual average temperature.

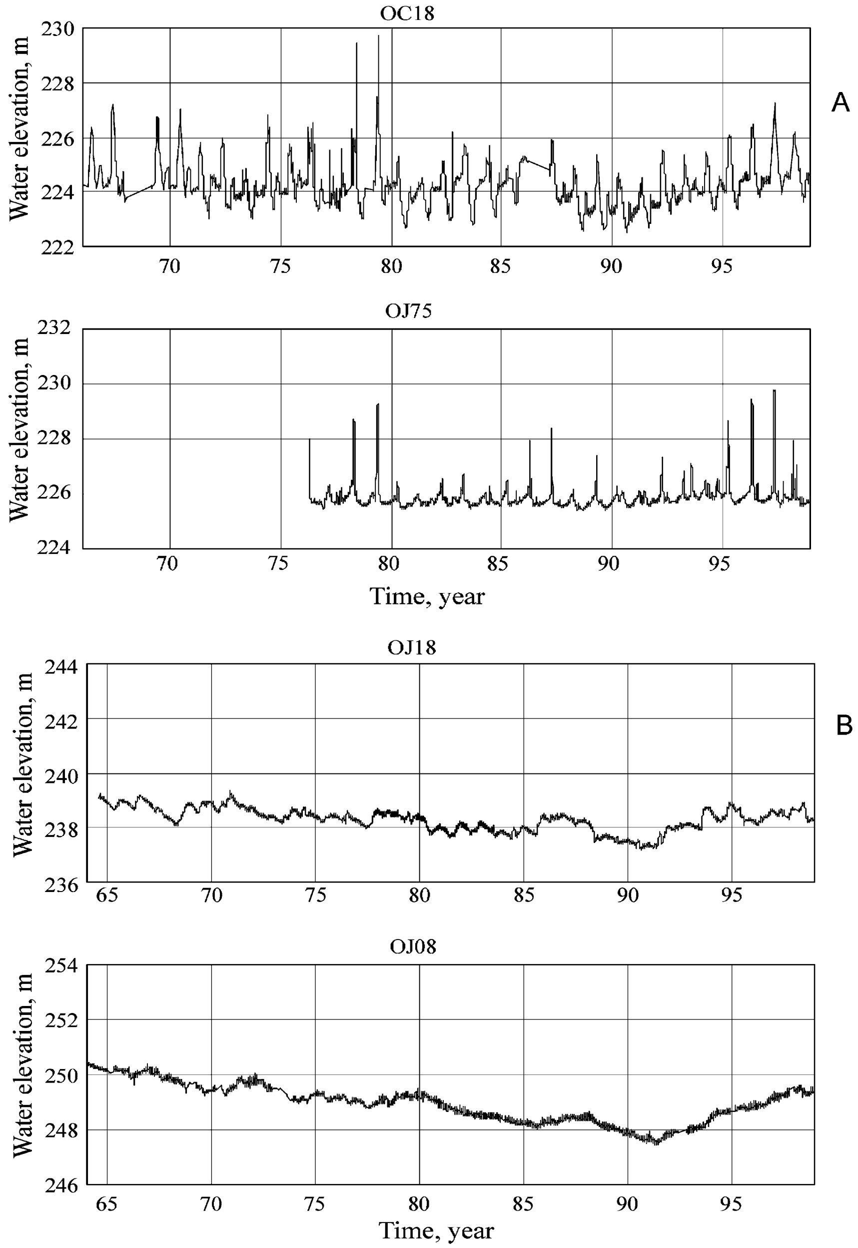

Fig. 8. Typical hydrographs in the upper carbonate aquifer, southern Manitoba, Canada, showing higher frequency component (A), and low frequency dominant component (B). Vertical axis indicates observed maximum daily groundwater elevation in meters.

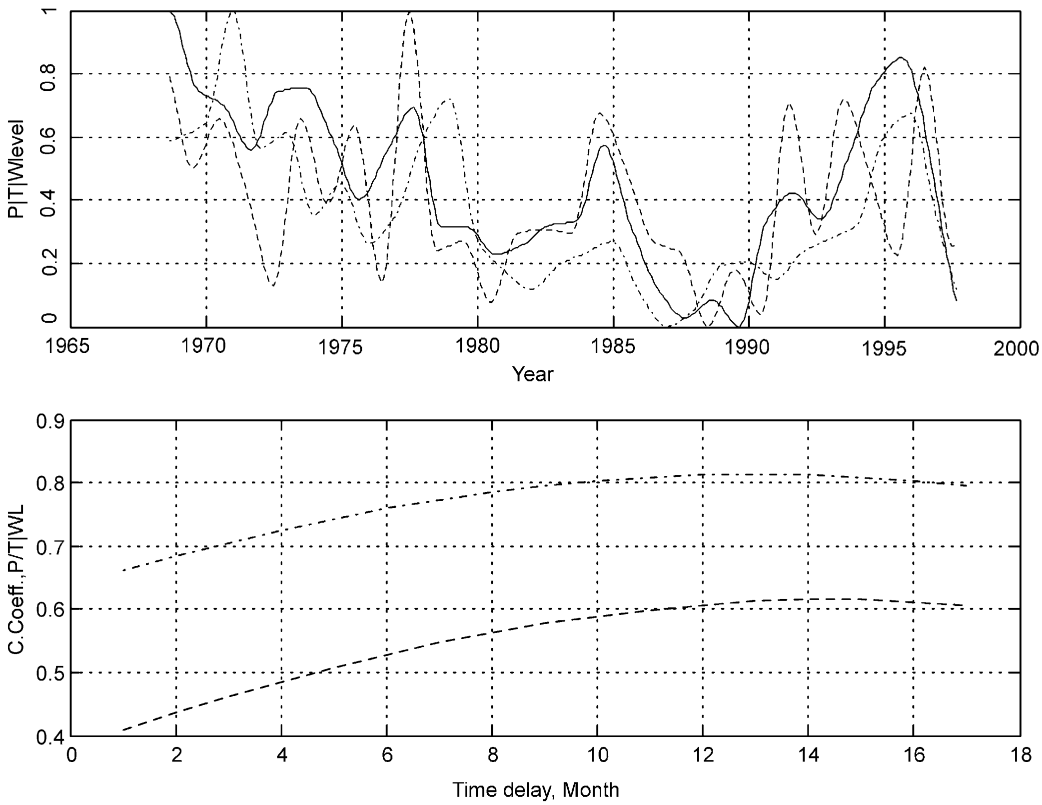

Fig. 9. Relationship between climatic variables and water level, normalized water level (solid), normalized annual precipitation (dashed) and normalized inverse of three year moving average annual temperature (dotted) (A). Correlation coefficients between water level and climatic variables as a function of time delay, with annual precipitation (dotted), and with inverse of three year moving average annual temperature (dashed) (B).

prevents eastward migration of saline water into fresh water bearing portions of the aquifer.

3.2. Data analysis

Two climatic variables, monthly precipitation and monthly average temperature, consisting of 63 years of records were collected from Winnipeg Airport meteorological station and investigated for their relationship with groundwater level variation. Eighty two hydrographs with groundwater readings since 1984 in the upper carbonate aquifer monitoring network were collected by the Manitoba Water Resource Branch and are used for this study (Fig. 5). These 82 observation wells are scattered in the Winnipeg and surrounding areas and cover an area of approximately 18,000 km^2 (180 km × 100 km). Various techniques were used in the data analysis. Those techniques include Fourier transform for studying the cyclicity, moving averaging for revealing long-term trends, normal probability paper plot for testing normality, cross correlation calculation for studying the relationship between climatic variables and groundwater levels (Davis, 1986; The MathWorks, 2000).

Fig. 6 shows the annual precipitation and five year moving average curve for the Winnipeg Airport, from 1938 to 1999. The five year moving average curve shows a clear declining trend from the mid 1950s to early 1990s. A Fourier analysis of the precipitation data indicates that despite the annual and seasonal cycles, the 3, 7, 12–14 and 29–30 year periods are observable from the monthly periodograms (Chen and Grasby, 2001). Any longer cycle (>30 years) cannot be revealed from 60 years of records. Whether the

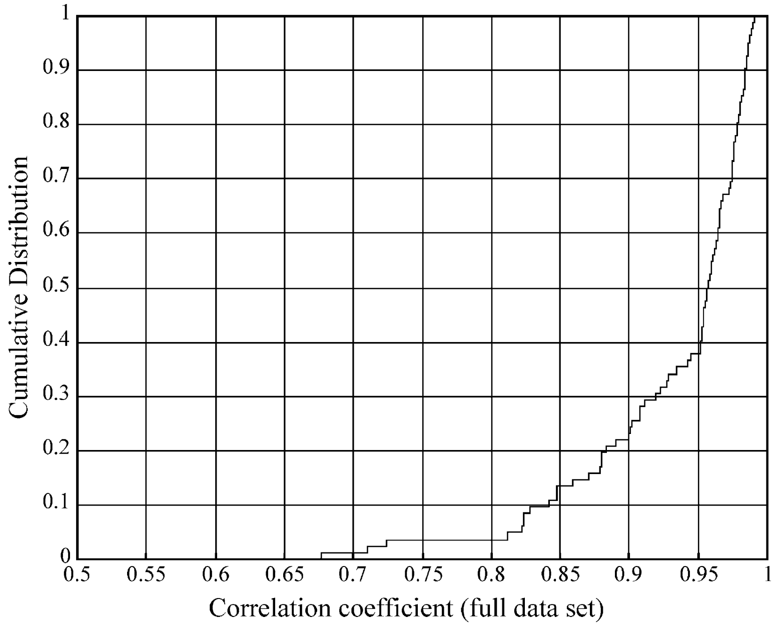

Fig. 10. Empirical cumulative distribution of the correlation coefficients between the observed and the predicted annual average water levels (full data set).

long-term trend depicted from the five year moving average in Fig. 6 represents part of a longer climatic cycle or reflects a true climate change is not clear. Statistical analysis of a normal probability paper plot in the same study indicates that the annual precipitation appears to be normally distributed with a mean value of 515 mm, and 10 and 90 percentiles of 400 and 651 mm, respectively.

Fig. 7 shows annual average air temperature and its five year moving average at the Winnipeg airport. The five year moving average shows a remarkable trend in increasing air temperature of almost 2.5 °C, from 1967 to 1990. A Fourier analysis indicates similar cycles to precipitation, of 3, 7, 15 and 25–29 years (Chen and Grasby, 2001). The annual temperature appears to be also normally distributed with a mean of 2.5 °C, and 10 and 90 percentiles of 1 and 3.7 °C, respectively.

Fig. 8 shows two typical hydrographs in this region. The data analysis indicates that groundwater level responses to precipitation are different from well to well due to the differences in recharge characteristics and the permeability of overlying sediments. In some cases, no high frequency events of individual precipitation were observed (Fig. 8(B)). The high frequency events are likely buffered in the aquifer due to the long distance to the recharge area. In other cases, high frequency events from hydrographs are common. This may indicate the existence of higher permeable channels connecting the aquifer to surface (Fig. 8(A)), and provide an evidence of the recharge to the aquifer by downward leakage of Day (1977). Groundwater data analysis shows that besides the most obvious one-year periodicity, quarter and half year as well as three to four year cycles are common on the hydrographs. Seven to eight and 13–14 year cycles are also observable from some of the long-term hydrographs. The 29–30 year cycle as seen from precipitation and temperature cannot be observed from the periodogram because the hydrograph contains insufficient records to determine a longer cycle.

By analyzing annual precipitation and its relation to water level variations, we found that the annual average water level is positively correlated to annual precipitation (Fig. 9), with a certain time delay, in most observation wells. The water level variation also displays a correlation with the annual average air temperature (Fig. 9) for most of the monitoring wells. We note that those wells with less obvious correlation with annual precipitation and/or

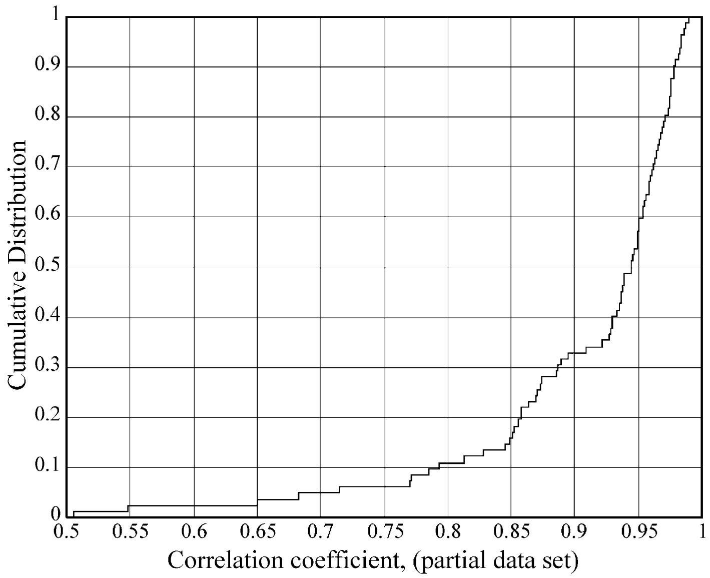

Fig. 11. Empirical cumulative distribution of the correlation coefficients between the observed and the predicted annual average water levels (using 3/4 of the data set).

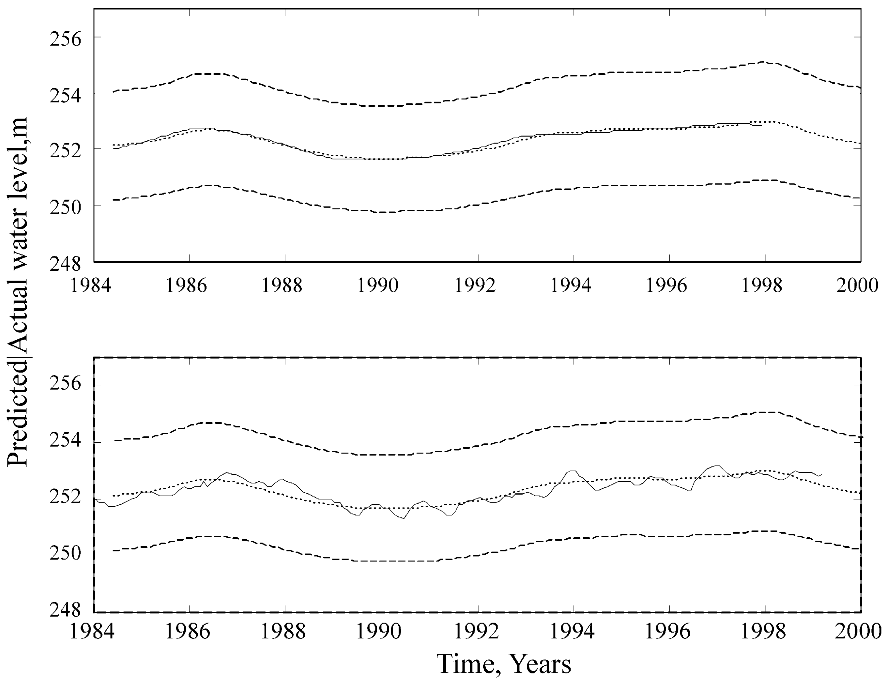

Fig. 12. Comparison of the observed and the predicted water levels using the established empirical model (partial data set). The dotted lines (central) represent the predicted expectation of water levels, the solid lines represent the observed water levels (above: annual average level, below: monthly average level), the dash lines represent the 95% confident intervals.

temperature are the wells with extensive seasonal withdrawal that lie within the drawdrown cone, in the Winnipeg area.

3.3. Prediction of groundwater level using the empirical model

Groundwater level time series from the carbonate rock aquifer monitoring network were used along with precipitation and temperature records to estimate the coefficients in the statistical model of Eq. (11). Fig. 10 is a cumulative distribution diagram showing the correlation coefficients of the observed and predicted water level values using the empirical model for the 82 wells that have records extending back to 1984. From Fig. 10, we can see that 60% of the wells analyzed have correlation coefficients better than 0.95, and 95% have correlation coefficients better than 80%. The overall average value of the correlation coefficient for all 82 wells is 0.93.

To test the empirical model for its capability of predicting future groundwater level variations in response to climate change, we took part of the historical observations of groundwater level and climatic data used to establish an empirical model, then applied the model to predict 'future' water levels. Fig. 10 shows the results by comparing the observed water levels with the predicted water levels. In this test (Fig. 11), the first 3/4 of the records were used to establish the empirical model from which the water levels in the later years were predicted. In general, the overall correlation coefficient between the observed water levels and predicted water levels are in a range from 0.50 to 0.98 with an average correlation coefficient of 0.92 for the 82 wells. More than 85% of wells have correlation coefficients better than 0.85 and about 90% of the cases have correlation coefficients better than 0.8. Fig. 12 shows one example of the comparison of the observed and predicted levels. The wells with a relatively poor prediction result are those either showing a poor correlation between the climatic variables and water level, or are locating in the far north or south in the study area

3.4. Discussion

The empirical model used in this study to predict future water levels from climatic variables is a statistical model based on water balance principles. The major advantages of this statistical model are that (a) the required inputs are minimal, the model requires neither detailed information with respect to the hydrological parameters and their spatial characteristics of the aquifer nor the recharge rate of the aquifer; and (b) the mathematical formulation of the empirical model is simple and computationally easy. As a consequence, the statistical model allows a more rapid and less expensive assessment of groundwater level changes in correspondence to climate scenarios with only limited information on hydrological parameter and recharge rate of the aquifer.

As with any method, the model that we developed has its weaknesses. First, because this empirical model is a statistical model, its prediction depends solely on the past water fluctuation patterns in relation to climatic variables. Anthropogenic impacts may weaken the correlation between groundwater level and climatic variables. This may account for some of the poor correlations between the climatic variables and water levels in the Winnipeg municipal area where water withdrawal and re-injection have been extensive. On the other hand, the model may not be able to distinguish between water level variations caused by human activity and those by natural climate change. For example, recent water re-injection in the Winnipeg municipal area has created a trend of rising water levels. Significant differences in modelling and predicted conditions (such as stopping water re-injection) may cause large uncertainties in the forecasting results. Therefore, the application of the current model in Eq. (11) is most suitable to areas where anthropogenic activity has a relatively lower effect on water levels than natural variations. However, as we suggested an additional term of water withdrawal or re-injection can be introduced to account for this impact.

Second, the model may generate larger uncertainties in the predicted water levels, if significant changes occurred in hydrological parameters (e.g. transmissivity) as a result of climate changes. For example, an apparent time lag variation in the time domain is observed in some of the hydrographs in this study. A time lag of 15–20 months is common in the later period after the early 80's drought, whereas a time lag of 8–15 months is more common before the early 80's drought in these wells. This may be related to unconfined portions of the aquifer becoming desaturated during prolonged dry periods, thus altering the transmissivity in the aquifer. This inference is similar to that of Larocque et al. (1998) who note that transmissivity in a karst aquifer in France varies when some conductive channels become desaturated during low water periods.

Third, observations of climatic variables should be representative for the whole study area. The climatic data used in this study were recorded at the Winnipeg airport. The climatic data may not represent the whole region, which could account for some of the relatively poor correlations between the climatic parameters and groundwater levels for some observation wells. Poor representation of the climatic variables from Winnipeg airport station may account for the poor predictions in the far north and south areas of this study.

4. Conclusion

We have demonstrated by the one-dimensional water flow model that variations in water recharges and groundwater levels have a similar fluctuation pattern with a time delay. The time delay is dependent on the characteristics of the aquifer and the recharge rates, and the distance between the recharge area and observation location. This relationship is indicated by a good correlation between recorded water level variation and the annual precipitation, which is a linear function of water recharge in a water budget model. Data analysis has shown that groundwater level variation has major cycles similar to the precipitation, which is also an indirect indication of the relationship between the water level variations and the recharge.

Recent records of annual precipitation and air temperature at the Winnipeg airport indicate that there are trends of increasing air temperature and decreasing precipitation. However, whether these trends are a reflection of global climate change or are part of a long-term periodicity of regional climatic phenomena is unknown.

A statistical model has been proposed in this study to relate climatic variables to the groundwater level in the southern Manitoba region based on simplified water flow and water balance models. A test using partial historical observations to predict the rest of the observations showed encouraging results with an overall correlation coefficient of 0.92 for the empirical statistical model. This method could be useful in an impact assessment of climate change on groundwater for a shallow aquifer. More case studies are necessary to test for the general applications of the proposed method to other settings, and deeper aquifers.

Acknowledgements

Bob Betcher and Frank Render of the Manitoba Water Branch provided support for this study. Manitoba Water Resources Branch provided historical monitoring wells records used herein. Canada Climate Adaptation Fund through Prarie Adaptation Research Corporation provided partial financial support for this study. The authors thank Dr Dale Issler of Geological Survey of Canada, Calgary who made constructive comments and suggestions for the original manuscript. This paper has benefited from the comments and suggestions made by M. Sophocleous, A. J. Jakeman, and an anonymous reviewer. This paper is Geological Survey of Canada contribution number 2001163.

References

Betcher, R., Grove, G., Pupp, C., 1995. Groundwater in Manitoba—Hydrogeology, Quality Concerns, Management. National Hydrology Research Institute, Environment Canada, Saskatoon, Saskatchewan p. 47.

Chen, Z., Grasby, S, 2001. Project report (Phase I): Data assessment of observation well hydrographs, Winnipeg case study, Climate influences on groundwater levels in the Prairies including case studies and aquifers under stress, as a basis for the development of adaptation strategies for future climatic changes. Geological Survey of Canada, Calgary, Alberta, p. 16.

Davis, J.C., 1986. Statistics and Data Analysis in Geology. second ed. Wiley, Toronto p. 646.

Day, M.J., 1977. Analysis of movement and hydrochemistry of groundwater in the fractured clay and till deposits of the Winnipeg area, Manitoba. MSc Thesis. University of Waterloo, Ontario, Canada, p. 210.

Freeze, R.A., Cheery, J.A., 1979. Groundwater, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 604 p.

Gan, T.Y., 1998. Hydroclimatic trends and possible climatic warming in the Canadian prairies. Water Resources Research 34, 3009–3015.

Gehrels, J.C., 1999. Groudwater level fluctuations, seperation of natural from anthropogenic influences and determination of groundwater recharge in the Veluwe area, the Netherlands. PhD Thesis. Vrije University, Amsterdam, p. 32.

Grasby, S., Betcher, B., Personal communication.

Larocque, M., Mangin, A., Razack, M., Banton, O., 1998. Contribution of correlation and spectral analysis to the regional study of a large karst aquifer (Charente, France), Journal of Hydrology 205, 217–231.

Maathuis, H., Thorleifson, L.H., 2000. Potential impact of climate change on Prairie groundwater supplies: review of current knowledge, Saskatchewan Research Council (SRC) Publication No. 11304-2E00, April 2000.

Mathematical handbook, 1979. People's Press, Beijing, pp. 737–738 (see also page 595).

McCabe, H.R., 1971. Stratigraphy of Manitoba, an introduction and review. The Geological Association of Canada, Special Paper no. 9, pp. 167–187.

Pach, J.A., 1994. Hydraulic and solute transport characteristics of a fractured glacio-lacustrine clay Winnipeg, Manitoba. MSc Thesis. University of Waterloo, Ontario, Canada, p. 200.

Render, F.W., 1970. Hydrogeology of the metropolitan Winnipeg area as related to groundwater supply and construction. Canadian Geotechnical Journal 7, 243–274.

Showstack, R., 2001. IPCC report cautiously warns of potentially dramatic climate change impact. EOS 82 (9), 113–120.

Singh, V.P., 1992. Elementary Hydrology. Prentice-Hall, Englewood Cliffs, New Jersey p. 356.

The MathWorks, 2000. User's guide for Statistics toolbox for use with Matlab.