WATER-LEVEL FLUCTUATIONS DUE TO EARTH TIDES AT PESHTIGO, WISCONSIN

by

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ABSTRACT

Water levels in an observation well near Peshtigo, Wisconsin, exhibit 3 cm fluctuations having semi-diurnal and diurnal periods. Fourier series analysis of tidal-gravity corrections and water-level fluctuations reveal two diurnal and two semi-diurnal waves with periods corresponding to established principle tidal waves. As the tidal-gravity correction increases (total gravity decreases) the water level in the well declines due to an expansion in pore volume caused by the tidal bulge of the solid earth.

The well is artesian and is completed in rocks of early Paleozoic age which are overlain by Pleistocene and Recent sediments in the Peshtigo River valley.

INTRODUCTION

Water levels in an observation well located in northeastern Wisconsin (approximately 45^{o} north latitude and 87^{o} 44' west longitude), about 2 km south of the city of Peshtigo, (Fig. 1), show regular fluctuations having an apparent period of about 25 hours and an amplitude up to 3 cm (Fig. 2). It was suspected that these fluctuations were caused by earth tides, therefore an analysis of fluctuations in water level, tidal gravity-corrections and barometric pressure was conducted. Similar comparisons have been made by Melchior (1978) for wells located elsewhere.

Water levels in two wells in Wisconsin, at Milwaukee and Richland Center, have been noted (Melchior 1966) to respond to fluctuations in tidal gravity. The well in Milwaukee is completed in Niagara Dolomite while the well at Richland Center terminates in rocks of Precambrian age. The amplitude of the water-level fluctuations was 2 to 3 cm, similar to those observed in the Peshtigo well. Melchior's (1966) note is the only published information on water-level fluctuations caused by changes in tidal gravity in Wisconsin.

The absolute gravity value at any point on the earth varies continuously as a result of the changing relative positions of the earth, sun, and moon. Time variations of absolute gravity are known as tidal-gravity fluctuations,

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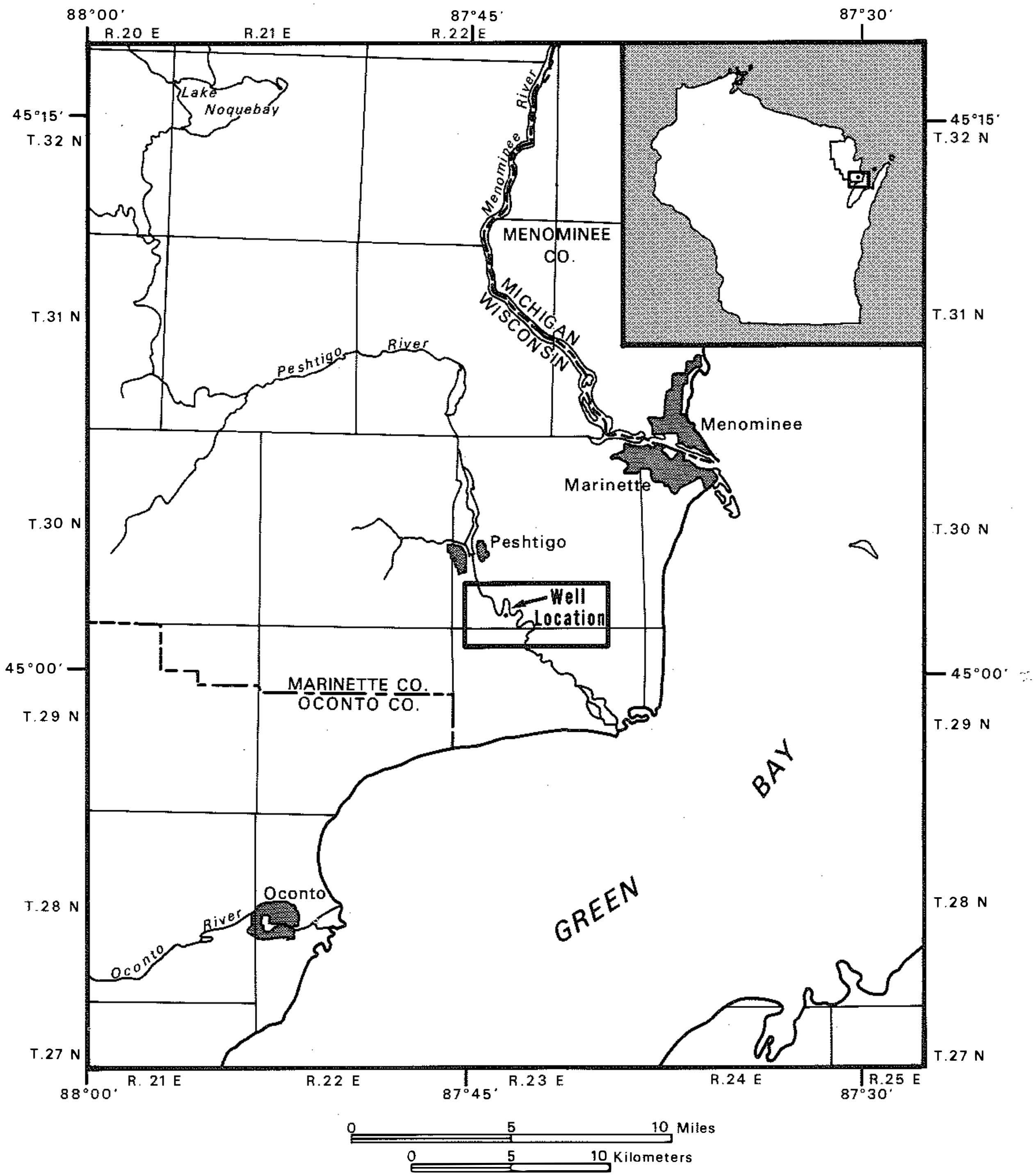

Figure 1. Location of Peshtigo Well, Mt-33.

whereas the up and down motion of the solid earth, in response to changes in total gravity, is a phenomenon known as earth tides. Tidal-gravity corrections are a time-sequence of positive and negative values which must be subtracted from absolute gravity values to give a constant gravitational acceleration at the point of interest. Expressed mathematically, for any instant in time, gravity minus the tidal-gravity correction equals a constant.

The relationship of water levels and the tidal-gravity correction is shown in Figure 3. As the tidal-gravity correction increases (absolute gravity decreases), the water level in the well falls. This behavior was noted by George and Romberg (1951) and Melchior (1966) and was attributed to dilation of the aquifer as the earth's crust bulges with decreasing gravity. When the tidal-gravity correction decreases (increasing gravity) the aquifer compresses slightly and water is forced into the well.

Earth tides have been recognized as the cause of periodic fluctuations of water level in wells by Robinson (1939), Richardson (1956), Stewart (1961), Marine (1975) and others (noted in Melchior, 1966) who made qualitative comparisons using lunar culminations. Tidal-gravity corrections can now be easily obtained from various sources, therefore there is no longer justification for analyzing water-level fluctuations caused by earth tides in such a qualitative manner. George and Romberg (1951) and Melchior (1966, 1978) demonstrated that the cause-and-effect relationship could be analyzed quantitatively by examining gravity fluctuations.

Two mechanisms besides earth tides could cause periodic fluctuations of water level in the Peshtigo well:

1. Ground-water pumpage (Peshtigo city wells are about 1 km away) and

2. Changes in total stress on the aquifer caused by;

a) Passing trains (railroad tracks are located 1.7 km away), and

b) Reservoir loading (a reservoir is located at Peshtigo for the purpose of generating electrical power).

In order to determine the apparent periodicity of water-level fluctuations in the Peshtigo well, a statistical analysis of measurements for the period of October 23, 1969 to November 26, 1969 was made. The period of the water-level fluctuations (Fig. 2 and 3) appears to be about 25 hours, which approximately coincides with the lunar day. The other mechanisms noted above are therefore removed from consideration by this analysis as possible causes of the water-level fluctuations because the trains, reservoir, or ground-water pumpage would be expected to have periods related to the 24-hour solar day.

WELL DATA

Elevation of the land surface at the well (Mt-33), drilled in 1968 during an environmental study for Badger Paper Mills, Peshtigo (Hackbarth, 1971), is about 181 m above mean sea level. The well is located in the flood plain of the Peshtigo River which flows in a broad, flat valley in this area.

The well is 153 m deep and has an 20-cm diameter casing to a depth of about 10 m, the remainder of the well is without casing. The open portion of the well is divided into three sections by rubber packers located at depths of 21 and 44 m and held in place by a 10 cm diameter pipe extending to the surface. Water levels thus can be monitored in the intervals 10 to 21 m, 21 to 44 m and 44 to 153 m. The only section of the well exhibiting the regular water-level fluctuations is that from 44 to 153 m. This portion of the well is completed in rocks of Cambrian and Ordovician age (Table 1). Regular daily fluctuations of water level were not observed in the two shallower segments.

The approximate elevation of hydraulic heads in the three segments of the well are; 181 m (10 to 21 m portion), 183 m (21 to 44 m portion), and 176 m (44 to 153 m portion). The water table is at an elevation of about 180 m at the well site which indicates that water is moving from the Sinnipee Group (Table 1) upward into the glacial drift and also downward into the underlying formations. The Peshtigo River is thus a discharge area for ground water at depths less than about 44 m.

Observations made during the drilling of the well indicate that the dolomite of the Prairie du Chien Group (Table 1) is dense, does not yield much water, and probably acts as an aquitard. The Jordan and St. Lawrence formations, although not actually tested, appeared to be capable of yielding about 10 L/s during air-rotary drilling. These two units probably represent the aquifer which experiences the fluctuations of water level measured in well.

Table 1. Stratigraphic succession and lithology

SYSTEM UNIT	Depth (m) FROM	 TO	LITHOLOGY
QUARTENARY			
Pleistocene	0	8.5	Sand
ORDOVICIAN			
Sinnippee Group	8.5	41.1	Dolomite
Prairie du Chien Group	41.1	102.1	Dolomite
CAMBRIAN			
Jordan Formation	102.1	117.7	Sandstone
St. Lawrence Formation	117.7	147.8	Dolomite
Tunnel City Group	147.8	153+	Sandstone

Stratigraphic interpretation by Wisconsin Geological and Natural History Survey - Log No. Mt-33.

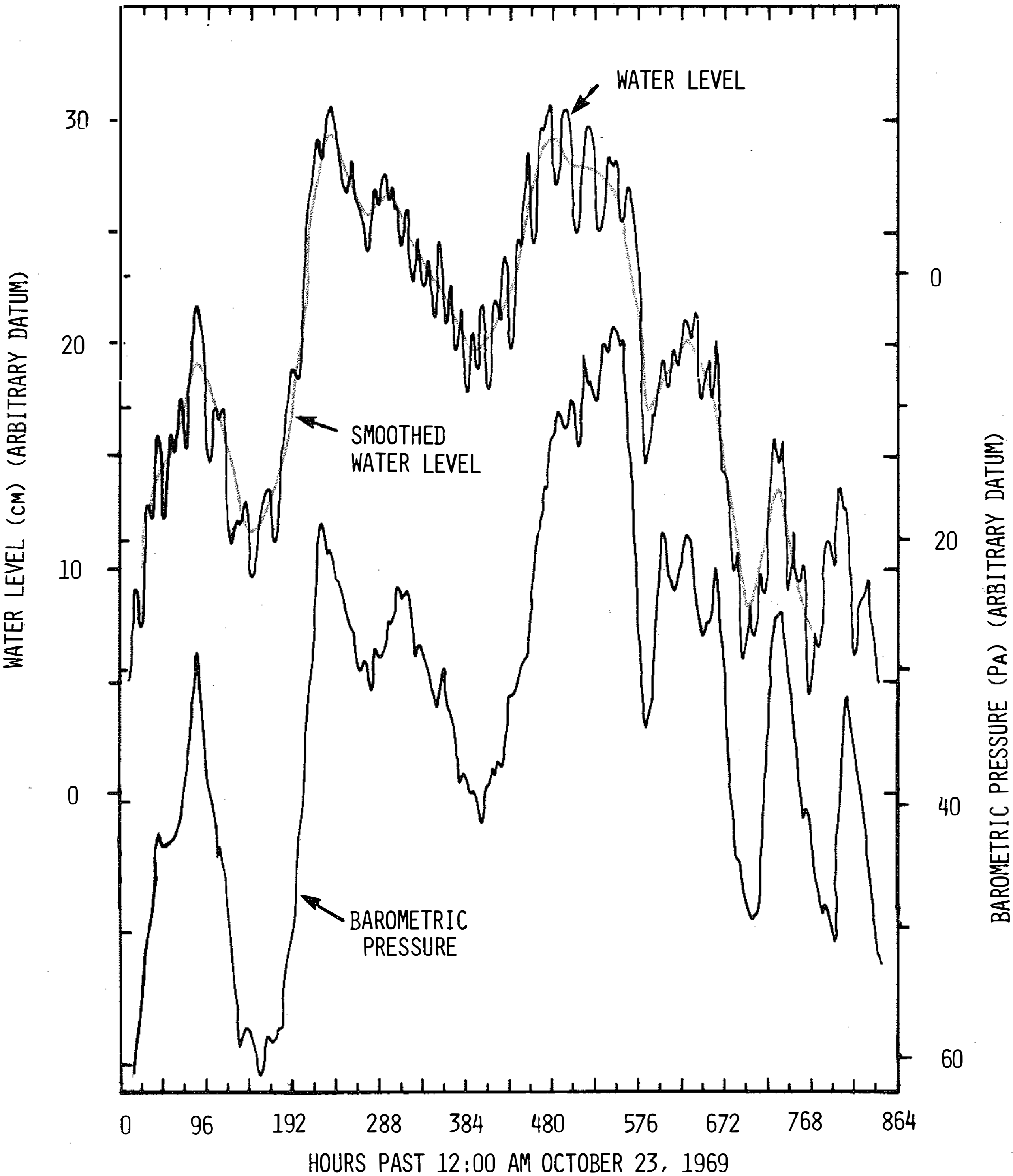

Figure 2. Water level and barometric pressure fluctuations in well Mt-33 on October 23, 1969.

DATA ANALYSIS

The water-level hydrograph of the well (Mt-33) was digitized at one-hour increments for the period from October 23 to November 26, 1969. Barometric pressures were obtained from a nearby recorder and were also digitized at one-hour intervals. Hourly tidal-gravity corrections at the well were calculated from tables given by Service Hydrographic de la Marine (1969).

Comparison of the graphs (Fig. 2) of barometric pressure (note that it is inverted) and water levels shows an abvious relationship. Water level appears to be responding to barometric pressure changes, at least to those with a period of one day or more, with the expected inverse relationship. An average barometric efficiency of 88 percent is indicated from analysis of nine of the major fluctuations shown on Figure 2. Autocorrelation (Davis, 1973) of the barometric record indicates however, that regular periodic fluctuations of atmospheric pressure did not occur. Therefore, variations in barometric pressure, although causing non-periodic changes of water level, were not contributing to the regular daily fluctuations and were eliminated as a possible cause of those fluctuations.

Further analysis of the digitized water-level data required the removal of variations other than those suspected to be caused by fluctuations in tidal gravity (for instance, the long-period barometric responses noted above). This was accomplished in two steps:

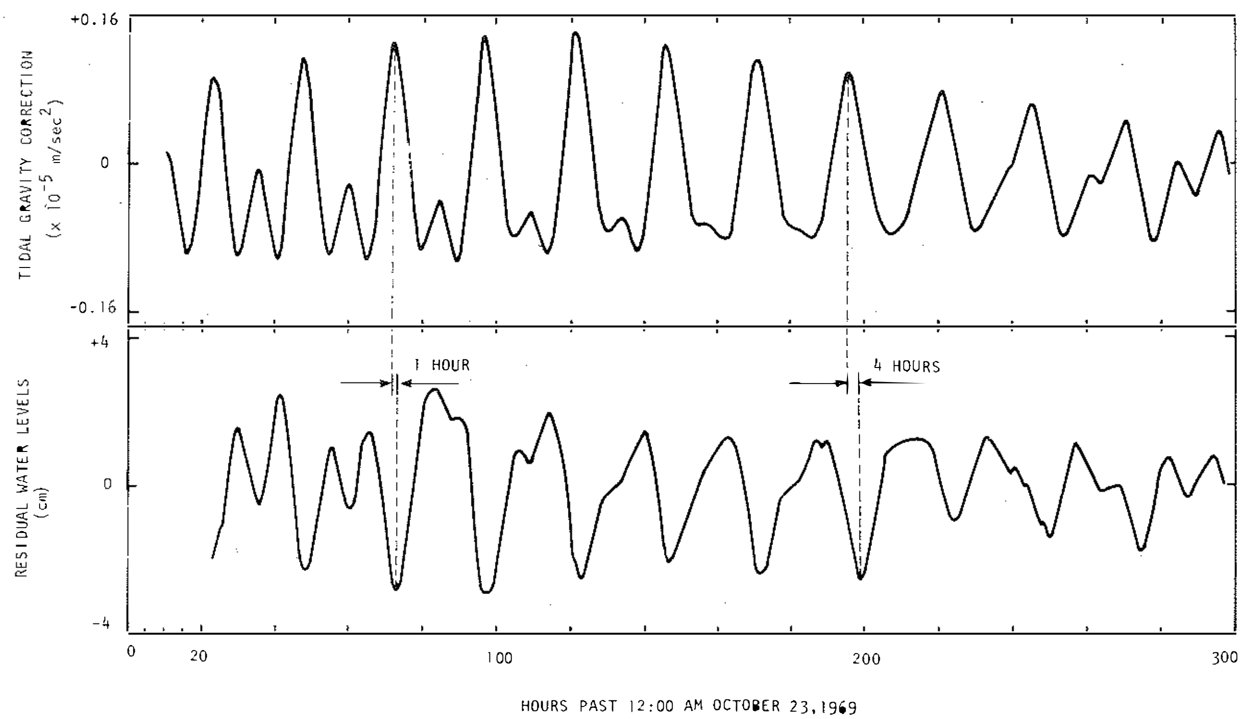

Figure 3. Tidal-gravity correction and residual water levels.

1. A new set of smoothed hourly water-level elevations was calculated by a 25-hour moving average technique. The moving average utilized information for 12 hours before and after each hourly data point. The smoothed curve is shown on Figure 2. The selection of 25 hours for a moving average was to eliminate fluctuations having semi-diurnal and diurnal periods. On the other hand, a longer interval for the moving average might tend to smooth out the broad fluctuations caused by barometric pressure changes (Fig. 2) and this was also undesirable.

2. The above set of smoothed data points was subtracted from the original set of water-level elevations to produce a new set of residual water levels (Fig. 3). The fact that the residual water levels are stationary (Davis, 1973) indicates that the above procedure was appropriate. Had the procedure been incorrect the residual water levels would not have plotted with such symmetry about the axis of zero fluctuation. Figure 3 presents only a 300-hour segment of the 817-hour period which was actually analyzed.

Fluctuations of the residual water-levels have an amplitude up to 3 cm and their correlation, in terms of time and amplitude, with tidal gravity corrections is apparent (Fig. 3). This set of residual water-levels and tidal-gravity corrections was further analyzed using a Fourier-series technique (Davis, 1973).

The Fourier-series technique confirms that the major wave forms of the residual water levels conform with those of the tidal-gravity correction (Table 2) and that both of these correspond, considering the length of time analyzed and the hourly increments of the two data series, with the periods of the principle tidal waves as noted by Melchior (1978). There is some minor uncertainty about the correspondence of the diurnal M_1 wave. However, this does not detract from the conclusion that the water-level fluctuations must be caused by earth tides.

The Fourier series allows calculation of the amplitude of any wave from the power assigned to it at a specified frequency (Davis, 1973). The ratio of the amplitudes of the four tidal-gravity waves should be the same as the ratios of the amplitudes of the corresponding water-level waves to prove a cause-and-effect relationship (Melchior, 1966). The corresponding wave-amplitude ratios are essentially equal (Table 2) which further confirms that the fluctuations of tidal gravity are causing the fluctuations of water levels. The wave-amplitude ratios for the diurnal (b) to semi-diurnal (c) water-level waves are very similar to values shown by Melchior (1978) for locations of similar latitude elsewhere.

Table 2. Summary of Fourier-series analysis of residual water levels and tidal-gravity corrections.

Wave*	Period**			Amplitude	
	Residual Water level, ± error (hours)	Tidal Gravity, ± error (hours)	Principle Tidal Waves (hours) (1)	Residual Water Level (cm)	Tidal Gravity ($x\ 10^{-5}$ m/sec^2)
a. K_1, P_1 waves	24.4 ± 1.1	23.7 ± 0.7	23.93&24.07	0.40	0.029
b. O_1 wave	26.8 ± 0.9	26.0 ± 0.8	25.82	0.38	0.021
c. M_2, N_2 waves	12.8 ± 0.2	12.4 ± 0.3	12.42&12.66	0.38	0.023
d. S_2 wave	12.2 ± 0.2	12.0 ± 0.3	12.00	0.14	0.008

WAVE-AMPLITUDE RATIOS

	Residual Water Level	Tidal-Gravity Correction
a/b	1.1	1.3
a/c	1.1	1.3
a/d	2.9	3.6
b/c	1.0	0.9
b/d	2.7	2.6
c/d	2.7	2.9

* Symbols refer to diurnal (subscript 1) and semi-diurnal (subscript 2) tidal waves of Melchior (1978).

** (2) Length of analysis is October 23 to November 26, 1969 (831 hours).

Theoretically, the response of the water level in the well to changes in gravity should be instantaneous (Robinson and Bell, 1971), however, a phase shift occurs between the tidal-gravity correction and residual water-level waves. The water level exhibits a phase shift (Fig. 3) which appears to vary from zero to four hours between the maxima or minima of the tidal-gravity correction and the minima or maxima of the residual water-level fluctuation. The apparent lag is probably due to errors in digitization of the water-level hydrographs. Splicing of recorder charts was necessary which may account for the increase in phase shift with increasing time.

SUMMARY

1. The well Mt-33 at Peshtigo has the following physical characteristics:

   a) the well is completed in Cambrian and Ordovician sandstones and dolomites,

   b) the Prairie du Chien Dolomite, a rock unit of low hydraulic conductivity, overlies the zone contributing water to the well,

   c) hydraulic head is 36 m above the top of the aquifer,

   d) the well is adjacent to the Peshtigo River where ground-water discharge occurs from depths less than about 44 m, and

   e) diurnal and semi-diurnal fluctuations of water level with an amplitude up to 3 cm are observed.

2. Fourier series analysis of residual water levels and tidal-gravity corrections revealed two diurnal and two semi-diurnal waves which correspond to principal tidal waves identified by Melchior (1978). This is strong evidence that the fluctuations of water level are caused by earth tides.

3. The fact that wave-amplitude ratios of corresponding tidal-gravity corrections and water-level fluctuations are approximately equal confirms a cause-and-effect relationship. Water levels vary inversely with tidal-gravity corrections.

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