Soil moisture depletion calculations for Winnipeg 1950-1963

Hamilton, J. J.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20375007
Technical Paper (National Research Council of Canada. Division of Building Research); no. DBR-TP-229, 1966-07

NATIONAL RESEARCH COUNCIL

DIVISION OF BUILDING RESEARCH

CANADA

SOIL MOISTURE DEPLETION CALCULATIONS FOR WINNIPEG 1950 - 1963

BY

J. J. HAMILTON

TECHNICAL PAPER NO. 229
OF THE
DIVISION OF BUILDING RESEARCH

OTTAWA

JULY 1966

PRICE 25 CENTS

NRC 9146

This publication is one of a series being produced by the Division of Building Research of the National Research Council as a contribution towards better building in Canada. It may therefore be reproduced, without amendment provided only that the Division is advised in advance and that full and due acknowledgment of this original publication is always made. No abridgment of this report may be published without the written authority of the Division. Extracts may be published for purposes of review only.

Publications of the Division of Building Research may be obtained by mailing the appropriate remittance, (a Bank, Express or Post Office Money Order or a cheque made payable at par in Ottawa, to the Receiver General of Canada, credit National Research Council) to the Publications Section, Division of Building Research, National Research Council, Ottawa. Stamps are not acceptable.

A coupon system has been introduced to make payments for publications relatively simple. Coupons are available in denominations of 5, 25, and 50 cents and may be obtained by making a remittance as indicated above. These coupons may be used for the purchase of all National Research Council publications.

A list of all publications of the Division of Building Research is available and may be obtained from the Publications Section, Division of Building Research, National Research Council, Ottawa, Canada.

NATIONAL RESEARCH COUNCIL
CANADA
DIVISION OF BUILDING RESEARCH

SOIL MOISTURE DEPLETION CALCULATIONS FOR WINNIPEG 1950 - 1963

by

J. J. Hamilton

Technical Paper No. 229
of the
Division of Building Research

OTTAWA
July 1966

SOIL MOISTURE DEPLETION CALCULATIONS FOR WINNIPEG 1950 - 1963

by

J. J. Hamilton

ABSTRACT

In areas of sub-humid climatic conditions, the moisture received in the form of precipitation is less than the amount that might potentially be used in processes of evaporation and transpiration. Winnipeg's climate is characterized by fairly large and protracted deviations from long-term mean temperature and precipitation conditions. During drought periods, plants draw heavily upon soil moisture in storage in the heavy clay subsoils, and the resulting soil volume change causes serious foundation problems for many engineering structures.

A soil moisture depletion calculation, cumulative over a number of years and based on Thornthwaite's potential evapotranspiration concept, has been found useful in evaluating the vegetation-climate factor in soil moisture and volume change studies. The competition of shallow- and deep-rooted vegetation for available soil moisture, the effects of planting or removal of trees on sites, or the covering of large portions of the ground surface with impermeable surfacings on the recharge of subsoil moisture are discussed. Empirical relationships between calculated soil moisture depletion and depth of the water table, vertical ground movements, and the failure of buried water-mains due to flexure, have been found useful in studies of these engineering problems.

SOIL MOISTURE DEPLETION CALCULATIONS FOR WINNIPEG

1950 - 1963

by

J. J. Hamilton*

Throughout the Prairie regions of Western Canada the soil is often unsaturated to varying depths for part or all of the year because the moisture received in the form of precipitation is less than the amount utilized by evaporation and plant transpiration. At elevations above the saturated zone the pore water is subjected to suction or, in other words, exists at pressures below atmospheric. When examined in routine soil mechanics tests, soils under the influence of suction or negative pore water pressure exhibit significantly different and usually more complex engineering characteristics than do saturated soils.

Terzaghi's effective stress concept, first published in 1923(1), has been generally accepted as a principle of soil mechanics upon which rational analysis of volume change and shearing strength of soils can be based. Early analyses dealt primarily with saturated soils comprised of a mineral soil phase and a liquid pore water phase. More recently the concept has been extended to unsaturated soils, which have a gaseous phase included in their pore fluid component and therefore exhibit the

---

* Research Officer, Prairie Regional Station, Division of Building Research, National Research Council, Canada

increased complexities of a three-phase system (2). The significance of soil suction or negative pore water pressures in relation to some aspects of soil mechanics was dealt with by Penner (3). At a special conference held in London in March 1960 (4) it was shown that much could be learned about the effects of climate and vegetation on soil moisture suction from the findings of agricultural and climatological research workers.

THE SOIL MOISTURE BUDGET

Agricultural scientists have recognized the need for keeping an account of the soil moisture available to plant life, but it has not yet become routine practice to prepare periodic maps reporting the "local and geographic differences in the amount of water available in the soil for nourishing plants," as envisioned by Koppen (5) in 1900. This development has been delayed by inadequacies in existing soil moisture instruments and the problem of gathering and processing the results from the large number of measuring stations required to describe conditions within even small geographic regions.

In 1948 Thornthwaite (6) published a climate classification system utilizing readily available climatological data. As a result, large areas of the world have been classified into climatic regions. For example, the Province of Manitoba has recently been mapped (7) according to the latest methods presented by Thornthwaite and his associates (8). According to this classification, the regional climate for the Winnipeg area is Dry Sub-humid (moist fringe). In general, "Manitoba lies in a climatic transition zone from dry to humid, one in which small changes in moisture or temperature will upset the balance" (7).

The civil engineer or architect interested in foundation performance prefers to describe the rainfall-potential evapotranspiration aspect of the weather in a graphic way. This report describes an adaptation of Thornthwaite's calculation for potential evapotranspiration that uses readily available data from meteorological reports (i.e., daily mean temperature and actual precipitation) in order to provide a graphical description of the moisture budget. The cumulative difference between calculated potential evapotranspiration and actual precipitation was termed "soil moisture depletion" by Bozozuk and Burn (9), and differs from Thornthwaite's "soil moisture deficiency" in that the "soil moisture storage" term is not included.

Calculated soil moisture depletion has been related in the Winnipeg area to <u>in situ</u> soil volume changes and shallow foundation performance, to measured soil moisture change, and to changes in water table elevations under grass covered test plots. Some comments are made on design implications and the possible extrapolation of these relationships into different vegetative or surface cover conditions.

CALCULATION OF POTENTIAL EVAPOTRANSPIRATION

Thornthwaite (6) found that the relationship between monthly mean daily temperature and potential evapotranspiration (adjusted to a standard month of thirty days, each having twelve hours of possible sunshine) for four selected sites in the United States was well expressed by an equation of the form

$$e = ct^{a}$$

in which e is the monthly evapotranspiration (cm)

t is the mean monthly temperature (°C) and

c and a are coefficients that vary from one place to another, and are small in cold climates and large in hot climates.

In order to calculate these coefficients, the following steps are carried out:

1. a monthly index is obtained, $i = (\frac{t}{5})^{1.515}$
2. the twelve monthly values are summed to give an appropriate heat index I; this index varies from 0 to 160, while a varies from 0 to 4.25 and can be expressed by the relation:

   $a = 0.000000675\, I^{3} - 0.0000771\, I^{2} + 0.01792\, I + 0.49239$
3. the coefficient c varies inversely with I.

The general equation for evapotranspiration is

$$e = 1.6\left(\frac{10t}{I}\right)^{a}$$

in which a has the value given by the previous equation.

The general equation gives unadjusted rates for potential evapotranspiration. As the number of days in a month ranges from 28 to 31 (a variation of nearly 11 per cent) and the number of hours of daylight (when evapotranspiration principally takes place) varies with the season and with latitude, it is necessary to reduce or increase the unadjusted rates by a factor that varies with the month and with latitude.

For calculations of potential evapotranspiration at Winnipeg, two tables (Table I and Table II) were developed by D. W. Boyd, Meteorologist seconded to the Division of Building Research from the Meteorological Branch, Department of Transport. The first gives unadjusted daily rates of potential evapotranspiration in inches for various daily mean temperatures from 32° to 89°F. The second lists correction factors that account for variations in the maximum duration of sunlight at 50°N (latitude of Winnipeg) for each day of the year.

Table III illustrates the procedures used in carrying out these calculations. The results presented are for the month of June 1954. In a typical calculation for any day, the following steps are carried out:

1. The daily mean temperature is obtained from the meteorological reports prepared by the Department of Transport and is entered in Column 2.
2. From Table I the unadjusted daily potential evapotranspiration is determined for this daily mean temperature and is entered in Column 3.

3. The correction factor for the length of sunlight is determined from Table II for the particular day for which the calculation is being made and is entered in Column 4.
4. The unadjusted daily potential evapotranspiration is multiplied by the correction factor to give the corrected potential evapotranspiration for the day (Column 5).

CALCULATIONS OF SOIL MOISTURE DEPLETION

Thornthwaite defined potential evapotranspiration as the amount of water that would be returned to the atmosphere if the soil and vegetation were provided with an unlimited supply of freely available water.

When evapotranspiration exceeds the amount of rainfall received by the soil surface, vegetation must draw on the moisture stored in the soil. The amount of soil moisture that can be retained by various soil types is a function of their texture, organic content and structure (10). For example, the approximate number of inches of water per foot of soil that is stored by various soils and available to plants for transpiration is as follows:

Fine sand	0.5 in. of water per foot of soil
Sandy loam	1.7 in. of water per foot of soil
Silty loam	2.5 in. of water per foot of soil
Loam	3.3 in. of water per foot of soil
Clay	4.5 in. of water per foot of soil

The efficiency of plants in removing water from storage through transpiration processes depends on the depth and distribution of their root system. As the total depth from which moisture is extracted closely approximates the depth of root penetration, it is of interest to consider some of the measured depths of root penetration for plants commonly found in Western Canada: common weeds, 2 to 8 ft; wheat, 3 to 6 ft; Scotch pine and Cottonwood, 1 to 5 ft; Elm and Caragana, 5 to 15 ft; Burr Oak, 10 to 20 ft; alfalfa, greater than 20 ft (10). Based on estimates of soil moisture storage, the total amount of water available to a plant growing on a heavy clay soil is 4.5 in. per foot of root penetration.

Differences between species of plants, as related to the various times when growth begins and transpiration rates increase in the spring, may be of significance in the total moisture requirement of plants during the growing season. Transpiration rate is also affected by the rate of development of the root system and the increase in leaf area of the plants. The depth and extent to which plants are successful in drawing upon the moisture stored in the soil is a function of the type of plant and the history of its growth. Ward (11) found in southern England that the height of a tree was a rough guide to the spread of its roots and the extent of possible damage to buildings, and that root competition resulting from proximity of other trees and the effects of paving over the root system, increased the horizontal extent of the roots.

Bozozuk (12) in 1962 reported on the damage sustained by shallow foundations in Ottawa due to the effects of tree growth.

To determine the amount of theoretical soil moisture depletion occurring during the day the precipitation (also from meteorological reports) for the day is subtracted from the corrected potential evapotranspiration (Columns 6 and 7, Table III). The soil moisture decrease is positive when the potential evapotranspiration is greater than the daily precipitation, and negative when the daily precipitation exceeds the potential evapotranspiration.

SOIL MOISTURE DEPLETION AT WINNIPEG

In initial trial calculations for Winnipeg it was assumed that the soil moisture storage was completely recharged each spring following snow-melting, and the "soil-moisture depletion" was calculated from that datum each year. Typical annual soil moisture depletion calculations are shown in Column 8, Table III. The total soil moisture depletion carried forward from 31 May 1954 was 0.30 in. This method of calculation, however, did not take into account soil moisture depletion carried over from one year to the next. Usually, total precipitation during the winter was much below that required to recharge the soil moisture storage completely. Similarly, due to this method of accounting, early spring rainfalls were sometimes indicated as run-off when no run-off or ponding was observed (see, for example, figures for 8 and 19 June 1954 in Table III). It became apparent that a method was needed for developing a cumulative total from year to year.

It was necessary to assume a zero datum for complete ground water recharging. After considering several years of meteorological records, the assumption was made that for grass covered areas the soil moisture storage was completely recharged after spring breakup in 1950, a spring in which extensive flooding occurred over much of the Red River Valley (13). It was also assumed that the effects of dew, frost and sublimation from snow were insignificant.

The cumulative soil moisture depletion calculated from the 1950 datum is listed in Column 9, Table III, and is plotted on Figure 1. This cumulative plot would be a true measure of actual changes in soil moisture conditions if plants were 100 per cent efficient in removing water from storage, regardless of depth and moisture stress; and if the assumptions of no run-off, and no subdrainage or upward inflow of moisture from aquifers below, accurately represented the actual field conditions.

In general, these ideal conditions do not exist, and changes in soils moisture storage will usually be less than indicated by the soil moisture depletion calculations. Penman (14) has proposed a "root constant" concept as a means of evaluating the effect of different types of vegetation and depth of rooting on the relationship between measured changes in soil moisture storage and calculated potential evapotranspiration. The root constant is defined as the amount of easily accessible water held in the soil within the depth of rooting, and an extra inch is added to allow for water that can be extracted from the soil below the roots. It is assumed that all of this is available for transpiration at the potential rate. If, during the growing season, the soil becomes sufficiently dry to impede transpiration, the calculated deficit can be reduced by means of a relationship involving the appropriate root constant for the type of vegetation (e.g., see Figure 52, p. 65, Black, Croney and Jacobs (15)). These authors used a value of 4 in. for grass-covered test plots in the vicinity of London, and showed a good correlation between soil moisture deficits estimated from meteorological data and deficits estimated from pore water pressure measurements.

The root constant concept is more difficult to apply in the Winnipeg area where the climate is considerably less humid than that of London and drought periods are more protracted. Comparisons of calculated soil moisture depletion with measured changes in moisture storage in the top 10 ft of the soil profile indicate that the effective depth of rooting of native grasses on undisturbed soil profiles is not a constant but is dependent on the moisture stress history of the plants. Following prolonged drought periods, their root systems develop to greater depths and can utilize moisture that was previously unavailable. There is evidence that grass roots may, under these conditions, derive moisture stored at depths of 4 ft or more in heavy clay areas. The depth of root penetration and suggested root constant for various types of vegetation in the Winnipeg area are listed in Table IV.

In residential and park areas the artificial watering of the ground surface varies widely, depending on land use and ownership, but usually the amount of water applied in excess of natural precipitation is less than can be utilized by the grass. The resulting competition between cultured grass and tree roots for the moisture available in the top 2 to 4 ft of the soil profile forces the trees to seek moisture from greater and greater depths and radii as the tree grows. In Winnipeg, tree roots have been observed at depths equal to or greater than those listed in Table IV, and at a radius from the tree equal to or greater than the height of the tree. In this situation the effects of the two root systems are additive, and the effective root penetration is dependent on the degree of competition of the grass and trees for moisture in storage. During drought the grass may utilize all of the moisture received by the soil in the form of rainfall so that the trees are forced to extend their root systems to new sources of soil moisture.

Even in a drought year in the Winnipeg area, it is doubtful whether natural grass or short rooted annual plants could derive more than 8 to 12 in. of water from storage. Where plants forming a dense surface cover compete for soil moisture with deep rooted perennials, however, it is conceivable that the annual demand upon soil moisture storage could reach 30 in. or more. It is probable that conditions or perennially cumulative soil moisture depletion exist wherever there is competition between shallow and deep rooted plants. During periods of peak moisture requirements a tree may severely desiccate the soil and cause negative moisture stresses ranging up to 15 tons per square foot throughout the root zone. Where tree roots grow under paved areas their annual moisture demand may be cumulative and in a short period of years very large depletions and negative moisture stresses may result.

RELATIONSHIPS BETWEEN SOIL MOISTURE AND OTHER VARIABLES

The cumulative soil moisture depletion calculation proposed in this report has been found useful by the author in estimating changes in soil moisture conditions in the Winnipeg area. Figure 2, published in an earlier paper (16), shows a good correlation between calculated soil moisture depletion and depth of the water table in a summer of prolonged drought; the empirical relationship being 4 in. of calculated soil moisture depletion, corresponding to 1 ft of ground water lowering. Other indications of such a relationship have been observed in connection with vertical ground movements under native grass and weed cover. In the above-mentioned paper it was shown that vertical ground movements in grass-covered test plots became significant at a depth of 8 ft when the calculated soil moisture depletion reached 32 in. of water.

The correlation between the calculated change in soil moisture depletion and the measured change in water content of the soil is not as good, and a calculated change of 4 in. in the SMD does not indicate a 4 in. change in moisture stored in a soil profile. Table V compares the calculated with the measured values for the same test plot at the University of Manitoba, where the water table measurements were made.

The poor correlation between calculated and measured soil moisture storage may be due to several factors. The actual change in soil moisture storage probably lags behind the calculated change because suction gradients must be established before moisture movement will take place. Moisture movement over varying distances must take place before plants can utilize the moisture. The rate of movement in heavy clay soils may be extremely slow, even under high stress gradients. Another factor contributing to time lags in the relationship could be that subsoil strata, still frozen long after surface snow melting commences, may limit the depth of moisture penetration at spring thaw. Very high suctions are developed in soil moisture adjacent to growing ice lenses in fine grained soils. These suctions may reach several tons per square foot, and may be higher than the highest suction induced by plant growth. It is not known whether or not subatmospheric stresses in the soil moisture, induced by frost action or carried over from the previous fall, have any important effect on the suction profile in the spring.

The fact that the soil profile at the University of Manitoba test plot is really a layered system, with a silt stratum between upper and lower clay strata, may also affect the response characteristics of the soil profile to changes in soil moisture stress. When moisture becomes available after prolonged drought, fissures and cracks in the overlying clay may allow rapid penetration of water under positive pressures down to the silt stratum, which would saturate quickly, giving rise to positive hydrostatic pressures in the silt and inter-connecting fissures. The overlying clay would then be wetting slowly from the top and bottom and walls of each crack, with the result that suctions would slowly decrease in the clay mass.

In this situation it is conceivable that soil moisture suction could still be high within the massive clay blocks, although positive hydrostatic heads might exist in the surrounding cracks and silt below. In a layered system such as this, where plant roots penetrate a fine textured stratum such as clay into a more pervious silt stratum below, most of the moisture stored in the silt stratum can be removed easily by the plants under low suctions. As this moisture is depleted, the plants then must develop higher suctions to remove moisture from the clay stratum.

SOME ENGINEERING APPLICATIONS

The climate in the Winnipeg area has been classified as Dry Sub-humid (moist fringe). The average precipitation over a long period of years very nearly equals the potential evapotranspiration during the same period. This means that occasional slight variations from average precipitation or temperature conditions results in significant changes in soil moisture conditions. Several years of slightly warmer-and-drier, or cooler-and -wetter, than average conditions often combine in what some consider to be long-term weather cycles. The result is a cumulative change or trend in soil moisture conditions. The cumulative soil moisture depletion calculation presented in this report gives a graphic indication of the precipitation-potential evapotranspiration balance. It indicates both long-term trends and their rate of change. It has been found useful in understanding and predicting movements of pavements, shallow foundations and buried pipes, and the volume change of soil profiles under grass or tree cover.

An empirical relationship has been found between the rate of water-main breaks due to flexure and the cumulative soil moisture depletion. During periods when the cumulative soil moisture depletion exceeds 16 in. the water-main flexural failure rate in the City of Winnipeg is much above normal, whereas when the SMD remains below this level water-main failures are at or below average (17). This is understandable in the light of previous remarks on competition between tree and grass roots for available moisture during drought periods. It has also been observed that buildings built during or following drought periods at sites where trees have been removed just prior to construction have undergone serious damage from heaving of shallow foundations andbasement floors. Similarly, street pavements placed on desiccated subsoils have subsequently heaved badly. Conversely, the growth of trees in areas where they have not previously grown has subjected subsoils to new demands on soil moisture and resulted in shrinkage and damage to structures founded at shallow depths.

In some urban districts large portions of the ground surface are shielded from natural precipitation and, to some extent, the subsoils are protected from evapotranspiration losses. Often street pavements, sidewalks, parking lots and buildings greatly change the run-off characteristics of an area. At the same time, efforts are made to preserve as many shade trees as possible in spite of the encroachments made on the surface area required for recharge of soil moisture. The only area of uncovered soil is often a narrow strip of grassed surface forming a boulevard or median dividing street pavements, sidewalks or parking areas. These areas usually receive no artificial irrigation because they are on public property and do not pond water during periods of heavy precipitation because they are well graded. As trees grow towards maturity they are forced to extend their root system to greater distances and depths, around and under nearby buildings, buried pipes, pavements or other structures on shallow foundations. The soil shrinkage resulting from their demands on soil moisture causes serious problems in many instances.

To eliminate or reduce root competition for soil moisture it may be advisable to incorporate any one or several of the following suggestions in landscape designs. Summer-fallow areas beneath trees equal to or larger than the canopy of the tree may be satisfactory in some instances in reducing the extent of root penetration. Where this is undesirable because of maintenance problems or unacceptable for aesthetic reasons, crushed or washed stone beds may improve infiltration and check the growth of grass or weeds. Where both lawns and trees are desired, holes or trenches backfilled with a pervious material or lined with permeable casings may aid infiltration of surface water to the root zone.

Various design features may be adopted on the basis of an increased understanding of cyclic or long-term changes in the soil moisture budget. Where differential soil volume change is expected beneath shallow foundations or buried pipes increased flexibility or strength is necessary. In some instances, enlightened construction scheduling may minimize the long-term effects of volume changes induced by climatic and vegetation factors. Environmental changes caused by construction or landscaping activities often disturb the dynamic equilibrium conditions long established by nature. This disturbance may have considerable effect on the performance of structures and may lead to serious maintenance problems.

CONCLUSIONS

1. A soil moisture budget, based on Thornthwaite's potential evapotranspiration concept, is considered to be a more rational technique of evaluating the vegetation-climate factor than the comparison of air temperature and precipitation records with long-term averages.

2. A cumulative soil moisture depletion budgeting procedure is required for the estimation of the potential use of soil moisture by vegetation and the magnitude of soil moisture stress for deep clay soil profiles in a region such as Winnipeg, where the soil moisture is not recharged every year.

3. Empirical relationships have been found between calculated soil moisture depletion, the elevation of the ground-water table and vertical ground movements. The cumulative soil moisture depletion technique has proven useful as a judgement factor in predicting or understanding the long-term performance of shallow foundations for structures on volume-changing clay soils.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the contributions made to this study by Professor A. Baracos and several students of the University of Manitoba. Grateful acknowledgement is also given his colleagues in the Division of Building Research for their assistance and guidance, in particular, C.B. Crawford and D.W. Boyd for reviewing this paper.

REFERENCES

1. Terzaghi, K. Die Berechnung der Durchlassigkeitsziffer des Tones aus dem Verlauf der hydrodynamischem. Spannungserscheinungen. Silz. Akad. Wissen. Wien Math naturw. KL. Abt. 11a, 132, 105-124.

2. Aitchison, G.D. and I.B. Donald. Effective Stresses in Unsaturated Soils. Proceedings, Second Australia-New Zealand Soil Mechanics Conference, Jan. 1956, p. 192-199.

3. Penner, E. Soil Moisture Suction - Its Importance and Measurement. Proc. ASTM, Vol.58, 1958, p. 1205-1217.

4. Pore Pressure and Suction in Soils. Butterworths, London, 1961, 151 p.

5. Koppen, W. Versuch einer Klassification der Klimate, vorzugweise noch ihren Bezichungen zur Pflanzenwelt. Geogr. Zeitschr., Vol.6, 1900, p. 603-604.

6. Thornthwaite, C.W. An Approach Toward a Rational Classification of Climate. Geographical Review, 38, 55-94, 1948.

7. Weir, T.R. Economic Atlas of Manitoba. Published by Department of Industry and Commerce, Prov. of Manitoba, 1960.

8. Thornthwaite, C.W. and J.R. Mather. Instructions and Tables for Computing Evapotranspiration and the Water Balance. Drexel Institute of Technology, Centerton, N.J., 1957.

9. Bozozuk, M. and K.N. Burn. Vertical Ground Movements Near Elm Trees, Géotechnique, Vol. 10, No. 1, 1960, p. 19-32.

10. Lassen, L., H.W. Lull and B. Frank. Some Plant-Soil-Water Relations in Watershed Management. U.S.D.A. Circular No. 910, Washington, D.C., October 1952, 64 p.

11. Ward, W.H. Soil Movement and Weather. Proceedings, Third International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, Session 4, p. 477-482.

12. Bozozuk, M. Soil Shrinkage Damages Shallow Foundations at Ottawa, Canada. The Engineering Journal, Vol. 45, No.7, July 1963, p. 33-37, (NRC 6984).

13. Rutherford, D.H. and A. Baracos. Damage to Houses - Red River Valley Flood 1950. National Research Council, Division of Building Research, NRC 2976, March 1953, 44 p.

14. Penman, H.L. Evaporation Over the British Isles. Quart. J. Roy. Met. Soc., 76(330) 372-383, 1950.

15. Black, W.P.M., D. Croney and J.C. Jacobs. Field Studies on the Movement of Soil Moisture. Road Research Technical Paper No. 41, D.S.I.R., R.R.L. London, 1958.

16. Hamilton, J.J. Volume Changes in Undisturbed Clay Profiles in Western Canada. Canadian Geotechnical Journal, Vol. 1, No. 1, Sept. 1963, p. 27-42.

17. Hamilton, J.J. Performance of Watermains Buried in Volume Changing Subsoils. (In preparation).

TABLE I

UNADJUSTED DAILY RATES OF POTENTIAL EVAPOTRANSPIRATION (IN.) FOR WINNIPEG, MANITOBA

°F	in.	°F	in.	°F	in.
		50	0.067	70	0.141
		51	0.071	71	0.145
32	0	52	0.074	72	0.149
33	0.004	53	0.078	73	0.152
34	0.007	54	0.082	74	0.156
35	0.011	55	0.085	75	0.160
36	0.015	56	0.089	76	0.163
37	0.019	57	0.093	77	0.167
38	0.022	58	0.097	78	0.171
39	0.026	59	0.100	79	0.175
40	0.030	60	0.104	80	0.179
41	0.033	61	0.108	81	0.186
42	0.037	62	0.111	82	0.192
43	0.041	63	0.115	83	0.197
44	0.045	64	0.119	84	0.203
45	0.048	65	0.123	85	0.208
46	0.052	66	0.126	86	0.213
47	0.056	67	0.130	87	0.217
48	0.059	68	0.134	88	0.221
49	0.063	69	0.137	89	0.225

TABLE II

CORRECTION FACTOR FOR MAXIMUM DURATION OF SUNLIGHT AT 50° NORTH

Day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	.68	.78	.91	1.07	1.22	1.34	1.36	1.27	1.13	.98	.82	.70
2	.68	.78	.92	1.08	1.23	1.34	1.36	1.27	1.12	.97	.81	.70
3	.68	.78	.92	1.08	1.23	1.34	1.36	1.26	1.12	.96	.81	.70
4	.68	.79	.93	1.09	1.24	1.34	1.36	1.26	1.11	.96	.80	.70
5	.69	.79	.93	1.09	1.24	1.35	1.35	1.26	1.11	.95	.80	.69
6	.69	.80	.94	1.10	1.24	1.35	1.35	1.25	1.10	.95	.80	.69
7	.69	.80	.94	1.10	1.25	1.35	1.35	1.25	1.10	.94	.79	.69
8	.69	.81	.95	1.11	1.25	1.35	1.35	1.24	1.09	.94	.79	.69
9	.69	.81	.95	1.11	1.26	1.35	1.35	1.24	1.09	.93	.78	.69
10	.70	.82	.96	1.12	1.26	1.35	1.34	1.23	1.08	.93	.78	.68
11	.70	.82	.96	1.12	1.26	1.36	1.34	1.23	1.08	.92	.77	.68
12	.70	.83	.97	1.13	1.27	1.36	1.34	1.22	1.07	.92	.77	.68
13	.71	.83	.97	1.13	1.27	1.36	1.34	1.22	1.07	.91	.77	.68
14	.71	.84	.98	1.14	1.28	1.36	1.33	1.22	1.06	.91	.76	.68
15	.71	.84	.98	1.14	1.28	1.36	1.33	1.21	1.06	.90	.76	.68
16	.71	.85	.99	1.15	1.28	1.36	1.33	1.21	1.05	.90	.75	.68
17	.72	.85	.99	1.15	1.29	1.36	1.33	1.20	1.05	.89	.75	.67
18	.72	.85	1.00	1.16	1.29	1.36	1.32	1.20	1.04	.89	.75	.67
19	.72	.86	1.00	1.16	1.30	1.37	1.32	1.19	1.04	.88	.74	.67
20	.73	.86	1.01	1.17	1.30	1.37	1.32	1.19	1.03	.88	.74	.67
21	.73	.87	1.02	1.17	1.30	1.37	1.31	1.18	1.03	.87	.73	.67
22	.73	.87	1.02	1.18	1.31	1.37	1.31	1.18	1.02	.87	.73	.67
23	.74	.88	1.03	1.18	1.31	1.37	1.31	1.17	1.02	.86	.73	.67
24	.74	.88	1.03	1.19	1.31	1.36	1.30	1.17	1.01	.86	.72	.67
25	.74	.89	1.04	1.19	1.32	1.36	1.30	1.16	1.01	.85	.72	.67
26	.75	.89	1.04	1.20	1.32	0.36	1.30	1.16	1.00	.85	.72	.67
27	.75	.90	1.05	1.20	1.32	1.36	1.29	1.15	1.00	.84	.71	.67
28	.76	.90	1.05	1.21	1.33	1.36	1.29	1.15	.99	.84	.71	.68
29	.76		1.06	1.21	1.33	1.36	1.28	1.14	.99	.83	.71	.68
30	.77		1.06	1.22	1.33	1.36	1.28	1.14	.98	.83	.71	.68
31	.77		1.07		1.33		1.28	1.13		.82		.68
TOTALS	22.24	23.47	30.67	34.35	39.75	40.71	41.08	37.35	31.65	27.83	22.73	21.10

TABLE III

ACCOUNTING METHOD FOR SOIL MOISTURE DEPLETION

MONTH June 1954 LOCATION Winnipeg RECORDS USED DOT

1	2	3	4	5	6	7	8	9
DAY	Mean Daily Temp. °F	Pot. (e-t) (in.)	Corr'n Factor	Corr'd (e-t) (in.)	Ppt'n. (in.)	Soil Moisture Change	Soil Moisture Depletion Ann.	Cum.
							0.30*	8.87*
1	43	0.041	1.34	0.05		0.05	0.35	8.92
2	46	0.052	1.34	0.07		0.07	0.42	8.99
3	52	0.074	1.34	0.10		0.10	0.52	9.09
4	58	0.097	1.34	0.13		0.13	0.65	9.22
5	63	0.115	1.35	0.16		0.16	0.81	9.38
6	66	0.126	1.35	0.17	0.13	0.04	0.85	9.42
7	62	0.111	1.35	0.15	0.82	-.67	0.18	8.75
8	53	0.078	1.35	0.11	0.82	-.71	0**	8.04
9	53	0.078	1.35	0.11		0.11	0.11	8.15
10	56	0.089	1.35	0.12		0.12	0.23	8.27
11	58	0.097	1.36	0.13	0.35	-.22	0.01	8.05
12	62	0.111	1.36	0.15		0.15	0.16	8.20
13	68	0.134	1.36	0.18	0.05	0.13	0.29	8.33
14	70	0.141	1.36	0.19	0.10	0.09	0.38	8.42
15	66	0.126	1.36	0.17	0.21	-.04	0.34	8.38
16	68	0.134	1.36	0.18	0.23	-.05	0.29	8.33
17	63	0.115	1.36	0.16		0.16	0.45	8.49
18	64	0.119	1.36	0.16	0.26	-.10	0.35	8.39
19	61	0.108	1.37	0.15	1.13	-.98	0**	7.41
20	63	0.115	1.37	0.16	0.02	0.14	0.14	7.55
21	61	0.108	1.37	0.15	0.21	-.06	0.08	7.49
22	64	0.119	1.37	0.16		0.16	0.24	7.65
23	73	0.152	1.37	0.21		0.21	0.45	7.86
24	69	0.137	1.36	0.19		0.19	0.64	8.05
25	67	0.130	1.36	0.18	0.30	-.12	0.52	7.93
26	62	0.111	1.36	0.15		0.15	0.67	8.08
27	67	0.130	1.36	0.18	0.05	0.13	0.80	8.21
28	74	0.156	1.36	0.21	0.03	0.18	0.98	8.39
29	62	0.111	1.36	0.15	0.92	-.77	0.21	7.62
30	51	0.071	1.36	0.10	0.01	0.09	0.30	7.71
31								
TOTALS		3.286		4.48	5.64	-1.16	0.30	7.71

* Soil moisture depletion on 31 May 1954

** On the annual soil moisture budget the surplus water on these dates must be considered to run off, but on the long-term budget it is assumed to reduce the cumulative depletion

TABLE IV

THE DEPTH OF ROOT PENETRATION AND SUGGESTED "ROOT CONSTANT" FOR VARIOUS TYPES OF VEGETATION IN WINNIPEG AREA

Plant	Root Penetration	Root Constant
Lawn grass (irrigated)	1 - 2 ft	4 - 8 in.
Native grass (no artificial watering)	2 - 4 ft	8 - 16 in.
Shallow-rooted trees and shrubs (Pine, Spruce, Willow, Cottonwood or young trees of the following types)	1 - 5 ft	4 - 20 in.
Intermediate-rooted trees (Elm, Aspen, Ash, Caragana, Boxelder, etc.)	1 - 12 ft	4 - 48 in.
Deep-rooted plants and trees (Alfalfa, Burr Oak, etc.)	to 20 ft or deeper	80 in. -

TABLE V

COMPARISON OF CALCULATED SOIL MOISTURE DEPLETION WITH ACTUAL CHANGE IN SOIL MOISTURE STORAGE AT U. OF M. TEST PLOT

Period	Oct/51 to Oct/52	Oct/52 to Mar/53	Mar/53 to June/54	June/54 to July/55	July/55 to Aug/55
Calc. change in soil moisture depletion (in.)	-9.5	+6.5	+6.0	+2.0	-5.0
Change in soil moisture storage (in.) Depth: 0 - 4 ft	-0.42	+1.64	+2.58	-0.20	-3.27
Change in soil moisture storage (in.) Depth: 4 - 10 ft	-3.40	+1.06	-2.58	+4.16	+3.92
Total change in storage (in.) Depth: 0 - 10 ft	-3.82	+2.70	0	+3.96	+0.65

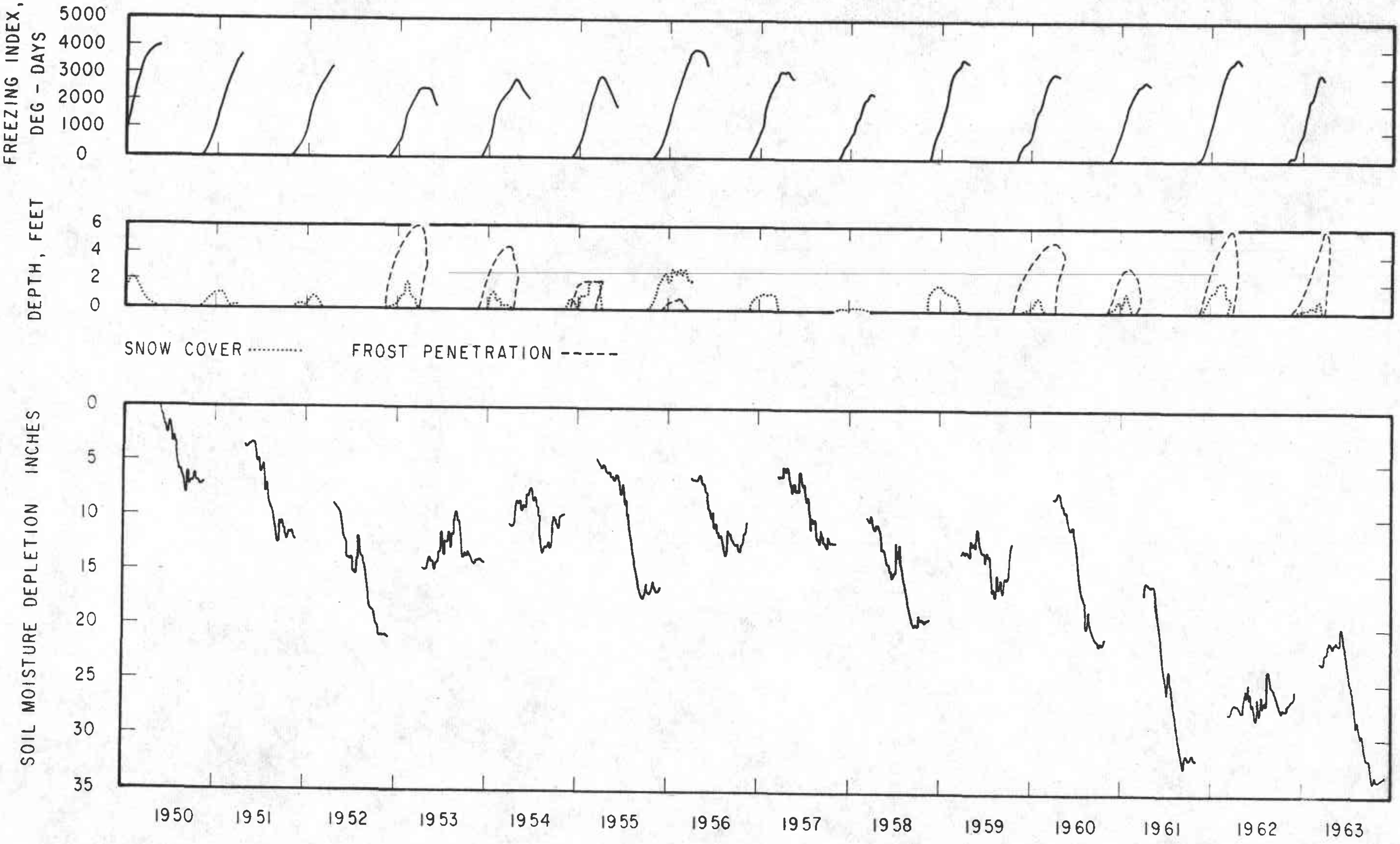

FIGURE I SOIL MOISTURE, SNOW COVER AND FREEZING CONDITIONS
WINNIPEG, MANITOBA

BR 3358-2

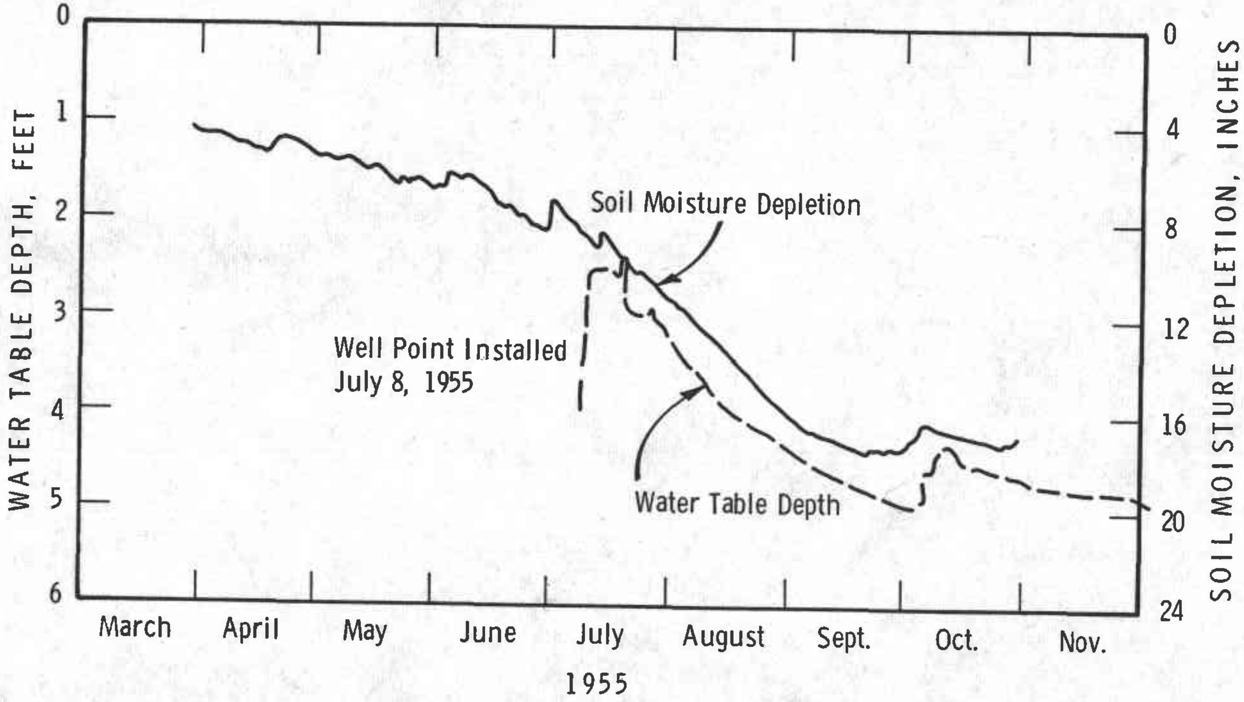

FIGURE 2

CALCULATED SOIL MOISTURE DEPLETION AND WATER TABLE DEPTH FOR THE SUMMER OF 1955 (GRASS-COVERED TEST PLOT AT THE UNIVERSITY OF MANITOBA).

BR 3358-1