2 Literature Review

2.1 Water Table Fluctuations

Observations of water table fluctuations have been made to determine the effect of the trees. Short term (<24 hours) and long term (>24 hours) fluctuations of the water table can be caused by several factors:

- Evapotranspiration (both short and long)
- Barometric presssure changes (short)
- Temperature changes (short)
- Recharge (both short and long)
- Inflow to and Outflow from the aquifer (long)

2.1.1 Water Table Fluctuations Due to Evapotranspiration

The process by which plants extract water from the soil and vaporize it to the atmosphere is called transpiration. The process is closely related to evaporation, and since it is often difficult to separate the two, they are usually grouped as evapotranspiration in a hydrologic budget (Dunne and Leopold, 1978, pg. 127). Sorensen et. al. (1999) studied pecan tree transpiration and compared the data with total calculated evapotranspiration. The study found that transpiration of the pecan trees was approximately 20 to 25% of the total ET. In most areas, evapotranspiration is the bulk of the hydrologic budget. It is estimated that two-thirds of the precipitation that falls in the United States returns to the atmosphere by transpiring from plants and evaporating from land/water surfaces (Dunne and Leopold, 1978, pg. 127). Globally evapotranspiration accounts for 62% of the precipitation that falls on land (Dingman, 1994, pg. 257).

Almost all U.S. research relating to evapotranspiration has been done in the western portion of the country, a very water poor region. Evaporation rates from water surfaces and transpiration from plants is very high due to the low humidity and high temperatures associated with the western United States. Plants drawing continuously upon groundwater were quickly identified as a problem for the west as the population grew. O. E. Meinzer (1927) coined the term “phreatophyte” in USGS Water Supply Paper 494 to classify plants that continually draw water from the saturated zone. Phreatophyte literally means “well plant” and became a term used in everyday language "for designating a group of destructive enemies that formerly were regarded merely as nuisances" (Robinson, 1958, pg. 2).

The so-called "phretophyte problem" is due to its "consumptive waste" in the west (Robinson, 1958, pg. 25). Consumptive use is defined as beneficial use of water by man whereas phreatophytes use water and expel it to the atmosphere without an obvious beneficial use. C. H. Lee was the first person to tackle the problem of quantifying evapotranspiration on a large scale. The City of Los Angeles saw tremendous growth in the early 1900s. The problem for Los Angeles, which remains a problem today, is satisfying the water needs of the people living there since it does not have a sufficient water source of its own. The city's first solution to the problem was to obtain the water rights to the Owen's River Valley (over 100 miles away) and transfer the water to the city through an aqueduct. The water table in the valley is shallow, so a large portion of the water was being directly transpired by the phreatophyte salt grass. Both of these actions reduced the flow of the Owen's River. Lee was to investigate a way to reduce the amount of evapotranspiration in the valley to increase yield to the city (White, 1932, pg. 7). He published his results in U.S. Geological Survey Water-Supply Paper 294 in 1912. Lee's solution was to lower the water table in the valley below the reach of the phreatophytes by pumping. Lee calculated that this action alone would save between 68,000 and 83,000 acre-feet of water annually, enough water to supply each one of 200,000 people with 300 gallons a day (White, 1932, pg. 7).

Another example of the importance of evapotranspiration occurred in Wagonwheel Gap, Colorado. The Weather Bureau noticed a much higher rate of runoff from a mountain slope after all the timber was cut. It is presumed that soil evaporation must have increased since the slope was more exposed to the sun and wind, but this could not outweigh the loss of transpiration and interception of the former forest (White, 1932, pg. 6). In an attempt to reduce evapotranspiration, some municipalities in Great Britain and South Africa have actually placed limits on "afforestation" in watersheds important to municipal water supply (Hewlett, 1969, pg. 89).

Transpiration is the vaporization of water from the stomata on the underside of the leaves. It is a physical process, meaning that it requires no metabolic energy from the plant to occur. The stoma opens when conditions are favorable for photosynthesis. This provides a pathway necessary for carbon dioxide to diffuse from the atmosphere into the leaf to be used for photosynthesis. A byproduct is the loss of water from the opening. In fact, transpiration has been called "a necessary evil" because so much water is lost in this manner compared to the benefit to the plant (Hewlett, 1969, pg. 79).

Although a substantial amount of water is lost from the plant, transpiration does provide a means for transporting water through the plant. Xylem cells provide the vascular system for plants. The benefit of this transportation process is that it maintains plant cell rigidity, or turgor, and allows mineral nutrients in the soil to be delivered throughout the plant (Dingman, 1994, pg. 275). The difference between evaporation and transpiration is that the plant has some control of the size of the stoma via the guard cells.

Three major factors affect the opening of the stomata:

1. light – stomata opens during day and closes at night
2. humidity – stomata openings tend to decrease as humidity decreases below its saturation value
3. water content of leaf cells – stomata tends to close if water contents become too lowOther factors affecting the size of the stomata are wind, CO_2 levels, and temperature (Dingman, 1994, pg. 275).

G. E. P. Smith, an irrigation engineer at the University of Arizona, first recognized the effects on groundwater levels due to the opening and closing of the stoma during the day. As early as 1915 Smith stated that he "long held the hypothesis that the water absorbed and transpired by mesquite and other trees constitutes the principal loss from the groundwater reservoir" (Meinzer, 1927, pg. 13). In 1916, Smith made observations of a daily rise and fall of the water table amidst phreatophytes (cottonwood and mesquite trees). The water table would begin to fall in the early morning and continue to fall throughout the day. After sundown, the water table would rise until the next morning and then the cycle would continue the next day. Smith demonstrated that the fluctuations were due to the phreatophytes, and it seemed that the "amount of fluctuation was proportional to the amount of water withdrawn" (White, 1932, pg. 8).

Researchers have since expanded greatly on the work of Smith. In 1932, W. N. White published U.S. Geological Survey Water Supply Paper 659-A entitled "A Method of Estimating Groundwater Supplies Based on Discharge by Plants and Evaporation from Soil." His research site was in the arid Escalante Valley (approximately 10 inches of rainfall annually) in the southwestern portion of Utah. White (1932) observed that the water table generally began to fall between 9 to 11 a.m. reaching its lowest level around 6 or 7 p.m. The water level then began to rise until the next morning. He also observed that generally the fall of the water table was greater than the recovery. The fluctuation was also seasonal, beginning in the spring at the first sign of foliage and stopping in the fall after a hard frost.

Figures 2.1 and 2.2 provide some examples of the data White observed. Figure 2.1 displays data from a well in a thicket of willows. Fluctuations of approximately 0.30 feet are observed in Graph A near the end of August. Graphs B and C show how the fluctuations die off in the month of October as the trees lose their leaves. Figure 2.2 displays data from a well in a field of pickleweed. Graphs B and C show the amplitudes diminish in the fall. The amplitudes in Graph A do not match those in Graphs B and C. The peaks occur during the day and the troughs occur during the night, opposite of that observed in the other graphs. The phenomenon observed in Graph A is due to barometric pressure and will be addressed in the next section. Other researchers that report data similar to that of White are Robinison (1958) and Troxell (1936).

Evaporation can also occur directly from the water table. Evaporation reduces greatly as depth to the water table increases to the point at which it becomes insignificant. Figure 2.3 shows the results of White's lab experiment relating to evaporation directly from the water table. White (1932) reported that evaporation was "comparatively high when the depth to water was 1 foot or less and was comparatively low when the depth to water was 2 feet or more". Evaporation rates drop below 10% once the water table is more than 30 inches below the ground surface. According to Robinson (1958, pg. 22), as soon as the capillary fringe drops below the surface, evaporation from the water table is effectively zero. Evaporation can occur to a very small degree at relatively large depths. Changes in barometric pressure effectively "pump" the aquifer by forcing fresh air in and pulling water vapor out.

2.1.2 Water Table Fluctuations Due to Barometric Pressure Changes

As previously mentioned, the fluctuations in Graph A of Figure 2.2 are due to changes in barometric pressure. This effect has been explained by L. J. Turk (1975) and others. Turk (1975) noticed fluctuations of 1.5 to 6.0 cm per day in a shallow fine-grained aquifer in Utah. Maximum water levels occurred during the late afternoon, and minimum water levels occurred during the morning. Turk (1975) attributed these fluctuations to temperature induced barometric

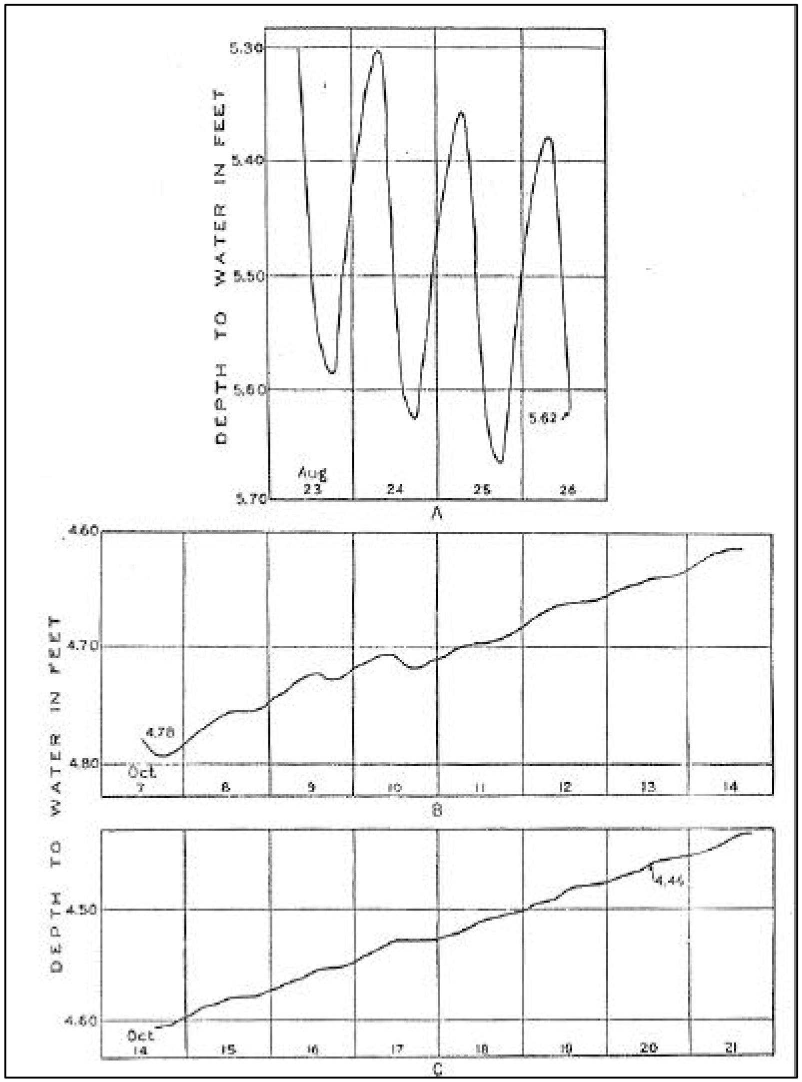

Figure 2.1 - Water levels in a thicket of willow trees in Escalante Valley, Utah. Graph A shows large fluctuations resulting from high transpiration rates during the month of August. Graphs B and C show little to no transpiration during the month of October. (Source: W. N. White, *USGS Water-Supply Paper 659-A*, 1932, pg. 40)

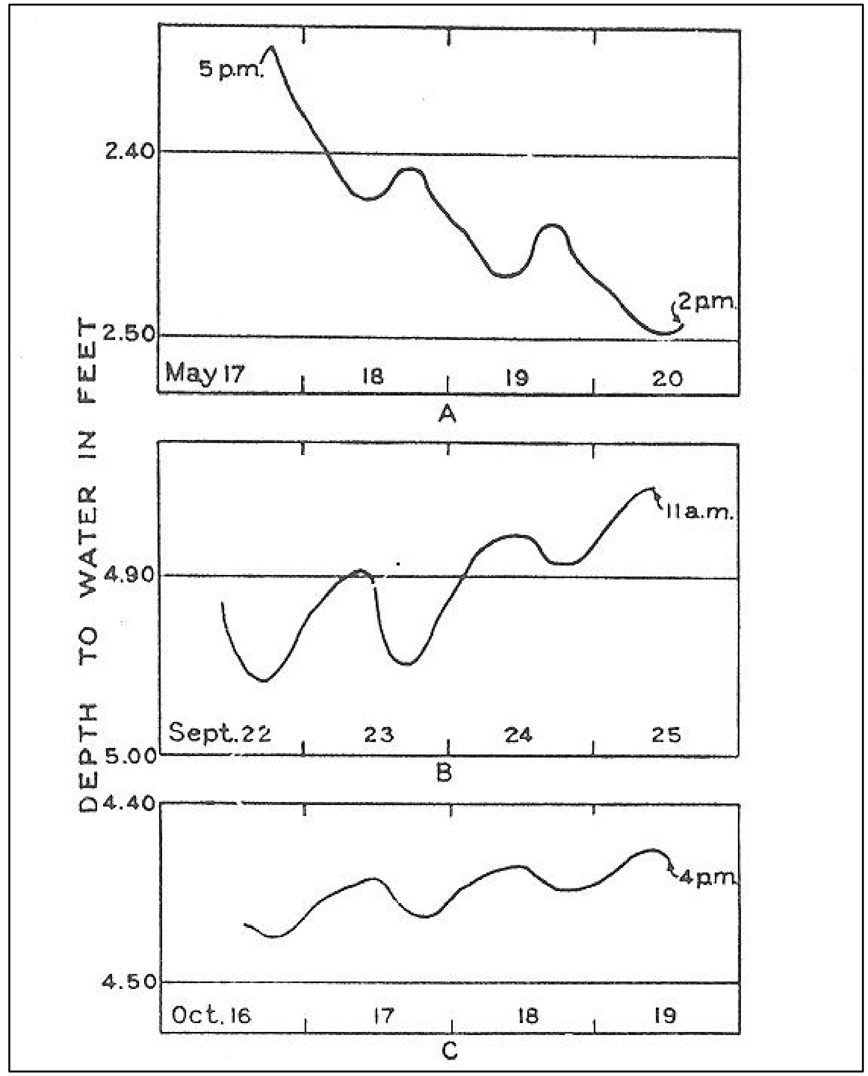

Figure 2.2 - Water levels in a field of pickleweed in Escalante Valley, Utah. Graphs A and B show fluctuations resulting from transpiration (peaks occur in afternoon). Graph C shows fluctuations in October due to changes in barometric pressure (peaks occur in the morning). (Source: W. N. White, *USGS Water Supply Paper 659-A*, 1932, pg. 39.)

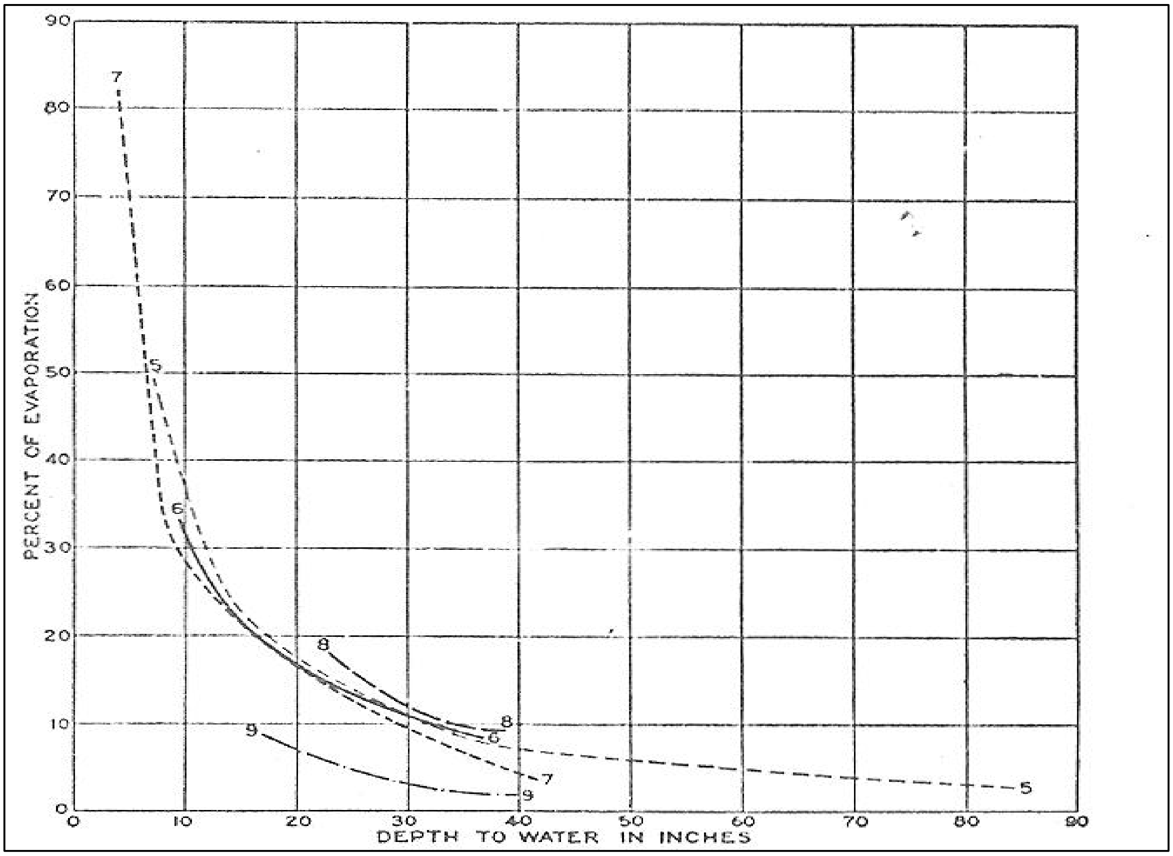

Figure 2.3 – White's Evaporation vs. Depth Experiment showing a dramatic drop in evaporation rates from the soil (<10%) when the depth to water is greater than 30 inches. (W. N. White, *USGS Water Supply Paper 659-A*, 1932, pg. 80.)

pressure changes during the day. As the temperature rises during the day, barometric pressure falls, and when the temperatures fall at night, barometric pressure rises.

During a recharge event, air can become entrapped between soil grains in the capillary zone and water table. The entrapped air is disconnected from the atmosphere. When the barometric pressure begins to fall as temperatures rise during the day, the entrapped air expands due to decreased pressure exerted by the atmosphere. Therefore, the air takes up more volume in the aquifer and capillary zone (forcing water out of the capillary zone and into the saturated thickness) which causes the water table to rise. Conversely, as the barometric pressure rises during the night the air bubbles shrink causing the water table to fall.

Turk (1975) set up an apparatus to test his hypothesis that the water table fluctuates directly with changes in air pressure. The experiment is similar to those conducted by Raffo (1954) and Norum and Luthin (1968). Aquifer material (obtained for the banks of the Colorado River near Austin, Texas) was placed 20 cm deep in a 1.35 m long, 0.9 m wide, and 0.75 m high sealed container. The air pressure inside the container could be controlled and two manometers were installed to measure the air pressure in the container and the water table elevation. The results support the hypothesis that as the air pressure increases the water table falls.

Other research by Peck (1960) and Norum and Luthin (1968) support the conclusions of Turk. Effects of barometric pressure are most pronounced in shallow and/or fine-grained aquifers. Shallow aquifers allow air to become more easily entrapped during a rainfall recharge event due to larger fluctuations. Fine-grained aquifers have a large capillary fringe allowing for a greater volume of water to be forced into the saturated zone from the capillary fringe as water is replaced by expanding air bubbles.

2.1.3 Water Table Fluctuations Due to Temperature Changes

Temperature indirectly affects the water table by causing fluctuations in barometric pressure, but temperature can also have a direct affect on water levels. A. F. Meyer (1960) determined through observation and experimentation that migration of water can be induced by changes in soil and water temperature. Meyer (1960) conducted his study relating to temperature changes and the water table in Minnesota. He noticed that in the spring there was a sudden rise in groundwater levels and that in the fall the water levels fell. Meyer (1960) attributed the rise in groundwater levels to decreased capillary action as groundwater temperatures increased. The groundwater level would subsequently fall due to increased capillary action as groundwater temperatures decreased. Experiments by other researchers have shown that as temperatures decrease, there is an increase in surface tension which increases capillary action (Turk, 1975, pg. 13). Meyer (1960) noticed a seasonal fluctuation in the shallow, fine-grained aquifer of 1 to 2 feet. It should be noted that seasonal temperature variations in Minnesota are extreme.

Fluctuations in groundwater levels due to changes in temperatures can also occur daily, not just seasonally. This can only happen if the water table is a few centimeters below the ground surface. It takes heat flux approximately three to six hours to travel to a depth of 15 cm (Turk, 1975, pg. 7). In Death Valley, California, Hunt et. al. (1966, pg. 9) found that there is little daily variation in groundwater temperatures just a few centimeters below the surface.

2.1.4 Water Table Fluctuations Due to a Recharge Event

During heavy rains, observations have been made of piezometers that show dramatic rises in the water table beyond what is reasonable for a recharge event (Freeze and Cherry, 1979, pg. 232). The sudden rise is followed by a sudden fall in the water table. The explanation for this event again features air pressure. During a heavy rain, the ground surface quickly becomes saturated. The saturation front then begins to move down toward the water table. Air in the vadose zone has no initial escape due to the sudden saturation of the ground surface. The air becomes compressed over the water table thereby increasing the air pressure just above it. The air pressure in the piezometers remains atmospheric since it is open to the atmosphere. Water from the aquifer is then forced into the piezometer because there is a greater pressure over the water table than there is in the piezometer. Air pressure just above the water table will soon equalize with the atmosphere and water levels in the piezometers will return to normal. The phenomenon is analogous to drinking out of a straw. The partial vacuum created in a straw (meaning there is greater pressure over the surrounding fluid than there is in the straw) forces fluid up the straw (Freeze and Cherry, 1979).

2.2 Quantifying Evapotranspiration

There are two very different schools of thought on how to quantify evapotranspiration. As P. G. Jarvis and K. G. McNaughton discuss in their 1986 article, "Stomatal Control of Transpiration: Scaling Up from Leaf to Region", plant physiologists and ecologists suggest that the stoma is the single most important factor in regulating evapotranspiration. Meteorologists emphasize the amount of energy it takes to evaporate water and that climatic factors are the most important (Jarvis and McNaugthon, 1986). Methods such as White's equation and direct measurement of transpiration from individual leaves and plants are consistent with the approach of plant physiologists while the Thornthwaite Method and Blaney-Criddle Formula follow the meteorologists' approach. Jarvis and McNaughton (1986) conclude that one point of view is not necessarily right and the other wrong, but merely differences in scale. When looking at the transpiration of an individual plant, the stoma is the most important controlling factor, but when looking at the transpiration of a forest, heat energy is the most important factor. Both methods are employed in determining evapotranspiration at the Oneida, TN site.

As a result of his observations of groundwater fluctuations in Escalante Valley, Utah, White (1932) developed an equation to determine the amount of water transpired by plants based on the fluctuations observed and specific yield:

$$q = y(24r \pm s) \tag{2.1}$$

q = depth of water withdrawn during 24 hours, in inches

y = specific yield of aquifer

r = hourly rate of rise of the water table from 12 a.m. to 4 a.m., in inches

s = net fall or rise of the water table during the 24 hour period, in inches

White (1932) assumes that there are no losses from the period of 12 a.m. to 4 a.m. Therefore, the tangent to this line is equal to the rate of groundwater recharge in the vicinity of the trees during this period. Assuming that the rate continues for 24 hours, 24r would equal the rise (or fall) in the water table for 24 hours due to groundwater recharge. This value, 24r, can be positive if gw recharge > 0, zero if gw recharge = 0, or negative if gw recharge < 0. During the afternoon, the effects of transpiration outweigh the effects of recharge so the water table does not continue to rise. The net fall or rise of the water table, s, is added or subtracted to the equation to account for the overall decline of the water table due to inflow or outflow. Figure 2.3 shows the application of White's equation to the Oneida site on September 5, 1999.

Troxell (1936) points out an error in White's equation. If it is assumed that transpiring trees create a cone of depression, then the rate of recharge can not be assumed constant for 24 hours. The rate of recharge would be greatest when the difference between the static head (water level outside cone of depression) and the cone of depression is the greatest. The rate of recharge would be the smallest when this difference was the smallest. Therefore, it is not correct to

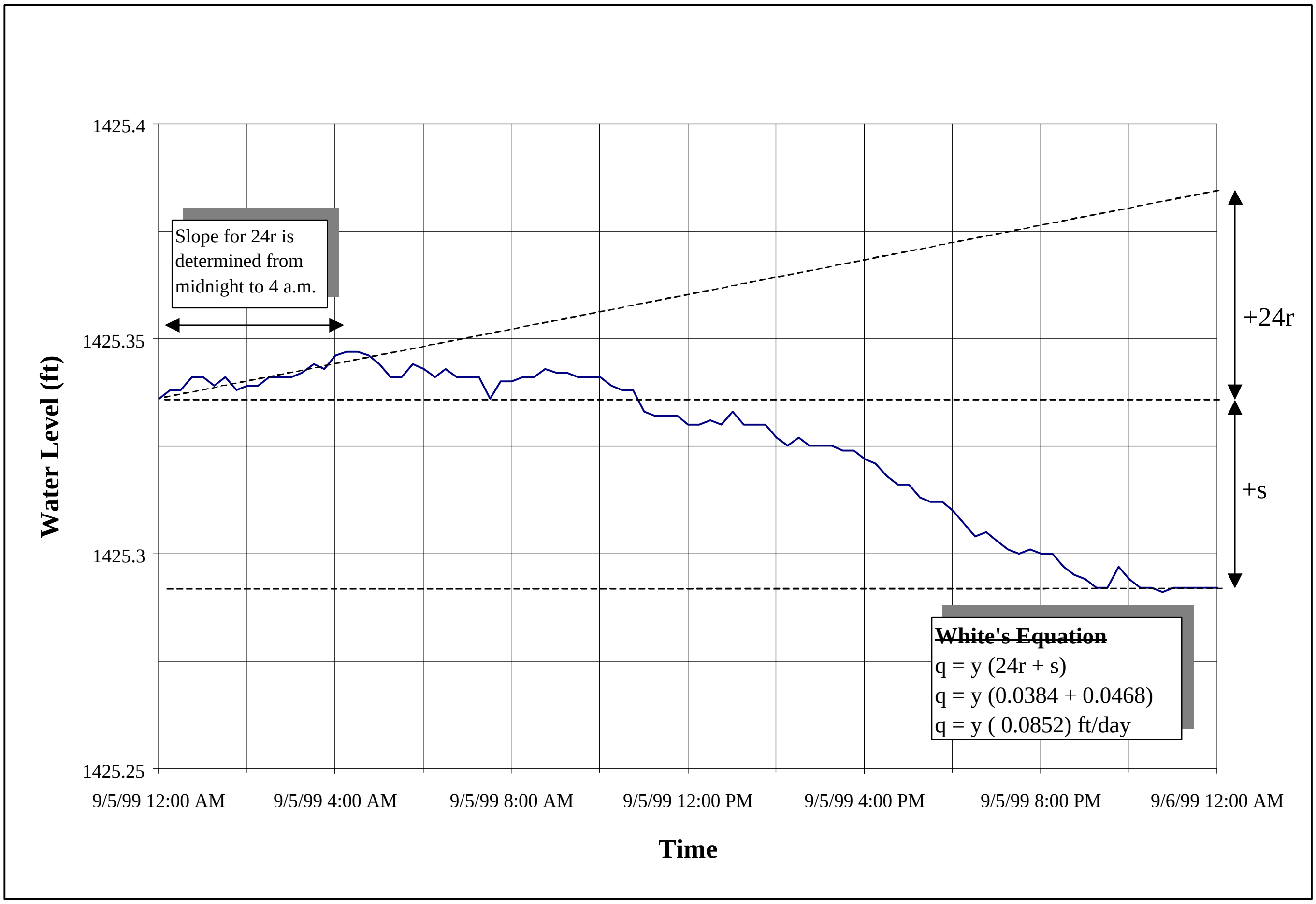

Figure 2.4 – Example of White's Equation on September 5, 1999, at the Oneida site

assume that recharge is a linear rate during the day. In actuality, the line should possess a maximum slope over the troughs of the groundwater curve and a minimum slope over the high points of the groundwater curve. The more the trees affect the water table, the greater the error.

In 1948, C. W. Thornthwaite developed an evapotranspiration formula based solely on energy expressed in monthly average temperature. The equation does not distinguish between vegetation and assumes the supply of water is unlimited. The Thornthwaite Equation (1948) is a widely used and proven method for determining evapotranspiration in temperate climates (Dunne and Leopold, 1978). The Thornthwaite Equation is as follows:

$$E_t = 1.6 \bullet \left[\frac{10 \bullet T_a}{I} \right]^a \tag{2.2}$$

E_t = potential evapotranspiration in cm/mo

T_a = mean monthly air temperature (°C), (data from National Weather Service)

$$I = \sum_{i=1}^{12} \left[\frac{T_{ai}}{5} \right]^{1.5} \tag{2.3}$$

I = annual heat index

$$a = 0.49 + 0.0179I - 0.0000771I^2 + 0.000000675I^3$$

2.3 Poplar Trees

Hybrid poplar trees are often used for phytoremediation. The trees are "fast-growers, perennial, long-lived (25-50 years) and tolerant of organic contamination" (Fetterolf, 1998). The poplar tree is a phreatophyte (seeks to draw water from the saturated zone) and can draw water from up to 15 feet (Jordahl et. al., 1996). In 1992, Hinckley et. al. determined water use by 4-year old hybrid poplars at Washington State University using sap flow measurements. The smallest tree (approximately 36 feet tall, 3.3 inches in diameter) was estimated to use between 5.3 and 6.9 gallons per day. The tallest tree (approximately 50 feet tall, 5.9 inches in diameter) was estimated to use between 10.3 and 13.5 gallons per day (Hinckley et. al., 1994). In measuring sap flow in pecan trees, Sorensen et. al. (1999) describe the procedure to measure sap velocities. Heat pulse needles are inserted into the tree trunk and a heat pulse is measured in the tree at a given distance from the source. The sap velocities are then converted to transpiration rates.