11. WATER TABLE FLUCTUATIONS BENEATH THE MALLEE SALINAS AND THEIR INFLUENCE ON SALT MIGRATION

11.1 Introduction

During the spring of 1979 diurnal water table fluctuations were noted in a shallow piezometer established on the floor of Macarthur's Lake (Figure 11.1) in the Raak boinka. The piezometer was established to investigate the relationship between the lake water and groundwater during the drying up of the lake. It was inserted into the lake floor to a depth of only one metre and slotted over the interval from 0.3 m below the lake floor to 0.3 m above the lake floor. Water levels were monitored by a Leopold–Stevens continuous water level recorder (Figure 11.2). Almost immediately after the lake had dried out, diurnal water table fluctuations commenced, ranging in amplitude from about 1 cm to 5 cm—the largest fluctuations occurring in mid-summer. The fluctuations continued until the following autumn, when the lake once again held water. Because the fluctuations were virtually from the lake surface, it was considered that the process could play a significant role in the movement of precipitated salts from the lake surface into the shallow groundwater system.

Figure 11.1 – Leopold-Stevens recorder station at Macarthur's Lake in the Raak boinka. At this site the casing is screened for 0.3 m above and below the lake floor so as to monitor either the lake level (when wet) or the water table (when dry).

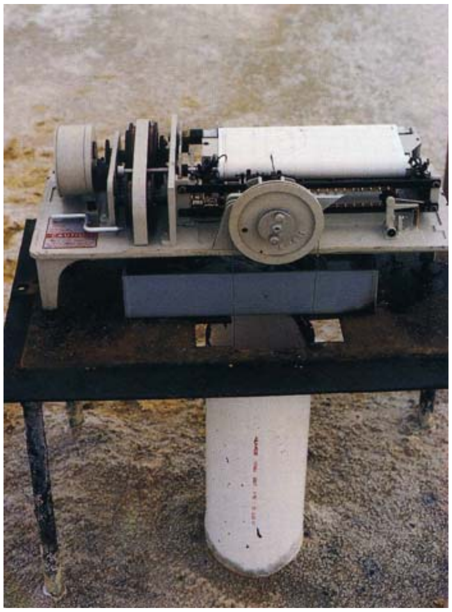

Figure 11.2 – Leopold-Stevens recorder (detail). This recorder is established on the floor of the main Raak salina, about 1 km north of Macarthur's Lake.

Figure 11.3 - Water level recorder situated on the lake floor at southwestern Lake Tyrrell.

The recorder is equipped with a rain gauge. When the water table drops below the lake surface at this site, it has a barometric efficiency approaching 1 - the diurnal fluctuation is superimposed on a six day cycle, brought about by the passage of high and low pressure systems.

Figure 11.4 - Hole dug through the salt crust at Lake Tyrrell. The fluctuating water table, seen here at a depth of about 10 cm, may come to the surface at times of low atmospheric pressure.

In order to determine the extent to which water table fluctuations occurred in other playa lake systems of northwestern Victoria, four recorders were established on lake floor piezometers and were monitored throughout the dry lake phase in 1980-81. In order to gain further data on the fluctuations the recorders were fitted with automatic rain gauges.

Recording stations were established at four places: the lakeward end of the T-P piezometer line in NW Tyrrell; offshore from the salt works at SW Tyrrell (Figure 11.3); on the main Raak salina at the eastern side of the Raak boinka; and at Macarthur's Lake. The Raak sites were chosen to determine whether salina size influences the fluctuations-Macarthur's Lake being only 200 m in diameter, while the main Raak salina is many kilometres long.

Marked lithological differences exist between the two Tyrrell sites: the southern site is underlain by fine - to coarse-grained sand to a depth of 70 m, while the northern site is underlain by clays.

Although not known at the time of establishing the piezometers, the Raak sites are both underlain by a clay sequence, covered by a thin sand sheet about five metres thick in the case of the main Raak salina. Diurnal water table fluctuations were observed at all four sites.

11.2 Character of the Fluctuations

Once the surface water has gone from the lakes the water table falls to about 1 cm below ground surface, at which point small amplitude diurnal fluctuations commence. These become stronger as the daily temperature increases during late spring and early summer. By November 1980, the amplitude of the fluctuations ranged from 1 to 3 cm; throughout the summer period they ranged from 1 to 4 cm and reached as much as 6 cm/day in late February. The diurnal fluctuations are, at times, superimposed on a falling (or rising) water table; however, water levels remained within 20 cm of the surface and usually were within 5 to 10 cm of the surface.

The summer of 1981 was very dry, and the water tables in the Raak boinka gradually fell to about 16 to 20 cm below the floors of the lakes. In early autumn, the strong summer fluctuations began to wane and by mid-March had virtually ceased, with water tables still well below the surface. For instance, at Macarthur's Lake fluctuations continued over the summer period, and the water table gradually fell despite the occasional rainstorms which briefly brought the water back to the lake surface. By early March, the water table was 15–16 cm down, at which depth the fluctuations had virtually ceased. The water table returned to the surface on 31st March after heavy rain, but soon began to fall again, with a distinct 2 cm daily oscillation, until it reached about 11 cm below the lake floor, after which fluctuations ceased.

Unlike the other three sites, the water table fluctuations at the SW Tyrrell site did not cease in March but continued with undiminished amplitude throughout the autumn reaching depths of 25 cm below the surface. As will be shown later, this area has a distinct fluctuation pattern not seen at the other sites.

11.2.1 Diurnal Water Table Fluctuations

In general, water tables fall overnight, reaching their lowest levels in the morning; they rise in mid-afternoon to peak in late afternoon and evening. The oscillations at southwestern Lake Tyrrell may at times lag several hours behind the other sites. The simplest fluctuations for southwestern Lake Tyrrell and the main Raak salina are shown in figure 11.5, covering the period 18—26 February 1981. Water table fluctuations are compared with atmospheric pressure and temperature data from the meteorological station at Mildura. (For comparative purposes the Tyrrell curve, which tends to lag behind the other stations, has been synchronized with the pressure data.) While the fluctuation pattern at Raak has a simple sinusoidal curve, inversely mirroring (note scale inversion) the temperature curve, that at Tyrrell more closely reflects the pressure fluctuation, which is a combination of the temperature induced, diurnal pressure oscillation superimposed on a less regular pattern of high and low pressures. In these examples, the water table fluctuates from 7 to 19 cm below the lake floor at Tyrrell and from 4 to 13 cm at Raak.

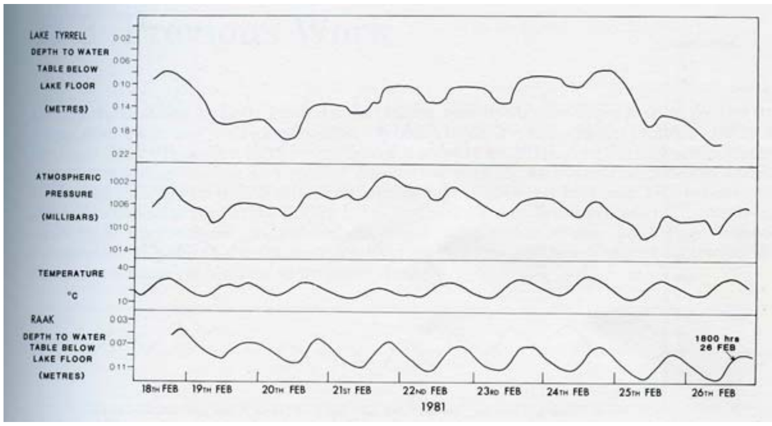

Figure 11.5 - Water table fluctuations at SW Lake Tyrrell and at the Raak main lake, with additional atmospheric pressure and temperature data, February 1981

A further set of data (Figure 11.6) is presented for Macarthur's Lake in the Raak boinka, situated about 100 km northwest of the Tyrrell site. The chart spans the period 21—30 January 1981, when the water table ranged from between 2 and 13 cm below the lake floor, the daily oscillation being from 2 to 5 cm. (The broad peak of 28 January was due to rain.) An unusual feature at Macarthur's Lake during this period is the development of semi-diurnal pressure fluctuations, with two daily maxima and minima. (Similar semi-diurnal peaks can also be faintly discerned from 20 to 22 February on Figure 11.5.) The absence of a comparable set of semi-diurnal water table fluctuations is seen to reflect the role of temperature in the reinforcement of only one of the two sets of pressure oscillations (see Temperature Induced Fluctuations below).

11.2.2 Water Table Fluctuations in Response to Low and High Pressure Systems

An additional feature, most clearly observed in the southwestern Tyrrell site, is the response of the water table to changes in the weather. This is reflected in larger scale fluctuations, often about 8-10 cm but occasionally reaching 20 cm. Under these influences, the record shows a broader six-day cycle, matching the pattern of high and low pressure systems passing across southern Australia. Diurnal water table fluctuations are superimposed on the broader cycles (Figure 11.7). Figure 11.7 shows water table levels at southwest Tyrrell from 6—18 February 1981, compared with air pressure data from the Bureau of Meteorology station at Mildura. The Mildura station lies 150 km to the northwest of Lake Tyrrell, and is therefore ahead of Tyrrell in receiving the weather: this has been adjusted by matching the Mildura data (as a unit) to the Tyrrell fluctuations.

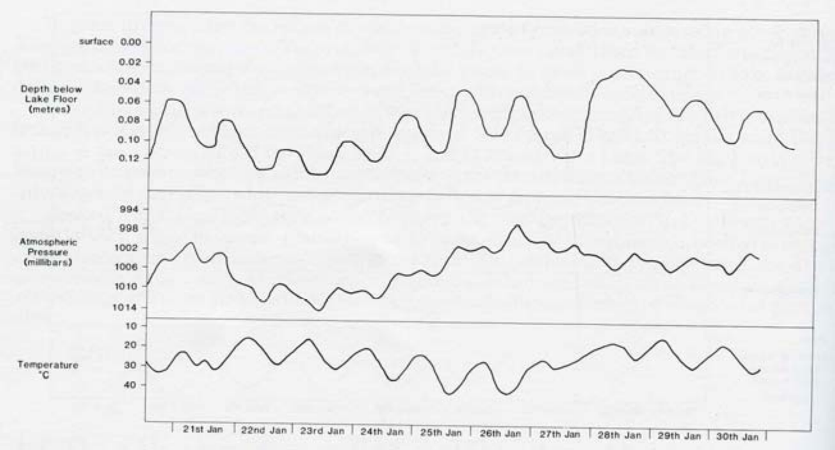

Figure 11.6 - Water table fluctuations at Macarthur's Lake, January 1981

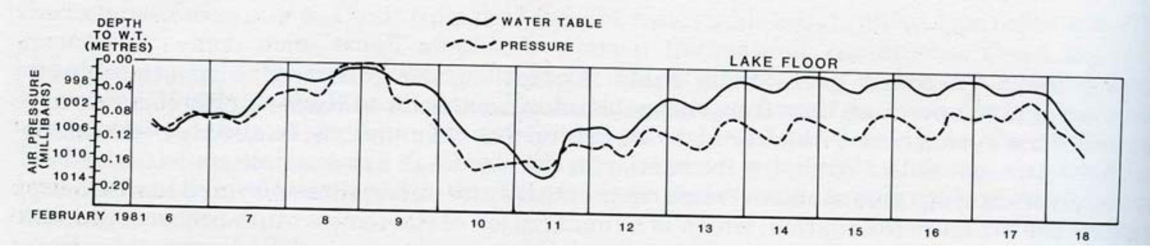

Figure 11.7 - SW Lake Tyrrell water table and barometric fluctuations

Despite the distance between the two stations, there is a remarkably clear match between barometric data and water table fluctuations. Of particular note is the almost 1:1 correlation between barometric pressure and water table fluctuation which is comparable to a barometric efficiency in confined aquifers of about 90-100%. During the 14-day period, the water table fluctuated over a vertical distance of 17.5 cm, being at the surface on the 8-9 and 14-17 February and at a depth of 17.5 cm below the surface on the 11th. Diurnal fluctuations are superimposed on a falling water table on 9-10,th and on a rising water table on the 11-14.th On 14-17th fluctuations with an amplitude of 2 cm from the surface occur. Of prime interest is the fact that the surface during this entire period was formed by a 7 cm halite crust through which the water table fluctuated (Figure 11.4).

11.3 Previous Work

Diurnal fluctuations in both groundwater tables and in stream flows caused by the daily evaporative cycle are well documented (White, 1932; Troxell, 1936; Tromble 1977; and Meyboom, 1967). However, in these instances water tables fall during the day under the high evapotranspiration regime and recover during the evening as evapotranspiration declines. They are at their lowest in late afternoon and highest in the early morning. This is the reverse of the situation occurring in the Mallee lakes and is not a significant process here. Small-scale water table fluctuations, not related to evapotranspiration cycles, have been variously documented. In general, the fluctuations fall into two groups: those induced by temperature changes and those responding to pressure changes.

11.3.1 Temperature Induced Fluctuations

The effects of a temperature gradient on moisture transfer within the soil water zone have been largely the province of soil scientists. Bouyoucos (1915) first showed that soil moisture moves from warmer to cooler soils. This work was confirmed by Lebedeff (1927), Taylor (1962), and Carey and Taylor (1962), who showed water movements from areas of high temperature to areas of low temperature in response to vapour pressure differences, and to matric potential gradients.

Gatewood et al. (1950) noted a sudden fall in water levels, coinciding with a sudden drop in temperatures as a cold front passed over tanks where experiments into water usage were being carried out. They showed that the addition of heated stones to the soil surface caused a sharp rise in the water table without any significant barometric change. Tison (1954) considered that the water level fluctuations observed by Gatewood et al. resulted from changes in surface tension on heating, causing the migration of capillary water into the water table, which consequently rose.

Meyer (1960) noted that as early as 1915 he had observed temperature induced fluctuations in water tables while he was experimenting on capillary rise in fine-grained sediments. Water levels rose when the soil column was warmed and fell when it was cooled. He noted similar effects in the field, in Minnesota, where winter lowering of temperatures was accompanied by a fall in the water tables, while spring warming saw a rise in water tables. He also observed diurnal fluctuations in shallow wells during winter: low levels being at 9.00 a.m. and high levels at 4.00 p.m., the extent of the fluctuation being roughly proportional to the daily temperature range. Meyer (1960) comments that the amount of water held by capillarity is greater in cold soils than in warm soils. He explains the fluctuations by the transfer of moisture between the capillary zone and the water table in response to temperature changes. Meyer considers the process to be primarily a migration of liquid water, induced by changes in soil temperature. The rapidity and extent of water transfer, he contends, could not be achieved by processes of vapour diffusion. This conclusion was also reached by Jumikis (1962). Diurnal fluctuations in shallow water tables under the Great Salt Plains of Oklahoma were observed by Davis (1968). In June 1968 the daily fluctuation averaged 7–10 cm, while the maximum depth to the water table was only 30 cm; daily maxima occurred between 6.00 p.m. and 9.00 p.m. while minima were between 8.00 a.m. and 10.00 a.m. Davis correlated the water level fluctuations with diurnal changes in temperature and relative humidity.

11.3.2 Atmospheric Pressure Effects on Shallow Water Tables

The effects of atmospheric pressure changes on water levels in unconfined aquifers are not as clearly defined as the effects on confined aquifers. However, Tuinzaad (1954) shows that where the capillary fringe lies within reach of the surface, atmospheric pressures can influence water tables. Peck (1960) showed that water level changes may be caused by the effects of pressure changes on air entrapped within the shallow groundwater. This study was confirmed experimentally by Norum and Luthin (1968), who considered that the pressure induced water table fluctuations were larger than those predicted by Peck's theoretical study. Bianchi and Haskell (1966) noted water table fluctuations when carrying out recharge experiments. They considered these to be caused by barometric pressure on air entrapped within he aquifer. Van

Hylckama (1968) observed diurnal fluctuations in evaporimeters, which he attributed to temperature induced pressure fluctuations. He considered, however, that half of the fluid occupying the pore space in the evaporimeter must be bubbles in order to provide sufficient air space to accommodate the observed barometric rise and consequent water table fall. An entirely different mechanism was suggested by Gilliland (1969). He proposed a rigid plate model as an alternative explanation to that of Peck for fluctuations in water table wells. He shows that if sufficient water is present, the soil water zone may act as a rigid plate for atmospheric pressure fluctuations. The water is suspended between the grains by surface tension. If a continuous layer exists, "any change in atmospheric pressure will be transmitted directly to the aquifer structure by the increased surface tension forces". If it is assumed "that the adjustment to pressure changes is instantaneous, the water table will rise or fall instantaneously". The existence of a rigid plate requires that the grain size of the surficial material satisfies the equation:

$$p < 4T/\partial Pa \tag{11.1}$$

Where T is the surface tension of the water
p is the effective pore opening and is approximately equal to the grain size
∂Pa is the change in atmospheric pressure

Gilliland considers that the increase in barometric efficiency of water table wells, caused by the entrapment of air in the soil zone by infiltrating precipitation (the Lisse effect of Meyboom, 1967), is a manifestation of the rigid plate model. He concludes that the barometric efficiency of a well is related not only to the properties of the aquifer but also to the properties of the overlying rigid plate and to infiltrated precipitation - the soil moisture zone is one manifestation of the rigid plate. An attempt to accommodate all the observations was made by Turk (1975), who had previously recorded similar diurnal fluctuations from beneath the Bonneville Salt Flats. Water tables fluctuated from 1.5 to 6 cm daily in summer and from 0.5 to 1.0 cm in mid-winter. Highest water tables were in late afternoon, with lowest in mid morning. Turk attributes the fluctuations to temperature induced atmospheric changes acting upon the capillary zone.

11.4 Discussion

In summary, three types of fluctuation are described above:

a. The diurnal fluctuation, with water tables high in late afternoon and low in the early morning (Meyer, 1960; Davis, 1968; Van Hylckama, 1968; Turk, 1975);
b. Falls in water tables related to seasonal cooling (Meyer, 1960; Turk, 1975);
c. Sudden falls in water tables in response to the passage of cold fronts (Gatewood et al., 1950).

The hydrology of the Mallee salinas differs from the above described sites in that water tables are only occasionally more than 20 cm below the surface and commonly oscillate within 2-4 cm of the surface. In the latter instances, the thickness of the capillary zone is less than 4 cm. In winter the salinas have a shallow water cover. A feature of the oscillation is the tendency for to attenuate at both the tops and bottoms, giving a considerable period in which water tables are static prior to reversing their direction. However, with the exception of the SW Tyrrell recorder the oscillations closely conform to the pattern of diurnal fluctuations described elsewhere. The feature not previously described in the literature is the larger amplitude oscillation linked to the passage of high and low pressure systems-this was, however, theoretically predicted by Peck (see below).

11.5 Cause of Fluctuations

Bouwer (1978) noted that water levels in piezometers do not always record the true level of the water table. This situation arises when there is a restricted transmission of atmospheric pressure change through the vadose zone to the water table, while at the same time a piezometer open to the atmosphere directly responds to the change. At the SW Tyrrell site, the near 1:1 correspondence between the barometric pressure and the water table fluctuations is in close accord with the theoretically derived values of 13.6 cm fall in water level with each 13.3 millibar rise in atmospheric pressure. The piezometer is clearly acting as a barometer and has a barometric efficiency which comes close to 1007. Since the water table is always within 25 cm of the surface, a simple test was applied to determine whether the piezometer reflects processes operating merely within the piezometer pipe or whether it shows a more general water table fluctuation. When the water table is shown as being at the surface (and at such times the salt crust is notably wet), a number of holes dug 20 cm into the lake floor filled with water, i.e. the water table is at the surface. Conversely, when the water table is shown as being well below the surface, holes dug through the salt crust show it to be in the sediment below the salt crust. They do not fill but instead show the same fluctuation as in the case of the water level recorder.

As Turk (1975) points out, the fluctuations may result from both temperature induced surface tension changes and temperature induced pressure changes - the processes are reinforcing and not separable in the field. They would quite adequately account for all previously observed diurnal fluctuations; however, in the case of the Mallee discharge lakes, Turk's mechanism of water movement between the water table and the capillary zone has some unusual implications. These stem from the limited extent of the capillary zone when the water table is only about 1-2 cm below the lake floor at the time when fluctuations first appear. This is about the same magnitude as the daily fluctuation, therefore, any explanation based on the transfer of water between the water table and the capillary zone requires that the capillary zone must accommodate a further 2 cm of water as the levels fall. This implies that the capillary zone, occupying an interval only a few centimetres above the water table, is at best only half saturated prior to the daily fall and absorbs a further two or more centimetres of water as the water level drops.

The process is even more unlikely when, as happened at southwest Lake Tyrrell in February 1981 (Figure 11.7), the oscillations were from the surface, and no capillary zone existed prior to the fall in water tables. Under these conditions, the alternative explanation of temperature induced pressure changes acting on air entrapped within the phreatic zone (Peck, 1960) becomes a more attractive mechanism. Indeed, a number of the characteristics of the water table fluctuations under the ephemeral Mallee salt lakes closely fit the theoretical and experimentally based concepts expounded by Peck. For instance, the almost 1:1 correspondence between water table and atmospheric pressure oscillations observed at Lake Tyrrell following the passage of high and low pressure systems comes close to the predicted values of $\partial Z/\partial P = -1/\rho$ when the water table is at the surface. Peck comments: "As the passage of weather disturbances (highs and lows) is associated with air pressure changes of as much as 50 gm wt cm^{-2} in not uncommon cases, considerable variation in the position of a water table near the surface can be expected". Additional details of Peck's work are given hereunder, with a short discussion on its implications when applied to ephemeral playa lakes. Peck provided a theoretical analysis for determination of the magnitude of water table fluctuations in response to atmospheric pressure acting on air entrapped in the water. The theoretical predictions were strongly supported by experimental data. Most relevant to this study is the observation that the maximum rate of change of water table height with air pressure occurs when he water table is at the surface – this situation arises once the surface water has gone from an ephemeral playa lake.

Commencing with the gas equation for entrapped air (applicable where the water table is within 900 cm of the surface),

$$V = CT/(P + \rho\ (Z-z))$$

(11.2)

Peck (1960) derives an equation for the water table fluctuation in response to atmospheric pressure changes.

$$\partial Z/\partial P = -CTh/\{(\sigma - \Phi_h)(P + pZ)\{P + \rho(Z-h)] + \rho CTh\} \tag{11.3}$$

Where C is the quantity of air entrapped in a unit volume of sediment
h is the height of sediment column measured from an impervious base
V is the volume of air entrapped in a unit volume of soil
P is the external air pressure
T is temperature
Z is the height of the water table above the impervious base
z is a vertical ordinate, positive upwards, with its origin at the base of the sediment column
σ is the porosity of the sediment
Φ is the apparent volumetric water content at `h' (= the volumetric water content plus the entrapped air)
ρ is the density of water in the sediment.

11.6 Implications of Peck's Equation for Water Table Fluctuations

Peck's equation indicates that a maximum response of the water table to atmospheric pressure change is:

$$\partial Z/\partial P = -1/\rho, \text{ when } (\sigma - \Phi_h)(P + \rho Z)\ P + \rho(Z-h)] \text{ becomes zero.} \tag{11.4}$$

This is obtained when Z equals h, i.e. the water table is at the surface, and Φ_h equals σ, i.e. the volumetric water content including entrapped air equals the porosity.

Peck confirmed experimentally that $\partial Z/\partial P \to -1/\rho$ as $Z \to h$. More recently, McWhorter and Sundae (1977) repeated Peck's analysis, adding that thick aquifers should exhibit larger water table fluctuations compared to those occurring in thin aquifers. Much greater aquifer thickness, more than any other factor, distinguishes the site at southwest Tyrrell from the other sites, where at best only a thin sand sheet covers an essentially clay sequence.

Thus, at southwest Lake Tyrrell, near optimum conditions for pressure induced water table oscillations occur once the surface water vanishes from the lake floor. Given a range of groundwater densities from about 1.1 to 1.2 g/cm^3, the barometric efficiency while the water table remains close to the surface would be approximately 85 to 90%. This is certainly the case at southwest Lake Tyrrell. However, in other situations, e.g. Macarthur's Lake in December 1980, the passage of lows and highs is not so much reflected by a sympathetic overall rise and fall in water tables, but instead by an increase and decrease in the amplitude of the diurnal oscillation, with the water table returning to within a few centimetres of the surface each day. The fluctuation pattern becomes more complicated with the addition of rain to the lake floor. Although the value of $\partial Z/\partial P$ changes very slowly as the water table falls below ground surface, a critical depth is reached whereupon there is a marked falloff in the amplitude of the water table fluctuation in response to a rapid change in (6 - ph). In Peck's example this occurs at a depth of 25 cm, however the decline in $\partial Z/\partial P$ soon levels off, to be virtually independent of water table depth–at about 35 cm below the surface.

This process may explain the virtual lack of significant water table oscillations in the recorders situated in the Raak boinka during the autumn of 1981, when water tables had fallen to several tens of centimetres below the lake floor. This seems to be a depth dependent feature, given the re-imposition of an oscillatory pattern once water levels again approach the surface following rain storms. While the southwestern Lake Tyrrell recorder faithfully conforms to the Peck model, the other recorders show characteristics which conform to this model to varying degrees at different times. At other times they depart from the model and may then be examined in terms of other models already discussed. This variation is not unexpected, given the differences in lithology and hydrology of the different sites and the roles of atmospheric pressure, temperature and precipitation.

11.7 Summary

In summary, therefore, all recorders show water table fluctuations beneath the dry playa lakes, the fluctuations commencing almost immediately after the lake dries out. The fluctuation patterns vary considerably–both between recorders and temporally at each recorder site. Since a single recorder gives a whole range of responses under differing combinations of conditions, there is no lack of data linking the fluctuation pattern to various factors such as atmospheric pressure, temperature, precipitation and water table depth. The problem where no single model fits is to disentangle the dominant factor or combination of factors operating at any one time. However, while the interpretation of data from the playa lakes should provide a further understanding of the interrelationships existing between the various factors, this must await further investigation.

11.8 Water Table Reflux the Influence of Water Table Fluctuations on the Reflux of Evaporite Salts

Undoubtedly, the most significant implication of the water table fluctuations for this study is the transference of salts from the lake surface into the shallow groundwater systems. In the case of the halite saturated re-solution lakes, halite precipitation commences almost immediately that evaporitic concentration gets underway: at Lake Tyrrell this builds up a 7 cm thick halite crust by the time the lake finally dries up. As the lake shrinks, the surface level of the brine gradually falls until it drops below the lake surface; it then becomes the water table at the top of the phreatic zone. At this point, diurnal fluctuations commence, with the water table 1 or 2 cm below the lake floor. Where a salt crust is present, the top of the crust acts as the lake floor, and the water table fluctuates through the newly deposited halite (Figure 11.4).

The lake waters do not normally reach the stage where magnesium salts precipitate before the water level drops below the lake floor effectively preventing further evaporative concentration. Should magnesium (and potassium) salts be precipitated during a snap drying of the lake under extreme temperature conditions, these salts would be quickly redissolved from the salt crust by the fluctuating groundwaters and thus lost to the surface. Chemical analyses of late-stage lake waters and the resulting salt crust and shallow groundwater brines are given in Tables 10.3, 10.4 and 10.5.

Within the throughflow lakes, halite precipitation only begins at a late stage of evaporation after halite saturation is reached; this may be preceded by a gypsum phase, during which gypsum is precipitated as a sugary textured mush (cf. Teller et al., 1982). At best, only a very thin salt crust remains when the lake dries out. In these instances, the shallow groundwaters are rarely saturated with NaCl and each time the water table reaches the surface, halite is removed. This process is accelerated by occasional rainstorms, which, apart from their leaching qualities, cause the water table to rise rapidly to the surface where it may remain for several days before again subsiding. Ultimately, the only salt left at the surface is a thin efflorescence due to capillarity.

Thus, the reflux of the salts from the lake surface into the shallow aquifer is assisted by diurnal water table fluctuations, which may in some instances be superimposed on a broader (approximately six-day) oscillation having a larger amplitude. The reflux process is essentially a hydrodynamic one, acting only after the lake has dried out. Where a permanent salt crust exists the oscillation of the water table through the crust removes any salts with which the shallow groundwaters are not already saturated. This process explains the absence of any significant deposits of magnesium and potassium salts from the thin evaporite bodies formed in playa lakes of the Murray Basin (see Chapter 10.3).

The process of summer reflux of evaporite salts by an oscillating water table under lake dry conditions *(water table reflux) is* markedly different to winter or lake-full reflux, when hydrostatic head provides the energy for outseepage of both salts and lake water.