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DEPARTMENT OF ENERGY,
MINES AND RESOURCES

BULLETIN 139

GROUNDWATER STUDIES IN THE ASSINIBOINE RIVER DRAINAGE BASIN

Part II: Hydrologic Characteristics of Phreatophytic Vegetation in South-Central Saskatchewan

Peter Meyboom

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PREFACE

The groundwater research program initiated in the Assiniboine River drainage basin in 1962 by the Geological Survey of Canada aims at qualitative and quantitative solutions of groundwater phenomena on the Canadian prairie.

This report, the second of a series of publications on particular facets of this research program, deals with the role of phreatophytes in the hydrology of a prairie drainage basin. It presents values of evapotranspiration and streamflow losses in some of the discharge areas that were discussed qualitatively in the first publication of this series.

Y. O. FORTIER,
Director, Geological Survey of Canada

OTTAWA, July 7, 1965

BULLETIN 139 — Grundwasserstudien im Stromgebiet des Assiniboine River

II. Teil: Hydrologische Merkmale der phreatophytischen Vegetation im südlichen Zentralgebiet Saskatchewans.

Von Peter Meyboom

БЮЛЛЕТЕНЬ 139 — Исследования подземных вод в сборном бассейне реки Ассинибойн

Часть II. Гидрологические характеристики фреатофитической растительности в южно-центральном Саскачеване.

Питер Мейбум

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Part II—Hydrologic Characteristics of Phreatophytic Vegetation in South-Central Saskatchewan

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Abstract

Seasonal groundwater consumption by phreatophytes in south-central Saskatchewan ranges from 2.5 inches to more than 40 inches. During 1963 and 1964 the average ratio between groundwater consumption and water losses from a class "A" evaporation pan was 0.58 with a range from 0.09 to 1.26.

The amount of groundwater consumption is, among other factors, determined by the depth to the water-table. Herbs and shrubs stop using groundwater when the water-table is more than 7 feet below surface; for trees, the threshold value may lie around 14 feet.

As phreatophytes grow mostly in river valleys, they cause streamflow depletion under natural and regulated flow conditions.

The results of the investigation indicate that — contrary to findings in the western United States — saltgrass (*Distichlis stricta*) is not phreatophytic in south-central Saskatchewan. Common phreatophytes in this region are Manitoba maple, willow, baltic rush, wolf willow, western cottonwood, buffalo berry, and slough grass.

Résumé

La consommation saisonnière d'eau souterraine par les phréatophytes dans le centre sud de la Saskatchewan varie de 2.5 à plus de 40 pouces. En 1963 et en 1964 le rapport moyen entre la consommation d'eau souterraine et les pertes établies dans une cuvette d'évaporation de classe «A» a été de 0.58 et a varié de 0.09 à 1.26.

La consommation d'eau souterraine est, entre autres facteurs, déterminée par la profondeur de la nappe phréatique. Les herbes et les buissons cessent d'utiliser l'eau souterraine lorsque la nappe est à plus de sept pieds sous la surface. Les arbres cessent vers quatorze pieds.

Comme les phréatophytes vivent surtout dans les vallées fluviales, ils peuvent assécher les cours d'eau, que l'écoulement soit naturel ou régularisé.

Les résultats des recherches indiquent que, contrairement aux découvertes faites aux États-Unis, l'halophyte (*Distichlis stricta*) n'est pas phréatophytique dans le centre sud de la Saskatchewan. Les phréatophytes communs à cette région sont l'érable négondo, le saule, le jonc de la Baltique, le saule de Wolf, le peuplier de Sargent, la sherpherdie argentée et la spartine pectinée.

INTRODUCTION

Since 1927, when Oscar E. Meinzer published his paper on "Plants as indicators of groundwater", it has been recognized that groundwater discharge by plants is a major debit item on the water balance of any semi-arid region. An outstanding contribution to the knowledge of groundwater consumption by plants was made in 1932 by Walter N. White of the United States Geological Survey. His report on phreatophytes in the Escalante valley (Utah) served as a model for many of the subjects covered in this bulletin. The most comprehensive treatise was written by Robinson (1958), who estimated that phreatophytes (excluding beneficial species such as alfalfa) in the seventeen western states transpire as much as 25 million acre-feet of water per year. Much research is in progress, as is evident from Robinson's latest review (1964) which lists forty-eight current phreatophyte studies for the western United States.

Knowledge of phreatophytes is indispensable in understanding the hydrology of prairie drainage basins. The writer's study of phreatophytic vegetation in south-central Saskatchewan started in the summer of 1962 with some incidental observations in the Arm River valley (Fig. 1). In 1963 continuous observations were made at twenty-two locations throughout the headwater region of Qu'Appelle River, but few of these records covered the entire growing period. In 1964 continuous records were restricted to the Arm River drainage basin and the vicinity of Watkins Ranch (Fig. 1). Thirty per cent of the twenty-three observation wells gave complete records for the months June, July, and August, some even until November, and values of consumptive use for the growing season of 1964 could be calculated for Manitoba maple (*Acer negundo*), willow (*Salix*), baltic rush (*Juncus balticus* var. *montanus*), wolf willow (*Elaeagnus commutata*), western cottonwood (*Populus sargentii*), and buffalo berry (*Shepherdia argentea*). Contrary to reports from the western United States, it was found that neither saltgrass (*Distichlis stricta*) nor alfalfa (*Medicago sativa*) is phreatophytic in south-central Saskatchewan.

This report is in five parts: (1) a general description of phreatophytes and their environment; (2) a discussion of the interpretation of water-level fluctuations; (3) a description of the phreatophytic vegetation and calculations of consumptive use; (4) a discussion of some factors that influence the amount of groundwater consumption; and (5) a section dealing with the effects of phreatophytes on streamflow and springs.

The author is grateful to Mr. John Hudson of the Saskatchewan Research Council for the excellent field lessons in plant taxonomy. Mr. Edward Shwedyk rendered good and imaginative assistance during the field seasons of 1963 and 1964.

Thanks are due to the citizens of Aylesbury, Craik, and Davidson for their friendly interest in the work, and particularly to the Watkins Brothers in Aylesbury for providing the luxurious living quarters of the Watkins Ranch and for giving free use of their land for the numerous experiments.

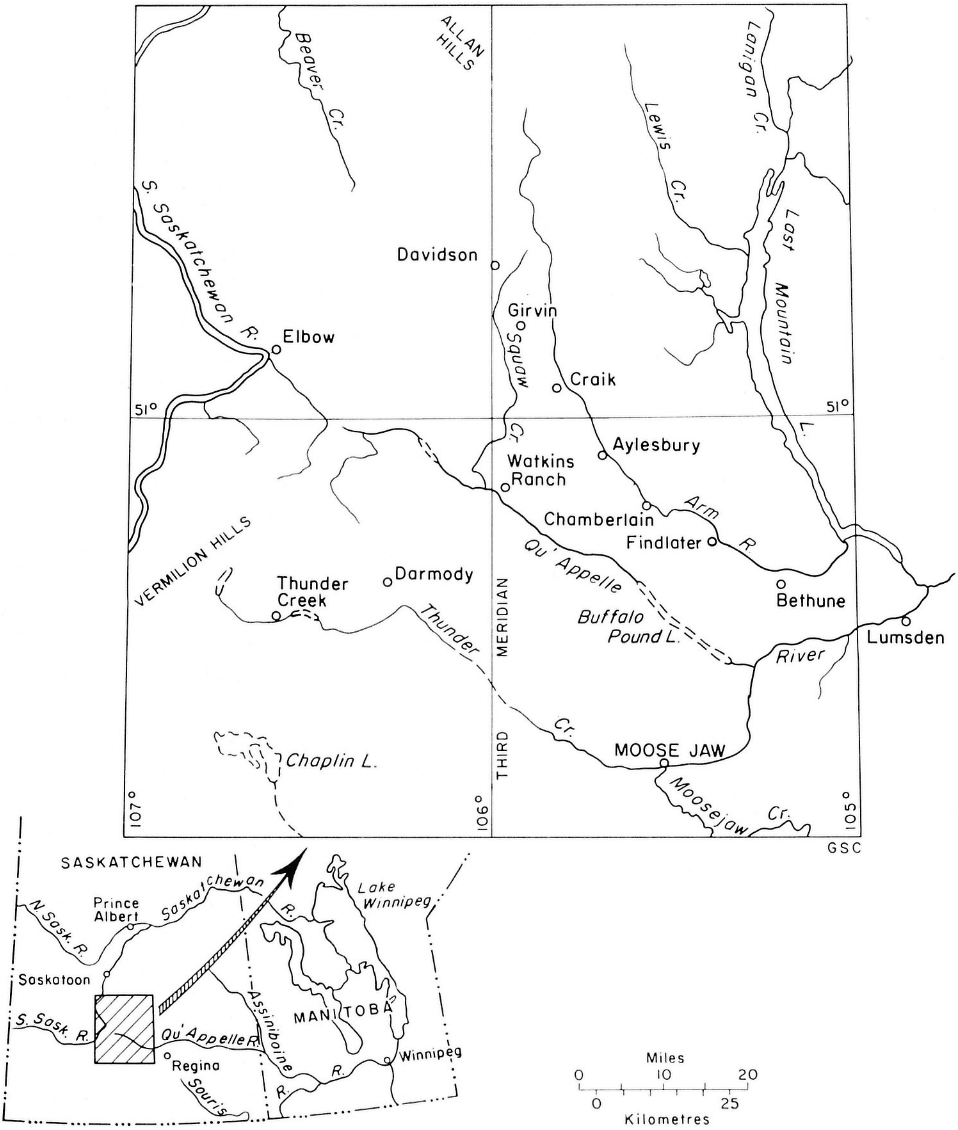

FIGURE 1. Location of rivers and places mentioned in report.

CHARACTERISTICS OF PHREATOPHYTES AND THEIR ENVIRONMENT

According to Meinzer's original definition (Meinzer, 1923a, p. 55), phreatophytes are plants that habitually obtain their water supply from the zone of saturation, either directly or through the capillary fringe. This definition may be somewhat misleading, however, because few species depend so rigidly on groundwater that they will not grow in areas with abundant soil moisture. On the prairies, where abundant soil moisture is normally lacking, a natural groundwater supply is a refuge for those plant species that would normally not survive in such a semi-arid environment. Under these circumstances the vegetation will be phreatophytic.

Evidence that the vegetation uses groundwater is provided by daily water-table fluctuations. In general, the water-table goes down during the daytime when evapotranspiration is rapid, and recovers at night. The level begins to drop between 9 and 11 a.m., reaches its lowest stage between 7 and 9 p.m., after which time it rises until 9 to 11 o'clock next morning. The daily fluctuations begin in the spring with the appearance of foliage and cease in the autumn after the killing frosts. They do not occur in areas where the water-table is far below the surface.

Evapotranspiration

The role of water in the life of a plant is fourfold: (1) it furnishes a chemical bond for the products of assimilation; (2) it maintains the cell turgescence; (3) it plays a role in the transport of ions; and (4) it governs the heat regulation. The amount of water involved in the last two processes accounts for about 99 per cent of all water used by a plant and is determined almost entirely by the process of evapotranspiration.

Evapotranspiration itself is not one of the vital functions of a plant, but rather a 'necessary evil' related to the gas exchange, which is required for photosynthesis and respiration. Photosynthesis is generally expressed as:

$$6CO_2 + 6H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

whereas respiration is the reversed process. Both functions require exchange of carbon dioxide and oxygen. This exchange is presumed to occur through the wet cell-membranes from and into the intercellular spaces of the leaf and ultimately through the stomata. The size of the stomata — and therefore the amount of evapotranspiration — is regulated by guard cells at either side of these leaf-openings.

When water evaporates from the moist surface of the spongy leaf cells, the sap concentration of these cells increases. This increased concentration produces an osmotic gradient between adjacent cells and innumerable compensating currents are set up, combining together into a single ascending water stream as long as evaporation continues.[1] The source of the stream is the soil and its path is through the wood vessels of the plant into the leaves.

Water transport, however, is not entirely a physical process. Apart from the passive water absorption caused by the osmotic gradient, there is an active water absorption by the roots, called root pressure. Root pressure is responsible for restoring the turgescence after a day of heavy transpiration, and for increasing the water content after leaf-fall. Investigators of active absorption give different views on the process. Makkink (1949) stated that the root pressure is not more than 2 atmospheres, whereas Gibbs (1950) reported values of 6 atmospheres. In terms of water transport, both these authors agree that active absorption can supply but a few per cent of the total quantity of water transpired.

During the night the stomata are closed and water losses from the plant are at a minimum. In the morning, with increasing light intensity, the stomata open and photosynthesis begins. Increasing transpiration causes a gradual rise of the osmotic gradient, and in the course of the day the plant can obtain soil moisture of increasingly higher tension. At this stage the plant has become a "physical water conduit" (Makkink, 1949). Nevertheless, the water uptake lags behind the transpiration and during early or late afternoon, as the leaf develops a moisture deficit, water losses are reduced by closure of the stomata. Photosynthesis diminishes accordingly and it is left to the process of active absorption to restore the turgescence of the plant tissue. It is shown in a later section how closely the water-table fluctuations in an area of phreatophytes reflect the daily progress of evapotranspiration.

Groundwater and Soil Moisture

As phreatophytes are characterized by their use of groundwater, it should be mentioned briefly what water is normally available to plant life. The classification of the occurrence of fluids in porous media that was made by Versluys (1916) distinguishes between four stages of moisture occurrence, depending on its relative continuity (Fig. 2). In the *pendular stage* the pore space is largely filled by vapour. Liquid exists only in small isolated rings around the grain contacts, which are the first regions where the force interaction between liquid molecules can dominate over the force interaction between liquid and solid molecules. Liquid occurrence is defined as being in the pendular stage at that moisture content at which the pendular rings begin to coalesce. The *funicular stage* is characterized by a moisture content whereby the pendular rings coalesce to such an extent that the liquid films become continuous throughout the pore space, enclosing the vapour phase entirely. In the *capillary stage* all pores are occupied entirely by liquid, but the liquid pressure within the pore space is less than the total pressure outside the system. The capillary stage is brought about by the molecular forces that are responsible for the surface energy. In the very narrow intergranular spaces the adhesive forces between the molecules of the liquid and the molecules of the solid exceed the cohesive forces between the molecules of the liquid. The capillary stage ends at

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[1] The amount of plant or soil suction is generally expressed in terms of a moisture potential, which is measured either in pF (which is log 10 of the suction measured in centimetres of water) or in atmospheres.

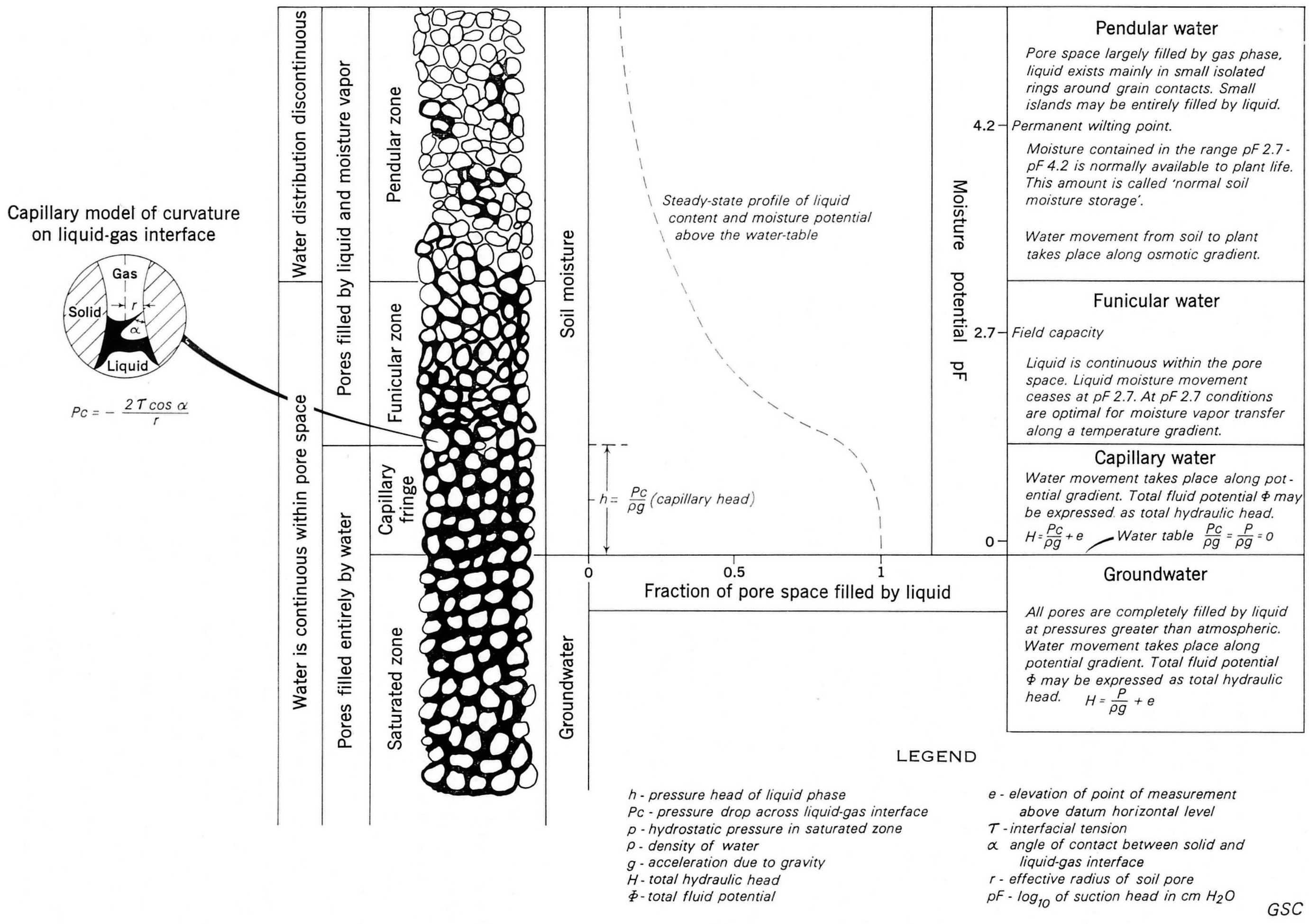

FIGURE 2. Schematic presentation of liquid occurrence in a porous medium and some empirical coefficients pertaining to certain energy conditions.

the *phreatic surface* (water-table), at which the atmospheric pressure and the hydrostatic pressure are in equilibrium. All pore spaces beneath the phreatic surface are completely filled with liquid under hydrostatic pressure, called groundwater, in contrast to the moisture above the phreatic surface, which is collectively referred to as soil moisture.

Figure 2 shows the steady-state profile of moisture potential above the water-table. The range of soil moisture normally available to plant life lies between pF 2.7 (field capacity) and pF 4.2 (permanent wilting point). The actual amount of water stored in the soil between pF 2.7 and pF 4.2 within the 4-foot root zone depends on the texture of the soil, and in Saskatchewan ranges from 4.2 inches in sandy loam to 8.8 inches in heavy clay (Staple and Lehane, 1955, Table 4). This quantity is commonly called "normal soil moisture storage."

Agronomists have paid considerable attention to the question whether upward capillary movement from the water-table could be responsible for replenishing the funicular zone. After an extensive study of the subject van 't Woudt and Hagan (1957) concluded that under field conditions the upward movement from the water-table is restricted for two reasons. First, the general occurrence of a well-structured topsoil with large pores underlain by progressively heavier soil with finer pores severely interferes with the effectiveness of capillary rise; secondly, the hydraulic conductivity of unsaturated soils is virtually zero. It has been shown by Childs (1957) that liquid moisture movement ceases at pF 2.7. In his study of Saskatchewan soils, Staple (1955) concluded that the hydraulic conductivity becomes negligibly small somewhere in the funicular zone at a tension of about 0.3 atmospheres, or pF 2.5.

Phreatophytes in Discharge Areas

Phreatophytes live by virtue of the nightly recovery of the water-table. If it were not for this replenishment, the water-table would soon be out of reach of the roots, and the vegetation would perish. This explains why phreatophytes are particularly common in groundwater discharge areas, for it is in those areas that the recovery potential is largest. As is shown in the final section of this report, in the absence of sufficient groundwater inflow, phreatophytes growing on streambanks and on flood plains may deplete the stream by inducing infiltration of surface water into the riverbanks.

Phreatophytes that use fresh water from a shallow water-table obtain their moisture supply at moisture potentials much below pF 2.7. This situation is not altogether advantageous, for the soil regions that are so close to saturation are not as well aerated as the higher zones. Normally, lack of oxygen has an inhibiting effect on the formation of roots, and pF 1.7 has been considered to be the lowest permissible limit of aeration. Moisture potentials that were measured in conjunction with phreatophytes at Watkins Ranch ranged from pF 2.3 to pF 2.0 in the interval from 0 to 4 feet below surface. Wesseling and van Wijk (1957) reported that 10 per cent by volume of air in the soil is the minimum air requirement for common plants. They commented, however, that willows did not show any retardation in growth rate until the concentration was reduced to about 0.5 per cent.

STUDY OF WATER-TABLE FLUCTUATIONS

Method of Investigation

The first observation wells installed for this study were hand-dug pits, 3 by 3 feet square and 4 to 5 feet deep. To prevent caving below the water-table, the wells were provided with a simple plywood cribbing, leaving sufficient room between the lower edge of the cribbing and the bottom of the well to ensure a response to changes in groundwater level.

During the summer of 1963 a start was made with drilling 10-inch diameter auger holes with a 6-horse power Minute Man mobile drill (Pl. I). The results

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PLATE I
Minute Man mobile drill, used to install 10-inch diameter observation wells.

were excellent. Two people could drill and complete an observation well 6 to 12 feet deep within an hour, a task that would have taken at least a day to accomplish using a hand auger. The part of the bore-hole below the water-table was cased with a fully perforated stove-pipe of 10-inch diameter. After the casing had been installed the well was cleaned with a perforated scoop that was attached to a long handle.

All observation wells were fitted with a Leupold Stevens type F recorder equipped with a 1:1 gauge scale and a time gearing of 1 inch to 24 hours. The instruments were placed on a wooden platform, which served as a protective cover over the well (Pl. II). The recorder charts that were used were subdivided into vertical intervals of 0.01 foot and horizontal intervals of 2 hours by a grid of horizontal and vertical lines. The recorders were activated by standard 5½-inch Leupold Stevens floats, which gave perfect records. Smaller floats were found to produce a step-like graph.

The response of an observation well to changes in groundwater level is a function of the diameter of the well and the permeability of the material. In order to minimize the time-lag between fluctuations of the water-table and those in the

PLATE II
Typical observation well with Leupold Stevens type F recorder, placed on a plywood platform.

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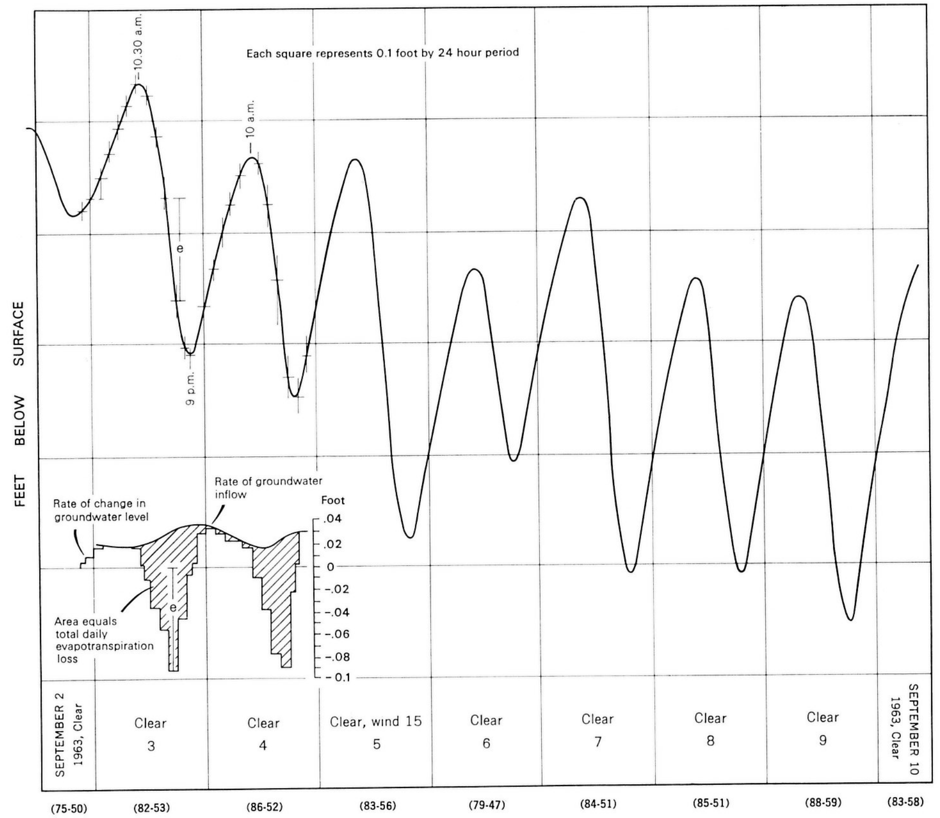
observation well, the well diameter should decrease with decreasing permeability. It was found, particularly in fine-grained materials, that the 10-inch bore-hole was a much more sensitive device to record water-level changes than the hand-dug well. The hydrograph from a 10-inch well in sandy loam showed barometric fluctuations of 0.002 foot over half-hour periods, whereas the recorder on the nearby hand-dug well merely registered the gross daily fluctuations. Moreover, the amplitude of the daily fluctuations in the larger well was 0.015 foot less than the amplitude of daily fluctuations observed in the small-diameter hole.

The effect of well diameter was even more pronounced in clay-loam. The diurnal fluctuations with an amplitude of 0.1 foot that were recorded in the small-diameter well showed merely as a sinuous water-table decline on the records from the large well. For these reasons only records from small-diameter wells have been used for the calculation of the values of consumptive use that are reported later in this bulletin.



Note: Figures in parentheses refer to temperature range (°F) at Davidson, from monthly records of Meteorological Observations in Canada; Meteorological Branch, Department of Transport

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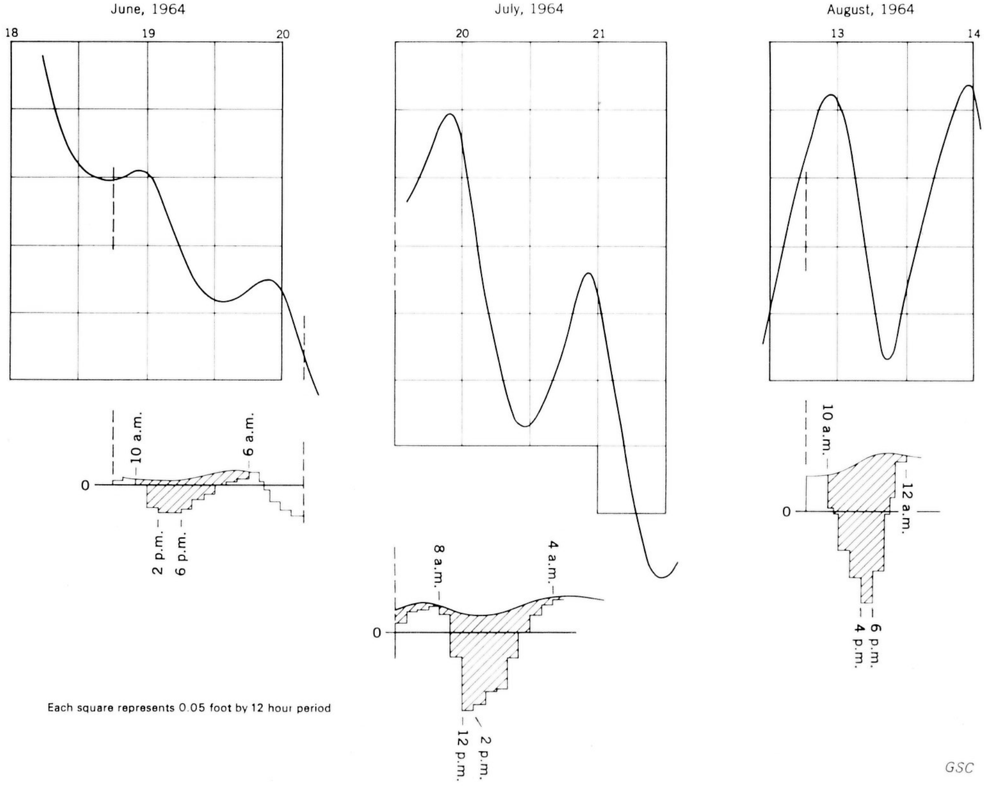
FIGURE 3. Typical diurnal water-table fluctuations in a field of baltic rush and wolf willow (record from observation well No. 1, Arm River near Davidson).

Hydrograph Characteristics

Analysis of Typical Phreatophytic Fluctuations

Figure 3 shows typical diurnal fluctuations of the water-table in a dense stand of wolf willow and baltic rush in the Arm River valley near Davidson. In the period shown the daily drawdown started between 8 a.m. and 10.30 a.m. and continued until 6 to 9 p.m. During the longer periods of daylight in July and August the drawdown continued until midnight, or even shortly thereafter. The difference in water-level elevation between the beginning and the end of the graph is part of the summer decline of the water-table. In the autumn, when the nightly recovery predominates over the daily drawdown, this trend reverses and the water level shows a day-to-day rise (cf. Fig. 9).

As already mentioned, phreatophytes grow in areas of groundwater inflow. Thus, referring to Figure 3, on September 3 at 10.30 a.m. the transpiration requirements of the vegetation were just balanced by the amount of upward-moving groundwater and the water level remained stationary as long as the two balanced.



IGURE 4. Records from observation well No. 1, Arm River near Davidson, showing the change in hours of maximum water uptake throughout the summer.

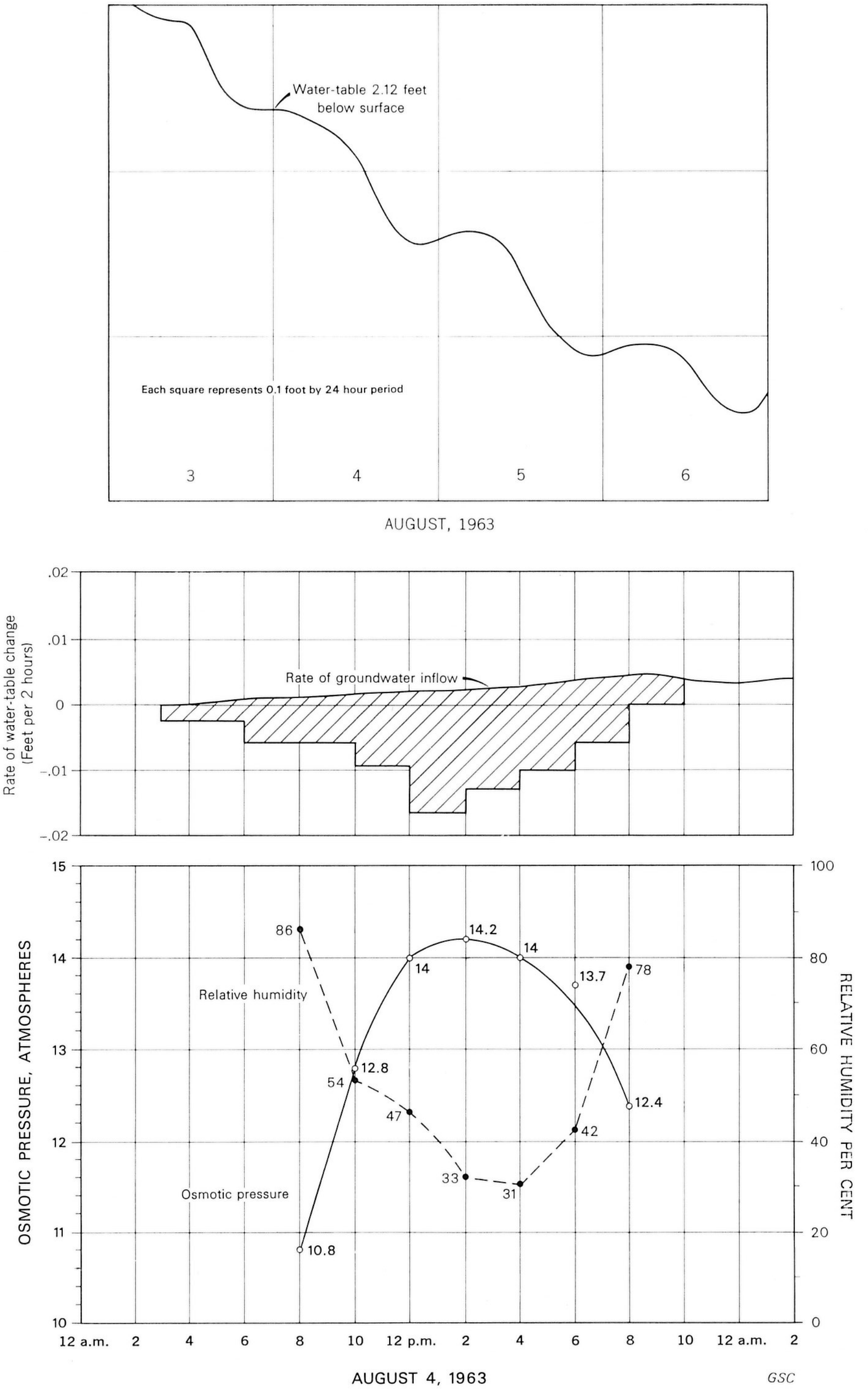


FIGURE 5. Relation of groundwater consumption by wolf willow to variations in relative humidity and osmotic pressure. Data recorded at Watkins Ranch, August 4, 1963.

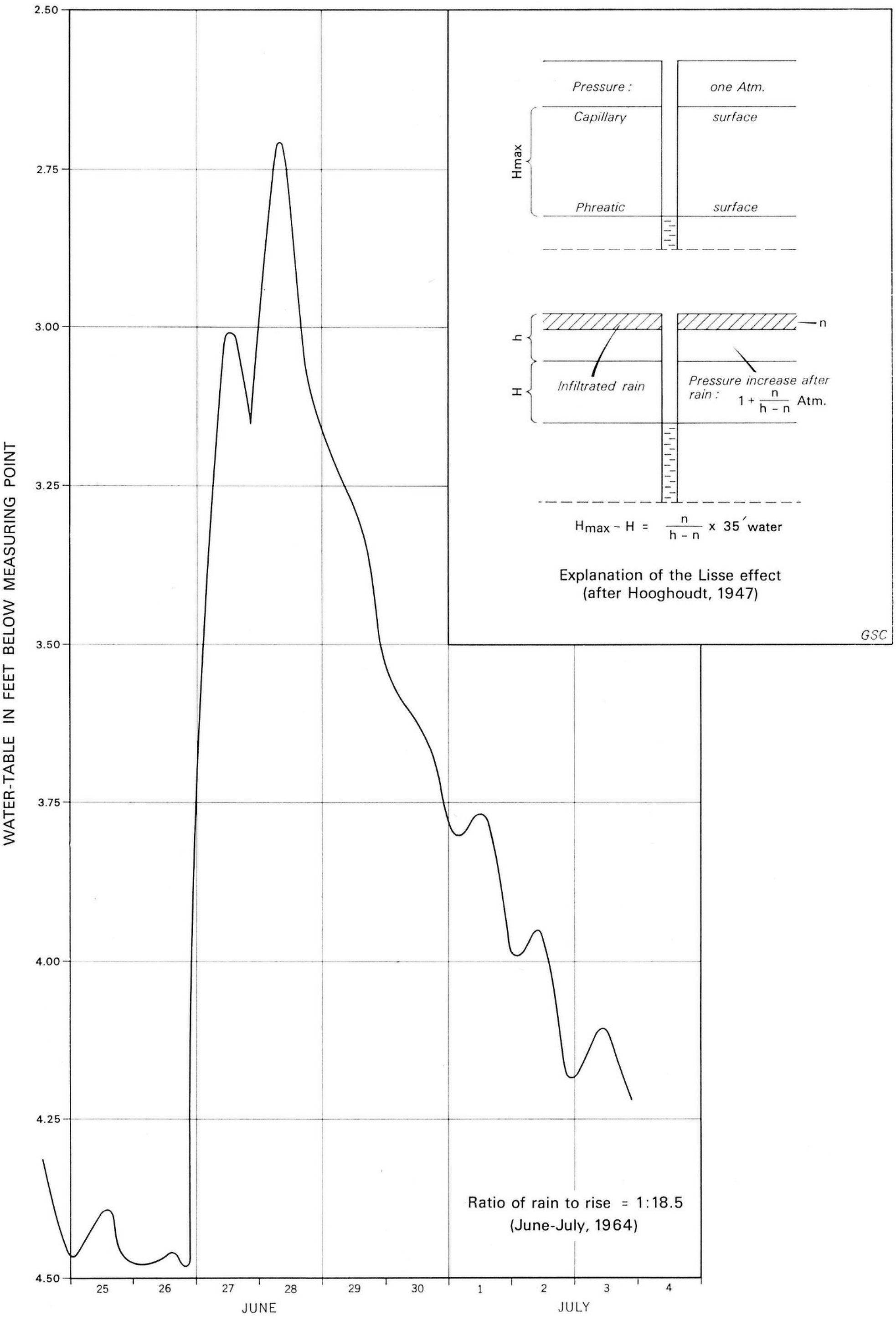


FIGURE 6. Example of the Lisse effect (record from observation well No. 10, baltic rush, Arm River near Davidson).

In the early afternoon, however, the plants were using all groundwater inflow plus some groundwater out of storage, resulting in a decline of the water-table. At 9 p.m. evapotranspiration had come to a standstill and upward groundwater-flow replenished the previous losses from storage, and the water-table rose.

Following this line of reasoning Troxell (1936) concluded that, "The groundwater record is merely an accumulative curve of the rates of groundwater inflow (plus) and the transpiration use (minus)." Troxell showed that by plotting the first derivative of the groundwater hydrograph the amount of water losses as well as the changing rate of groundwater inflow could be determined graphically. This procedure, known as the Troxell analysis, is shown on the bottom of Figure 3. As is indicated in this diagram, on September 3 measurable groundwater losses started at 10 a.m., reached a maximum between 4 and 6 p.m., and dropped to zero by midnight. The graphic differentiation shows also the small percentage of water that may be withdrawn by active absorption. For example, if the water losses after sunset are considered to be brought about by root pressure, it can be seen that these quantities indeed amount to less than 10 per cent of the total water losses of the day.

Figure 3 shows furthermore that maximum evapotranspiration occurred between 4 and 6 p.m. and not — as was mentioned in the introduction — during the early afternoon. Examination of the records of the same observation well reveals that the hours of maximum water uptake vary throughout the summer (*see* Fig. 4). Hours of maximum evapotranspiration in the middle of June are from 2 to 6 o'clock in the afternoon, in July from noon until 2 p.m., and in August and September in the late afternoon, between 4 and 6 o'clock.

Anticipating a more detailed account of consumptive use, it may be remarked here that the moment at which evapotranspiration starts to diminish is not related to the absolute amount of water transpired earlier in the day. For instance, in June reduction commences after evapotranspiration of 0.07 inch, in July after 0.108 inch, in August and September after 0.324 inch.

The correlation between daily variations in relative humidity, rate of evapotranspiration, osmotic pressure, and water-table elevation is shown in Figure 5. The diagram shows part of the groundwater hydrograph, recorded in a dense stand of wolf willow at Watkins Ranch. The enlarged graphical differentiation of August 4, 1963, shows that after small evaporation losses during the night transpiration started at 6 a.m. and reached a maximum between noon and 2 o'clock in the afternoon. With increased evapotranspiration the osmotic pressure[1] in the upper leaves of wolf willow rose from 10.8 atmospheres at 8 a.m. to 14.2 atmospheres at 2 p.m. Following the maximum water uptake, groundwater consumption diminished after 2 o'clock and dropped to zero by midnight. The osmotic pressure

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[1] The osmotic pressures were measured with a thermo-electric osmometer, model 301-A, manufactured by Mechrolab Inc., Mountain View, California. The instrument operates on the principle of vapour-pressure lowering. The osmometer was calibrated with NaCl solutions ranging in concentration from 0.1 to 1 mole, giving a theoretical range of osmotic pressures from 4.2 to 42.8 atmospheres. With the aid of Walter's tables (Walter, 1936) a calibration curve was constructed relating the instrument readings (ohms) directly to the osmotic pressure at freezing point of the cell fluid. Although the nulldetector of the instrument permitted measuring resistance changes of 0.01 ohm, the osmotic pressures that were determined from the nomogram were taken to the nearest tenth of an atmosphere.

declined similarly from 14.2 to 12.4 atmospheres by 8 o'clock in the evening. Note that the reduction in evapotranspiration started when the relative humidity was still going down (Fig. 5).

To appreciate the magnitude of the effects that may temporarily disturb the regularity of the typical phreatophyte fluctuations, it is necessary to explain briefly how other natural processes affect the position of the phreatic surface. The effects of rain, barometric pressure, and temperature are discussed below; of these, the effects of rain are the most important.

The Effects of Rain

It is a common observation that the water-table at 2 or 3 feet below surface in light sandy soils rises fast and substantially after the lightest of rains. The observed relation between rainfall and rise is commonly of the order of 1:18 (Fig. 6). This effect was described by Hooghoudt (1947), who referred to it as the *Lisse effect,* after the village of Lisse in Holland where the effect was first observed.

The explanation of the Lisse effect, which bears no relation to groundwater recharge, has to be sought in the behaviour of the capillary fringe. Figure 6 shows schematically the position of the capillary fringe before the rain. Rain infiltrating evenly into the light soil acts as a tightly closing lid compressing the air above the capillary fringe. If "n" is the depth of rain penetration and "h" the distance from the surface to the top of the capillary fringe, the pressure increase of the air above the capillary fringe is given by Hooghoudt as:

$$\frac{h}{h\text{-}n} - 1 = \frac{n}{h\text{-}n} \text{ atmosphere} = \frac{n}{h\text{-}n} \text{ x } 35 \text{ feet water.}$$

the negative capillary head, which at first amounted to $-H_{max}$ has now become $-H_{max} + \frac{n}{h\text{-}n}$. Equilibrium will be re-established once the phreatic surface has risen the amount $H_{max} - H$ or $\frac{n}{h\text{-}n}$ x 35 feet of water. Thus with a capillary fringe at 20 inches below surface, 1 inch of rain, which infiltrates to a depth of 1 inch, will cause a rise of the phreatic surface of 1.75 feet, giving a normal rain/rise ratio of 1:20.

It has been observed in the Qu'Appelle valley that the rapid rise of the water-table alongside Qu'Appelle River caused an immediate increase in streamflow (cf. Fig. 12). This explains why light showers sometimes cause a disproportionate increase in run-off.

As the surface soil dries out, the original H_{max} will be re-attained, commonly within 10 days. The optimum condition for the Lisse effect exists with a water-table at about 2 feet below surface. When the water-table falls, the effect diminishes.

The writer has never observed it in areas where the water-table was deeper than 4 feet.

Where the phreatic surface is so shallow that the capillary fringe reaches the surface, rain produces an almost instantaneous rise of the water-table, which at first glance is somewhat similar to the Lisse effect (Fig. 7). However, the rise is seldom as high and it is always followed by an equally fast decline. Hooghoudt (1947) ascribed the rapid decline to evaporation and he called it the *Wieringermeer effect,* after the Wieringermeer polder in Holland where it was first studied. The fast decline is caused by evaporation from an incipient capillary fringe in which the menisci have not yet reached a maximum curvature. Water is removed until the maximum negative capillary head has been established, then the decline of the water-table stops. The preceding rise due to the rain is called the *reversed Wieringermeer effect.* Hooghoudt (1947) duplicated both effects experimentally.

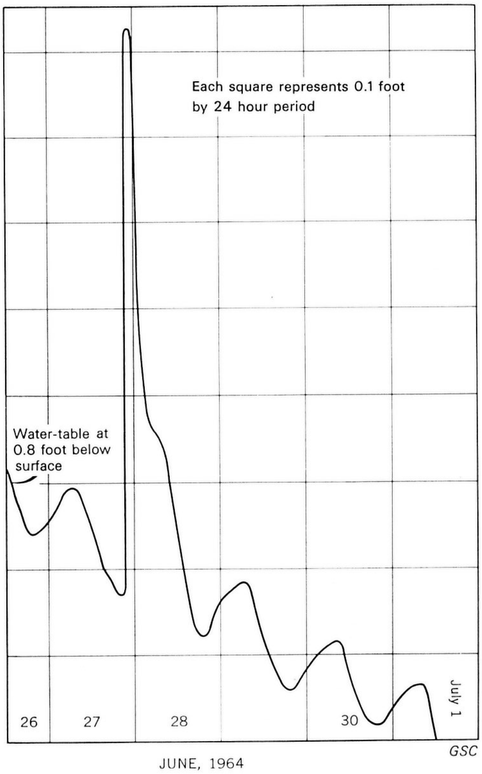


FIGURE 7. Example of the Wieringermeer effect (record from observation well No. 23, willow, Watkins Creek).

The Effect of Barometric Pressure

The effects of changes in barometric pressure are slight, but they are clearly noticeable, particularly during thunderstorms (Fig. 8). The explanation of the barometer effect is the same as for the Lisse effect. The sudden decrease in barometric pressure causes a temporary pressure difference between the atmosphere in the well and the air entrapped in the soil. This pressure difference has the same effect as the increased air pressure that was mentioned as the cause of the Lisse effect, and the phreatic surface rises accordingly. In phreatophyte studies the effect is rarely significant. On the prairie, however, where summer cloudbursts are often associated with thunderstorms, barometric fluctuations such as shown in Figure 8 often precede a Lisse effect or a reversed Wieringermeer effect.

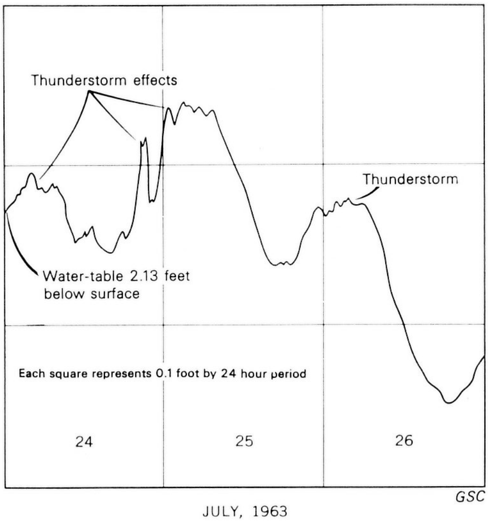


FIGURE 8. Barometer effect during thunderstorms (record from observation well No. XVII, western cottonwood, South Saskatchewan River near Riverhurst).

The Effect of Temperature

Robinson (1958) stated that the factor exerting the greatest influence on the use of groundwater by phreatophytes is temperature. Hence, the largest daily fluctuations may be expected to coincide with the highest mean daily temperatures. This aspect of the influence of temperature has already been shown to some extent in Figure 4 and is discussed more fully in conjunction with consumptive use. As far as the effects of temperature changes on the water-table are concerned, it can be seen from the following expression that the capillary rise is directly proportional to the interfacial tension:

$$-\mathrm{H} = \frac{2\tau \cos. \alpha}{r_{ct} \quad \rho g} \qquad \text{where}$$

$-\mathrm{H}$ — capillary rise above the water-table

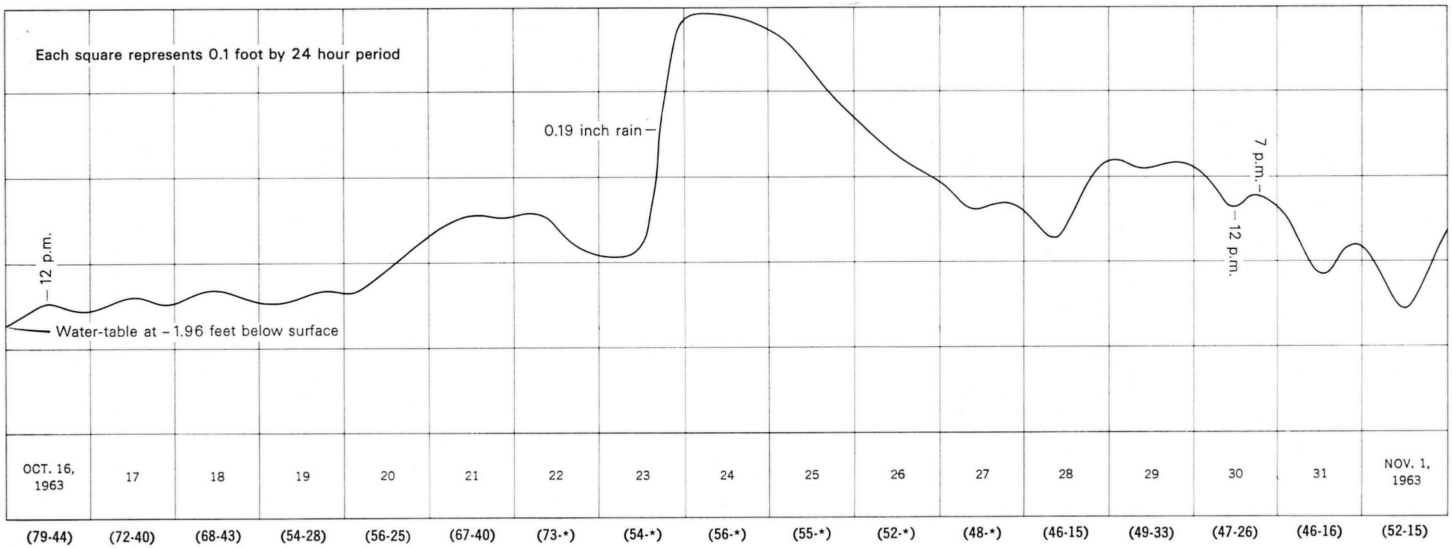
τ — interfacial tension

r_{ct} — radius of capillary tube (effective pore size)

α — angle of contact between solid and liquid-gas interface

ρ — density of liquid phase

g — acceleration due to gravity.



Note : Figures in parentheses refer to temperature range (°F) at Davidson, from monthly records of Meteorological Observations in Canada; Meteorological Branch, Dept. of Transport. Asterisk indicates no record.

GSC

FIGURE 9. Seasonal and temperature effects. The daily water-table fluctuations become less during autumn, and the day-to-day trend of the water-table reverses from downward to upward. From October 27 to November 1, the hydrograph shows water-table fluctuations in response to changes in surface temperature. (Record from observation well No. 1, wire rush and wolf willow, Arm River near Davidson.)

King (as quoted by Meinzer, 1923b) was the first investigator who described that in accordance with daily temperature fluctuations the water level in an experimental well *rose daily* and fell during the night. Meinzer quoted this experiment to illustrate how the lower interfacial tension during the higher daytime temperature caused a decrease in capillary rise and a consequent rise of the phreatic surface. Van 't Woudt and Hagan (1957) referred to the same process, when commenting that higher summer temperatures decrease the water-holding capacity of the soil.

Summer soil-temperatures in Saskatchewan[1] show daily fluctuations of up to 12° F in the upper 10 cm of the soil, diminishing to 2 to 3° F in the range from 10 to 20 cm. In the region below 20 cm the temperature remains unaffected by daily variations and decreases gradually from 65°F at 20 cm to 53°F at 150 cm. Thus, if the capillary fringe would be within the zone of daily temperature fluctuations, one could expect diurnal water-table fluctuations in response to daily changes in capillary rise. These fluctuations would be in *reverse order* to those of the phreatophytes. In Saskatchewan, the temperature effect has not been observed during the summer, partly because the capillary fringe is generally below the zone of temperature fluctuations, and partly because the phreatophyte fluctuations would overshadow the effect.

The situation is different during October and November, however, when the water-table has risen due to autumn rains and to the excess of nightly recovery over daily drawdown (Fig. 9). During this time of the year there may be frost at night and relatively warm weather during the daytime. This was so in October 1963 when the surface temperatures fluctuated between 16°F at night and 50°F during the day. Meanwhile, the upper soil layers had already cooled to 44°F, resulting in a downward *increase* in temperature from 44°F at 20 cm to 53°F at 150 cm.

Under these circumstances, two conditions could have produced diurnal water-table fluctuations of the type shown in Figure 9. First, the capillary fringe was probably within reach of the daily temperature fluctuations and varied in accordance with daily variations in interfacial tension. Secondly, there might have been water-vapour transfer along a temperature gradient, upward during the night, from the capillary fringe to the cooler surface, and downward during the day when the thermal gradient was reversed.

Fluctuations like those shown in Figure 9 were observed during October 1963 as well as October 1964, although the fluctuations during the cooler days of October 1964 did not exceed 0.02 foot per day.

Estimating Consumptive Use From Daily Water-Table Fluctuations

A good approximation of the amount of groundwater lost through evapotranspiration can be obtained from the diurnal water-table fluctuations by using either the White method or the Troxell analysis method.

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[1] From monthly record of meteorological observations in Canada; Canada Department of Transport, Swift Current Experimental Station, Saskatchewan.

White's Method

White (1932, pp. 60, 61, 69, and 81) suggested the following equation to compute the total quantity of groundwater withdrawn by evapotranspiration during a 24-hour period:

$q = y\ (24 \pm s)$ where

q is the depth of water withdrawn from an infinitesimal area, in feet,

y is the specific yield of the soil in percentage by volume,

r is the hourly rate of groundwater inflow in feet per hour (r, which has to be the average rate for the 24-hour period is found from the water-table rise between midnight and 4 a.m. or between 2 and 6 a.m., depending on the duration of the drawdown), and

s is the net rise or fall of the water-table, in feet, during the 24-hour period.

The quantities on the right-hand side of the equation, with the exception of y, are measured directly from the hydrograph. Daily values of $24r \pm s$ are tabulated for each month and their summation gives the total amount of monthly evapotranspiration, uncorrected for specific yield. The procedure is shown in Figure 10.

The Troxell Analysis

As was pointed out in a previous section, Troxell's graphical differentiation of the hydrograph shows the daily progress of evapotranspiration as well as the daily changes of groundwater inflow. The latter can be seen to vary inversely with the elevation of the water-table (Fig. 10). Quantitatively, the difference between the curves of the rate of inflow and the rate of water-level change gives the rate of evapotranspiration. The area between the two curves equals the daily volume of evapotranspiration losses; the resulting figure is uncorrected for specific yield.

The writer found that the Troxell analysis gave values for consumptive use that were consistently 4 to 6 per cent higher than those that were calculated with the White method (Fig. 10). However, White's method probably gives more accurate results, for it permits estimates of $24r \pm s$ to the nearest 0.002 foot and also requires less subjective judgment than the Troxell analysis. For these reasons the White method was used to calculate the values of groundwater consumption reported later in this bulletin.

Determination of Readily Available Specific Yield

The uncorrected values of consumptive use obtained by the method of either White or Troxell have to be multiplied by White's factor "y", which is specific yield. The actual amount of water that is drained from a soil when the phreatic surface is lowered over a certain distance is controlled by the capacity of the soil to yield water under the pull of gravity. The capacity is expressed as *specific yield,* which is defined as the ratio of (1) the volume of water that a saturated soil will yield by gravity to (2) the volume of the soil. Although simple in concept, specific yield is difficult to measure, for its value depends on the duration of the drainage.

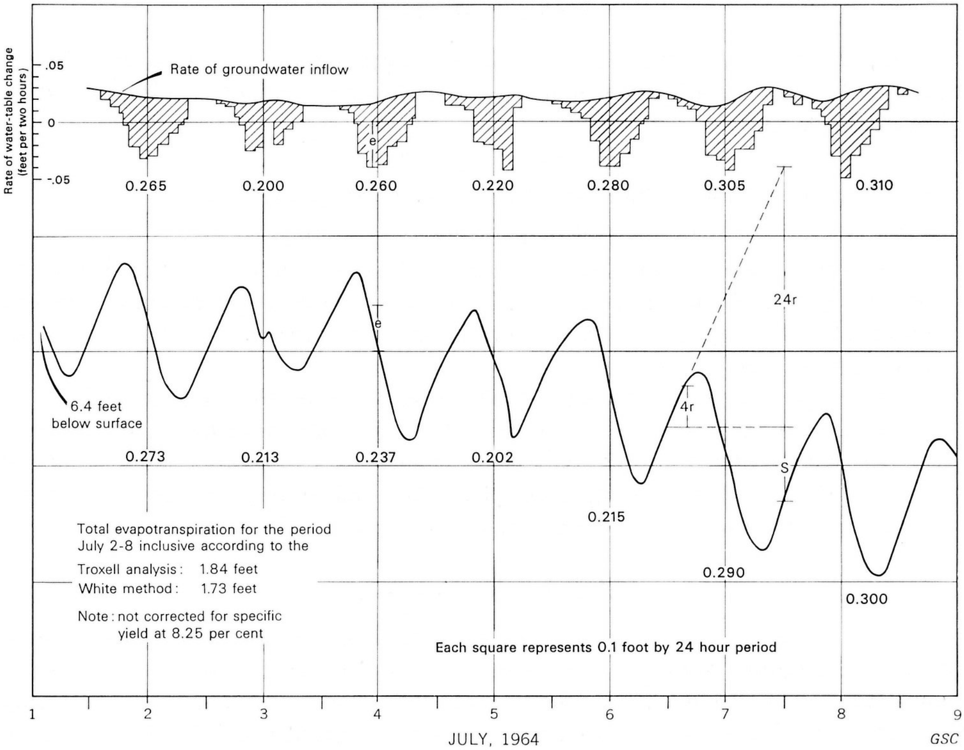

FIGURE 10. **Demonstration of the White method and the graphic differentiation according to Troxell (record from observation well No. 3, Manitoba maple, Arm River near Chamberlain).**

King (as quoted by Meinzer, 1923b) showed that the true specific yield of a fine sand (sand #100) is about 20 per cent. However, he obtained this value after a drainage experiment that lasted 2½ years. After one day of the experiment only one half of the ultimate yield had drained out. For the purpose of the following discussion this amount will be called *readily available specific yield* and its numerical value is taken as 50 per cent of the true or ultimate specific yield.

White may have intuitively referred to what the writer has called 'readily available specific yield' rather than true specific yield, for the experimental values of specific yield that he used in his calculations of consumptive use support this idea.

Specific yield can be determined in many ways. Meinzer (1923b) listed seven principally different methods, one of which is based on calculation of the specific retention of a soil from its grain-size distribution. *Specific retention* of a soil is the ratio, expressed as a percentage by volume, of (1) the amount of water the soil will retain after saturation against the force of gravity to (2) its own volume. It can be seen that the interconnected porosity of a soil or rock is the sum of specific retention and specific yield. Specific retention is analogous to the agricultural concept of *field capacity,* which is defined as the lowest moisture content, expressed as a percentage by weight, to which the soil may be brought by drainage alone.

In the absence of suitable equipment to measure specific yield directly, estimating it from specific retention and soil porosity had one important advantage over other indirect methods, in that published information is available on field capacities and saturated moisture contents of soils in southern Saskatchewan (Staple and Lehane, 1955). The method used in this study was developed in 1907 by Briggs and McLane. They determined the "moisture equivalent" of more than 100 samples of saturated soil by subjecting them to a centrifugal force of 3,000 times the force of gravity. From these experiments they found that each per cent of clay (sediments less than 0.005 mm in diameter) in the samples corresponded to a retentive power of 0.62 per cent of moisture (by weight), and each per cent of silt (0.005–0.05 mm) corresponded to a retention of 0.13 per cent of moisture. They also found that each per cent of fine sand (0.05–0.25 mm) had a rention of 0.002 per cent of water, whereas each per cent of sand (0.25–2 mm) had a power to retain 0.022 per cent of water.

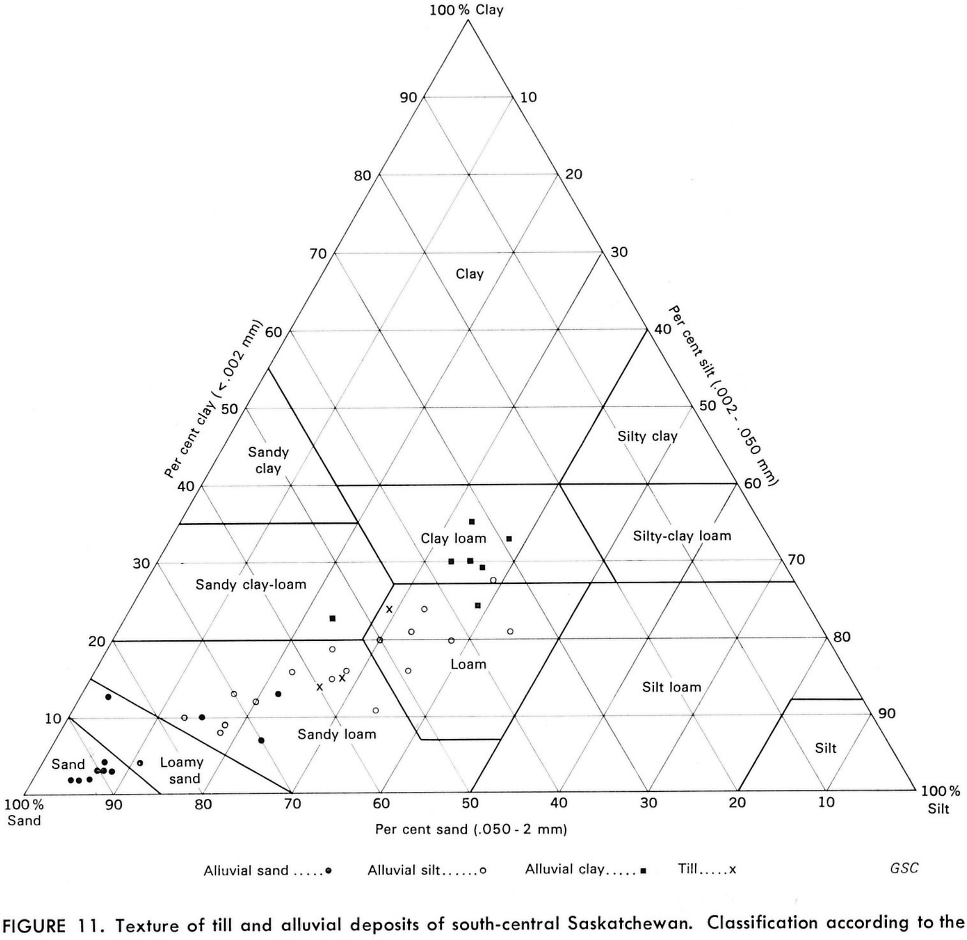

FIGURE 11. Texture of till and alluvial deposits of south-central Saskatchewan. Classification according to the U.S. Department of Agriculture.

TABLE I. Average Values of Water Retained and Yielded By Soils In South-Central Saskatchewan

						a	b	c	d = axbxc	e		
Number of samples	Soil texture[1]	Grain size distribution, % by weight				Moisture retained[2] % by weight	Piper's correction factor	Specific gravity of soil[3]	Moisture retained % by volume	Saturated moisture content % by volume[4]	Specific yield, % by volume	
		<0.005 mm	0.005—0.05 mm	0.05—0.25 mm	0.25—2 mm						actual y e − d	readily available $y' = 0.5y$[5]
7	sand	4	5	33	58	4.46	1.4	1.65	10.30	30	19.70	9.75
2	loamy sand	9.5	6	15.5	69	8.22	1.2	1.50	14.80	33	18.20	9
15	sandy loam	16	18	42	24	12.90	1.0	1.50	19.35	36	16.65	8.25
8	loam	26.5	30	31	12.5	20.64	1.0	1.40	28.90	47	18.10	9
6	clay loam	38.5	27.5	23	11	27.87	1.0	1.35	37.62	50	12.38	6.25

[1] Soil texture classification is based on 2-micron clay (*see* Fig. 11)

[2] Calculated from the retention coefficients of Briggs and McLane (1907)

[3] From Israelsen, 1962, Table 7.4

[4] From Staple and Lehane (1955) and Israelsen (1962, Table 7.4)

[5] Taken to the nearest 0.25 per cent

Subsequent work by Piper (1933) indicated that the ratio of centrifuge moisture equivalents to field capacity is close to unity for moisture equivalents between 12 and 34 per cent by weight. For moisture equivalents of less than 12 per cent (sand and loamy sand), however, the ratio increases progressively. At a moisture equivalent of 5 per cent the ratio is 1.4. This means that moisture equivalents below 12 per cent that are calculated with the retention coefficients given by Briggs and McLane have to be adjusted by Piper's correction factor before they can be used as a reliable estimate of field capacity.

During the field stage of the phreatophyte study, representative samples of the material at and below the water-table were taken from each observation well. Complete grain-size analyses were done for all samples and the materials were grouped according to the standard textural soil classes of the United States Department of Agriculture[1] (Fig. 11). Next, the amount of moisture that could be retained by each sample was calculated with the given retention coefficients and the average amount of moisture retained was determined for each textural soil class (Table I). Piper's correction factor was applied to the average values for sand and loamy sand. The figures obtained by this procedure compared favourably with the values of field capacity of Saskatchewan soils reported by Staple and Lehane (1955).

Values of true specific yield of each soil class were obtained by subtracting the average amounts of moisture retained from the average values of saturated moisture content as given by Staple and Lehane (1955), and Israelsen and Hansen (1962). The answer was multiplied by the specific weight of each soil class, to convert the amount of water yielded from per cent by weight to per cent by volume. For reasons explained above, the resulting values were divided by 2 to obtain the *readily available specific yield* of all soil classes. Average values of moisture retention and specific yield for each soil class encountered during the investigation are summarized in Table I.

Since it would not be justified to calculate values of specific yield for each individual sample by using average values of porosity and specific weight, the estimates of consumptive use given in the next section are all based on the average values of readily available specific yield shown in Table I. Thus, for each observation well, the textural soil class of the material below the water-table was determined from its grain-size distribution, and the corresponding value of y' (to be used as "y" in White's equation) was taken directly from Table I.

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[1] Note that this classification is based on the 2-micron clay.

PHREATOPHYTES IN SOUTH-CENTRAL SASKATCHEWAN

Summary of Field Observations on Phreatophytic and Non-Phreatophytic Vegetation

During the preliminary stages of this study a list was made of all potential phreatophytes of south-central Saskatchewan (*see* Table II), by selecting those plant species that were common to Robinson's list of phreatophytes and Budd's flora of the Canadian prairies (Budd, 1957).

TABLE II. Plant Species Common to Robinson's List of Phreatophytes and Budd's Flora of the Canadian Prairies

Species	Common Name	Reference[1]
Acer negundo L. var. *interius* Sarg.	Manitoba maple	R.32, B.182
Atriplex hastata L.	halberd-leaved orache[2]	R.32, B.96
Distichlis stricta (Torr.) Rydb.	saltgrass[2]	R.56-59, B.50
Juncus balticus Willd. var. *montanus* Engelm.	baltic rush[2]	R.36, B.66
Medicago sativa L.	alfalfa	R.59-61, B.168
Populus	poplar	R.61-64, B.80-81
Salicornia rubra L.	red samphire[2]	R.38, B.100
Salix	willow	R.64-66, B.82
Shepherdia argentea Nutt.	buffalo berry	R.39, B.194
Suaeda depressa Wats.	western sea-blite[2]	R.39, B.101

[1] R. refers to Robinson (1958) page number; B. refers to Budd (1957)
[2] Alkali tolerant, common in saline meadows

The phreatophytic behaviour of each of these species was tested in the field and additional observations were done on species that occupied apparent groundwater habitats, but which were not listed by Robinson. Finally, a number of observations were carried out on species that were already found to be phreatophytic at certain locations, but which grew also at sites where a deep water-table seemed to preclude a phreatophytic existence. Whether or not a species was

PLATE III. Aerial photograph of Arm River between Chamberlain and Findlater showing the location of observation well No. 3 in dense forest of Manitoba maple. *MTS 17301-61* phreatophytic was judged solely by the presence or absence of the characteristic daily water-table fluctuations.

A summary of these field observations follows, including pertinent data on depth to water, water quality (Table V) and groundwater consumption. The available seasonal values of groundwater use are compiled in Table VI. The precise locations of all observation wells, arranged according to the following sequence of discussion are given in Table XI.

Acer negundo L. var. *interius* Sarg. — Manitoba maple

Manitoba maple is the common maple of the prairies. It is a medium-sized tree, about 40 feet high, which forms dense forests on the river flood plains. The phreatophytic nature of Manitoba maple was tested at two places in the valley of Watkins Creek (Fig. 1) and at two places in the Arm River valley (near Chamberlain and near Findlater), in the only reach of Arm River where the valley contains a forest of Manitoba maple (Pl. III). The trees were found to be phreatophytic at all sites.

The water-table at these places was 5 to 7 feet below surface and did not fall more than 1.5 feet during the summer. Because of the relatively deep phreatic surface, the effects of rain and rapid evaporation were barely noticeable on the hydrographs. Seasonal consumptive use by Manitoba maple was determined at the two Arm River sites during the summer of 1964 and amounted to 21.12 and 16.56 inches respectively.

The growth of Manitoba maple indicates groundwater of good quality.

Atriplex hastata L. — halberd-leaved orache

This annual species is common in saline meadows and around alkali sloughs. Two saline areas with *A. hastata* as a minor component of the plant community were studied in the Arm River valley near Bethune, but no phreatophytic fluctuations were observed.

Distichlis stricta (Torr.) Rydb. — saltgrass

Saltgrass grows in abundance in saline meadows of the prairies. It is one of the best known phreatophytes in the western United States, for "more work has been done in determining the use of water by *D. stricta* than has been done for any other phreatophyte" (Robinson, 1958, p. 57).

The species was studied near Findlater and at two locations near Bethune. At Bethune the Arm River valley is very saline, as shown by the white efflorescences of sodium sulphate. The writer's study of the flow system at Bethune revealed upward movement of relatively saline water (3,300 ppm total dissolved solids) from the Middle Beechy Sandstone Member (Bearpaw Formation) at a depth of 200 feet. Near-surface concentration due to upward movement and subsequent evaporation has produced extremely saline groundwater at shallow depths in the valley. The water that was taken from one of the observation wells contained over 75,000 ppm total dissolved solids (Table V).

The pasture vegetation at Bethune is made up of about equal percentages of saltgrass, wild barley (*Hordeum jubatum* L.), and western sea-blite (*Suaeda depressa* Wats.), with minor quantities of halbred-leaved orache (*Atriplex hastata* L.), Nuttall's alkali grass (*Puccinellia nuttalliana* (Schultes) Hitchc.), and gumweed (*Grindelia perennis* A. Nels). The average depth to the water-table at the Bethune sites was 2.5 and 6 feet. The wells responded to influences of rain and barometric pressure, but neither showed diurnal water-table fluctuations.

At the Findlater site, the water-table was 6 feet below surface. The pasture vegetation consists of saltgrass and a few meagre bushes of western snowberry (*Symphoricarpos occidentalis* Hook.), neither of which was found to be phreatophytic.

From these observations it had to be concluded that saltgrass could not be considered as a phreatophyte in the area under discussion. This conclusion is consistent with Dodd's conclusion regarding saltgrass (Dodd, 1960). After studying the osmotic pressures of plants in saline areas of Saskatchewan, Dodd (p. 221) found that the osmotic pressure of saltgrass ranged from 21.7 atm to 47.8 atm during one summer. He interpreted this wide range as an indication of "a high osmotic pressure of the soil solution and a lack of sufficient soilmoisture, either from runoff or from capillary flow from the water-table."

Juncus balticus Willd. var. *montanus* Engelm. — baltic rush

Baltic rush or wire rush is the most common rush of the prairies (Budd, 1957). It grows in wet places and on sandy and saline shores throughout the area. Its phreatophytic nature was confirmed in the Arm River valley east of Davidson. There, the river occupies a gentle valley not more than 50 feet deep and half a mile wide. The valley walls show three distinct zones of vegetation (Pl. IV):

(a) an upper zone, made up of prairie grasses, reaching from the edge of the valley to about half-way down;
(b) a middle zone of not more than 40 feet wide consisting of wolf willow (*Elaeagnus commutata* Bernh.); and
(c) a lower zone, reaching from the wolf-willow shrubs to the river and consisting principally of wire rush, locally mixed with low bushes of western snowberry, or patches of slough grass (*Beckmannia syzigachne* (Steud) Fern.).

It seems to this author that baltic rush is a true phreatophyte in the sense of Meinzer's definition. It *habitually* feeds on groundwater. The species has a high salt tolerance, but its occurrence is certainly not restricted to saline areas. The chemical composition of groundwater utilized by baltic rush in combination with other phreatophytic species is given in Table V.

From the records of observation well No. 10, consumptive use by baltic rush from June 1 to November 1, 1964 was calculated to be 22.80 inches with an average water-table position of 3 feet below surface. The diurnal fluctuations reached a maximum amplitude of 0.15 foot during August and stopped abruptly at September 19.

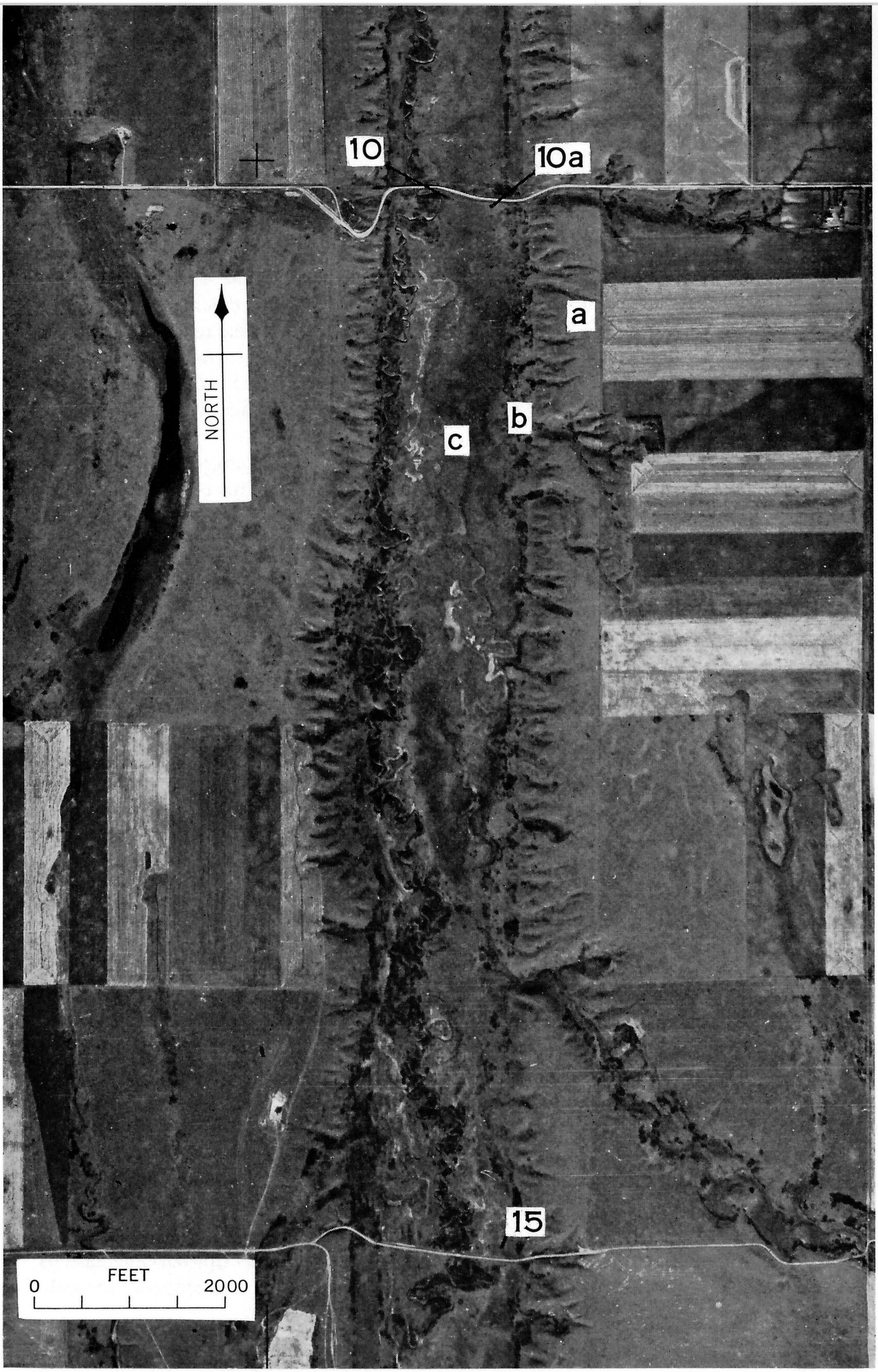


PLATE IV. Aerial photograph of Arm River east of Davidson, showing vegetation zones in the gently sloping valley; (a) prairie grasses, (b) wolf willow, (c) baltic rush and scattered bushes of snowberry. Numbers indicate wells. *MTS A15536-135*

Medicago sativa L. — alfalfa

Since White's description of Mr. Hendrickson's alfalfa field (*in* Meinzer, 1927), alfalfa may be considered as the classical phreatophyte. Because of its tolerance to salts, its deep tap root, and its economic importance as a forage crop, alfalfa is sometimes regarded as the ideal plant to substitute for uneconomic phreatophytes. The species was introduced in western Canada as a fodder crop and has become a common plant throughout most of the prairies.

The writer studied the relation between alfalfa and groundwater at Watkins Ranch, where the alfalfa was grown for fodder on a small irrigated sand delta, spreading from Watkins Creek into the Qu'Appelle valley (*see* Pl. X). The water-table in the well on the delta was 6 feet below surface, and showed no daily fluctuations. Another observation well was put down in a community pasture of the Saskatchewan Department of Agriculture, where alfalfa had been established without irrigation on an upland sand-plain. In July 1963, the water-table in this area stood at 8.75 feet below surface, but no phreatophytic fluctuations were recorded. These observations show that the alfalfa grown there is not phreatophytic.

Populus — poplar

The genus *Populus* is represented by eight species on the Canadian prairie, three of which occur in south-central Saskatchewan: *Populus tremuloides* Michx., aspen poplar or trembling aspen; *P. balsamifera* L., balsam poplar; and *P. sargentii* Dode, western cottonwood or river cottonwood.

Aspen poplar is the typical tree of the bluffs in the parkland and of the forests in the northern parts of the Prairie Provinces. Aspen poplar grows in pure stands, except in poorly drained soil, where it may be associated with balsam poplar (Bird, 1961). The writer studied the relation between aspen poplar and groundwater at two locations. The first site was a large grove of tall mature trees growing on ground moraine with a water-table at 8 feet below surface. The observation well was very sensitive to changes in barometric pressure (probably because of the rather poorly permeable till and great depth to the water-table), but phreatophytic fluctuations did not occur.

The second site was a poplar bluff in an ancient, sand-filled tributary to Qu'Appelle River. The water-table was 5 feet below surface and the trees produced slight fluctuations with an amplitude of a few hundredths of a foot per day. It was calculated that the consumptive use for August 1963 amounted to a mere 0.87 inch.

Aspen poplars do not generally occupy typical groundwater habitats and they should not be considered as phreatophytes. Aspen poplar is the only *Populus* species that is not restricted to "river bottoms and wet places" in Budd's description of poplar habitats (Budd, 1957, pp. 80–81). Bird (1961) found that aspen poplars growing around a permanent or temporary slough tend to occupy the higher ground in a zone around a central ring of willows.

The observations in the abandoned stream channel, on the other hand, suggest that the species may locally be phreatophytic in the transition area between parkland and open grassland. This would be in line with Coupland's observation

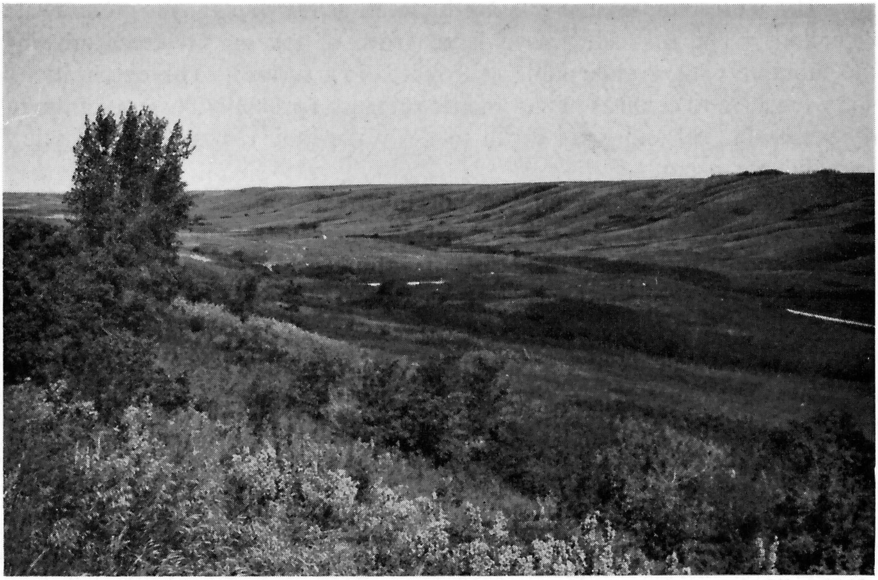
(Coupland, 1950) that in locations where the moisture supply is sufficient *P. tremuloides* may advance from the edge of the parkland into the grassland.

Populus sargentii – the western cottonwood – is the common tall poplar along many prairie rivers (Pl. V). This tree, which reaches 40 to 100 feet in height, is

P.M., 1-8-63

A. Flood plain forest along South Saskatchewan River near Riverhurst.

PLATE V. WESTERN COTTONWOOD



PM., 1-27-62

B. Isolated trees marking side-hill spring in the Arm River valley near Chamberlain.

PLATE VI. Aerial view of Arm River at Edwards Ranch. Forest of western cottonwood (a) marks reach of abundant groundwater discharge from gravel deposits (d), at lower elevations the valley supports a dense growth of willow (b), and next to the river are lush meadows (c) with slough grass and baltic rush. Efflorescences of sodium-sulphate are visible in the valley upstream and downstream from Edwards Ranch. *MTS A17297-37* definitely phreatophytic. Its relation to groundwater was studied on the flood plain of South Saskatchewan River near Riverhurst and in Arm River at Edwards Ranch, where a small forest of tall cottonwood trees marks a reach of abundant groundwater discharge (Pl. VI).

Records from the observation well at Edwards Ranch from June 1 till September 20, 1964 indicated a total consumptive use of 42.24 inches, the largest amount recorded. Although the trees produced a maximum drawdown of 0.2 foot per day during August, the water-table remained at an average depth of 2 feet below the surface throughout the summer.

P.M., 2-8-64

A. Dense growth of willow along Watkins Creek.

PLATE VII. WILLOW

P.M., 2-24-64

B. Willow rings in hummocky moraine of Allan Hills. Groves of aspen poplar occupy higher ground between willow rings and open grassland.

Salicornia rubra L. — red samphire

Salicornia is a low annual that turns bright crimson at maturity and gives a reddish colour to the margins of saline sloughs in summer and early autumn. Although the species may indicate groundwater discharge areas, its preference for a habitat seems to be determined by the salt content rather than the availability of groundwater. Dodd (1960) found that the shallow roots of *Salicornia* are outside the influence of groundwater.

Salix — willow

There are over 400 species of willows on the prairie, most of which are difficult to identify. The three most common species that can be recognized with some certainty are *Silax interior* Rowlee, sandbar willow; *S. petiolaris* Smith, basket willow; and *S. discolor* Muhl., pussy willow.

Sandbar willow grows in heavy stands along the sandbars and on low banks of streams. Bird (1961) reported it from sandhills ". . . where subsoil water is available." With respect to the establishment of sandbar willow Bird commented that "it is not the presence of running water that is necessary . . . but denuded soil with an abundant water supply." The basket willow is a small tree that grows in low places and along streams. Bird (1961) mentioned its characteristic occurrence about the margins of sloughs in a zone between high and low water levels. The common pussy willow grows in better drained ground than do sandbar and basket willow. It is found around sloughs in a zone just above the basket-willow zone, and below the aspen forest or open grassland (Bird, 1961).

The writer investigated the relation between willows and groundwater at ten sites, and a summary of the findings is given in Table III. The most striking discovery was that at four locations the phreatophytic fluctuations stopped gradually or abruptly during late July or early August, without any apparent correlation with depth to water or the texture of the subsoil material. The data presented in Table III illustrate that willows can reach groundwater to a depth of at least 7 feet.

Willows in river valleys (*S. petiolaris* and *S. interior*) are undoubtedly phreatophytic, at least during part of the summer. The factors that control the phreatophytic existence of willows around sloughs are not yet fully understood, but it is evident from the observations in Table III that pussy willow may or may not be phreatophytic. This conclusion is in agreement with Bird's habitat description for the species.

Willows prefer water of good quality (Table V), and a large number of salinity measurements made by the writer in sloughs surrounded by willows indicate that they are generally associated with water containing less than 1,000 ppm total solids. Groundwater consumption by willows around a contact spring near Girvin amounted to 13.47 inches during the summer of 1963. Willows around a temporary slough in hummocky moraine of the Allan Hills (Pl. VII B) consumed 10.56 inches of groundwater during the summer of 1964.

TABLE III. Summary of Findings Concerning the Relations Between Willows and Groundwater

Location and number[1] of observation well (*see also* Table XI)	Period of record	Phreatophytic fluctuations	Range of water level during period of record (feet below surface)	Main species	Texture and nature of material	Comments
Arm River valley Valley bottom at Chamberlain W½-9-22-26W2^d(IX)	June 13–Sept. 1 1963	yes	2.38–6.18	*S. petiolaris*	loam (alluvium)	Poor record. Site subject to periodic flooding
Valley bottom at Chamberlain W½-9-22-26W2^d(2)	May 27–Aug. 24, 1964	yes (from June 6–August 1)	7.40–9.00	*S. petiolaris*	loam (alluvium)	Daily fluctuations stopped suddenly at Aug. 1. Water level remained constant after Aug. 1
Valley bottom at Findlater SE22-21-25W2^d(6)	May 30–Aug. 8, 1964	yes (from May 30–July 20)	0.85–5.35	*S. petiolaris*	loam (alluvium)	Daily fluctuations stopped at July 20 (−3.34′). Water level declined rapidly after @ 0.2 ft/day
Side-hill spring near Girvin NW14-25-28W2^d(II)	June 9–Sept. 10, 1963	yes	1.40–1.75	*S. discolor*	loamy sand (eroded till)	Perfect record (*see* Table VI)
Side-hill spring near Chamberlain SW9-22-26W2^d(X)	June 16–Sept. 9, 1963	yes	0.20–5.00	*S. discolor?*	clau loam (till)	Record shows strong Lisse effects
Willow ring in hummocky moraine, Allan Hills SE15-29-29W2^d(9) (*see* Pl. VII B)	June 2–Nov. 13, 1964	yes	1.95–7.38	*S. discolor* *S. petiolaris*	sandy loam (till)	Good record (Table VI) Daily fluctuations stopped gradually between Aug. 28 and Sept. 2
Willow ring in ground moraine NW4-23-27W2^d(21)	June 23–July 15, 1964	no	4.35–6.45	*S. discolor?*	— till	Water level declined rapidly @ 0.1 ft/day
Willow ring on upland sand plain NE35-22-29W2^d(XXI)	July 16–Aug. 23, 1963	no	8.59–9.00	—	sandy loam (alluvial sand)	Water level declined slowly @ 0.01 ft/day
Valley bottom Watkins Creek NW15-22-29W2^d (XV and 22) (*see* Pl. VII A)	June 10–Aug. 8, 1964	yes	0.46–3.00	*S. petiolaris* *S. discolor* *S. interior*	loam (till-wash)	Phreatophytic fluctuations stopped gradually after Aug. 3, at −2.82 feet
	June 26–Aug. 11, 1963	yes	2.64–4.16	idem	idem	Phreatophytic fluctuations stopped gradually after Aug. 8 at −4.09 feet. Water-table declined @ 0.04 foot afterwards

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[1] Roman numerals refer to 1963 measurements, arabic numberals indicate 1964 observation wells (*see also* Table XI).

Shepherdia argentea Nutt. — buffalo berry

Buffalo berry, which is a thorny shrub from 4 to 15 feet high, is common around sloughs and in coulées throughout the southern prairie region. Its occurrence in the headwater region of Qu'Appelle River is restricted to the Qu'Appelle valley and to a few places in the Arm River valley. The area investigated by the writer is close to the northern limit of occurrence of the species. Dense bushes of buffalo berry were noticed farther south in Saskatchewan, particularly in the valley of Frenchman River.

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PLATE VIII
Bushes of buffalo berry in Qu'Appelle valley at Watkins Ranch. (The site is indicated by (c) on Pl. X.)

Buffalo berry was found to be phreatophytic in the Qu'Appelle valley, where it grows on the sand delta at Watkins Ranch (Pl. VIII). Three wells were installed near isolated groves of *Shepherdia*. In the first the water-table declined from 6.57 to 7.94 feet below surface during the summer of 1964: the consumptive use amounted to 2.64 inches. The water level in the second well, which was drilled next to the *Shepherdia* bush shown in Plate VIII, fell from 3.40 to 4.59 feet during the summer of 1964: the consumptive use amounted to 7.89 inches. The third observation well did not show diurnal fluctuations.

At the site of the second observation well four tensiometers[1] were installed at 1, 2, 3, and 4 feet below surface. The measurements, which are summarized in Table IV, indicate that during June the soil-suction was uniform throughout the profile and did not exceed 20 centibars (pF 2.3). This condition changed gradually during July when the soil moisture content of the upper foot decreased, resulting in soil-suction of more than 30 centibars. During the second week of August the soil-suction in the upper foot exceeded 85 centibars (pF 2.94), which

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[1] Soil moisture gauge Model P. Manufactured by Soilmoisture Equipment Co., Santa Barbara, California, U.S.A.

TABLE IV. Summary of Soil-suction Measurements Underneath Shepherdia argentea *at Watkins Ranch (1964)*

June						July						August					
Date	Soil-suction (centibar) at				Depth to water-table (feet)	Date	Soil-suction (centibar) at				Depth to water-table (feet)	Date	Soil-suction (centibar) at				Depth to water-table (feet)
	1′	2′	3′	4′			1′	2′	3′	4′			1′	2′	3′	4′	
11	19	14	12	13[1]	−3.40	1	19	17	11	15	−3.40	2	63	21	12	14	−4.30
15	15	15	11	13	−3.54	6	21	18	12	15	−3.90	13	82[2]	25	16	19	−4.53
20	17	17	12	15	−3.37	9	25	19	13	17	−3.99	18	dry	28	18	19	−4.63
26	18	17	11	15	−3.72	16	26	18	11	16	−4.10						
						20	34	21	17	17	−4.17						
						25	44	17	12	17	−4.31						
						29	51	19	13	16	−4.26						

[1] Although the 4-foot tensiometer extended below the phreatic surface, the soil moisture gauge did not show a zero reading.

[2] 85 centibars represent the practical working limit of tensiometers.

NOTE: 1 centibar is equivalent to a suction head of 10.21 cm water (pF 1.008). "Field capacity" exists at approximately 49 centibars (pF 2.7), whereas fluid movement ceases at approximately 31 centibars (pF 2.5).

was the working limit of the tensiometer. The 2-foot zone showed a slight increase in soil-suction during this period but the readings never exceeded 28 centibars.

The measurements shown in Table IV suggest that some fluid movement from the water-table to the soil surface was possible until the third week in July. After that time the hydraulic conductivity of the upper soil layer had become zero (pF 2.5 at 31 centibars). The marked decrease in groundwater consumption by *Shepherdia* during July and August may thus be partly related to the cessation of evaporation losses through the soil.

As a means of comparison between the conditions in the valley and on the uplands, the writer installed tensiometers on the adjacent prairie. These instruments registered minimum values of 75 centibars at the 4-foot level, whereas the cups at 1 foot, 2 and 3 feet were dry after 2 or 3 days.

Suaeda depressa Wats. — western sea-blite

Suaeda is a low-growing annual or perennial species that is common in saline meadows. There are two forms, the species *depressa* and the variety *erecta.*

TABLE V. Chemical Analyses of Groundwater Associated with Various Types of Vegetation

(parts per million, except as indicated)

	vegetation and well number					
	Willow and box elder	Saltgrass	Wolf willow and baltic rush	Wolf willow and buffalo berry	Willow	Seaside arrow-grass
Chemical composition	XV	V	I	XIV	VI	XII
conductive (micromhos)	1404	56683	4832	1116	400	7674
total solids	1020	75105	4122	767	255	5353
Ca	148	0	121	71.5	48.4	60.9
Mg	68.9	9277	438	80.2	24.8	79.3
Na	68.0	10900	540	58.0	11.2	1748
K	7.2	10.5	10.3	7.8	3.2	6.9
CO_3	0.0	0.0	0.0	0.0	0.0	26.4
HCO_3	252	990	684	287	254	1431
SO_4	580	38540	2619	382	29.6	1757
Cl	12.9	15880	38.1	8.0	2.7	950
S.A.R.	1.16	24.28	5.1	1.12	0.33	34.7

According to Budd (1957, p. 101) the variety is a little more plentiful than the species. Both were studied in the saltgrass community of Bethune, but no phreatophytic fluctuations were observed.

It follows from these observations that 50 per cent of the species listed in Table II are indeed phreatophytic in south-central Saskatchewan. It is paradoxial that those found not to be phreatophytic are all halophytes, which at first (Meyboom, 1966) were considered the most likely phreatophytes of all.

The following species do not appear in Table II, but their relation to groundwater was nevertheless investigated as they are common in coulées and river valleys over the prairie.

Elaeagnus commutata Bernh. — wolf willow

Wolf willow is a shrub from 2 to 12 feet high with silvery leaves and brown scurfy twigs (Pl. IX). It is very common in sandy soils where moisture is plentiful. The use of groundwater by wolf willow was investigated at five sites, each of which is discussed below. It was found that wolf willow is a moderate phreatophyte in sand areas where the water-table is less than 6 feet below surface.

The first observation well was in a mixed stand of wolf willow, snowberry, and roses, in the Arm River valley northeast of Davidson. The valley at this place contains an extensive sand delta fanning out from a small tributary creek. The delta is 40 feet thick near the centre of the valley, and the water-table is 1 foot to 3 feet below surface. The fine fluctuations shown in Figures 3 and 4 were recorded in the observation well at this location.

PLATE IX
Silvery leaves of wolf willow.

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The writer formerly (1962) ascribed these fluctuations to the entire shrub community, which led to the conclusion that snowberry (*Symphoricarpos occidentalis* Hook) and roses (mainly *Rosa woodsii* Lindl.) had to be phreatophytic too.

However, careful measurements elsewhere in the Arm River valley in pure stands of snowberry (SE 3-26-28-W2^d and SW 1-23-27-W2^d) as well as in stands of snowberry mixed with roses (SE 22-25-28-W2^d) disproved this hypothesis conclusively. Neither snowberry nor roses were found to be phreatophytic.

These findings restricted the cause of the daily fluctuations in the first well to wolf willow plus possibly the herbaceous components of the vegetation, which were principally baltic rush and perennial sowthistle (*Sonchus arvensis* L.). The phreatophytic nature of baltic rush has been mentioned already, whereas the writer's measurements at the fringe of a meadow with tall sowthistles in the valley of Thunder Creek (W½ 36–19–5–W3^d) had shown that sowthistle also could be phreatophytic. Hence, the observations in the first well did show the presence of a phreatophytic plant community, but they were inconclusive with regard to wolf willow *per se*. Values of consumptive use for this community during the growing seasons of 1963 and 1964 amounted to 29.52 and 30.72 inches respectively, with an average depth to water of 1.5 feet (Table VI).

The second well was installed in a pure stand of wolf willow on the sand delta of Watkins Ranch. There, the phreatophytic nature of wolf willow could be established beyond doubt. From June 25 to August 31, 1963, the water-table dropped from 1.11 feet to 2.66 feet below surface. The groundwater consumption during this period was 6.17 inches.

The third well was in the Arm River valley near Davidson, in the zone of tall wolf willow between the higher zone of prairie grass and the lower zone of wire rush (cf. Pl. IV). Between June 9 and August 18, 1964, the water level in this well dropped from 5 feet to 7.49 feet below surface. Phreatophytic fluctuations superimposed on the overall downward trend were noticeable until July 17, but became negligibly small once the water level had fallen below 6.5 feet. Consumptive use from June 9 until July 31 amounted to 1.65 inches (cf. Table VII).

The fourth well was in the Arm River valley near Craik. The vegetation in this part of the valley consists predominantly of prairie grasses, whereas mixed stands of wolf willow, snowberry, and roses are confined to an incised channel, about 150 feet wide and not more than 6 feet below the general level of the valley floor. The water-table hydrograph that was recorded in the incised stream channel showed phreatophytic fluctuations when the water-table was less than 4.90 feet below surface. Once the water-table fell below that depth, the fluctuations diminished markedly. For reasons mentioned above, wolf willow was considered to be the chief phreatophyte in this plant community. Records from this well showing the relation between bank-storage effects due to upstream water-releases, and consumptive use by the streambank vegetation, are shown in Figure 13.

The affinity of wolf willow to groundwater was studied also in dense pure stands of wolf willow on the upland sand plain east of Watkins Ranch, where the deposit of fluvio-glacial sands is at least 12 feet thick. During July 1963 the water-table stood at 8.8 feet below surface and declined at a rate of 0.01 foot per day without showing phreatophytic fluctuations.

The foregoing observations indicate that wolf willow is a moderate phreato-

TABLE VI. Summary of Data on Groundwater Consumption by Phreatophytic Vegetation in South-Central Saskatchewan

Plant community	Well number	Year	Groundwater consumption (C), inches					K[1] for the period	C/E[2] for the period	Mean depth to the water-table (ft)	Readily available spec. yield
			June	July	August	Sept.	Period				
Wolf willow and baltic rush	I	1963	3.60	8.76	9.84	7.32	29.52	1.16	0.93	1.75	9%
	1	1964	6.00	12.84	11.16	0.72	30.72	1.35	0.91	1.50	9%
Baltic rush	10	1964	5.88	8.40	7.08	1.44	22.80	1.00	0.68	3.00	8.25%
Pussy willow	VI	1963	1.55	6.02	5.90	—	13.47	0.65	0.52	1.50	9%
	9	1964	3.24	5.52	1.80	—	10.56	0.52	0.37	4.75	8.25%
Manitoba maple	3	1964	5.88	8.28	5.64	1.32	21.12	0.93	0.63	6.00	8.25%
	4	1964	3.96	7.80	4.80	—	16.56	0.81	0.58	5.00	9%
Western cottonwood	5	1964	10.92	17.52	9.84	3.96	42.24	1.72	1.26	2.00	8.25%
Buffalo berry	17	1964	0.96	1.20	0.48	—	2.64	0.13	0.09	7.25	8.25%
	19	1964	3.96	2.76	1.17	—	7.89	0.38	0.28	4.00	9.75%
Hawthorn	III	1963	0.48	1.80	0.96	—	3.24	0.16	0.13	3.00	6.25%

[1] Blaney's consumptive-use coefficient

[2] Ratio of groundwater consumption (C) and total net water loss (E) from class "A" evaporation pan at Regina airport (*see* Table VIII).

phyte in sandy areas where the water-table is less than 6 feet below surface. The occurrence of wolf willow is not necessarily determined by groundwater alone and the species *per se* is therefore no indicator of a high water-table.

Crataegus — hawthorn

Species belonging to the hawthorn genus are shrubs or small trees with alternate leaves and sharp spines on the stems. The species are difficult to identify, but the specimens that were studied in the valley of Squaw Creek near Craik, probably belong to *C. columbiana* Howell. Budd (1957) described the species as "fairly plentiful in woodlands and on riverbanks throughout the area."

The isolated clump of hawthorn bushes in Squaw Creek valley was definitely phreatophytic, although its groundwater use during the summer of 1963 amounted to only 3.24 inches.

Beckmannia syzigachne (Steud) Fern. — slough grass

Slough grass is a tall tufted, erect annual grass growing in sloughs and other moist places. Its relation to groundwater was determined in a pure stand in the Arm River valley where the average depth to the water-table was 2 feet. In August, the phreatophytic fluctuations had an amplitude of 0.25 foot per day, a magnitude comparable to the fluctuations underneath western cottonwood. Unfortunately the well was disturbed frequently, and, with the exception of July, the records had too many gaps to permit calculation of groundwater use during the summer. The value for July, amounting to 11 inches, has been included in Table VII.

Triglochin maritima L. — seaside arrow-grass

Seaside arrow-grass is a stout perennial marsh plant, which is common on saline playas and near saline lakes. Its phreatophytic nature was established in a saline marsh near Darmody, but the records are of poor quality.

Wheat

An interesting series of observations was made in a wheatfield west of Aylesbury (SW 27-22-28-W2^{d}) on Asquith fine, sandy loam, developed on alluvial sand. From July 5 until August 14 the water-table dropped from about 5 feet below surface to 7 feet. At first, the hydrograph showed a daily drawdown followed by a nightly stabilization, but after July 30 phreatophytic fluctuations were very much in evidence, having an amplitude of one hundredth of a foot per day. On August 4, the wheat was harvested and the fluctuations stopped immediately. Following the harvest, the water-table — which had been declining at a rate of 0.03 to 0.06 foot per day — started to recover at a rate of 0.01 foot per day.

The daily groundwater consumption was about 0.04 inch per day and the total consumption from July 5 until August 14 amounted to approximately 1.5 inches, or roughly 25 per cent of the total water-use of wheat during that period. The rooting depth of grain crops is about 4 feet (Wesseling and van Wijk, 1957, Table 13).

DISCUSSION OF GROUNDWATER CONSUMPTION BY PHREATOPHYTES

Factors Affecting Groundwater Use By Phreatophytes

It is known from the literature (Robinson, 1958; Blaney, 1954) that groundwater consumption by phreatophytes is directly proportional to temperature and density of growth, and inversely proportional to depth to the water-table. Some aspects of these relations are described in the following sections.

Depth to Water

In addition to the values of consumptive use given in Table VI, Table VII presents values of groundwater use during July 1964, as determined from records of thirteen observation wells. Parabolic and linear models were tested for fit by least squares for the regression of groundwater consumption (y) in inches, with depth to the water-table (x) in feet. The best fitting model was the linear regression $y = -2.04\,x + 14.22$, based on data of *shrubs and herbs only*. The correlation coefficient of -0.80 is significant at the 1 per cent level. Although the regression does not explain more than 64 per cent of the observed spread, it does indicate that the depth to water is the most important variable governing groundwater consumption.

It should be remembered that the records of groundwater use represent both evaporative and transpirative discharge — evaporation from the soil and 'transpiration' from the vegetation. Hence, part of the increase in groundwater consumption with decreasing depth to water is due to the increased evaporation from the soil surface. The term 'evapotranspiration' also reflects this idea.

It can be calculated from the regression equation that groundwater consumption by phreatophytic shrubs and herbs (on the average) ceases when the water-table lies 7 feet below surface. By introducing the 95 per cent confidence limits about the average ($\pm$ 5.14 inches) it is found that groundwater consumption may stop when the water-table lies anywhere between 4.6 and 8.6 feet below surface.

Groundwater consumption by trees (wells 2, 3, 4, and 5, Table VII) is significantly higher than for shrubs and herbs. All values for July 1964 fall outside the 95 per cent confidence limits of the shrub-herb regression line. Although the data are too few to calculate an individual regression for trees, the available values

TABLE VII. Consumption during July 1964

Well No.	x	y	Vegetation
1	3.00	12.84	wolf willow and baltic rush
2	8.25	9.48	willow
3	6.75	8.28	Manitoba maple
4	5.40	7.80	Manitoba maple
5	1.50	17.50	western cottonwood
9	4.50	15.52	willow
10	3.00	8.40	baltic rush
10a	4.44	1.98	baltic rush
13	4.75	2.06	wolf willow
15	2.00	11.00	slough grass
16	6.50	0.64	wolf willow
17	7.75	1.19	buffalo berry
19	4.00	2.76	buffalo berry

x average depth to water-table (feet) during July
y groundwater consumption (inches) during July

suggest that groundwater consumption by trees ceases when the water-table lies deeper than 14 feet below surface.

The relation between consumptive use and depth to water plays an important role in determining the groundwater consumption in a valley where the transverse water-table gradient is less than the transverse gradient of the valley bottom. It was mentioned in the previous chapter that Arm River east of Davidson occupies a gentle valley, not more than 50 feet deep and a half mile wide. Three observation wells were placed at various points in the valley: one 14 feet away from the river amidst a dense growth of baltic rush (No. 10); a second, 370 feet away from the river but still in the zone of baltic rush (No. 10a); and a third, 480 feet away from the river in the zone of wolf willow (No. 16), a mile upstream from No. 10. During July 1964, the average depth to water in these wells was respectively 3, 4.44, and 6.50 feet (*see* Table VII). The amounts of groundwater consumption were 8.40, 1.98, and 0.64 inches.

From these observations a smooth curve was sketched relating the quantity of groundwater consumption (y) to the distance from the measuring point to the river (x) in feet. The area under this curve represents the total amount of groundwater lost through evapotranspiration over the entire width of the valley. Without knowing the exact expression for the dependence of y on x one can nevertheless approximate the area of the region under the curve $y = f(x)$ by such methods as the trapezoidal rule or Simpson's parabolic rule.

Applying Simpson's parabolic rule to the 500-foot zone of wire rush and wolf willow, we obtain the following estimate of groundwater evapotranspiration in a 1-foot strip across the valley:

$\int_{0}^{500} f(x)dx \approx h/3(y_0+4y_1+2y_2+4y_3+..2y_{n-2}+4y_{n-1}+y_n)$ where $h = (b\text{-}a)/n$,

in which b and a are the limits of integration and n is a positive even integer. For $n=10$, h equals 50 feet and the values of groundwater consumption at 50-foot intervals (y_0, y_1, . . . y_n) are taken from the graph $y=f(x)$. For July 1964 this approximation yields a value for evapotranspiration of 156 cubic feet (or 0.0036 acre-foot) for a 1-foot strip of the phreatophytic zone. Along a mile of river valley this adds up to 19 acre-feet.

As Arm River east of Davidson occupies a very asymmetrical position in the valley (*see* Pl. IV), 19 acre-feet per mile is representative of the entire valley width, and need not be multiplied by 2.

Baseflow from the same side of the valley during July 1964 was about 0.5 acre-foot per mile, which shows that in this type of valley the ratio between groundwater discharge by evapotranspiration and groundwater discharge by drainage can be 40:1. It can be calculated also that records from one observation well, 230 feet away from the river, would have given the equivalent value of uniform evapotranspiration over the entire valley.

Temperature and Humidity

The effects of temperature and humidity on groundwater consumption were studied qualitatively in an experimental greenhouse that covered 1,152 square feet of the wolf willow vegetation around observation well No. XIV on the delta of Watkins Ranch. The greenhouse was 9 feet high and was made of clear transparent plastic tacked to a wooden frame of 'two-by-two's'. Another observation well in the same wolf willow stand was drilled 6 feet away from the greenhouse, and observations were made from August 19 to 27, 1963.

On August 19, the average daytime temperature inside the greenhouse was 84° F and outside the greenhouse 76° F. The largest difference was measured at 3.30 p.m. when the inside temperature was 85° as compared to 67° outside. The average daytime relative humidity inside the greenhouse was 67 per cent — 30 per cent higher than the average relative humidity outside the tent. During the morning and early afternoon the difference was as much as 40 per cent (72 and 32 per cent respectively). Air movement inside the tent was negligible. The overall effect of the greenhouse, therefore, was an 8-degree increase in temperature and a 30 per cent increase in relative humidity.

Prior to the construction of the greenhouse, groundwater consumption by wolf willow at this site was about 0.035 inch per day. At the completion of the greenhouse this rate doubled immediately, whereas the rate of groundwater consumption outside the greenhouse remained unchanged. From August 19 at 8 p.m. until August 25 at noon, the total groundwater consumption inside the tent was 0.32 inch, whereas the consumptive use of the vegetation outside the tent was 0.14

inch. Once the greenhouse was taken down, the daily consumptive use of the vegetation at the site of the tent went back to 0.03 inch per day.

Graphic differentiation of the records inside and outside the greenhouse revealed that the different amounts of groundwater consumption were not related to differences in duration of the period of evapotranspiration (10 a.m. till 8 p.m. in both wells), but simply to different intensities. Thus for the same period the inside well registered twice the evapotranspiration rate of the outside well.

These measurements indicate two things: first, that the increases in temperature and humidity inside the tent were accompanied by roughly a 100 per cent increase in evapotranspiration; and secondly, that measurements of groundwater consumption by means of one well are true point-measurements with a minimum of interference from nearby conditions.

The explanation for the increased evapotranspiration meets with the paradox that the effect of humidity on the use of groundwater is generally assumed to be in reverse order to that of temperature. Robinson (1958, p. 19) stated that the rate of use decreases with increasing humidity and vice-versa, whereas the consumptive use increases with increasing temperature. If this is true, the observations show that the effect of the relatively slight rise in temperature is far greater than the opposite effect of the rise in relative humidity.

Consumptive-Use Coefficients According to Blaney

Blaney (1952) estimated evapotranspiration by phreatophytes from climatological data by correlating measured amounts of evapotranspiration with monthly temperature, monthly percentages of yearly daytime hours, and growing period. The correlation is expressed by:

$U = KF = \text{sum of } kf$ where:

U = consumptive use in inches, for the period,

F = sum of monthly consumptive-use factors for the period (sum of the products of mean monthly temperature and monthly per cent of daytime hours of the year),

K = empirical consumptive-use coefficient for the period,

$f = t \times p/100$ monthly consumptive-use factor,

t = mean monthly temperature, °F,

p = monthly per cent of daytime hours of the year[1]

k = monthly consumptive-use coefficient,

$u = kf$ monthly consumptive use, in inches.

The consumptive-use coefficients 'k' and 'K' can be determined for each plant species or for each plant community, from measured values of consumptive use. These empirical coefficients are then used to transpose the results of careful measurements of evapotranspiration to similar areas where such measurements have not been done, but for which climatological records are available.

Consumptive-use coefficients 'K' were calculated for all plant species or plant

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[1] Daytime hours for south-central Saskatchewan were obtained from *The Observers Handbook*, Royal Astronomical Society of Canada, edited by Ruth J. Northcott.

communities for which seasonal values of groundwater consumption were available (Table VI). The 'K' values range from 1.72 to 0.13 and show an appreciable spread for the same species even under very similar conditions (cf. wells 1 and I or 3 and 4 in Table VI).

Groundwater Consumption by Phreatophytes Compared with Water Losses from a Class "A" Evaporation Pan

The ratio of groundwater consumption (C) and total net water losses (E) from an evaporation pan (Table VIII) was found to be a more consistent coefficient for a given species or plant community than the consumptive-use coefficient 'K' (*see* Table VI). The average C/E ratio is 0.58, which indicates that evapotranspiration by phreatophytes, on the whole, is less than evaporation from large bodies of water. The latter is related to pan "A" evaporation by an approximate factor of 0.7.

TABLE VIII. Water Losses (inches) from Class "A" Evaporation Pan at the Regina Airport[1]

Year	June	July	August	September
1963	7.07	10.45	8.29	6.04
1964	8.36	11.01	9.22	5.04

[1] Monthly record of meteorological observations in Canada; Meteorological Br., Canada Dept. of Transport.

The highest C/E ratio was computed for western cottonwood (1.26), which may indicate that the mass-transfer term of the total evapotranspiration equation plays a very important part in the evapotranspiration from these tall isolated trees. However, this ratio is still well below 1.61, which was reported by Blaney (1954, Table 3) for cottonwoods growing in San Luis Rey, California.

EFFECTS OF PHREATOPHYTES ON STREAMFLOW AND SPRINGS

As phreatophytes live by virtue of a shallow water-table and a constant water supply, their most common occurrence on the prairies is in river valleys and around springs, where both requirements are satisfied by continuous groundwater inflow. During dormancy of the streambank vegetation, groundwater inflow makes up the baseflow of the river and (if the amount of replenishment is large enough) it will continue to do so throughout the growing period. White (1932) and Troxell (1936) noticed, however, that during the growing season streamflow in areas of phreatophytes showed daily fluctuations that were similar to the fluctuations of the water-table. During this study of phreatophytes in south-central Saskatchewan the author observed the same phenomenon. The following examples show the magnitude, mechanism, and results of these fluctuations.

Qu'Appelle River

Since 1958, the summer flow of Qu'Appelle River above Buffalo Pound Lake (Fig. 1) has been maintained by pumping from South Saskatchewan River at Elbow. After the early summer rains of 1963, however, conditions in Buffalo Pound Lake were such that pumping was discontinued during July and August, resulting in natural low-flow conditions in the Qu'Appelle. From August 9 to 27 this flow was measured continuously at Watkins Ranch by means of an automatic water-level recorder and a 90-degree triangular weir. The hydrograph of the river during that period is shown in Figure 12. A survey of the river channel showed that all flow represented by this hydrograph originated within 2 miles upstream from the weir.

The fluctuations of the water-table adjacent to the river are also shown in Figure 12. This hydrograph was obtained from observation well No. XVI near a dense stand of buffalo berry (*see* Pl. VIII), about 600 feet away from the river.

Comparison of the two graphs shows that from August 9 to 16 minima in stream discharge coincided with minimum water levels, both of which occurred between 8 and 10 p.m. After August 16, however, moments of minimum streamflow were progressively delayed until they did not occur before 9 or 10 o'clock of the next morning. In the following calculations the writer has assumed that even though the minimum might occur during the next calendar day it had to be attributed to evaporation of the previous day. The rapid rise of the water-table after slight rains of August 11 and 17 was not included in the computations, as it was not related to consumptive use.

The regular fluctuations in discharge signify either that the amounts of groundwater inflow differed from day to night or that some river water was induced to infiltrate into the banks of the river during the daytime. As far as the latter mechanism is concerned, the width of a possible zone of induced infiltration can be calculated from the relation between the transverse water-table gradient and the magnitude of the phreatophyte fluctuations. During the period of observation the water-table gradient was 0.005 towards the river, which means that phreatophytic fluctuations of 0.1 foot may have caused drawdown below river level in a strip of 20 feet along both river banks. It follows that phreatophytes beyond this zone have merely reduced streamflow indirectly by intercepting groundwater before it reached the river.

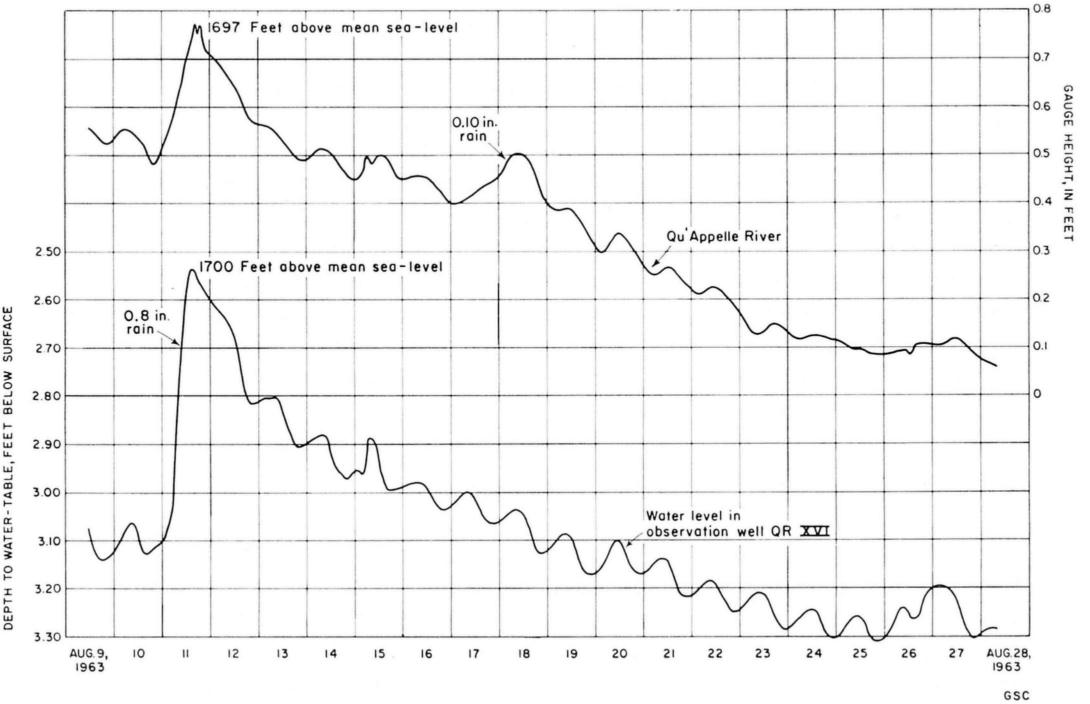

FIGURE 12. Fluctuations of streamflow and water-table elevation due to transpiration by phreatophytes. Records obtained in Qu'Appelle valley at Watkins Ranch.

It is irrelevant which mechanism was the more important during the period of observation, the fact is that the recorded streamflow fluctuations represent water losses due to transpiration by the valley vegetation. These losses can be estimated by assuming that the maximum observed rate of discharge is the same as the daily mean rate of discharge under conditions of no depletion. Hence, the curve obtained by connecting the points of maximum discharge approximates the probable flow of the stream if there were no transpiration losses. This procedure has been used to analyze the fluctuations from August 10 to August 24. Table IX shows that the total quantity of water lost during that period amounted to 1.30 acre-feet. It should be stressed that this volume is not necessarily a loss in the sense of a negative increment. Apart from the narrow zone in which induced infiltration doubtless played a role, it is more likely that most transpired water was intercepted before it reached the stream.

To what area of phreatophytes have these quantities to be related? The shrub vegetation near the gauging station at Watkins Ranch consists of 10 per cent of buffalo berry and 90 per cent of mixed stands of roses, snowberry, and wolf willow. The consumptive use of wolf willow was determined from two separate observation wells, both about 700 feet away from the river. The writer has calculated that the groundwater consumption by buffalo berry amounted to 0.21 foot of water between August 10 and 24, 1963, whereas wolf willow consumed 0.04 foot during the same

TABLE IX. Evapotranspiration Losses from Qu'Appelle River

(in acre-foot per day, computed as the difference between maximum and daily mean rates of discharge)

Date (August 1963)	Rate of discharge, cfs.			Transpiration (acre-foot per day)
	Max.	Min.	Mean	
10	0.78	0.70	0.74	0.08
11 (rain)	—	—	—	—
12	0.97	0.78	0.87	0.20
13	0.78	0.70	0.74	0.08
14	0.74	0.68	0.71	0.06
15	0.72	0.65	0.68	0.08
16	0.67	0.60	0.63	0.08
17 (rain)	—	—	—	—
18	0.72	0.58	0.65	0.14
19	0.59	0.48	0.53	0.12
20	0.54	0.42	0.48	0.12
21	0.46	0.38	0.42	0.08
22	0.40	0.26	0.33	0.14
23	0.29	0.25	0.27	0.04
24	0.25	0.18	0.21	0.08
			Total depletion of streamflow . . .	1.30 acre-foot

period. Integration of these values over the area of growth (about 16 acres), taking into account the respective vegetation densities, yielded an estimate of total consumptive use of 0.92 acre-foot.

This value indicates that 70 per cent of the streamflow depletion can be accounted for by the vegetation in the immediate vicinity of the gauging station. Although the vegetation upstream from Watkins Ranch is not strikingly phreatophytic, there is no doubt that the isolated bushes of buffalo berry (*see* Pl. X) and the scattered stands of wolf willow along the stream channel are more than sufficient to account for the remaining 30 per cent of the losses.

The situation just described is one where the river is still essentially draining. If the amounts of induced infiltration are moderate, the stream may even show slight downstream gains. It has been said in the previous paragraphs that actual thieving from the river can occur in the zone of induced infiltration only. This zone may be expected to be particularly significant in wide river valleys with very slight transverse water-table gradients. However, the following example shows that substantial thieving can result also from a sudden rise in river level, such as occurs during water releases from a reservoir.

Arm River

With respect to its hydrogeological and botanical conditions, the Arm River valley can be subdivided into five parts, one of which extends from Girvin to Chamberlain (Fig. 1). This reach of the river receives little groundwater inflow and the predominant valley vegetation consists of dry-prairie grasses, whereas mixed stands of roses, snowberry, and wolf willow or willow are confined to an incised channel, which is about 150 feet wide and not more than 6 feet below the general level of the valley floor. The streamflow in this stretch of the river is governed by a dam at Craik (Fig. 1).

During the summer of 1964 the flow in Arm River below Craik ceased and water was released from the Craik reservoir twice, once in July and once in August. Both releases gave rise to appreciable bank-storage effects, which were noticed in all observation wells between Craik and Aylesbury. The following analysis demonstrates that bank-storage and subsequent evapotranspiration caused a considerable reduction in the streamflow that resulted from the releases.

Figure 13 shows the water-table hydrograph that was recorded in the incised stream channel, 2 miles downstream from the dam and 54 feet away from the river (observation well 13). This hydrograph has three distinct phases: a rise from July 8 to 15; a steep decline from July 15 to 23; and a more gentle decline from July 23 to 27. Filtration into the banks became noticeable at midnight of July 8–9 and the water-table continued to rise until 6 a.m. July 15. In total the water-table in this well rose 0.93 foot. From a careful survey the amount of water stored in both banks on July 15 was calculated to be 2.48 acre-feet per mile of stream channel, assuming an overall value of 10 per cent specific yield of the valley sediments. Applying White's analysis to the diurnal fluctuations in the rate of inflow from July 8 to 15, the writer calculated that the consumptive use of the phreato-

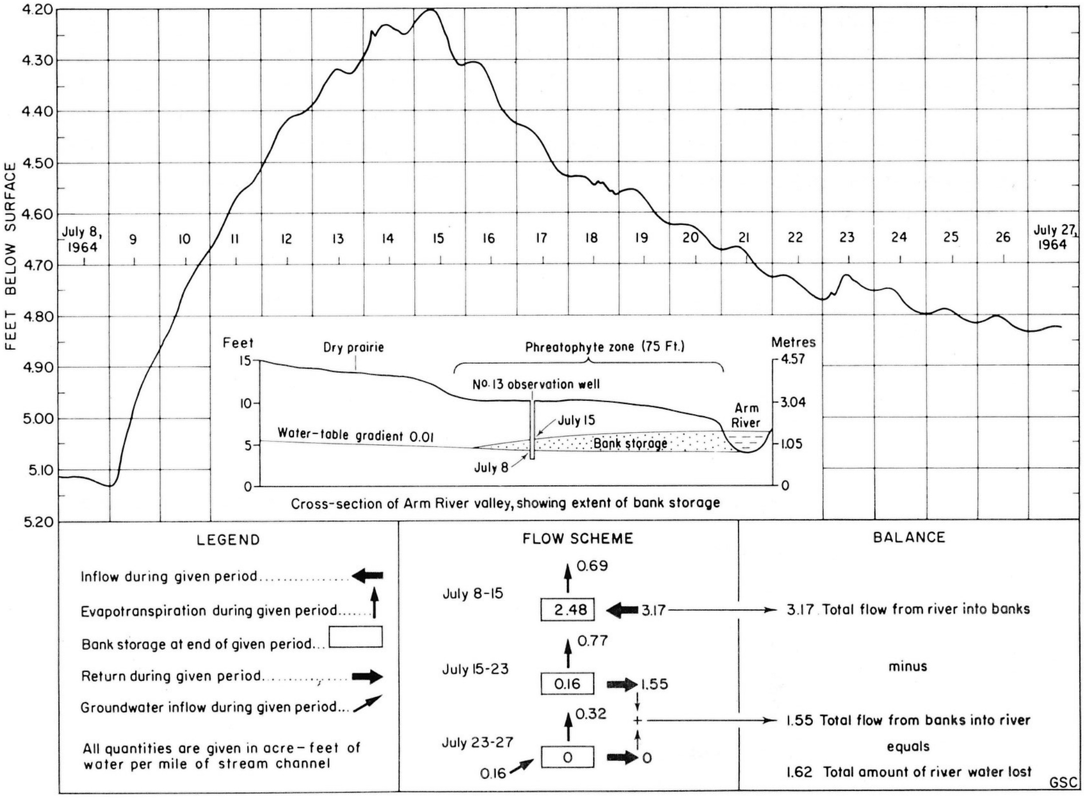

FIGURE 13. Water-table hydrograph from observation well No. 13, showing bank-storage effect in Arm River valley.

phytes in the incised channel came to 0.69 acre-foot per mile of channel. Thus, during the first phase, the total inflow from the river into the banks amounted to 3.17 acre-feet per mile.

Outflow from the banks began on July 15, and it was determined from the relation between water-table and river level that on July 22 only 0.16 acre-foot/mile was left in storage. Evapotranspiration by phreatophytes accounted for 0.77 acre-foot/mile during the period of outflow. By subtracting evapotranspiration and the volume remaining in bank storage from the amount of original inflow it was calculated that 1.55 acre-feet/mile has returned to the river between July 15 and 23.

From July 23 to 27, phreatophytic consumption was 0.32 acre-foot/mile, from which it can be concluded that the vegetation transpired all the water remaining in bank storage as well as 0.16 acre-foot/mile of inflowing groundwater. Hence, the return flow of the final phase was zero. The total amount of river water lost could subsequently be determined by subtracting the return flow of the second phase from the total volume of original inflow, thus disregarding the 0.16 acre-foot/mile additional groundwater inflow as a possible loss, because under pre-release conditions this amount would not have contributed to streamflow either. The water balance of the entire period shows that the losses amounted to 1.62 acre-feet/mile of stream channel. As the entire release from the Craik dam was about 60 acre-feet, it can be estimated that phreatophytes in the river valley between Craik and Aylesbury diminished the artificial flow in Arm River by at least 24 per cent.

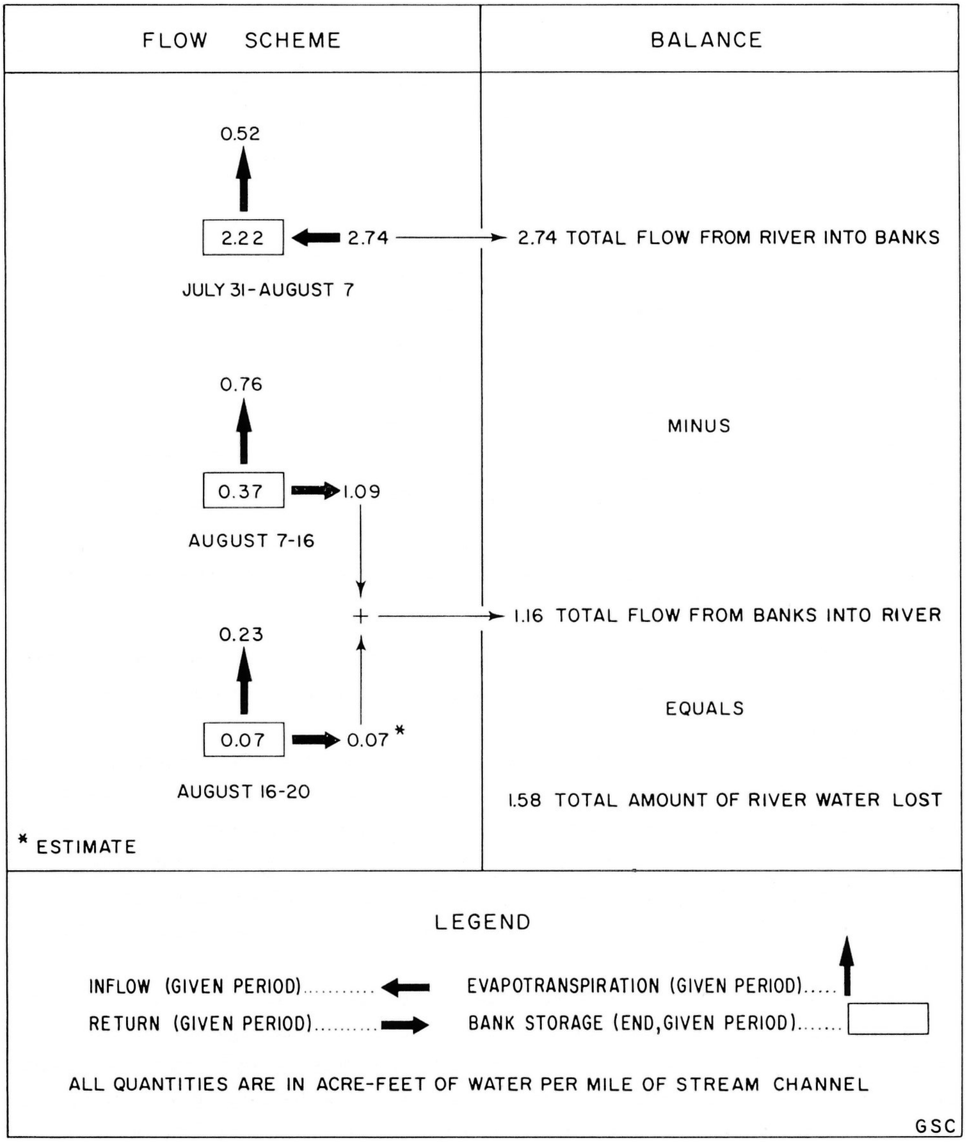

FIGURE 14. Partial water balance of Arm River below Craik dam from July 31 to August 20, 1964.

Using values of groundwater consumption obtained elsewhere in the Arm River valley, one may estimate the magnitude of streamflow losses that would have occurred if the narrow incised channel had contained phreatophytes that consumed more water. Two possibilities have been considered, one where the plant community would have been dominated by willow, and one where the vegetation would have been predominantly Manitoba maple. These calculations, which are summarized in Table X, suggest that under the conditions mentioned, streamflow depletion would have amounted to 86 and 88 per cent respectively of the total release.

Bank-storage effects owing to the second release were observed from July 31 to August 21. Figure 14 shows the graphical presentation of the water balance during each of the three phases of the second release. The total losses during the second release were somewhat less as evapotranspiration during the third phase did not consume all water left in bank storage, leaving some for continued outflow. The total return-flow was therefore somewhat larger than during July. Nevertheless, the total amount of river water lost is of the same magnitude as the losses incurred during the first release.

TABLE X. Actual and Hypothetical Streamflow Losses from Arm River between Craik dam and Aylesbury, July 8 to 22, 1964

as caused by different types of riparian vegetation occupying a 75-foot strip at each bank

Vegetation	Inflow[1] Evapotransp.	Bank st.	Total	Return	Net loss
Wolf willow (actual)	0.69	2.48	3.17	1.55	1.62
Willow (hypothetical)	3.17	2.48	5.65	nil	5.65
Manitoba maple (hypothetical)	3.37	2.48	5.85	nil	5.85

[1] All quantities are expressed in acre-feet of water per mile of stream channel.

Watkins Creek

The third example of streamflow depletion deals with observations that were done in Watkins Creek (Pl. X). Watkins Creek joins Qu'Appelle River about 9 miles upstream from Buffalo Pound Lake and occupies one of the typical steep-walled valleys that are so common along the major prairie rivers. Watkins Creek is not a permanent stream; its flow is generally interrupted from June or early July till October.

From May 27 to June 8, 1964, continuous records of Watkins Creek were obtained from two 90-degree triangular weir boxes, which were fitted with automatic water-level recorders. The distance between the weir boxes, which were of the type recommended by the United States Department of Agriculture (Israelsen and Hansen, 1962) was about 1,000 feet. Fluctuations of the water-table due to phreatophytes were recorded in a separate observation well.

The phreatophytic vegetation along this reach of Watkins Creek is dominated

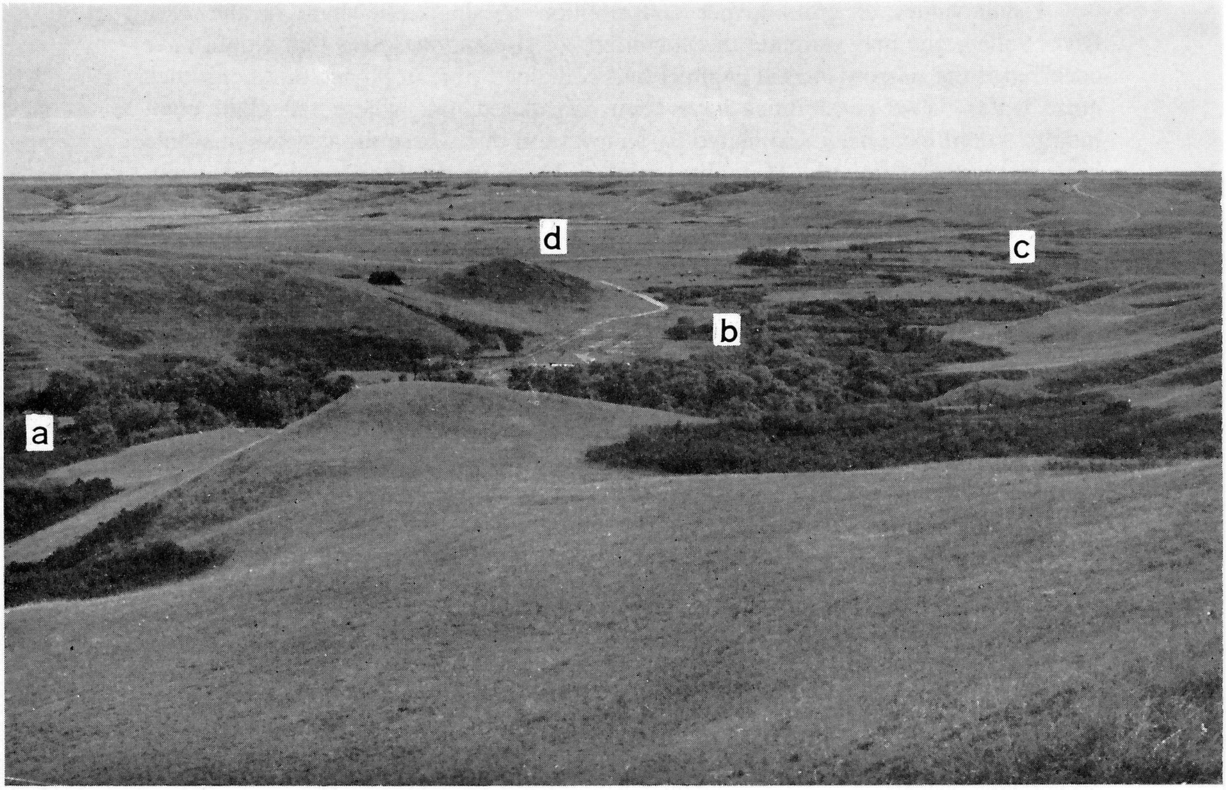

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PLATE X. General view of Watkins Ranch at the confluence of Watkins Creek and Qu'Appelle River; (a) and (b) indicate the approximate positions of the two weirs used in the stream-loss study of Watkins Creek; (c) is the non-cultivated part of the sand delta covered with wolf willow and buffalo berry, whereas (d) is the cultivated part of the delta, sown with alfalfa. The dark bushes bordering the alfalfa field are also buffalo berry. Width of view is about 1.5 miles.

by a lush growth of Manitoba maple and various willow species (Pl. X), which presents a pleasant contrast to the dry prairie of the surrounding hills. The total area of phreatophytes between the two weirs amounts to 4.23 acres.

The hydrograph of the upstream weir (Fig. 15a) shows the characteristic diurnal fluctuations in streamflow that occur in areas of phreatophytes. The maxima and minima in this graph coincide closely with the fluctuations of the water-table. Figure 15b shows a plot of the incremental discharge between the upstream weir and the downstream weir. It is apparent from this graph that the creek was gaining from May 25 to May 27, that it was losing during the daytime and gaining at night from May 27 to 28, and that it was losing continuously after May 28. These stages are believed to reflect the change from conditions of full bank storage after the spring floods to the dry river bed of the early summer.

The total streamflow depletion, as computed from Figure 15b, amounted to 0.18 acre-foot. During the same period the consumptive use of the vegetation was

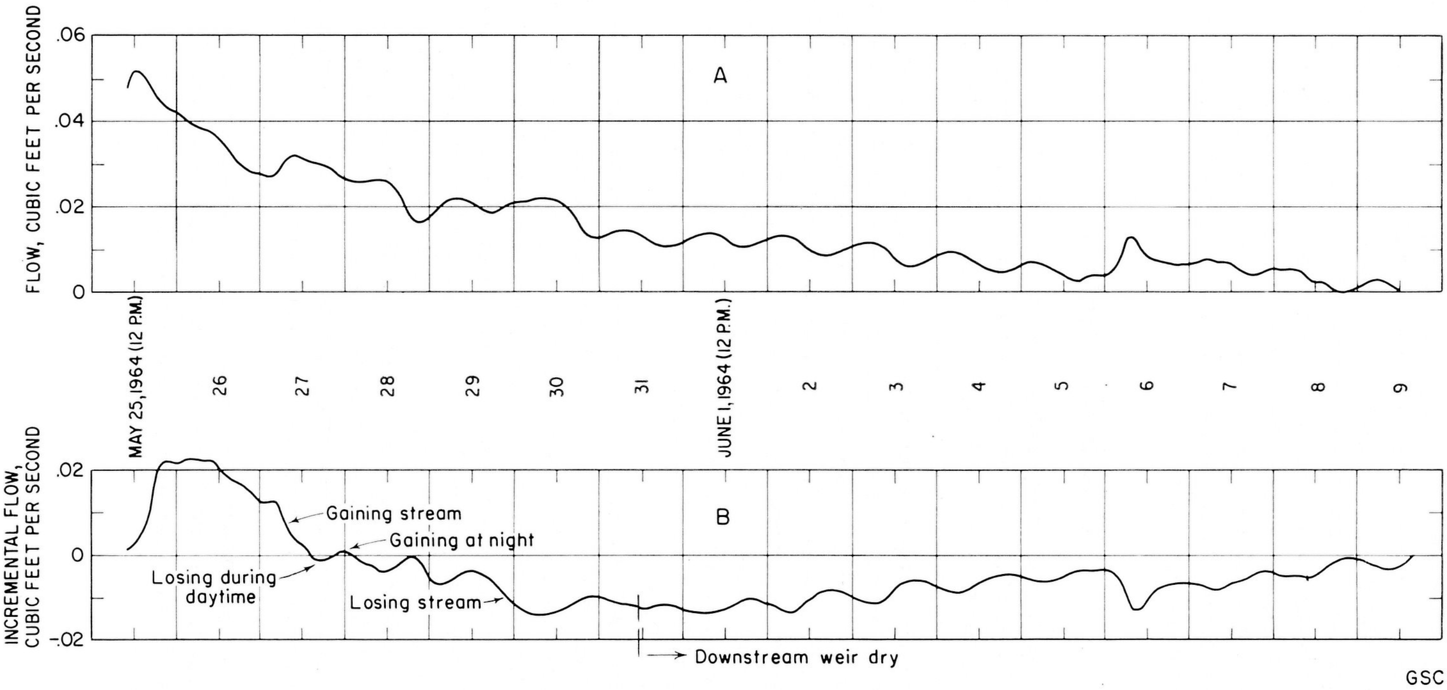

FIGURE 15. a. Stream hydrograph of upstream weir in Watkins Creek;
b. Plot of incremental discharge between upstream weir and downstream weir in Watkins Creek.

0.32 acre-foot. In other words, the vegetation was supplied with 0.18 acre-foot of water from the creek; the remaining 0.14 acre-foot had to be made up by groundwater. It was calculated from the rate of water-table decline that 50 per cent of the amount of groundwater consumed was withdrawn from storage, indicating that the rate of groundwater consumption was about twice the rate of natural replenishment. These considerations lead to the conclusion that the vegetation was responsible not only for all of the streamflow reduction when there was still flow in part of the creek, but also for the drying up of the stream in June, which was clearly a result of the declining water-table.

Chamberlain Springs

Phreatophytes may cause streamflow depletion in yet another manner, namely by diminishing the yield of side-hill springs that normally contribute to the river. The records (Fig. 16) from one of the side-hill springs near Chamberlain (Pl. V B) have been taken as an example of this process.

The spring itself is groundwater outflow from a boggy semicircular depression, about 50 feet in diameter and about 40 feet above the valley floor. The depression is densely covered with baltic rush mixed with some wild mint (*Mentha arvensis* L. var. *villosa* S. R. Stewart) and star-flowered Solomon's seal (*Smilacina stellata* (L.) Desf.). Around the marsh, on somewhat higher ground, are dense bushes of willow and some dogwood (*Cornus stolonifera* Michx.). Somewhat higher still is a mixed zone of snowberry and roses grading into wolf willow. Above the wolf willow zone is prairie. A small gully lined with willow and wolf willow runs from the spring to Arm River.

On June 16, 1963, the outlet of the marshy depression was excavated to fit an observation well (No. X). The spring flowed continuously at a rate of 2 or 3 gallons per minute until July 1, when the flow stopped from 4 p.m. till 2 a.m. The drop in water level during the interruption was only 0.02 foot. After this date interruptions of ever-increasing duration occurred every day, and on July 5 discharge stopped altogether. Spring flow resumed during brief periods on July 9 and 18, owing to strong Lisse effects after unusual amounts of rainfall. However, after July 20 evapotranspiration exceeded groundwater inflow and the water level in the boggy area fell 2.9 feet from July 20 to September 9. Phreatophytic fluctuations of 0.15 foot per day were recorded until September 9, when they stopped abruptly. The water level remained constant after that date until the end of the observation period.

Groundwater consumption by the vegetation surrounding the spring amounted to 4.91 inches during July and 3.65 inches during August, somewhat less than the consumptive use by the vegetation around the side-hill spring near Girvin (*see* Table VI, well VI).

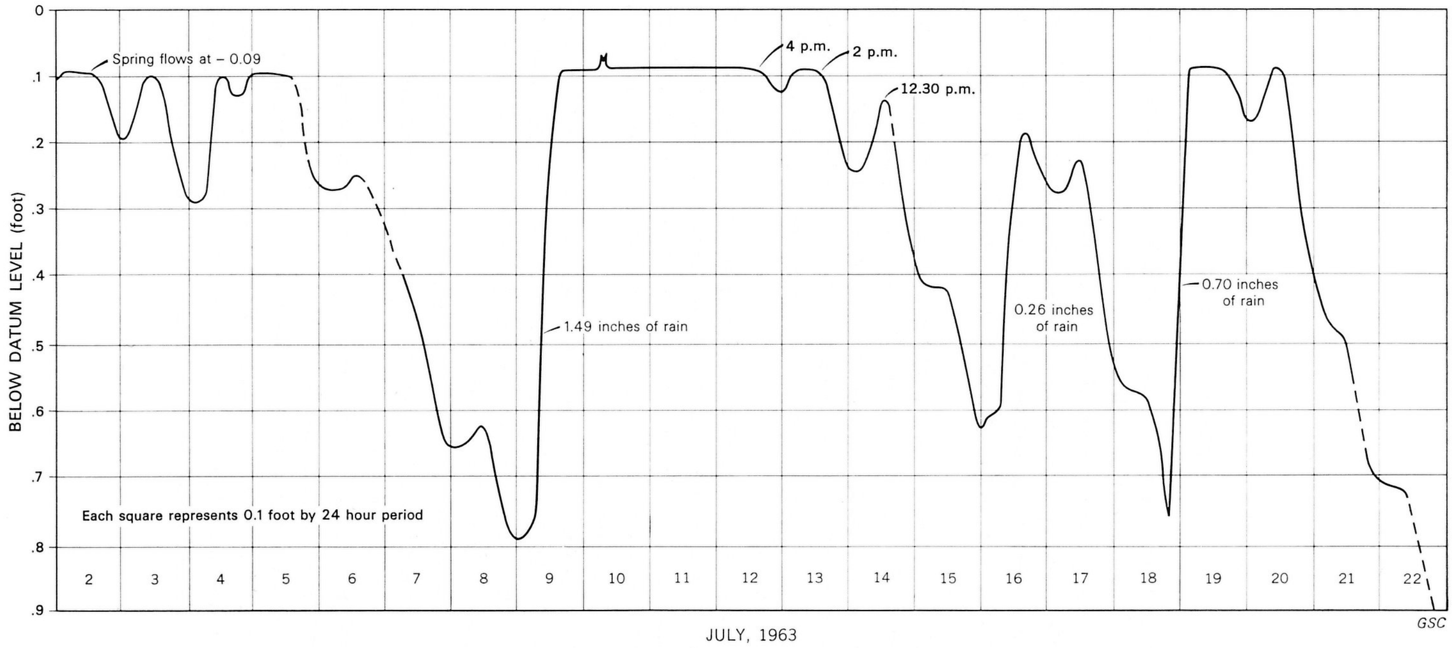

FIGURE 16. Hydrograph of water-table in side-hill spring near Chamberlain (record from observation well No. X, willows, baltic rush, Arm River).

CONCLUSIONS

The hydrological characteristics of phreatophytic vegetation in south-central Saskatchewan are summarized as follows:

1. Using the daily fluctuations of the water-table as a criterion for phreatophytes, the plant species found to be phreatophytic were: Manitoba maple, baltic rush, western cottonwood, various species of willow, buffalo berry, wolf willow, hawthorn, slough grass, seaside arrow-grass, and in one location wheat.
2. Seasonal groundwater consumption by these plants ranged from 2.64 inches to 42.24 inches. During 1963 and 1964 the average ratio between groundwater consumption and water losses from a class "A" evaporation pan was 0.58, with a range from 0.09 to 1.26, which indicates that evapotranspiration by phreatophytes is generally less than evaporation from open-water surfaces.
3. The amount of groundwater consumption is a function of the depth to the water-table. A linear correlation between consumption and depth to water suggested that herbs and shrubs stop using groundwater when the water-table is more than 7 feet below surface. For trees, the threshold value may lie around 14 feet.
4. the ratio between groundwater discharge by evapotranspiration and groundwater discharge by drainage may be as large as 40:1 in a gently sloping valley where the transverse water-table gradient is less than the transverse gradient of the valley floor.
5. During a rise in average daytime temperature of 8°F and a rise in average relative humidity of 30 per cent, groundwater consumption was found to increase by 100 per cent.
6. Phreatophytes cause streamflow depletion under natural and regulated flow conditions, regardless of whether the stream is influent or effluent. Indirect losses occur whenever groundwater is intercepted by the vegetation before it reaches the river. Direct losses from the river occur in a zone of induced infiltration brought about by the vegetation, or from bank storage, brought about by water releases from an upstream reservoir.

TABLE XI. Location of Observation Wells[1]

Vegetation	Well No.[2]	Location		
		Sec.	Tp. R. Mer.	Description
Acer negundo L. var. *interius* (Britt) Sarg.	XXII	SW	15-22-29-W2^d	Watkins Creek
idem	3	NE	4-22-26-W2^d	Arm River at Chamberlain
idem	4	SE	33-21-25-W2^d	Arm River near Findlater
idem	23	NW	15-22-29-W2^d	Watkins Creek
Distichlis stricta (Torr.) Rydb.	V	E½	36-20-24-W2^d	Arm River near Bethune
idem	7	W½	36-20-24-W2^d	idem
idem	8	SE	13-21-25-W2^d	Arm River near Findlater
Juncus balticus Willd. var. *montanus* Engelm.	10 and 10a	NW	34-26-28-W2^d	Arm River east of Davidson
Medicago sativa L.	XIII	SW	11-22-29-W2^d	Qu'Appelle Valley at Watkins Ranch
idem	XXI	NE	35-22-29-W2^d	community pasture
Populus tremuloides Michx.	XX	NE	24-23-29-W2^d	aspen grove on ground moraine
idem	XVIII	NW	31-22-28-W2^d	idem in abandoned stream channel
Populus sargentii Dode	XVII	SE	32-22-7- W3^d	South Sask. River near Riverhurst
idem	5	SE	22-21-25-W2^d	Arm River at Edwards Ranch
Salix petiolaris Smith	IX, 2	W½	9-22-26-W2^d	Arm River at Chamberlain
idem (?)	6	SE	22-21-25-W2^d	Arm River at Edwards Ranch
Salix discolor Muhl.	VI	NW	14-25-28-W2^d	Arm River near Girvin
idem (?)	X	SW	9-22-26-W2^d	Arm River near Chamberlain
Salix sp.	9	SE	15-29-29-W2^d	willow ring in Allan Hills
idem	21	NW	4-23-27-W2^d	willow ring in ground moraine
idem	XXI	NE	35-22-29-W2^d	willow ring in upland sandplain
idem	XV, 22	NW	15-22-29-W2^d	Watkins Creek
Shepherdia argentea Nutt.	XVI	NE	9-22-29-W2^d	Qu'Appelle River at Watkins Ranch
idem	17, 18, 19		idem	idem

Vegetation	Well No.[2]	Location		
		Sec.	Tp. R. Mer.	Description
Elaeagnus commutata Bernh.	I.1	SE	4-28-28-W2^{d}	Arm River northeast of Davidson
idem	XIV	NE	9-22-29-W2^{d}	Qu'Appelle River at Watkins Ranch
idem	16	SW	22-27-28-W2^{d}	Arm River near Davidson
idem	13	NE	7-24-27-W2^{d}	Arm River near Craik
idem	XIX	NW	9-22-28-W2^{d}	upland sand plain
Symphoricarpos occidentalis Hook	VIII	SE	22-25-28-W2^{d}	Arm River near Girvin
idem	12	SW	1-23-27-W2^{d}	Arm River near Aylesbury
idem	14	SE	3-26-28-W2^{d}	Arm River near Davidson
Sonchus arvensis L.	XI	W½	36-19-5-W2^{d}	Thunder Creek at Thunder Creek
Crataegus columbiana How.	III	NW	12-24-29-W2^{d}	Squaw Creek near Craik
Beckmannia syzigachne Fern.	15	SW	27-26-28-W2^{d}	Arm River near Davidson
Triglochin maritima L.	XII	NW	1-21-3-W3^{d}	Saline marsh near Darmody

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[1] Arranged according to the sequence of discussion in the second part of this bulletin

[2] Roman numerals indicate 1963 wells, arabic numerals indicate 1964 wells

REFERENCES

Bird, R. D.
1961: Ecology of the aspen parkland of western Canada in relation to land use; *Canada Dept. Agr.,* Res. Br., Publ. No. 1066, 155 pp.

Blaney, H. F.
1952: Determining evapotranspiration by phreatophytes from climatological data; *Trans. Am. Geophys. Union,* vol. 33, No. 1, pp. 61–66.
1954: Consumptive use of groundwater by phreatophytes and hydrophytes; *Internat. Assoc. Sci. Hydrology,* Rome Assembly, Publ. 37, Tome II, pp. 53–62.

Briggs, L. J., and McLane, J. W.
1907: The moisture equivalent of soils; *U.S. Dept. Agr.,* Bur. of Soils, Bull. 45.

Budd, A. C.
1957: Wild plants of the Canadian prairies; *Canada Dept. Agr.,* Experimental Farms Service, Publ. 983, 348 pp.

Childs, E. C.
1957: The physics of land drainage; *in* Drainage of agricultural lands; *Am. Soc. Agronomy,* Monograph VII, edited by J. N. Luthin, pp. 1–66.

Coupland, R. T.
1950: Ecology of mixed prairie in Canada; *Ecol. Monographs,* vol. 20, pp. 271–315.

Dodd, J. D.
1960: Plant successions in saline areas of Saskatchewan; unpubl. Ph.D. thesis, *Univ. Saskatchewan,* Dept. Plant Ecology.

Gibbs, R. D.
1950: Botany, an evolutionary approach; Blakiston, Philadelphia.

Hooghoudt, S. B.
1947: Waarnemingen van grondwaterstanden voor de landbouw; *Commissie voor Hydrologisch Onderzoek TNO,* Verslagen Technische Bijeenkomsten 1–6, pp. 94–110, The Hague (published, 1952).

Israelsen, O. W., and Hansen, V. E.
1962: Irrigation principles and practices; New York, John Wiley and Sons, 447 pp.

Makkink, G. F.
1949: Betrekkingen tussen cultuurgewassen en bodemvocht; *Commissie voor Hydrologisch Onderzoek TNO,* Verslagen Technische Bijeenkomsten 1–6, pp. 185–201, The Hague (published, 1952).

Meinzer, O. E.
1923a: Outline of groundwater hydrology, with definitions; *U.S. Geol. Surv.,* Water Supply Paper 494, 68 pp.
1923b: The occurrence of groundwater in the United States; *U.S. Geol. Surv.,* Water Supply Paper 489, 321 pp.
1927: Plants as indicators of groundwater; *U.S. Geol. Surv.,* Water Supply Paper 577, 91 pp.

Meyboom, P.
1962: Patterns of groundwater flow in the Prairie Profile; *National Res. Council,* Third Can. Hydrology Symposium, pp. 5–35.
1966: Groundwater studies in the Assiniboine River drainage basin: Pt. I, The evaluation of a flow system in South-Central Saskatchewan; *Geol. Surv. Can.,* Bull. 139.

Piper, A. M.
1933: Notes on the relation between the moisture equivalent and the specific retention of water-bearing materials; *Trans. Am. Geophys. Union,* pp. 481–487.

Robinson, T. W.
1958: Phreatophytes; *U.S. Geol. Surv.,* Water Supply Paper 1423, 84 pp.
1964: Phreatophyte research in the Western States, March 1959 to July 1964; *U.S. Geol. Surv.,* Circ. 495.

Staple, W. J., and Lehane, J. J.
1955: Soil moisture and agricultural meteorology; *Can. Dept. Agr.,* Soil Research Laboratory, Swift Current, Sask., Prog. Rept. 1948–1954, pp. 9–23.

Troxell, H. C.
1936: The diurnal fluctuation in the groundwater and flow of the Santa Ana River and its meaning; *Trans. Am. Geophys. Union,* p. 496–504.

Versluys, J.
1916: De capillaire werkingen in den bodem; Ph.D. thesis, Delft, Holland.

Walter, H.
1936: Tabellen zur Berechnung des osmotischen Wertes von Pflanzen-preszsaften, Zuckerloesungen und einzige Salzloesungen; *Ber. Deut. Bot. Gesellsch.,* Bnd. 54, p. 328.

Wesseling, J., and van Wijk, W. R.
1957: Soil physical conditions in relation to drain depth, *in* Drainage of agricultural lands; *Am. Soc. Agronomy,* Monograph VII, edited by J. N. Luthin, pp. 461–505.

White, W. N.
1932: A method of estimating groundwater supplies based on discharge by plants and evaporation from soil; *U.S. Geol. Surv.,* Water Supply Paper 659-A.

Woudt, B. D. van 't, and Hagan, R. M.
1957: Crop responses at excessive high soil moisture levels, *in* Drainage of agricultural lands; *Am. Soc. Agronomy,* Monograph VII, edited by J. N. Luthin, pp. 514–579.

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