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RESEARCH RESULTS FROM MARMOT CREEK EXPERIMENTAL WATERSHED, ALBERTA, CANADA

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INTRODUCTION

The Alberta Watershed Research Program is a co-operative effort on the part of eight federal and provincial agencies. Marmot Creek experimental watershed, established in 1962, is the most intensely instrumented and has the longest period of record of the basin projects in the program. Objectives and description of the basin were treated in detail by Jeffrey (1965) and are covered here only briefly. Instrumentation has been described by Shimeld (1968).

Description and Objectives of Marmot Basin

Marmot basin is about 31 km west of Calgary, Alberta, in the Kananaskis River valley. Three sub-basins and an area below their confluence comprise the 9.4 km^2 basin. Topography is steep, aspect is generally east, and elevation ranges from 1,585 to 2,805 m above m.s.l. Forest cover is predominantly *Picea engelmanii* and *Abies lasiocarpa*, with timberline at approximately 2,290 m. The basin is heavily instrumented for meteorological phenomena, surface flow and groundwater.

The main objectives of the experimental basin are:

1. To determine the hydrology of the basin with particular reference to the interrelation of precipitation, streamflow, and groundwater;
2. To determine the effect of commercial timber harvest and subsequent regrowth in subalpine spruce-fir upon the hydrology of the area, and
3. To develop methods for and to determine the effects of purposive manipulation of high-elevation, non-commercial spruce-fir forests upon water yield and regime.

Objectives are to be met by research combining plot studies and the treatment-basin/control-basin approach.

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Results

Soil Classification for Hydrology

A study was carried out to describe, classify, and map the soils of the basin, to determine their hydrologic characteristics, and to interpret this information for watershed management purposes (Beke 1969). The basin is highly variable with respect to the nature and kinds of soils present. Such complexity is related to rapid changes in the effective combination of the soil forming factors within relatively short distances, which has been shown to be characteristic of mountainous areas. Soils are well drained and range from Gray Luvisols at lower elevations to Humo-Ferric Podzols and Dystric Brunisols to Regosols at the higher elevations. Soils of the alpine tundra region of the basin support Griggs' (1946) hypothesis that timberline in the Rocky Mountains effects a climatic-tension zone.

A large proportion of the mountain soils of the basin cannot be accommodated by the Canadian system of soil classification as described by the National Soil Science Committee (Nat. Soil Sci. Comm. 1968). It appears that the criteria are not flexible enough to allow for mountain soils not exhibiting all the characteristics designated. For example, the apparent lack of gleying or mottling in poorly drained soils excludes these soils from the Gleysolic Order which is supposed to accommodate them.

The soil parameters selected for interpretive use relative to hydrology of the area were minimum infiltration rate, depth to impeding soil horizon, dispersion ratio, and compressibility ratio. Minimum infiltration rates range from 0.5 cm/hr to 17.8 cm/hr. Infiltration rates are generally higher than the maximum recorded rainfall on the basin (2.5 cm/hr).

Dispersion ratios (determined by Middleton's (1930) method of estimating the susceptibility of the upper mineral-soil horizon to water erosion) are generally greater than 10 per cent, indicating by Middleton's criterion that the soils are erodible. Gray Luvisol and Gleysol soils generally have the higher dispersion ratios while Humo-Ferric Podzols and Eutric and Dystric Brunisols have the lower ratios.

Moisture capacity (both total and available) was closely related to depth of the impeding horizon. Most soils have an impeding stratum (generally because of increased clay content) within 12 in (30.5 cm) of the mineral surface. Capacities range as high as 4.9 in (12.4 cm) for available moisture and 10.2 in (25.9 cm) for total moisture, these occurring in Dystric Brunisols.

The basin was mapped on the basis of the suitability of soils for management for water yield. This in turn was dependent on minimum infiltration rates and depth to the impeding horizon. Alpine and Dystric Brunisols were found to offer the greatest possibility for water yield improvement.

Water Balance Studies

To provide the basis for the complete research program, studies have been carried out using various approaches of estimating the components of the hydrologic cycle.

Groundwater—Stevenson (1967) calculated a water balance for Marmot basin using the equation:

$$P = R + ET + \Delta S + U + L \tag{1}$$

where:

P = precipitation;
R = streamflow;
ET = evapotranspiration;
ΔS = storage change;
U = underflow;
L = basin leakage,

and

$$S = \Delta S_{sw} + \Delta S_s + \Delta S_v + \Delta S_g \tag{2}$$

where:

sw = surface water;
s = soilwater;
v = intermediate vadose water;
g = groundwater.

Underflow (U) (flow-out of the basin under the weir) and basin leakage (L) (groundwater flow into or out of the basin at the topographic divides) were both assumed to be negligible; U because of the relative impermeability of the foundation rocks under the weir, and L because topographic and phreatic divides coincide. Change in water storage at the surface (ΔS_{sw}) and within the soil (ΔS_s and ΔS_v) are assumed to be zero for the budget period.

Equation (1) then becomes:

$$P = R + ET + \Delta S$$

and equation (2):

$$\Delta S = \Delta S_g$$

Also:

$$\Delta S_g = \Delta H \,.\, Y_g$$

where:

ΔH = change in mean groundwater stage in inches;
Y_g = gravity yield,

and:

$$Y_g = R_g / \Delta H$$

where R_g = base flow contribution to streamflow.

Base flow (R_g) was taken as the average streamflow (R) during January 1 to March 20 1966, a period during which streamflow is entirely groundwater runoff, or base flow. Table 1 is the calculated hydrologic budget where precipitation (P), streamflow (R), and change in mean groundwater stage (ΔH) have been measured; gravity yield (Y_g) and change in groundwater storage (ΔS_g) have been calculated; and evapotranspiration (ET) the amount of precipitation unaccounted for by R and ΔS.

Stevenson (1967) also calculated a groundwater budget using the model:

$$G_r = R_g + ET_g + \Delta S_g$$

where:

G_r = groundwater recharge;
ET_g = evapotranspiration losses from the water table.

TABLE 1. The hydrologic budget for Marmot basin for the period August 25, 1965 to August 25, 1966

Precipitation, P	34.75 in.	(88.26 cm)
Streamflow, R	20.56 in.	(52.22 cm)
Change in groundwater stage, ΔH	−13.20 in.	(33.53 cm)
Gravity yield, Y_g	0.048 in./in. ΔH	(0.048 cm/cm ΔH)
Change in groundwater storage, ΔS_g	−0.63 in.	(1.60 cm)
Evapotranspiration, ET	14.82 in.	(37.64 cm)

Groundwater recharge (G_r) for a particular recharge event was calculated as $Y_g \times$ the difference between peak stage after recharge and the projection of the recession curve under the peak. The sum of these products for each recharge event during the period August 25, 1965 to August 25, 1966, is the groundwater recharge for the period. Groundwater runoff (R_g) was measured from the base-flow hydrograph and converted to area-inches. The base-flow hydrograph was obtained by relating mean groundwater stage of four index wells (in the reservoir materials from which base flow was derived) to streamflow from Marmot Creek during low-flow recession periods when streamflow consisted entirely of base flow. This relation is linear; the regression line was extended to obtain base-flow contribution to streamflow at high groundwater stages, and a base-flow hydrograph was plotted for the year. Groundwater storage (ΔS_g) was calculated as described previously. The groundwater budget is given in table 2. The hydrologic budget (table 1) showed total evapotranspiration as 14.82 in. (37.64 cm) of which 9.00 in. (22.86 cm) were from groundwater (table 2). The remaining 5.82 in. (14.78 cm) were supplied then from the vadose zone, which includes the soil-moisture zone. Considering the generally high infiltration rates and high water table over much of the basin, it seems reasonable that 61 per cent of total evapotranspiration is supplied by groundwater (as shown by the groundwater budget).

TABLE 2. The groundwater budget for Marmot basin for the period August 25, 1965 to August 25, 1966

Streamflow, R	20.56 in.	(52.22 cm)
Groundwater recharge, G_r	15.09 in.	(38.33 cm)
Base-flow, R_g	6.91 in.	(17.55 cm)
Change in groundwater storage, ΔS_g	−0.63 in.	(1.60 cm)
Evapotranspiration losses from water table, ET_g	9.00 in.	(22.86 cm)

Energy balance—A study was carried out on the basin during August 1965, in which estimates of heat flux and evapotranspiration rates were made (Munn and Storr 1967). Instrumentation used in the study was not operative during the three rainy periods in the month. The study was further simplified by dealing with daily rather than hourly heat fluxes, so that the assumption may be made that soil-heat flux and forest-heat storage terms in the energy balance equation are very small. Therefore,

$$Q_N = Q_H + Q_E$$

where:

Q_N = vertical flux of net radiation above the canopy;
Q_H = vertical flux of sensible heat above the canopy;
Q_E = vertical flux of latent heat above the canopy.

For the observation period, mean daily net radiation (Q_N) was calculated as 365 langleys/day. The next assumption was that at night (1830 MST to 0630 MST) when net radiation is negative and there is a temperature inversion, evapotranspiration is negligible so that $Q_N = Q_H$. The period to be considered then was 0630 to 1830 MST when net radiation is positive (estimated as 436 langleys/12 hours). Other assumptions made were:

1. Soil-heat conduction and forest-heat storage can be neglected for the 12-hour period because the diurnal waves of these two components in a forest are never in phase with that of net radiation;

2. There was sensible-heat transfer upward because of a lapse condition above the canopy during most of the 12-hour period. Therefore;
3. The latent heat flux must have been less than the net radiation. The upper limit assumed as reasonable for Q_E was 80 per cent of Q_N, or 349 langleys/12 hours. Now,

$$Q_E = LE$$

where:

L = latent heat of evaporation;
E = evapotranspiration rate per unit area.

So an upper limit for water loss from the canopy for the dry-weather period is 0.6 $gm/cm^2/day$. Since the trees did not appear to be under any moisture stress and the forest floor was not completely dry, a lower limit was assumed to be 20 per cent of net radiation, i.e., 87 langleys/12 hours, or 0.15 $gm/cm^2/day$ water loss.

This range of daily dry-weather water loss (0.15 to 0.6 gm/cm^2) was narrowed somewhat by extrapolation from studies at Petawawa, Ontario, and a final rough estimate of daily water loss was 0.3 gm/cm^2. This amounts to 0.3 area-cm/day or approximately 30 cm for a 100-day growing season.

Another energy budget study was carried out in July, 1967 (Storr 1970) in which the Bowen ratio (R) concept was used to partition net radiation (Q_N) between latent heat flux (Q_E) and sensible heat flux to air (Q_H). The Bowen ratio was determined by measuring gradients of temperature and vapor pressure above the evaporating surface (the forest canopy) and using the equation (assuming the pressure at the sensor location to be 820 mb):

$$R = 0.28 \frac{T_2 - T_1}{e_2 - e_1}$$

where:

R = the Bowen ratio;
T_1 and T_2 = temperature in °F at beginning and end of given period;
e_1 and e_2 = vapor pressure in millibars at beginning and end of period.

Evapotranspiration was then calculated from:

$$ET = \frac{Q_N - Q_G}{L(1+R)}$$

where: Q_G = vertical heat flux to ground and vegetation.
Relatively large errors in R produce relatively small errors in ET.
Two assumptions are made:

1. There is no flux or radiative divergence;
2. The gradients of temperature and vapor pressure are measured below the boundary layer.

Instrumentation included a CSIRO net radiometer to measure Q_N, and two sets of wet and dry Rosemount platinum resistance bulbs (protected by aspirated cylindrical shields) to measure temperature and humidity above the forest canopy (about 100 feet above ground). Calculated evapotranspiration for the July 8-26, 1967 period, averaged 0.18 inches/day (0.46 cm/day). An interesting sidelight of this study was the relationship shown between the Bowen ratio and wind direction and sky condition. With cloudy sky, mean daytime Bowen ratios were 0.49 with downslope wind, 0.86 with upslope wind. During sunny periods ratios were 0.19 and 0.78 for upslope and downslope winds respectively.

Eddy correlation within the forest—An investigation of turbulence within the forest on Marmot basin was carried out in August 1965 (McBean 1968) in which turbulent heat fluxes calculated by the eddy-correlation method did not even approximately balance the net radiation. The difference may have been due partly to instrument response, but it was felt that the inhomogeneous environment of the basin necessitates spatial as well as temporal averages of the turbulent heat fluxes and the net radiation.

Snow Relationships

To determine the relationship of snow accumulation to elevation and forest-stand density, five 10-point snow-courses were chosen on a central ridge in Marmot basin. Courses are in the same forest-cover type (spruce-fir), have approximately the same slope and aspect, and range in elevation from 1,950 to 2,230 m above m.s.l. The regression of snow-water equivalent at the 50 points was calculated on stand density and elevation for 10 measurement dates during 1965-1967. A measure of stand density was obtained using the Bitterlich point-sampling technique and the three angles sizes, 104.18, 147.34, and 208.38 minutes. The relation was linear but both intercept and slope vary with measurement date. Best fit was provided by measurements taken approximately at maximum snowpack. For example, the final model for the measurements of April 12, 1966 was:

$$SWE = 0.01032E - 50.57 + 0.2871\,[3(C_3) + 2(C_2 - C_3) + (C_1 - C_2)]$$

where:

SWE = snow-water equivalent of the snowpack, in inches;
E = elevation above m.s.l., in feet;
C = number of trees tallied using the Bitterlich point-sampling system. Subscripts 1, 2 and 3, refer to angle sizes 104.18, 147.34, and 208.38 minutes, respectively.

The multiple correlation coefficient was 0.91, and the standard error of estimate as a percentage of the mean, 22.0.

A computer contour program (Cole, Jordan, and Merrian 1967) was used to produce a contour map of the water equivalent of the basin snowpack based on a 5- by 10-chain grid sampling of 200 points (Golding 1970). The program fits a quadratic surface by the least-squares method to the xyz coordinates in order to calculate values of intersections on a superimposed grid. Thirteen 1-inch contour intervals were used. Greater success was achieved with a program by Turner (1968) in which polynomial regression surfaces were fitted to the irregularly-spaced data and using 2-inch (5.1 cm) contour intervals.

The computer contour program was used in order to provide a comparison of total snowpack and pattern of accumulation from place to place and year to year in an objective, repeatable manner.

Snowpack Ablation

Harlan (1969) reported that only a small percentage of snowpack water equivalent was accounted for by increased soil-moisture storage after snowmelt on Marmot basin. He concluded that this is consistent with infiltration theory, and that transmission of snowmelt directly through the soil profile could occur while soil moisture was less than field capacity. However, some ablation will be accounted for by evaporation or sublimation. Storr (1968) stated that whereas it is unlikely that a significant amount of snow is lost to the atmosphere through radiation during winter months, some snow is evaporated during the spring. During Chinook conditions (i.e., foehn-type winds), however, loss of up to 0.5 in./day (1.27 cm/day) seems probable. The lack of data on the parameters needed to calculate the loss during Chinooks has resulted in a study being carried out on Marmot basin to measure these parameters as well as to estimate, using snow lysimeters, the amount of loss during Chinooks.

Watershed Calibration

Two of the three-sub basins of the watershed will be treated eventually to determine the effects of forest-cover manipulation on streamflow quantity and regime. With six years of record, the Langbein (1960) method of correlating deviations in log units from the geometric mean of each month's discharge indicated standard errors of estimate too high to consider the basins calibrated for the purpose indicated. Correlation of annual flows in acre-feet has given better results, but we are presently running the analyses to determine what improvement may be realized using water years other than October 1-September 30.

CONCLUSION

The basic networks are being maintained on the watershed and studies of the hydrologic systems are continuing. When calibration of the sub-basins has been obtained at the statistical level of precision required, one sub-basin will be logged by a method, at present in the design stage, to illustrate a commercially-feasible system consistent with watershed protection. Effects of the treatment will be evaluated for water quantity, quality and regime.

The Marmot Creek experimental watershed has shown the value of a well-documented set of objectives to precede the research program. This is particularly the case where the research and network establishment are to be carried out co-operatively by many agencies. The objectives should not be considered unalterable or inflexible. As knowledge is gained in the program, objectives may well change. However, they do provide the basic framework within which to work, and the continuity that might otherwise be lacking where many agencies are working together.

The objectives should be the out-growth of a well-considered problem analysis, an analysis that should be reviewed periodically in order to determine if the problems and the suggested direction of attack still hold.

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