# Experiments with the surface heat and water budgets of the Canadian Middle North

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ABSTRACT

The effects of surface changes on the heat and water budgets of the Canadian Middle North have been studied for the region of The Pas, Manitoba, using a surface energy balance model and daily synoptic and radiosonde observations for the period July 1967–June 1968. Comparisons have been made with the results of a previous, similar, investigation for the same period for the Boreal region of Moosonee, Ontario. The latter region showed a positive water budget for all surface types, i.e., runoff, while The Pas showed a substantial water deficit for all surface types except that of rock. This deficit was calculated when using similar surface type descriptions to those of Moosonee (bare ground, forest, lake and rock). As the river runoff measurements indicate a moderate annual regional water surplus, it was concluded that there may be conditions at The Pas which reduce evaporation and which are not generally typical for other areas previously examined. Such possibilities have been investigated. The main point of interest proved to be the characteristics of vegetation types like lichen, which has marked water retention properties because it generates strong resistance to evaporation. In order to obtain a realistic water budget for the region it thus becomes essential to ascertain in considerable detail the structure of the vegetation cover and to calculate the evaporation from each of the various surface types. The composite regional water budget for 1967–1968 proved to be approximately balanced. Open water showed high evaporation loss and lakes can only exist in the region by receiving water from surfaces of rock, lichen, moss or thin soil. Maintaining an increased water area, as behind reservoir dams, would require either reduction in forest covered land or the import of water from outside the region. Large-scale destruction of moss and lichen would apparently have far reaching consequences for the regional water budget.

## 1. Introduction

A great variety of micro- and mesoclimate types can be realized under a given weather condition in a particular geographical area. A patch of forest or grassland, a road surface, bare rock, a lake or river, all exhibit characteristics which govern the details of their specific heat and water budgets. If one excludes the ocean and the desert surfaces of sand or ice and snow, it appears that nearly all climatic variants can be realized in most areas. The regional climate, resulting from the interaction of atmosphere and surface, is thus the sum of the fractional contribution of the various surface types present. And, if one speaks of climatic change induced by altered surface conditions, it is not generation of the climate of a new surface type which is discussed but, rather, the expansion of one type at the expense of others.

Nevertheless, if the areal distribution of a particular surface type is altered, then the heat and water budgets of the remaining types will, of course, be influenced. This happens for two reasons—first, because the surface air will be modified differently and will then react in a dissimilar manner with the ground downstream. However, the mixing of the air is quick and the advection usually rapid, so the changes in the surface type must be quite marked and extend a considerable distance upwind before air mass modification becomes significant. Secondly, if the surface type is altered it may have consequences for its water budget. If the changed surface uses more or less water than before, the runoff will be different. Since the water

Table 1. *Annual water budget, Moosonee, Ont.*

| | Water surplus |
|---|---|
| Bare ground, water storage capacity 5 cm | 41.20 cm |
| Bare ground, water storage capacity 20 cm | 31.50 cm |
| Dense coniferous forest | 23.73 cm |
| Lake, 33 m deep | 32.95 cm |
| Rock | 67.25 cm |

motion is very much slower than the air motion, the result will be different water budgets in adjacent localities, hence a change in surface heat budgets and regional climate.

The water budget is unique. If the available water exceeds the water demand of the atmosphere at a certain locality (the potential evapotranspiration), then an increase in the water supply will have no consequence for the regional heat budget or climate. The extra water goes into surface or ground water runoff and is of interest only to the hydrologist and not to the climatologist. However, when the water supply falls below the demand, the surface heat budget is influenced profoundly. The energy now not used for latent heat transport is transferred to the atmosphere via sensible heat flux, which requires increased surface temperature. This is climate change.

In order to study the effects of surface changes on the heat and water budgets of the Canadian Boreal forest region, one year of surface and radiosonde data (July 1967 – June 1968) from The Pas, Manitoba, were used to calculate, for each day, the individual surface energy balance terms for a variety of surface conditions. Comparisons were made with a similar investigation previously carried out for the same period for Moosonee, Ontario (Vowinckel & Orvig, 1974). The location of The Pas and Moosonee are, respectively, 53°58′ N; 101°06′ W; 272 m asl, and, 51°16′ N; 80°39′ W; 0 m asl.

If changes occur in surface characteristics, all parameters of the heat and water budgets at the ground will be affected, and in the present study only such local changes are considered, i.e., it has been assumed that the air mass, which interacts with the changed surface, remains unmodified. Thus the simulation requires only different surface constants. Such changes have been simulated by the programme called "EBBA" (Vowinckel & Orvig, 1972).

## 2. The water budget at The Pas

In the following, the possible climatic effects of surface changes are expressed by the altered water budget. It was pointed out above that if the precipitation is greater than the water demand (and if each surface type shows a surplus) then surface changes will not affect the area directly via the water balance. The runoff will change, but the heat budget will not be affected by any water deficit. Such surplus water condition exists in the area of Moosonee, Ontario, where all surface types have a positive water budget as shown in Table 1 (Vowinckel & Orvig, 1974).

The region of The Pas, Manitoba, has an abundance of swamps and lakes, and might be expected to show conditions similar to Moosonee. Table 2 gives the corresponding values for The Pas. It is apparent that the usual mid-latitude surface types, including a lake, all show a substantial water deficit with the exception of a rock surface. Paved or concrete surfaces and natural rock have minimal water storage capacity, consisting only of the water used to wet the surface and the water which might be held in small depressions in the rock. In the programme "EBBA" this water is treated similarly to interception, i.e., the water loss is split into two components. The first is used for wetting the surface (here assumed to be 1 mm for each occurrence of precipitation), and the second is the amount evaporated from this

Table 2. *Annual water budget, The Pas, Man.*

| | Water deficit |
|---|---|
| Bare ground, water storage capacity 5 cm (initially saturated) | −11.0 cm |
| Bare ground, water storage capacity 20 cm (initially saturated) | −21.35 cm |
| Dense coniferous forest, water capacity 10 cm (initially saturated) | −16.19 cm |
| Lake, 33 m deep | −25.31 cm |
| Rock | +27.75 cm |

Table 3. *Surface types within a radius of 55 km from The Pas*

| | |
|---|---|
| Area of Water | 13.87 % |
| Area of Swamp | 31.60 % |
| Area of Land | 54.53 % |

wet surface during the duration of precipitation. The evaporation is calculated using the water demand figure for the particular day. The inability to store water makes a rock surface a generator of runoff even under very dry conditions with little precipitation.

Table 3 shows the areas covered by lake, swamp and various land surfaces within a radius of ½ degree latitude from The Pas. A comparison of Tables 2 and 3 indicates that it seems impossible to balance the water budget in the area. A conceivable alternative would be that the total river runoff is negative, i.e. that net import by river flow into the region compensates for the deficit caused by evaporation. The hydrological balances for a number of catchment areas over six years are reflected in Table 4, which gives the annual runoff measured in two rivers: the Saskatchewan and Sturgeon. It is evident that there is no water deficit in the region but, rather, a moderate surplus.

It might be that there occurs an annual gain by ground water flow of a magnitude which would allow net export of water by the rivers and, at the same time, a negative meteorological water budget (greater evaporation than precipitation). This possibility has not been checked as it seems unlikely in view of the large quantities of water involved.

It might be argued that the results simply indicate errors in the programme EBBA. However, it has been used in a number of other studies of various areas, and the calculated water budget figures have shown reasonably close correspondence to hydrological calculations and observations. The alternative is that there are conditions present, in the region of The Pas, which reduce evaporation and which are not generally typical for other land areas previously examined. Such possibilities have been investigated and are described in the following.

## 3. Experiments with the water budget

There are a number of factors which can change the water budget. First, there may be a significant water surplus at a certain time of the year, which provides runoff sufficient to make up for the deficits of rivers, lakes and swamps. Second, there may exist conditions which sharply reduce the availability for evaporation of existing water.

In the first case, a temporary water surplus is generated if more water is made available than can be removed from the surface by infiltration. Very intense precipitation or rapid snow melt are examples. In the programme used for these studies, the surface runoff is governed by the infiltration rate and the time necessary for the surface water to reach a water channel.

Table 5 shows the results of test calculations, allowing the infiltration period to change by a factor six. The values indicate an increase in runoff with less infiltration efficiency. The infiltration duration generally stipulated in this study is 3 hours. It is apparent that annually about 3 cm less runoff would result from a more efficient infiltration. This is about 6% of the precipitation. No test gave zero runoff. Infiltration can occur in spring only after the ground has thawed. This includes frozen layers below the surface, otherwise they act as barriers to water movement and runoff would occur even if sufficient time were available for infiltration.

The values in Table 5 indicate that only the snow melt period is critical for runoff, as large quantities of water are then suddenly made

Table 4. *Annual regional runoff (cm) in two rivers*

| | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 |
|---|---|---|---|---|---|---|
| Saskatchewan between | | | | | | |
| Prince Albert and The Pas | 0.26 | 0.10 | 0.11 | 0.03 | 0.32 | 0.17 |
| Sturgeon River | 14.2 | 9.0 | 6.7 | 8.0 | 12.0 | 12.9 |

Table 5. *Runoff for different infiltration period durations (cm)*

| Duration (h) | J | F | M | A | M | J | J | A | S | O | N | D | Year | % of precipitation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0.43 | 5.59 | 0.82 | 0 | 0 | 0 | 0.10 | 0 | 0 | 0 | 0 | 6.94 | 16 |
| 3 | 0 | 0.43 | 5.59 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.02 | 14 |
| 6 | 0 | 0 | 3.28 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.28 | 8 |

available. When incorporating the possible additional water in the areal water budget (Table 2) it is apparent that this change is quite insufficient to effect a balanced budget.

Turning to the possibility that the existing water may not be readily available for evaporation, such availability will depend on the soil water storage capacity and on the speed with which stored water can be transported to the atmosphere.

Test runs show that soils with small water holding capacity will have relatively light evaporation and large runoff. The first few centimeters water holding capacity will have the greatest influence on these processes; when the storage capacity reaches 10 cm the runoff is no longer affected by storage. It can be concluded that bare rock or very thin soil will exercise a significant influence on runoff and on the water budget of surrounding areas. In a region of a permanent or temporary water deficit, the amount of lake surface which can be maintained will be greatest where the surface is rock. Using The Pas synoptic data, the calculated evaporation and runoff show that the region could maintain lakes on 37% of the surface if the rest of the area were rock. In reality the extent of rock is small. From air photographs and maps it is estimated that less than 3% of the The Pas area is rock outcrop. In terms of the regional water budget, the soil water storage capacity effects are not very important.

There remains the possibility that stored water is not readily available for evaporation. A significant difference exists between a vegetated surface and bare ground. Vegetation extracts water from a deep layer, proportional to the root density distribution. Thus, the water extraction proceeds nearly unimpeded, even with a dry surface layer, and is independent of leaf surface area and of infiltration rate.

The evaporation from a bare surface diminishes sharply once the top soil dries out, because the water conducting capillaries break and soil water transport must be accomplished by water vapour diffusion. The composition of the soil is important in this process, the smallest water loss occurs in coarse grained sandy soils.

The programme permits variations in the availability of the water held in different soil layers. It is stipulated how much water, of the total water demand, is supplied by each ground layer. The soil moisture tension is then determined, for each layer, given the water demand and the water deficit of the layer (Vowinckel & Orvig, 1972). Experiments were performed, using different values of water availability. Three surface types and five water layers are shown in Table 6. The difference in annual evaporation between ground types 1 and 2 was close to 5.5 cm (about 3 300 cal.). Between types 3 and 2 the difference was 7.5 cm (4 500 cal.). The vascular vegetation cover thus evaporates considerably more than the other types, although the results for bare ground are mainly of academic interest as far as the region of The Pas is concerned, since the air photographs reveal no extended or recognizable area of bare ground.

The point of interest is therefore to investigate possible vegetation types which may have water retention properties similar to bare soil.

Table 6. *Percent contribution to the water demand by different ground layers*

| | Layer | | | | |
|---|---|---|---|---|---|
| Ground type | 1 | 2 | 3 | 4 | 5 |
| 1. Bare ground | 80 | 15 | 3 | 1 | 1 |
| 2. Vegetation | 35 | 30 | 20 | 10 | 5 |
| 3. Lichen-type | 90 | 5 | 2 | 2 | 1 |

Table 7. *Runoff (RO) (cm/month and year), latent heat flux (QE) (cal $cm^{-2}$ $day^{-1}$) for each month, annual total QE (cal $cm^{-2}$ $year^{-1}$), net runoff (net RO) (cm $year^{-1}$)*

All terms given for three different assumptions of top layer water holding capacity. July 1967 – June 1968

| Water holding capacity of top layer (cm) | Jan. | | Feb. | | March | | April | | May | | June | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RO | QE | RO | QE | RO | QE | RO | QE | RO | QE | RO | QE |
| 0.1 | 0 | 5.0 | 0.59 | 11.4 | 5.83 | 37.7 | 1.48 | 71.6 | 0 | 81.5 | 0 | 116.7 |
| 0.5 | 0 | 5.3 | 0.38 | 11.8 | 5.87 | 45.3 | 0.60 | 88.1 | 0 | 86.9 | 0 | 132.2 |
| 1.0 | 0 | 5.3 | 0.49 | 11.6 | 5.48 | 63.1 | 0.28 | 109.5 | 0 | 73.7 | 0 | 120.0 |

| Water holding capacity of top layer (cm) | July | | Aug. | | Sept. | | Oct. | | Nov. | | Dec. | | Year | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RO | QE | RO | QE | RO | QE | RO | QE | RO | QE | RO | QE | RO | QE | Net RO |
| 0.1 | 0 | 138.5 | 0 | 110.7 | 0 | 89.5 | 0 | 36.3 | 0 | 17.9 | 0 | 4.1 | 7.90 | 22 029 | 8.46 |
| 0.5 | 0 | 146.8 | 0 | 122.0 | 0 | 99.3 | 0 | 46.0 | 0 | 18.9 | 0 | 3.9 | 6.85 | 24 640 | 3.72 |
| 1.0 | 0 | 150.5 | 0 | 122.6 | 0 | 107.6 | 0 | 34.6 | 0 | 17.9 | 0 | 4.0 | 6.25 | 25 054 | 1.57 |

Rouse et al. (1971, 1972) pointed out that lichen and similar plants generate strong resistance to evaporation.

## 4. Lichen (Cladonia alpestris)

Unlike higher, vascular, plants the lichens do not have conductive tissues. Accordingly, after a period of evaporation a dry layer will be generated on top. This vegetation type will therefore act basically as a non-vegetated surface of coarse material. In the present study it is assumed that type 3 of Table 6 will apply. In test runs up to this point it was assumed that all layers of the ground had equal water holding capacity. As the upper soil water layer now must coincide with the lichen layer, the amount of water in this layer is prescribed. Its water holding capacity must be set smaller than that of the deeper layers.

The thickness of the live lichen carpet is assumed to be between 3 cm and 10 cm. Wet lichen tissue may fill between 0.02 and 0.1 of this volume. Thus, between 0.06 cm and 1 cm of water can probably be held in this layer. The water holding capacity of the deeper layers will be quite high as they consist, at least partly, of organic material. In the present calculations the capacity has been assumed to be 10 cm water. This amount will satisfy the requirement that no significant water deficit is generated in these layers at any time of the year. Otherwise the actual value assigned is not very important for the water budget calculations. It is apparent that with small water holding capacity of the first layer, the effect shown in Table 6 will be enhanced. Test runs were performed with water holding capacities in the first layer of 0.1 cm, 0.5 cm and 1 cm water. The monthly and annual runoff and latent heat flux resulting from daily synoptic observations in 1967–1968 are shown in Table 7.

The annual values of Table 7 include both runoff and net runoff. The former refers to that calculated by the energy budget programme EBBA. The ground water content and amount of snow on the surface will both have changed from the beginning to the end of a particular year. These values represent temporary storage and must be considered in the water balance. The net runoff is that which would occur if the storage values are set to be similar at the beginning and end of the year.

The values shown in Table 7 indicate that runoff would occur only during three months of the year. All experiments discussed so far show that there would be a water deficit during the summer, and the measured precipitation would be unable to make up the depleted soil water until the following winter. The only exception to this condition is, as always, surfaces of rock.

Table 8. *Composite annual water budget for the area of The Pas, Man. (cm)*

| Percent of area | Surface type | Water budget of surface type | Contribution to regional water budget |
|---|---|---|---|
| 3 | Rock | +27.75 | +0.83 |
| 2 | Bare soil | + 2.00 | +0.04 |
| 5 | Coniferous, wet | −13.26 | −0.66 |
| 5 | Coniferous, no inflow | + 0.46 | +0.02 |
| 7 | Grass, shrub, thin soil | + 6.84 | +0.48 |
| 32.5 | Land surface, lichen covered | + 8.46 | +2.75 |
| 5 | Swamp, deciduous, wet | −16.45 | −0.82 |
| 26.6 | Swamp, moss, moss-lichen | + 5.00 | +1.33 |
| 13.9 | Water, 33 m deep | −25.31 (−34.84)[a] | −3.52 (−4.84)[a] |
| Total surplus (+) or deficit (−) | | | +0.45 (−0.87)[a] |

[a] Value in bracket for 16 m depth.

The values for Net Runoff in Table 7 appear to be approximately inversely proportional to the water holding capacity in the top layer. Details of the water budget of this region are, therefore, highly affected by the type of vegetation covering this thin surface layer. It has, so far, been assumed that the top layer should represent lichen vegetation. From examination of air photographs the impression is created that the major part of the region, classified as swamp on topographical maps, is covered by a sphagnum-type moss. Such vegation will have characteristics somewhat similar to lichen, but less extreme.

## 5. Conclusions—the regional water budget

Table 8 shows the composite water budget for the area of The Pas, Manitoba. An uncertainty is the depth and size of the regional water bodies. A uniform diameter of 100 km was assumed in the calculations. This is probably rather large, with the result that the water budget will come out more positive, because a large lake evaporates proportionately less than a small one. As for the depth, 33 m seems a reasonable assumption. However, calculations for an average lake depth of 16 m are given in brackets in Table 8.

For the land area was assumed 3% rock and 2% bare shallow soil with 5 cm water holding capacity. The rest of the land area is either lichen, grass-shrub, or coniferous forest. The forest in the area is not dense. The allocation of 10% to forest represents the surface covered by trees if these were found together in a dense stand. Grass-shrub is estimated to cover 7% of the surface, and the rest of the land, 32.5% is lichen-covered. The swamp area is considered to make up 5% by well watered deciduous vegetation, either trees or a dense lower vegetation, and the rest, 26.6%, being sphagnum and similar types of vegetation.

These estimates of surface types were made after consulting air photographs and topographical maps. The areas could, certainly, be evaluated more exactly and especially the water holding capacity of the ground might be tested, giving better values for this basic parameter. Certain conclusions can, however, be drawn from the present results.

Table 8 shows an approximately balanced water budget. The most important fact is that the open water areas cannot exist in this region without a very large supply of water from other localities. A significant supply for this deficit can only come from rock, lichen-moss vegetation or thin soils with light vegetation.

If the water covered surface was extended to any degree, for example by the building of reservoir dams, then the water surplus area would have to be extended also. This would be at the cost of the productive vegetation (forest), or water from outside the region would have to be supplied to cover the increased water deficit. If neither of these possibilities existed, the mean water level would fall until the various areas again became balanced.

It seems likely that both sphagnum and

lichen act as cover for a soil-humus with a large water holding capacity. The fact that these areas can function as the main water source is solely attributable to the water insulating effect of this type of vegetation. Any other vegetation on such soil-humus would have an annual water deficit of 15–20 cm. Large-scale destruction of this vegetation type, either deliberately or accidentally as by fire, would apparently have far reaching consequences for runoff, lake levels and the productive vegetation.

The natural conditions in the region described are very sensitive to large-scale interference with the environment. The size of the area with these characteristics is unknown. It depends on the amount of precipitation and its distribution in time, and on existing surface conditions. From a cursory examination of climate and vegetation maps the area might be quite large, but it will be necessary to base heat and water budget calculations on actual observations from a number of stations to assess its extent.

## Appendix. A brief description of the Model EBBA

The following is a very brief and condensed summary of the most important features and sequences of calculation in the energy budget programme.

A. *Calculation of astronomical factors.* Solar constant for the particular day, declination of the sun and latitude. Standard parameters are used, such as mean distance of the sun, eccentricity of the orbit, orbital angle of equinoxes and the radius and temperature of the sun. This calculation is done once per day; all other calculations are done for shorter time steps. The present application of the programme was based on two calculations per day, once for night and once for daylight hours.

B. *Atmospheric profiles and clouds.* Radiosonde temperatures and humidities, and surface cloud and hydrometeor observations, are used to derive detailed profiles of temperature, moisture and cloud amount. These parameters are specified for 17 levels and layers of the troposphere.

C. *Short wave radiation.* The results of short wave radiation parameters calculated in A and B are used in conjunction with specified ozone and dust distributions (considered constant for a particular experiment) to calculate absorption and scattering coefficients for short wave radiation and the resultant energy arriving at the surface. This radiation is reduced (SGA) by an albedo value derived from the surface conditions—viz. snow or ice cover and thickness, soil moisture, type of vegetation cover, etc.

D. *Atmospheric long wave radiation.* Specifying a uniform $CO_2$ distribution, and using the profiles from B as well as the radiation tables of Kondratyev, the atmospheric back radiation (RLD) is calculated and, similarly, the long wave upward radiation stream in the atmosphere.

E. *Turbulent fluxes (QE and QS), ground heat flux (FG), and terrestrial radiation (RLU).* Use is made of the surface energy balance equation:

$$SGA + RLD - QE - QS - FG - RLU = 0$$

The absorbed short wave radiation (SGA) and back radiation (RLD) are known. The other terms depend *inter alia* on the surface temperature. If it is assumed that the physical processes governing these terms are known, then they can be obtained by an iterative process where the surface temperature is changed until the equation is balanced. The following relations and conditions are employed:

1. Heat conduction in the ground is made dependent on water content in five distinct layers, as well as on soil type (which is considered uniform with depth). The ground heat flux (FG) is obtained from conduction and temperature profiles in 12 layers below the surface.

2. Interaction between earth and atmosphere takes place at two levels: at the ground surface and at the vegetation surface, the latter having a variable areal extent.

3. The synoptic wind speed observation is regarded as representative for the top of the vegetation and the wind speed decreases in the canopy towards the ground with a gradient proportional to the vegetation mass.

4. The sensible heat flux (QS) is obtained by a bulk transfer formula including both thermal and dynamic causes of turbulence.

5. The latent heat flux (QE) is obtained from potential evapotranspiration calculated with the same bulk transfer formula, modified for the following:

Table A 1. *Surface energy fluxes (cal cm$^{-2}$ day$^{-1}$ and year$^{-1}$)*

| | The Pas (1968) | | | | | | | Moosonee (1 July 1967 – 30 June 1968) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | SGA | RLD | RLU | QE | QS | FG | Precip. cm. | SGA | RLD | RLU | QE | QS | FG | Precip. cm. |
| Jan. | 42 | 382 | 446 | 4 | −4 | 23 | 2.52 | 58 | 367 | 447 | 4 | 0 | 26 | 1.72 |
| Feb. | 69 | 412 | 481 | 9 | 7 | 17 | 0.42 | 92 | 395 | 476 | 7 | 15 | 10 | 1.72 |
| Mar. | 216 | 502 | 599 | 37 | 72 | −11 | 0.65 | 156 | 480 | 573 | 32 | 31 | 1 | 3.45 |
| Apr. | 364 | 546 | 689 | 101 | 107 | −12 | 4.32 | 264 | 573 | 675 | 90 | 57 | −13 | 8.45 |
| May | 457 | 643 | 799 | 97 | 197 | −7 | 2.97 | 480 | 635 | 785 | 152 | 162 | −16 | 1.95 |
| June | 477 | 716 | 872 | 96 | 212 | −12 | 5.45 | 463 | 688 | 835 | 141 | 161 | −13 | 8.67 |
| July | 482 | 735 | 876 | 155 | 180 | −7 | 6.80 | 405 | 763 | 878 | 183 | 89 | −17 | 10.50 |
| Aug. | 369 | 720 | 841 | 102 | 144 | −2 | 6.87 | 378 | 735 | 862 | 139 | 108 | −3 | 7.55 |
| Sept. | 242 | 702 | 804 | 104 | 34 | −2 | 4.92 | 259 | 701 | 818 | 33 | 117 | 8 | 3.35 |
| Oct. | 121 | 607 | 694 | 21 | 20 | 7 | 2.05 | 121 | 625 | 705 | 38 | 13 | 10 | 4.72 |
| Nov. | 58 | 511 | 573 | 9 | −1 | 12 | 3.07 | 54 | 518 | 588 | 9 | −12 | 14 | 5.17 |
| Dec. | 28 | 414 | 470 | 3 | −13 | 18 | 2.82 | 45 | 445 | 514 | 4 | −7 | 21 | 4.20 |
| Year | 89 396 | 210 291 | 248 564 | 22 550 | 29 239 | 724 | 42.86 | 84 801 | 211 405 | 248 968 | 25 505 | 22 401 | 852 | 61.45 |

(*a*) The active plant mass and plant stomata action.

(b) Soil moisture potential, separately for five layers.

(c) Precipitation interception and free water at the surface.

(d) Root development and depth of penetration for the particular plant community specified.

6. Terrestrial radiation (RLU) is calculated assuming black body emissivity.

F. *Change in vegetation.* The values of radiation, evaporation and soil water and temperature are next used to calculate plant growth or decay. Thus the vegetation amount is updated.

G. *Updating of other parameters before the next time step.* The various energy budget terms are used to update the following parameters before the beginning of the next time step: ground temperature in 12 layers, snow and ice depth on the surface, depth of ground frozen, water content in five distinct soil layers, water content remaining in interception storage.

The time step is now ended and the next commences, requiring new synoptic and radiosonde observations. If the time step is too short to allow a new radiosonde ascent the turbulent fluxes are used to adjust the old radiosonde according to the heat gain or loss by these fluxes. In the case of atmospheric energy gain, dry adiabatic convective transfer is assumed below the condensation level and wet adiabatic above; for heat loss an inversion is assumed, the intensity and height of which are inversely proportional to the wind speed.

As an example of calculated values, Table A 1 shows surface energy fluxes for The Pas and Moosonee for an average day of each month and for a year, using twice-daily synoptic and radiosonde observations, for conditions of a grass covered sandy soil with water holding capacity of 6 cm.

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# ЭКСПЕРИМЕНТЫ ПО БЮДЖЕТУ ТЕПЛА И ВОДЫ У ПОВЕРХНОСТИ НА КАНАДСКОМ СРЕДНЕМ СЕВЕРЕ

Для района Пас (Манитоба) на канадском среднем севере изучаются эффекты изменения бюджета тепла и воды у поверхности с использованием модели энергетического баланса поверхности и ежедневных синоптических и радиозондовых наблюдений за период июль 1967 г.–июнь 1968 г. Проводится сравнение с результатами предыдущих аналогичных исследований для того же периода для района Борил в Мусони (Онтарио). Последний район обнаруживает положительный бюджет воды для всех типов поверхности, т. е. сток, тогда как район Пас обнаруживает существенный дефицит воды для всех типов поверхности за исключением каменистой. Подобный дефицит получался и для района Мусони, когда задавалось аналогичное описание поверхности (голая земля, лес, озеро, камни). Так как измерения речного стока указывают на умеренный годовой приток воды, то был сделан вывод, что в районе Пас, возможно, существуют условия, уменьшающие испарение, и которые в целом не типичны для других рассмотренных областей. Подобные возможности также были исследованы. Наиболее интересным моментом оказались характеристики растительности типа лишайников, которые обладают ярко выраженным свойством удерживать воду, поскольку они оказывают сильное сопротивление испарению. Для получения реалистичного бюджета воды для этого района оказалось существенным установить детально структуру растительного покрова и подсчитать испарение с каждого типа поверхности. Полный региональный бюджет влаги за 1967–1968 гг. оказался приблизительно сбалансированным. Открытая вода обнаруживает сильную потерю за счет испарения, и поэтому озера могут существовать в этом районе, только получая влагу с поверхности камней, лишайников, мхов или тонкой почвы. Поддержание возрастающей водной площади, например, резервуаров, созданных плотинами, требует или уменьшения лесного покрова или переброса воды из других районов. Уничтожение в больших масштабах мхов и лишайников, по-видимому, имеет далеко идущие последствия для регионального бюджета воды.