# GRID SQUARE RUNOFF MODEL 1/

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By

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## Introduction

Long-range planning for water resources in semi-arid regions such as the Okanagan basin in British Columbia requires dependable analytical methods for estimating flows. There has been substantial *water use* development in the Okanagan, but little natural flow data has been collected. Most available hydrologic regionalizing techniques are either not applicable due to such shortage of natural flow data (6), or inadequate due to British Columbia's mountainous terrain. This paper describes the results of a runoff regionalization procedure carried out by the author (7) in which the grid square technique was developed to estimate mean monthly sub-basin runoff. This work was part of the Canada-British Columbia Okanagan Basin Agreement, a comprehensive water resource study of the Canadian portion of the Okanagan River, which was completed in 1973.

The Okanagan River basin from its source in British Columbia to the Osoyoos Lake outlet in Washington (see Figure 1) covers an area of 3,190 square miles (8,260 sq.km.). The basin, part of the interior plateau region, contains one main valley oriented in the north-south direction. Elevations range from 910 feet (280 n) to 7560 feet (2300 m) above sea level with a mean basin elevation of 3580 feet (1090 m). The area has a semi-arid climate which is caused by the shielding effect of the Coast Range Mountains on westerly storms. Mean annual temperature ranges from 50°F (10°C) at the low elevations to 370F (2.8°C) at the high elevations. For the same range of elevation, mean annual precipitation varies from 12 inches (350 mm) to 42 inches (1070 mm). Streamflow originates from depletion of winter snowpacks at higher elevations with its flow pattern modified through tributary storage regulation for agricultural use. Very little surface runoff originates from elevations below 4000 feet (1200 m). Low-land benches are irrigated primarily for tree fruit production. Mid elevations consist of grassland and upper elevations of forest cover.

The original grid square method (8) uses meteorological, hydrometric and physiographic data to assess the mean annual temperature, precipitation, evaporation and runoff distribution over large areas. First, the study area is divided into a large number of grid squares and physiographic parameters are determined for each square. Available meteorological data are then compiled and multiple regression is used to derive equations which relate observed precipitation and temperature to physiographic parameters. These equations are then used to estimate temperature, precipitation and evaporation for all grid squares; runoff is obtained by subtracting evaporation from precipitation for each square. Runoff from all the squares is summed to obtain an estimate of the runoff for the basin. If the computed runoff disagrees with the recorded runoff, the precipitation for each square is adjusted and the procedure is repeated (iterated) until the computed runoff approaches the observed runoff to the desired degree. Since the primary objective of this study was the production of mean monthly runoff estimates, a monthly modeling component was developed to simulate snowmelt and resultant runoff on a grid square basis. The precipitation and evaporation components were essentially those in the form that resulted from previous work of the author (4, 5).

## Application of the Grid Square Method to the Okanagan River Basin

The application of the grid square method to the Okanagan basin (7) involved a number of preliminary steps. First, monthly temperature, precipitation and snow course data were reviewed and extracted for stations with *a* satisfactory record. Where required, missing data were estimated. Although various time periods were used in the study, the standard period, 1931 to 1960, will be discussed here in which a total of 17 temperature, 19 precipitation and 5 snow course stations were used. These stations were obtained from within a hydrologic zone surrounding the Okanagan River drainage boundary from approximately 14 to 25 miles which was derived from an extensive analysis of computer plots of regression input

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data. Observations of snow course water equivalent data were combined with observations of accumulated winter monthly precipitation data at meteorological stations to form a composite sample of independent winter season precipitation variables for regression analysis. The addition of higher elevation snow course data to the lower elevation meteorological station data not only increases the sample size but, more importantly, it improves the definition of precipitation distribution since most precipitation falls at higher elevations.

The second major step in the procedure consisted of establishing a five kilometer size grid of 500 squares covering the basin (Figure 1) from a composite standard topographic map (scale of 1:250,000). It was felt that a 5 km size would more adequately describe the hydrologic variation of the Okanagan basin than would 10 km which formed the basic grid size of all previous grid square method studies (1, 4, 5, 8, 10). A smaller grid resulted in more squares (500 5 km compared to 125 10 km squares) for a finer resolution of hydrologic estimates for a study basin of highly varied topography. The map was then used for extracting physiographic data for both the stations and grid squares. Physiographic variables found significant in the multiple regression analysis are listed below with descriptions.

(a) Elevation: The mean elevation of *a* square was obtained by averaging nine elevation points at the grid square corners, intermediate sides and the center.

(b) Land Slope: An index of average land slope of a grid square was considered using two independent methods:

i) Horton's Method - consists of counting the number of contour lines crossing two perpendicular center lines of the square which are parallel to the sides.

ii) Plane Fitting Method - involves computation of planes through four elementary squares to produce an average plane of best fit for the grid square.

(c) Azimuth of Slope: The azimuth is referred to the slope of the four squares defined by the Plane Fitting Method.

(d) Distance to Barrier: The index adopted was the distance along two wind directions from the center of a square to a line drawn along the divide of the Coast Range Mountains. The line was positioned roughly parallel to the Pacific coast, thus eliminating the need for Distance to Sea as an additional physiographic variable (1, 10).

(e) Latitude Index: This was the distance from the center of each square to an arbitrary east-west line drawn parallel to the grid system 88 kilometers south of the 49° latitude.

(f) Barrier Height: The barrier height is defined as the difference between the highest elevation along *a* given line (same wind directions as in (d) above) and an average elevation for the base or trough of the barrier on the leeward side obtained by visual inspection. For each square a weighted average was calculated from values measured along five parallel lines evenly spaced over a width of 14.3 kilometers centered over the given square.

(g) Shield Effect: The shield effect is defined as the summation of the barrier height and other local barrier heights along a given line. The barriers considered along the two wind directions were the Coast Mountains and the local Thompson and Okanagan mountain barriers.

(h) Meteorological Parameter PmH: A method for computing the distribution of monthly and annual precipitation over mountainous areas was developed by Danard (2, 3). An equation for the dependence of precipitation amount on orography is derived from simple physical considerations with the basic predictor being the mean vertical water vapour transport (PmH) caused by air mass flow over undulating terrain through a horizontal unit area at a level H. This depends on the average slope of a region 4° longitude by 2°40° latitude centered on each grid point.

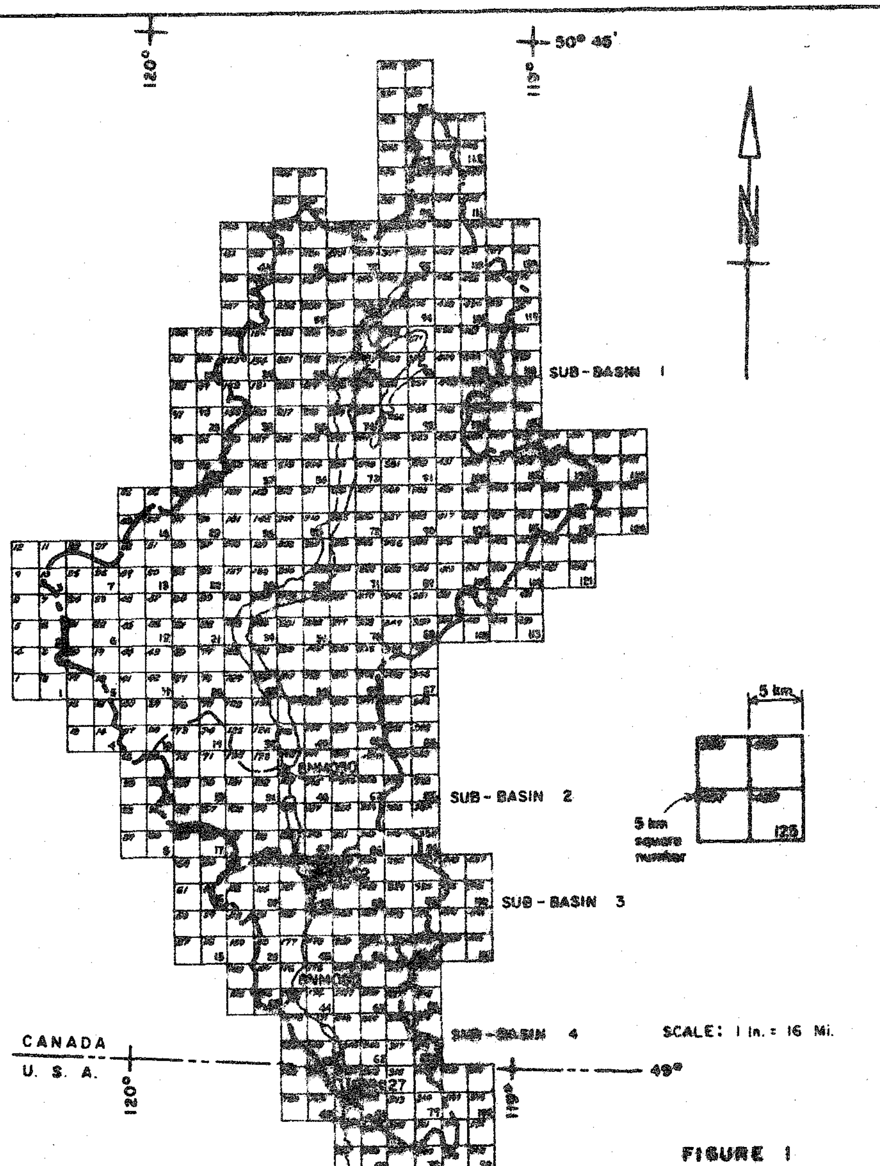


FIGURE 1
GRID SQUARE LAYOUT
ON THE OKANAGAN RIVER
DRAINAGE BASIN

To relate the temperature and precipitation data (dependent variables) to physiographic parameters (independent variables) a standard stepwise regression computer program was used to derive multiple linear regression equations on *a mean* monthly basis. In addition, six winter season precipitation regression equations were derived for variable season lengths, starting in November and December and ending in February, March and April. The equations were then used to estimate mean monthly temperature and precipitation for each grid square from the square's physiographic characteristics.

## Grid Square Runoff Model

The next step in the application of the grid square method was the development of a grid square runoff model to simulate mean monthly runoff. Two independent water balance methods were developed, the Water Balance Runoff Method and Finite Difference Runoff Method.

The Water Balance Runoff Method is based on the Thornthwaite water balance procedure (9) and on certain added features which preserve the continuity of water flow within the year and satisfy simplified hydrologic cycle characteristics. Monthly runoff is calculated by assuming different retention periods for water sources from snowmelt and rainfall. In monthly water balance calculations, it was determined that for Okanagan semi-arid conditions approximately 35% of the water made available from melting snow runs off during the first melt month and 50% of the remainder in each of the following months. Monthly snowmelt is calculated from a modified U.S. Corps of Engineers snowmelt equation using winter season precipitation estimates.

$$M = 1.8\ T\ (0.074N + 0.007P)$$

where: M = monthly snowmelt (in. water)

T = monthly temperature (°C)

N = number of days in the month

P = total monthly precipitation (in.)

For runoff originating from rainfall Thornthwaite (9) assumes that for one month periods, 50% of surplus water appears as runoff with the remaining water detained on the watershed for runoff during the next month. Since the Okanagan basin is a semi-arid region with approximately 20% of its precipitation resulting in runoff, a form of soil moisture budget was developed in which soil moisture deficit is replenished first, at the end of the yearly dry spell by rainfall when a water surplus condition exists and second, at the start of the melt season by snowmelt if a deficit still remains after the fall season. Those squares which display a total annual moisture deficit (i.e., annual potential evapotranspiration greater than precipitation) have no resultant runoff and the model simply defines zero runoff in each month.

The Finite Difference Runoff Method is based on the solution of *a* series of water content finite difference equations as proposed by Danard (2). In this model rainfall and snowmelt are calculated and added to give the runoff available at the source. This procedure is repeated for each square and totals of water source (S) and evapotranspiration terms (E) are accumulated for each sub-basin. If W represents the total water content of the sub-basin its change with time is given by

$$\frac{dW}{dt} = -R + S - E$$

where the runoff R is given by

$$R = kW$$

The first equation is solved numerically in finite difference form for each month. In the second equation the runoff coefficient term represents an exponential decay or gradual decrease with time of water content from an area that has been subjected to an input of *a* water source (e.g., rainfall or snowmelt). These k terms were optimized for the Okanagan

River basin conditions by a slight trial and error adjustment to minimize final computed runoff errors. k varies throughout the year in accordance with the basin response to available runoff. It has higher values in the spring with saturated soil to give faster response to resultant runoff (0.3 for May and 0.25 for June) and lower values in the summer, fall and winter when dry soil conditions give slower response to resultant runoff (0.2 for July through March). A value of k of 0.15 for April which was observed to give a better monthly runoff distribution would result from initial soil priming (especially pronounced in semiarid regions) and reservoir replenishment at the start of the melt season. It should be noted that adjustment or optimization of runoff coefficients was carried out in the model development stages rather than in the computer production runs. The optimization was restricted to slight adjustment of the monthly runoff coefficients which caused only minor shifts or redistribution to the monthly distribution of runoff within the year. No adjustment (iteration) or water balance constraint is imposed on the annual total estimates which thus remain an original or first estimate of the hydrologic components of P, E and R.

Simulated runoff from both methods was then compared with the observed or true basin runoff on four major sub-basins of the main stem Okanagan River (Figure 1) and their sum for a total basin comparison. These sub-basins are located upstream of the streamgauging station (8NM050) at Penticton and between the gauging stations at Okanagan Falls (8NM002), Oliver (8NM085) and Oroville (8NM127). The observed runoff used to check the simulated monthly runoff of each sub-basin is the measured flow of the river at its gauging point with an adjustment for monthly lake storage change, direct lake precipitation and evaporation, and for consumptive (e.g., irrigation) use affecting it. Of the adjustment components, only consumptive use was totally estimated.

## Results

The regression analysis revealed that the most significant independent variables were station elevation, latitude index, distance to barrier and the meteorological predictor, $P_{mH}$. In the standard period used, elevation was significant at the 1% F-level in all monthly temperature equations and latitude in all but three. Elevation was also the most significant variable in the monthly precipitation equations. Multiple correlation coefficients for temperature equations ranged between 0.89 and 0.99 and for precipitation equations between 0.79 and 0.94.

The grid square runoff model program uses the temperature and precipitation equations to estimate mean monthly temperature, precipitation, potential and actual evapotranspiration, snowmelt and runoff for each grid square. Grid square runoff estimates were summed to produce sub-basin runoff. The initial estimates were of sufficient accuracy in simulating mean monthly runoff that iteration was not applied. All estimates were thus presented on a first estimate basis so that a direct check of the estimated runoff could be made with the observed runoff. The results of the runoff model program runs showed a mean annual runoff estimate error for the total basin (Okanagan River above Oroville) of 9% for the Finite Difference Runoff Method and 12% for the Water Balance Runoff Method for the standard (1931-1960) period. There is fairly good agreement between estimated and observed runoff in the high runoff producing months of April through August. Runoff errors for the low runoff producing months are expected to be high because of the small runoff quantities involved (0.5 inches runoff from September to March, 12% of the annual). The Okanagan Lake region (sub-basin 1) which is the largest (2324 sq.mi.) and the most important sub-basin displays similar accuracy in mean monthly runoff simulation. The Skaha Lake region (sub-basin 2) had a mean annual runoff error of 76%. This area is suspected to be in a rain shadow as indicated by other hydrologic studies and reports. There are no standard period meteorological stations in sub-basin 2 to define or check the precipitation distribution and therefore it was not possible to iterate the program in this region. Considering the small size and low runoff of sub-basins 3 and 4 their runoff estimates appear to be reasonable (with errors of +29% and -36%, respectively).

The mean annual standard period hydrologic estimates were also presented in map form showing mean annual isopleths. Those squares which displayed a total annual moisture deficit (i.e., annual potential evapotranspiration greater than precipitation) have no resultant runoff and the grid square runoff model program simply equates actual evapotranspiration to precipitation and gives zero runoff. This was the case for all grid squares below approximately 4000 feet elevation.

Summary and Conclusions

This paper is based on a study and resulting report by the author (7) who describes the application of the grid square method to the Okanagan River basin. A grid square runoff model was developed with a runoff modeling component to simulate snowmelt and resultant runoff on a mean monthly basis. Hydrologic estimates, based on the 1931-60 study period, were presented for a five kilometer grid covering the Okanagan River basin above Oroville, Washington as outlined in Figure 1. The results of this work have been used to estimate regional hydrologic characteristics for various tasks of the Okanagan Study and for the final Okanagan Study report, as well as for various other water supply studies using smaller watersheds.

The main program of the grid square runoff model accepts input from multiple regression equations which relate temperature and precipitation data to physiographic data for the grid squares which cover the study region. The program uses a standard method to calculate evaporation (from temperature and precipitation as derived by the equations) and a water balance approach to determine runoff for each square. This approach minimizes natural inconsistencies (e.g., changes of surface and groundwater storages are minimal) and errors, especially when long time periods of study are used. Hence, input to the grid square program in the form of regression equations is the largest limiting factor that determines the magnitude and errors of the resultant estimated runoff. This and the fact that the Okanagan region is semi-arid with a high concentration of man-made water resource interference certainly make large runoff errors conceivable when a water balance approach is used on a first estimate basis. In this context the monthly runoff results obtained without iteration appear to be good. The grid square runoff model itself is certainly not error proof since natural and estimate errors are equalized and cancelled out when mean monthly and annual periods and a large number of finite element grid squares are used.

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