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The Effects of Urbanization on the Water Balance of the Fishtrap Creek Basin, Northwest Washington and South Central British Columbia

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THE EFFECTS OF URBANIZATION ON THE WATER BALANCE OF THE FISHTRAP CREEK BASIN, NORTHWEST WASHINGTON AND SOUTH CENTRAL BRITISH COLUMBIA

by

Charles S. Lindsay

Accepted in Partial Completion

of the Requirements for the Degree

Master of Science

Dean of the Graduate School

Advisory Committee

Chairman

MASTER'S THESIS

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MASTER'S THESIS

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A Thesis

Presented to

The Faculty of

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December, 1988

ABSTRACT

The Fishtrap Creek basin is located in northwest Washington State and south central British Columbia. Land use in the basin is predominantly agricultural. Moderate urbanization in the past thirty-five years has increased impervious surface area in the basin from 1.8 to 8.0 percent. Monthly water balances were derived in order to quantify the effect of changing land use on the discharge of Fishtrap Creek. Stream discharges calculated from these water balances, constructed for 1952 through 1953 and 1987 through 1988, compare well with measured monthly and annual stream discharges. The favorable comparison indicates that the water-balance variables are in general reliable. However, in months following long periods of dry weather, calculated discharge was much higher than measured discharge. The discrepancy is probably because the standard water balance method does not account for water stored in the vadose zone below the rooting depth of the vegetation or the time lag required for the water to infiltrate through this zone and into the groundwater reservoir. To interpret the results of changing land use on the discharge of Fishtrap Creek, a hypothetical water balance was calculated incorporating the climatic data for 1952 through 1953 and the land use as of 1988. In effect, climate was held constant while land use changed with time. The hypothetical water balance predicted that, as a result of changing land use, a 7.8 percent increase in annual stream discharge would have occurred if the 1952 through 1953 climate had occurred again in 1987 through 1988. Of this 7.8 percent increase, 2.7 percent is due to increased overland flow and 5.1 percent to increased groundwater discharge. The predictions based on the hypothetical water balance are supported by comparison of actual storm events. For comparable storms, stream discharge was higher in the 1987 - 1988 period than in 1952 - 1953.

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INTRODUCTION

Due to increasing urbanization in the Pacific Northwest and more intensive farming of its remaining arable land, quantitative evaluation of the water resources there is becoming increasingly important. One example is in the Fishtrap Creek basin (Figure 1) where both the city of Clearbrook, British Columbia, and the Washington State Department of Ecology have interests. Because of recent (1978-1987) flooding on a branch of Fishtrap Creek, citizens filed several lawsuits against the city of Clearbrook, British Columbia. Residents claimed that increased upstream urbanization in the basin created higher peak discharge and increased flood damage.

The Washington State Department of Ecology is presently evaluating commercial and domestic water rights in the Fishtrap Creek basin. Due to concern about the effects of autumn low-flow discharge in the stream on local and anadromous fish, the Washington portion of the basin has been closed to the acquisition of new water rights since the 1940's. In 1987, new legislation enabled the Washington State Department of Ecology to issue additional domestic and commercial water rights in the basin. As a consequence, the State of Washington has renewed interest in the seasonal flow characteristics of the stream.

Thornthwaite (1948) and Thornthwaite and Mather (1955, 1957) developed a procedure for calculating water balances that permits the quantitative evaluation within a basin of hydrologic factors such as soil moisture storage, actual evapotranspiration, water deficit, and water discharge. To improve the correlation between monthly predicted and measured stream discharge, Mather (1981) and Thomas (1981) developed methods to assess 1) overland flow generated by intense precipitation events, and

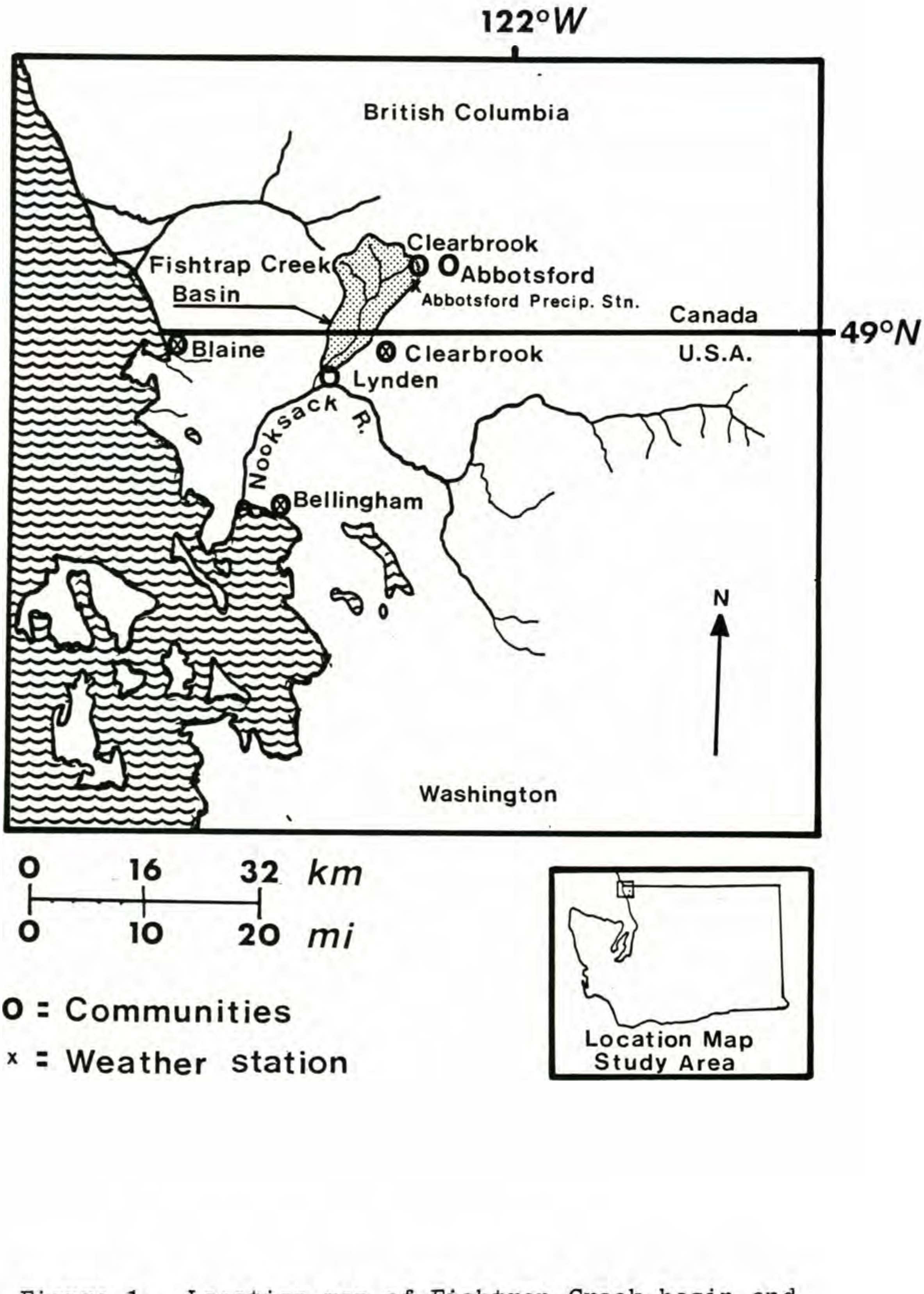


Figure 1. Location map of Fishtrap Creek basin and weather stations.

2) adjusted monthly precipitation to account for periods when much of the precipitation falls during the last part of the month.

The purpose of this study is to evaluate the effect of land-use changes from 1952 through 1988 on the water balance and seasonal stream discharge of the Fishtrap Creek basin. The Fishtrap Creek basin is amenable to such evaluations because both precipitation (input) and stream flow (output) data are available. Using a water-balance method based on climatic data, I quantified the effects of urbanization on the seasonal discharge of the Fishtrap Creek basin in north central Whatcom County, Washington, and south central Matsqui District, British Columbia (Figure 1).

STUDY AREA

Land use in the Fishtrap Creek basin is predominantly agricultural. The basin extends from about 145 m above sea level near its headwaters to 8 m above sea level where it enters the Nooksack River. Above the stream gage (Figure 2), the stream has two major tributaries: Weachter Creek that drains the northwest portion of the basin, and Enns Brook that originates near Clearbrook, British Columbia.

The drainage area (37.6 km^2) above the stream gage has been altered by interbasin diversions, ditches and sewers, that were constructed in the 1960's and 1970's. These diversions decreased the drainage area of the stream from 41.7 km^2 (Walker, 1960) to 37.6 km^2 (Figure 2). Intrabasin diversions occur where water is diverted directly from streams or the unconfined surface aquifer to adjacent fields for irrigation.

Urbanization in the Canadian portion of the Fishtrap basin has increased over the past forty years primarily due to the development of

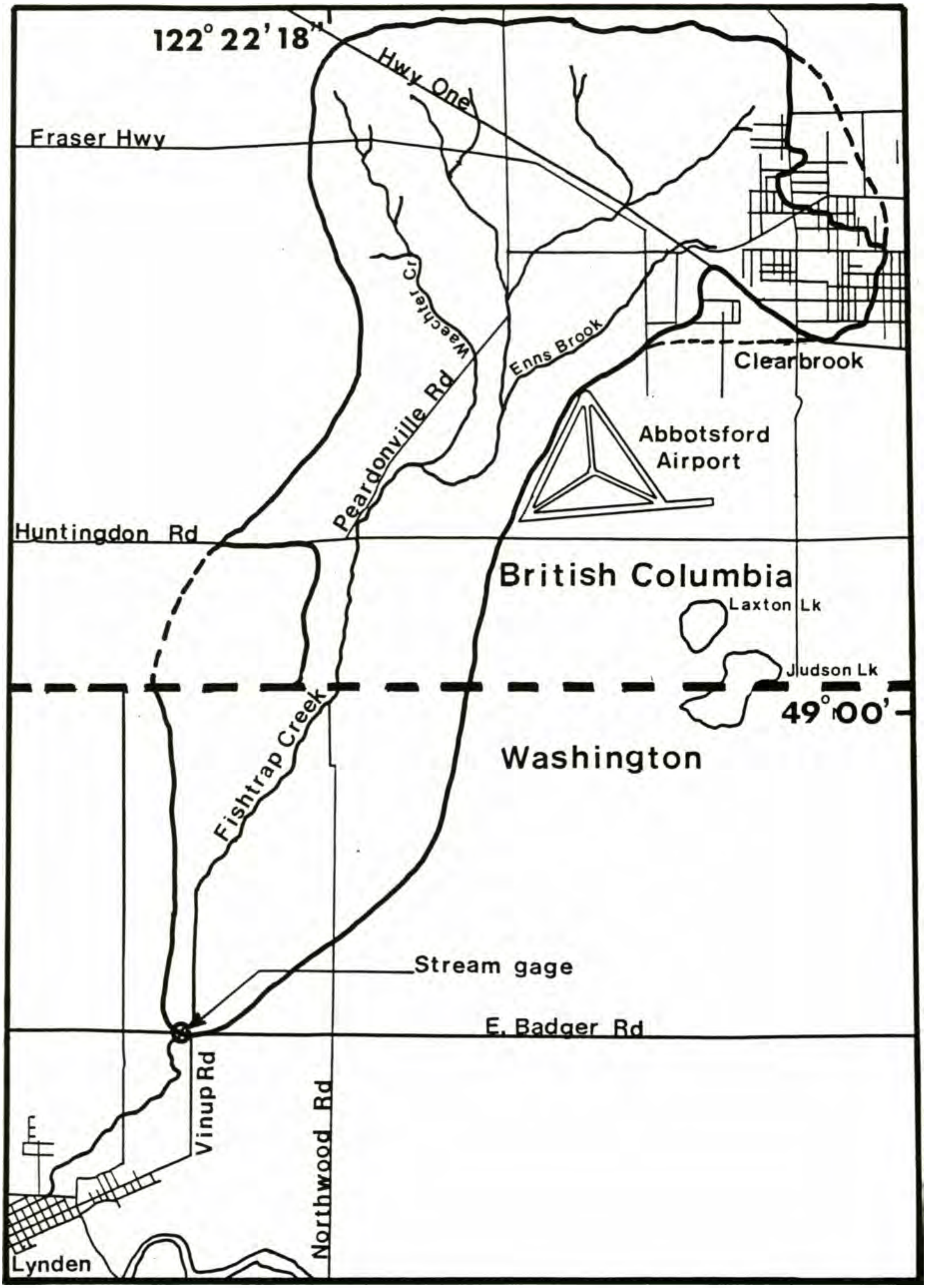


Figure 2. Fishtrap Creek catchment, showing location of stream gage used for collection of 1987 - 1988 stream discharge data. Dashed lines indicate pre - 1970's boundary.

large residential areas near Clearbrook, British Columbia (Figure 2). Based on aerial photographic analysis, mapped areas of impervious surface increased from 1.8 percent of the basin area in 1953 to 8.0 percent of the basin area in 1988.

The average soil in the Fishtrap Creek basin is a silt loam with an average thickness of 737 mm (Golden, A., written communication, Soil Conservation Service, 1978). The soil is underlain by approximately 15 m of Sumas outwash gravels with subsidiary peat and Bellingham glaciomarine drift (Easterbrook, 1976; Armstrong, 1981) (Figure 3). Average linear velocities of groundwater in the Sumas outwash gravels range from 0.5 to 5.0 m / d and porosities from 25 to 35 percent (Creahan, 1988).

LAND USE IN THE FISHTRAP CREEK BASIN: 1953 AND 1988

The land use in a basin has major control on several water-balance parameters including interception, overland flow, potential evapotranspiration, and soil moisture. These parameters influence water surplus and total discharge from the basin.

Two time periods (1952 - 1953 and 1987 - 1988) were chosen for use in the study. The 1952 - 1953 time period was chosen for the following reasons; aerial photographs showing land use and Fishtrap Creek stream discharge data was available for this time period and most of the development of the basin occurred after 1953. The recent time period (1987 - 1988) was chosen because land use could be mapped and stream discharge could be measured at this time.

Land for both periods was divided into seven categories: pasture, crops, woodlands, residential areas, roads, industrial areas and lawn grass (Table 1). Land use in the Canadian portion of the basin for 1952 - 1953 was determined from aerial photographs obtained from the Ministry of

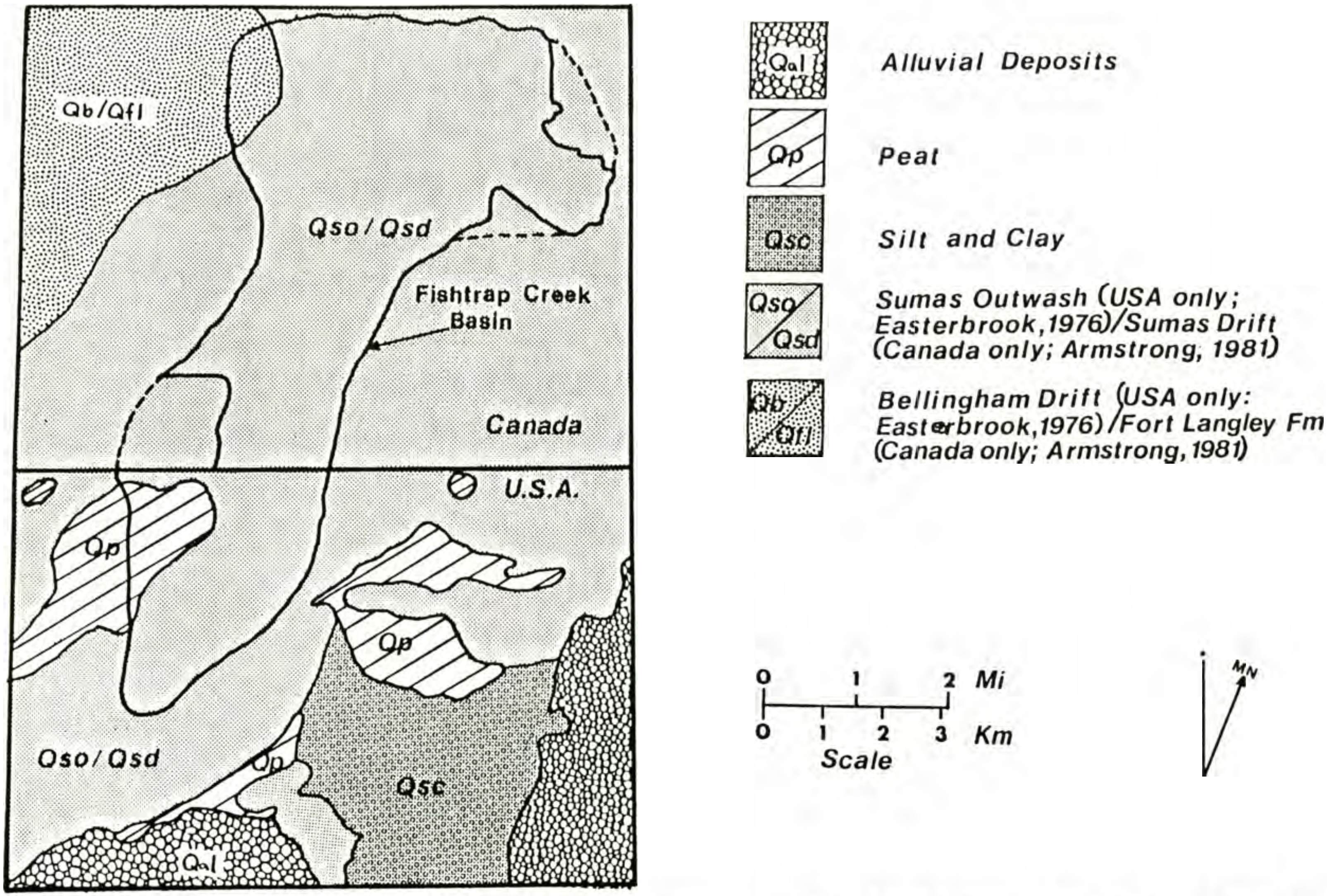


Figure 3. Geologic map of the Fishtrap Creek basin. (after Easterbrook, 1976; Armstrong, 1981)

Table 1. Unadjusted land use in the Fishtrap Creek basin.

Land-use	% Basin 1952-53	% Basin 1987-88	% Imp *	% Imp Surface + 1952-53	% Imp Surface + 1987-88
Pasture	60.3	44.1	.0	.00	.0
Crops	10.4	15.3	.0	.00	.0
Woodlands	23.8	17.7	.0	.00	.0
Residential	2.5	12.9	20.0	.50	2.6
Roads	1.0	4.0	100.0	1.0	4.5
Industrial	.9	3.5	40.0	.36	.9
Lawn grass	1.1	2.6	.0	.0	.0
Totals	100.0	100.1	----	1.86	8.0

* % impervious surface for the specified land use (Muller, 1969).

\+ % impervious surface in the land use for both time periods.

Table 2. Adjusted land-use percentages in the Fishtrap Creek basin.

Land-use	1952-53	1987-88
Pasture	60.3	43.8
Crops	10.4	15.2
Woodlands	23.8	17.6
Lawn grass *	3.7	15.4
Impervious *	1.8	8.0
Total	100.0	100.0

* Residential, road, and industrial land-use categories (from Table 1) are allocated to either lawn grass or impervious land use based on definition of percent impervious in Muller (1969). See text for further explanation.

Environment, Victoria, British Columbia. Land use for the same period in the Washington portion was determined from aerial photographs housed in the Geography library at Western Washington University.

The land-use categories were defined by the following criteria. "Pastures" are grassy areas used to graze cattle or horses. The "crops" category includes cultivated fields of mostly strawberries, raspberries, or corn. During the non-growing season some of these crops are plowed under and the ground remains bare until the next planting. "Woodlands" include all forested areas; alder, vine maple, pine, and fir are the most common trees, and deciduous trees are more abundant than conifers. "Lawn grass" includes parks, golf courses, and yards near houses. "Residential" areas are those areas of high housing density. "Roads" includes all highways and county roads. "Industrial" areas typically have large expanses of impervious cover such as parking lots, roofs, and storage areas.

In rural areas, lawns, driveways, and roofs are areally insignificant and were not mapped in either time period. Also, the 1952 - 1953 aerial photographs were of insufficient detail to allow mapping of these small areas of impervious surface and lawn grass.

Percentages of impervious surface in the residential, roads and industrial land-use categories (fourth column, Table 1) were determined using estimates of impervious surface and lawn grass areas per land-use category as calculated by Muller (1969). Muller (1969) calculated these percentages based on a detailed study of the urbanization in north central New Jersey. For these three categories only, I calculated the amount of impervious cover (versus grass cover) for the two time periods (fifth and sixth columns, Table 1). Based on the above modifications, I calculated the final adjusted land-use percentages for the Fishtrap basin summarized in Table 2.

THE WATER BALANCE

A water balance of a drainage basin quantitatively defines the relationship between the addition of water, principally by precipitation, and the loss of water by interception, evapotranspiration and runoff. Water balances were calculated for two annual periods, June 1952 through May 1953 and June 1987 through May 1988. Each water-balance computation was initiated using data from eight months prior to the start of the year of interest to assure that starting values of soil moisture and detained water would be realistic for the months of June 1952 and June 1987.

The components of the water balance (Dunne and Leopold, 1978) are explained below and in the glossary at the end of the text.

$$P = I + Is + AE + DST + OF + DGS + GR + IR \qquad (1)$$

Precipitation (P) is the amount of water that naturally falls on the basin. Precipitation can either infiltrate, be discharged as overland flow, or be intercepted by impervious surfaces and evaporated. Interception (I) is the amount of precipitation that is intercepted by impervious surfaces or vegetation surfaces and evaporated back to the atmosphere. Interception storage (Is) is the maximum amount of water that vegetation or impervious surfaces can store on their surfaces. Actual evapotranspiration (AE) is the water lost from a basin by direct evaporation from the soil surfaces, ponds, lakes, rivers and by transpiration of vegetation. Soil moisture (ST) is the amount of water stored in the root zone of the soil. Soil moisture is a function of precipitation, actual evapotranspiration, soil properties and surface vegetation. Change in soil moisture (DST) is the difference in the average amount of soil moisture from one month to the next. Overland flow

(OF) is the amount of precipitation that runs off impervious and vegetated surfaces, enters stream channels and is transported out of the basin. Groundwater storage (GS) is the amount of water in the groundwater reservoir. Groundwater is recharged by water that percolates down through the unsaturated zone to the water table. Change in groundwater storage (DGS) is the month-to-month change in the groundwater reservoir. Groundwater runoff (GR) is the amount of water that leaves or enters the basin each month due to groundwater flow. Irrigation withdrawal (IR) is the amount of water removed from the stream or unconfined surface aquifer to water crops during dry summer and fall months.

With the exception of precipitation, the above variables were not measured directly in the Fishtrap Creek basin. Procedures I used to calculate these variables are discussed below. I calculated total runoff (a sum of overland flow and groundwater runoff) from the basin by estimating all other components of the water balance (equation 1) and calculating total runoff as the residual.

I had independent field measurements of water discharge out of the Fishtrap Creek basin from a gaging station operated by the United States Geological Survey (USGS) during 1952 and 1953 (field-measured stream discharge should be equivalent to total runoff from the basin). I established a gaging station (Figure 2) in approximately the same location as the previous USGS gaging station for the period June 1987 to May 1988. Therefore, for both 1952 - 1953 and 1987 - 1988, I had discharge data (Appendix C) that could be compared to the total runoff data calculated from the water balance.

CALCULATION OF COMPONENTS OF THE WATER BALANCE

Precipitation

The daily, monthly, and yearly precipitation for the Fishtrap Basin was determined from daily rainfall data for precipitation stations at Abbotsford, British Columbia, and Clearbrook, Washington (Figure 1) for October 1951 through May 1953 and October 1986 through May 1988.

Monthly precipitation was modified to account for: 1) periods when most of the precipitation falls during the last part of month, and 2) additional precipitation that runs off the impervious surface onto vegetated surfaces. When precipitation occurs at the end of a month, a portion of the precipitation will be available to recharge the soil and groundwater reservoirs in the following month. To account for this, I added one half of the precipitation that fell during the last three days of a month to the next month's precipitation total (Thomas, 1981).

When precipitation falls on impervious surfaces, a small amount is intercepted and evaporates back to the atmosphere. The remaining water either flows from impervious surfaces on to adjacent vegetated surfaces and then infiltrates, or runs off to the sewer system and then to streams and leaves the basin. I estimated (based on the known distribution of sewers in Clearbrook, British Columbia) that the stream runoff component is 30 percent. This addition to stream runoff (OFI, or overland flow from impervious surface) is accounted for in the overland flow component (see below). The remaining 70 percent flows off impervious surfaces and infiltrates. The infiltrated water is added to the other land-use categories as extra water off impervious surfaces (X).

Interception

Interception (I) and interception storage (Is) (Tables 3 and 4) are dependent on the form, density, and surface texture of the groundcover as well as on climatic factors (Dunne and Leopold, 1978). I estimated interception percentages and interception storage amounts for five ground covers: crops, pasture, grass, woodlands and impervious surface (Tables 3 and 4).

The dominant crop types in the basin are corn, raspberries, and strawberries. Corn intercepts about 16 percent of the gross precipitation in the growing season but only 3 percent during low development months (Lull, 1964). There are no data available for interception on strawberries and raspberries. However, based on their lower vegetation density, I assumed strawberries and raspberries have a lower interception capacity than corn. Reasonable interception values are 10 percent for growing months and 3 percent for non-growing months (Table 3).

Field grasses (pasture and lawn) may intercept as much as 20 percent of gross precipitation during individual storms (Dunne and Leopold, 1978). In the Fishtrap Basin, pasture and lawn grasses are generally short (10 to 50 mm) due to cutting and grazing, which would lower interception values. On this basis, I estimated interception percentages for lawn grass and pasture areas to range from 5 percent in the winter and 10 percent in the summer (Table 3).

Monthly interception by woodlands in the Fishtrap Basin was estimated using the linear regression equations of Helvey and Patric (1965) (see footnote, Table 3). The equations were developed for forests dominated by deciduous trees in the eastern United States. The equations, one for the growing season and the other for the non-growing season, are

Table 3. Monthly interception percentages

Month	Crops	Pasture	Grass	Woods *	Impervious +
June	10.0	10.0	10.0	est.	est.
July	10.0	10.0	10.0	est.	est.
August	10.0	10.0	10.0	est.	est.
September	10.0	10.0	10.0	est.	est.
October	3.0	5.0	5.0	est.	est.
November	3.0	5.0	5.0	est.	est.
December	3.0	5.0	5.0	est.	est.
January	3.0	5.0	5.0	est.	est.
February	3.0	5.0	5.0	est.	est.
March	3.0	5.0	5.0	est.	est.
April	10.0	10.0	10.0	est.	est.
May	10.0	10.0	10.0	est.	est.

* Monthly interception by woods was calculated using the following equations (Helvey and Patric, 1965).
$I = (0.059 * P) + (0.02 * S)$ for nongrowing season.
$I = (0.083 * P) + (0.036 * S)$ for growing season.
Where I = monthly interception (mm), P = monthly rainfall (mm), S = number of storm events in the month (mm).

\+ Interception off impervious surface was calculated by subtracting an estimated amount (Table 4) of precipitation from each storm event. This subtracted amount was adjusted for seasonal changes in evaporation rates.

Table 4. Interception storage amounts (mm).

Month	Crops	Pasture	Grass	Woods	Impervious
June	1.0	1.0	1.0	1.5	5.0
July	1.0	1.0	1.0	1.5	5.0
August	1.0	1.0	1.0	1.5	5.0
September	1.0	1.0	1.0	1.5	5.0
October	0.0	0.5	0.5	1.2	4.0
November	0.0	0.5	0.5	1.2	3.0
December	0.0	0.5	0.5	1.2	2.0
January	0.0	0.5	0.5	1.2	2.0
February	0.0	0.5	0.5	1.2	2.0
March	0.0	0.5	0.5	1.2	3.0
April	1.0	1.0	1.0	1.5	4.0
May	1.0	1.0	1.0	1.5	5.0

based on precipitation and number of storm events for a particular time period (see footnote, Table 3). Interception storage for deciduous trees ranges from 1.5 mm per storm in the growing season to 1.2 mm per storm in the non-growing months (Table 4) (Helvey and Patric, 1965).

Interception storage on impervious surfaces (roads, walls, parking lots, ect.) ranges from 1.5 to 5 mm per storm event (Dunne and Leopold, 1978; Mather, 1979). For this study, I assumed that for every storm event a certain amount of water was intercepted and evaporated. I adjusted these values for seasonal changes in evaporation rates (assuming higher evaporation rates in warmer months) for the course of the year (sixth column of Table 4).

Potential evapotranspiration

Potential evapotranspiration is the maximum amount of water that can be removed from the basin by transpiration of vegetation and evaporation from soil surfaces, ponds, lakes, and rivers (Dunne and Leopold, 1978).

I calculated potential evapotranspiration by the Penman (1948) energy balance method (Appendix A). This method utilizes direct measurements of temperature, solar radiation, windspeed, vapor pressure, and sunshine duration to calculate values of potential evapotranspiration.

Soil moisture

Soil moisture (ST) is the amount of water stored in the root zone of the soil. The change in soil moisture with time (DST) is a function of precipitation, actual evapotranspiration, soil properties and surface vegetation. If the pore space in the root zone of a soil is filled with water and all extra water has drained away due to gravity, the soil is at field capacity.

Soil moisture content at field capacity (ST) can vary because the available water holding capacities (AWC) of soils can also vary. Fine sands will hold much less water than silts and clays. In addition, plants have deeper roots in sandy soils than in silts and clays. Thus, soil moisture at field capacity (ST) is a function of rooting depth and available water capacity (Dunne and Leopold, 1978):

$$[\text{Root depth (m)}] \times [\text{AWC (mm/m)}] = [\text{ST (mm)}] \qquad (2)$$

Rooting depths (Table 5) for different land-use areas were measured at sites in the basin during February 1988. I chose measurement sites within areas of pasture, lawn grass, and crops by closing my eyes and throwing a shovel into a selected parcel of pasture, lawn grass, or crops. Where the shovel landed, I measured the rooting depth. This procedure was performed ten times each for these three land-use categories and an average rooting depth was determined. Woodland rooting depths were estimated (Thorthwaite and Mather, 1957). For pastures, lawn grass, and crops, rooting depths were adjusted to a greater depth during the peak growing months; this adjustment in turn increased the field capacity seasonally.

The Soil Conservation Service (SCS) (Golden, A., written communication, Soil Conservation Service, 1978) has identified nine different soil types in the Washington portion of the basin and has measured their available water capacities (Table 6). Using this information, I calculated soil moisture at field capacity (ST) using equation 2 for each soil type and land-use area. Based on relative abundance of the land-use categories, I then calculated a weighted average value of ST (Table 7) for use in the water-balance calculations.

Table 5. Measured rooting depths (mm) of vegetation in the Fishtrap Creek basin.

	Grass	Pasture	Crops	Woods *
1	120	170	240	est.
2	140	150	280	est.
3	160	150	260	est.
4	150	160	200	est.
5	150	160	230	est.
6	160	180	200	est.
7	130	160	200	est.
8	150	180	250	est.
9	140	180	260	est.
10	150	120	250	est.
Average	145	161	237	1250
Std Dev	13	19	29	----

* Estimate for woods was based on rooting depths obtained from Thornthwaite and Mather (1957). See text for further explanation.

Table 6. Available water capacities (AWC) (mm) of soils in the Fishtrap Creek basin.

Soil *	% of Basin	AWC	Average AWC
32B	13	450	58.5
32D	7	334	23.4
32E	5	187	9.4
39A	4	156	6.2
39C	10	156	15.6
73A	15	143	21.5
77A	9	130	11.7
79A	11	100	11.0
80A	26	128	33.3
Weighted Average AWC =			190.6 mm +

* Golden, A., written communication, SCS, 1978.

\+ Average AWC, weighted by percent of basin.

Table 7. Soil moisture at field capacity capacity (mm): monthly averages weighted by percentage of basin.

	1952 - 1953	1987 - 1988
June	90	76
July	92	77
August	92	77
September	92	77
October	90	75
November	87	73
December	85	70
January	81	67
February	81	67
March	84	70
April	87	73
May	89	75

Table 8. Monthly overland flow (mm) in the Fishtrap Basin.

	1952 - 1953		1987 - 1988	
	OFV*	OFI+	OFV*	OFI+
June	0	0	1	0
July	0	0	0	1
August	0	0	0	0
September	0	0	0	0
October	0	1	0	0
November	0	0	6	2
December	9	1	19	4
January	80	2	3	2
February	20	1	3	2
March	4	1	4	3
April	1	1	6	4
May	0	0	4	3

* Overland flow from vegetated surfaces (From SCS method, 1972).

\+ Overland flow from impervious surfaces (Calculated from water intercepted by impervious surfaces).

Overland flow from vegetated surfaces

Total overland flow (OF) is comprised of overland flow from vegetated surfaces (OFV) and overland flow from impervious surfaces (OFI) (see Interception) (Table 8).

I estimated overland flow from vegetated surfaces (OFV) using tables and graphs developed by the Soil Conservation Service (Mockas, 1972). This method, which utilizes information on slope, groundcover, soil type, and antecedent precipitation, is completely described by Mockas (1972), Dunne and Leopold (1978), and Mather (1981).

To calculate OFV the hydrologic soil group must first be determined. The Soil Conservation Service has classified soils from A through D (Mockus, 1972) on the basis of runoff potential, soil group A having the lowest potential for runoff. I determined the hydrologic soil group as a weighted average of the soils present in the basin. Each soil type (A - D) was weighted by the percentage of the basin it occupied (Table 6). The average soil type is between a C and D classification.

I then determined the five-day antecedent soil moisture on the basis of rainfall records for the five preceding days. I selected an appropriate runoff curve and determined the actual amount of monthly overland flow that occurred in each land-use area (Dunne and Leopold, 1978) (Table 8).

I assumed that overland flow leaves the basin in the month in which it was generated. However, if heavy rainfall occurs near the end of a month, a portion of the overland flow generated is carried over into the next month. Carry-over was accounted for by delaying that component of overland flow generated during the last three days of the month. Forty percent of OF was delayed from the last day, thirteen percent from the second to last day, and two percent from the third to last day (estimated from Fishtrap Creek hydrographs of storm events).

Irrigation withdrawals

The amount of water withdrawn from the unconfined surface aquifer in the Washington side of the basin was estimated from water rights registered with the Washington State Department of Ecology. On the basis of personal observation and conversations with local farmers, I assumed irrigation only occurred in the dry months of summer and early fall (June - October) because it would be impractical and expensive to irrigate when it is not needed. I also assumed that, because potential evapotranspiration is much higher than actual evapotranspiration in the summer, water withdrawn for irrigation was not available to recharge the water table because it was transpired or evaporated.

RESULTS

The water-balance calculations for 1952 - 1953 (Table 9; Figure 4) and for 1987 - 1988 (Table 10; Figure 5) provide both a graphical portrayal of monthly changes in precipitation, actual evapotranspiration, potential evapotranspiration, and stream runoff (Figures 4 and 5) and a calculated estimate of both monthly and total yearly water discharge (stream runoff) out of the Fishtrap Creek basin (Rows 20 of both Tables 9 and 10). (For a complete description of how I calculated water balances for these periods, see Appendix A.)

Gaging station data for these same one-year periods (Appendix B) provides total monthly and yearly stream discharge volumes (Row 21, tables 9 and 10). Therefore, runoff is assessed both by field measurement and by calculation of residual values using the standard water balance scheme described in Appendix A.

Table 9. Water-balance calculation for the Fishtrap Creek basin, 1952 - 1953.

Components *	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
1. P	81	23	27	42	52	27	168	373	106	119	91	56	1166
2. AP	-1	1	0	-1	-8	9	-7	-19	25	-7	6	2	0
3. X	1	0	0	0	1	0	2	5	1	1	1	1	14
4. I	8	2	3	4	3	2	9	19	5	6	8	5	74
5. OFV	0	0	0	0	0	0	9	80	20	4	1	0	115
6. OFI	0	0	0	0	1	0	1	2	1	1	1	0	7
7. EP	72	22	24	37	41	34	144	258	107	103	88	53	985
8. PE	105	125	99	63	25	0	9	18	22	50	75	111	702
9. EP-PE	-33	-103	-75	-25	16	34	135	240	85	53	13	-58	283
10. Acc Wl	-52	-155	-230	-256	0	0	0	0	0	0	0	-58	-751
11. ST	47	16	7	5	21	55	85	81	81	84	87	46	615
12. DST	-21	-32	-9	-2	16	34	30	-4	0	3	3	-41	-23
13. AE	93	54	33	39	25	0	9	18	22	50	75	95	513
14. S	0	0	0	0	0	0	105	244	85	50	10	0	494
15. IR	.2	.2	.2	.2	.2	.0	.0	.0	.0	.0	.0	.0	1.0
16. AR +	53	35	23	15	10	7	110	317	298	249	177	119	1413
17. DET	35	23	16	10	7	5	73	213	199	167	119	80	947
18. GR	17	12	8	5	3	2	36	105	98	82	59	39	466
19. OF	0	0	0	0	1	0	10	82	21	5	2	1	122
20. TRO	17	12	8	5	4	2	46	187	119	87	61	40	588
21. MRO	17	12	7	8	8	8	28	189	135	73	68	41	594

* P, precipitation; AP, additional precipitation; X, extra water from impervious surface; I, interception; OFV, overland flow off vegetated surfaces; OFI, overland flow off impervious surfaces; EP, effective precipitation; PE, potential evapotranspiration; Acc Wl, Accumulated water loss; ST, soil moisture; DST, change in soil moisture; AE, actual evapotranspiration; S, surplus; IR, irrigation withdrawals; AR, available for runoff; DET, detained water; GR, groundwater runoff; OF, total overland flow; TRO, total calculated runoff; MRO, measured runoff.

\+ 53 mm of water was carried over from May.

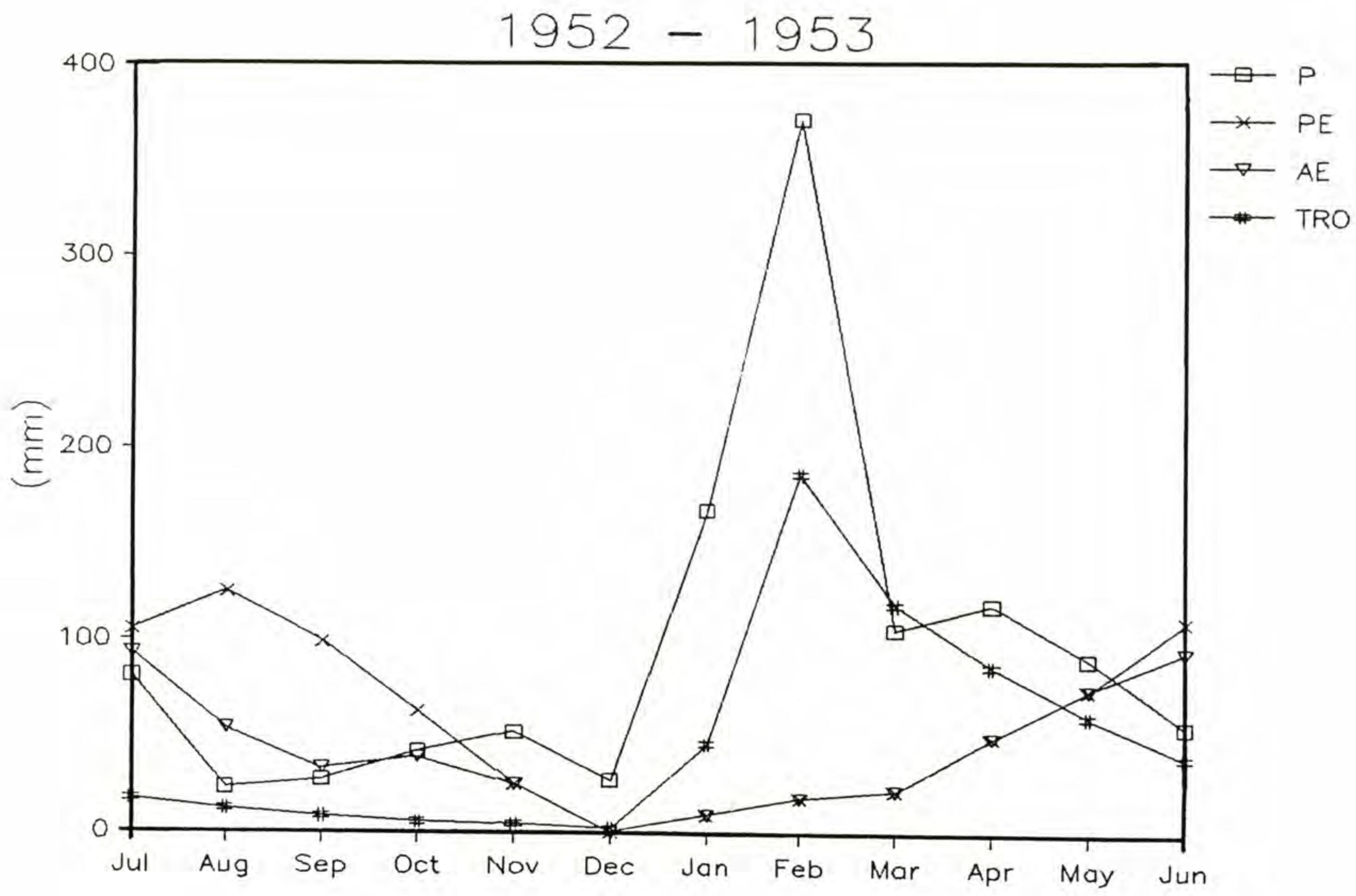


Figure 4. Graphical water balance for 1952 - 1953.

Table 10. Water-balance calculation for The Fishtrap Creek Basin, 1987 - 1988.

Components *	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
1. P	24	49	15	29	17	86	168	94	93	133	140	150	997
2. AP	25	-2	2	0	-8	8	-5	-5	5	-7	-6	7	14
3. X	1	2	1	1	1	5	9	5	5	7	8	8	53
4. I	3	5	2	3	1	5	8	5	5	7	14	17	75
5. OFV	1	0	0	0	0	6	19	3	3	4	6	4	46
6. OFI	0	1	0	0	0	2	4	2	2	3	4	3	22
7. EP	46	43	15	27	9	85	141	84	93	120	117	141	921
8. PE	97	129	84	58	18	23	0	8	23	49	52	84	624
9. EP-PE	-50	-86	-69	-31	-9	62	141	76	70	71	65	57	296
10. Acc Wl	-50	-136	-205	-236	-245	0	0	0	0	0	0	0	-873
11. ST	39	13	5	3	3	65	70	67	67	70	73	75	550
12. DST	-36	-26	-8	-2	0	65	5	-3	0	3	3	2	3
13. AE	83	69	22	29	9	23	0	8	23	49	52	84	451
14. S	0	0	0	0	0	0	136	79	70	68	62	55	470
15. IR	1.4	1.4	1.4	1.4	1.4	.0	.0	.0	.0	.0	.0	.0	7.0
16. AR +	72	47	30	19	11	7	141	173	186	192	191	183	1251
17. DET	48	31	20	12	7	5	94	116	124	129	128	123	838
18. GR	24	15	10	6	4	2	46	57	61	63	63	61	413
19. OF	1	1	0	0	0	8	23	5	5	7	10	7	68
20. TRO	25	16	10	6	4	11	69	62	66	70	73	67	479
21. MRO	34	15	6	4	4	11	49	59	65	69	88	71	475

* P, precipitation; AP, additional precipitation; X, extra water from impervious surface; I, interception; OFV, overland flow off vegetated surfaces; OFI, overland flow off impervious surfaces; EP, effective precipitation; PE, potential evapotranspiration; Acc Wl, Accumulated water loss; ST, soil moisture; DST, change in soil moisture; AE, actual evapotranspiration; S, surplus; IR, irrigation withdrawals; AR, available for runoff; DET, detained water; GR, groundwater runoff; OF, total overland flow; TRO, total calculated runoff; MRO, measured runoff.

\+ 74 mm of water was carried over from May.

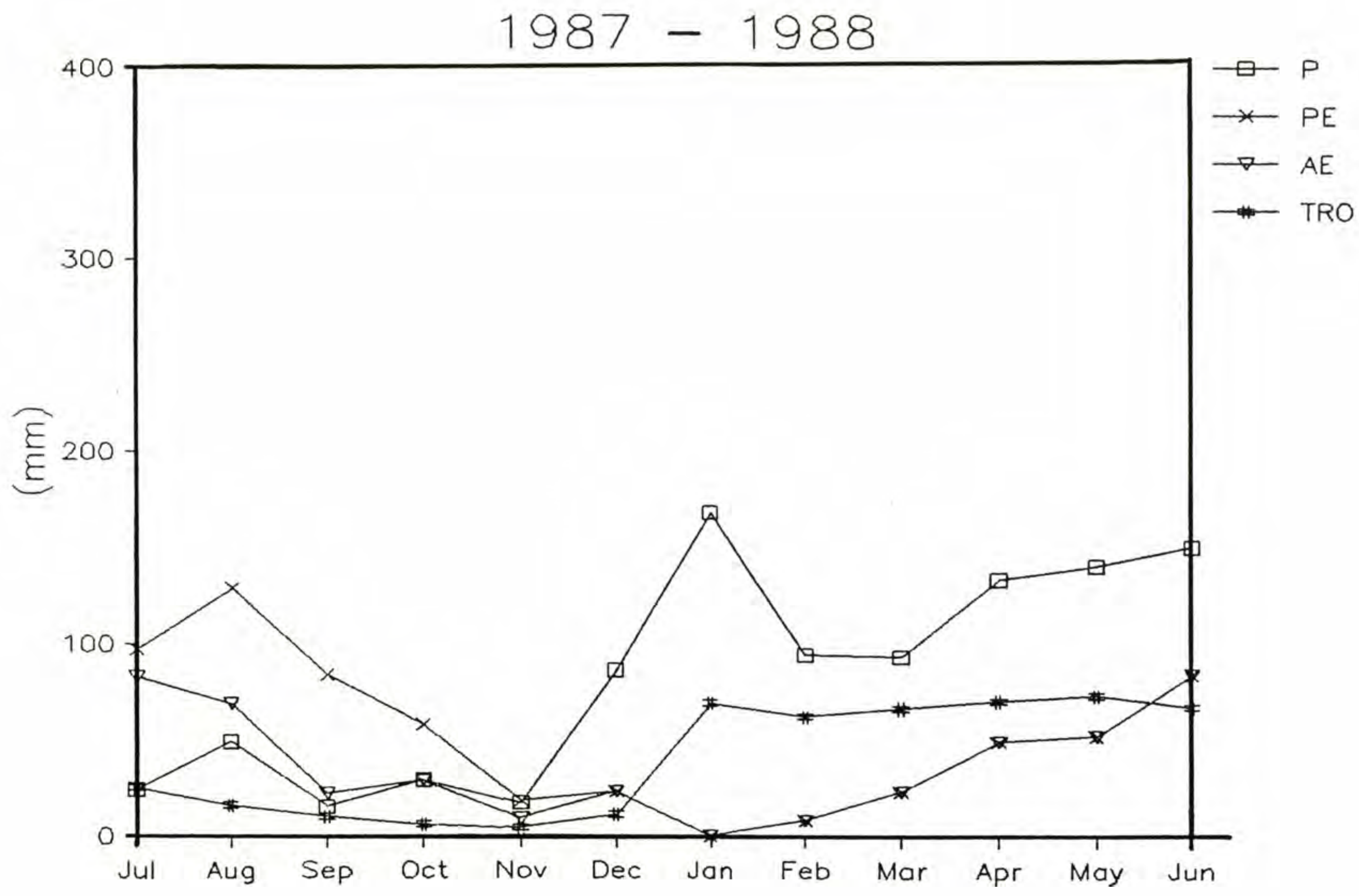


Figure 5. Graphical water balance for 1987 - 1988.

Assuming the field-measured discharge values are reliable, the accuracy of the runoff value obtained from the water-balance method (Row 20, Tables 9 and 10) can be examined by comparing the field-measured and water-balance-calculated runoff values (Table 11). The difference between measured and calculated stream discharge for both time periods (column 4, Table 11) is in general small.

Measured and calculated stream discharges for both time periods are also compared graphically (Figure 6). The best fit line defining the correlation of measured versus calculated discharge is close to a 1:1 relation (the slope of the best fit regression line for 1952 - 1953 is 1.01, for 1987 - 1988 slope is 0.93), which should be the case because the measured and calculated values of monthly discharge should be equal.

Water balance for 1952 - 1953

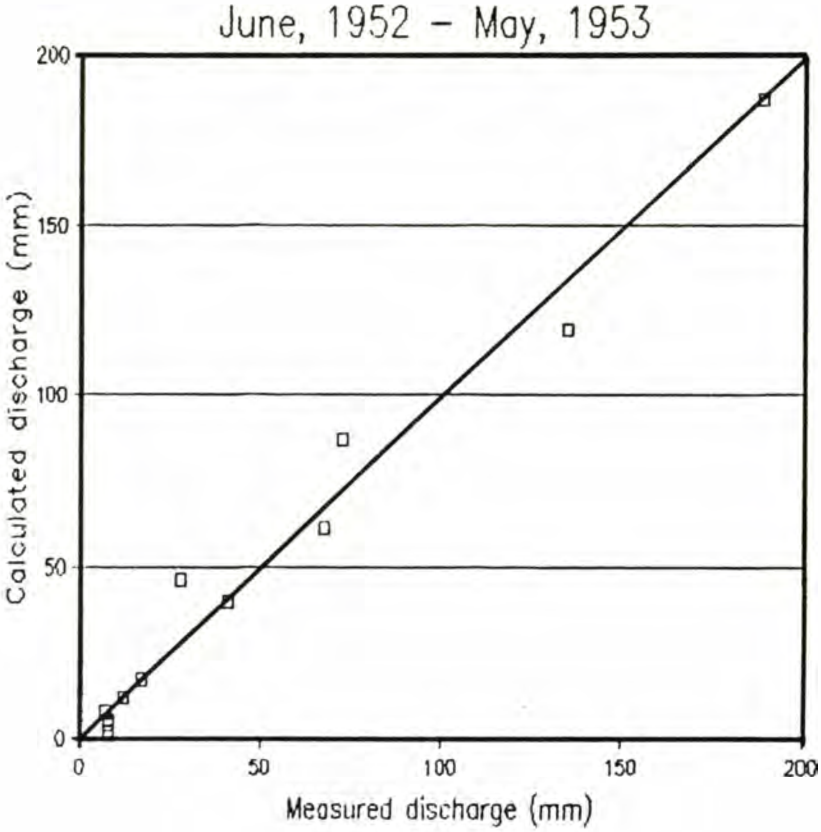
The annual measured stream discharge (MRO) for 1952 - 1953 was 594 mm (stream gage data) versus the stream discharge of 588 mm (TRO) calculated by the water-balance method (Tables 9 and 11). Monthly calculated discharges for the 1952 - 1953 water balance were close to the monthly measured amounts with seven months showing values within 5 mm of the measured discharge. The largest deviation was an 18 mm difference in December 1952 (Table 11). In June and July 1952 the measured and calculated discharges were equal.

For the 1952 - 1953 water balance, total input was partitioned amongst the output and storage components in the following manner: interception, 5.7 percent; overland flow off vegetated surfaces, 8.8 percent; overland flow off impervious surfaces, 0.5 percent; soil moisture storage, 3.5 percent; actual evapotranspiration, 39.4 percent; irrigation withdrawals, 0.08 percent; groundwater storage, 6.1 percent; and groundwater runoff, 35.8 percent (Figure 7).

Table 11. Monthly and annual comparison of measured and calculated stream discharge (mm) in the Fishtrap Creek basin, 1952-1953 and 1987-1988.

Time Period	Measured Stream Discharge *	Calculated Stream Discharge +	Difference between Measured and Calc. Discharge @
June 1952	17	17	0
July	12	12	0
August	7	8	-1
September	8	5	+3
October	8	4	+4
November	8	2	+6
December	28	46	-18
January	189	187	+2
February	135	119	+16
March	73	87	-14
April	68	61	+7
May 1953	41	40	+1
Total 1952-53	594	588	+6
June 1987	34	25	+9
July	15	16	-1
August	6	10	-4
September	4	6	-2
October	4	4	0
November	11	11	0
December	49	69	-20
January	59	62	-3
February	65	66	-1
March	69	70	-1
April	88	73	+15
May 1988	71	67	+4
Total 1987-88	475	479	-4

* United States Geological Survey data (1952-1953) and data collected for this study (1987-1988).
\+ Water balance calculations, Tables 9 and 10 .
@ Positive = measured greater than calculated.



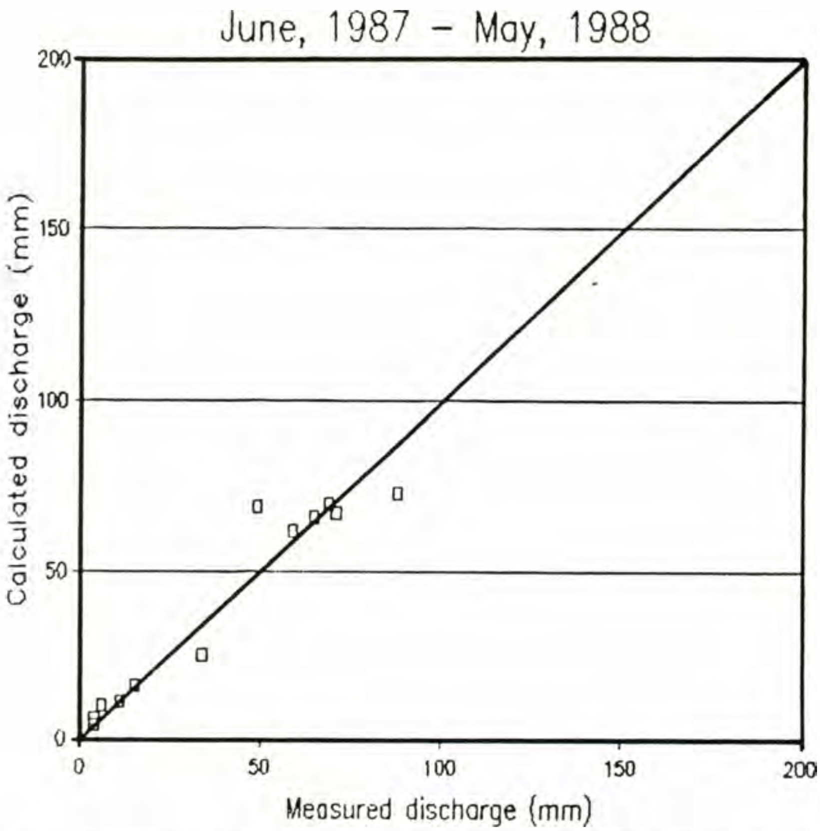


Figure 6. Correlation between calculated and measured discharge, 1952 - 1953 and 1987 - 1988.

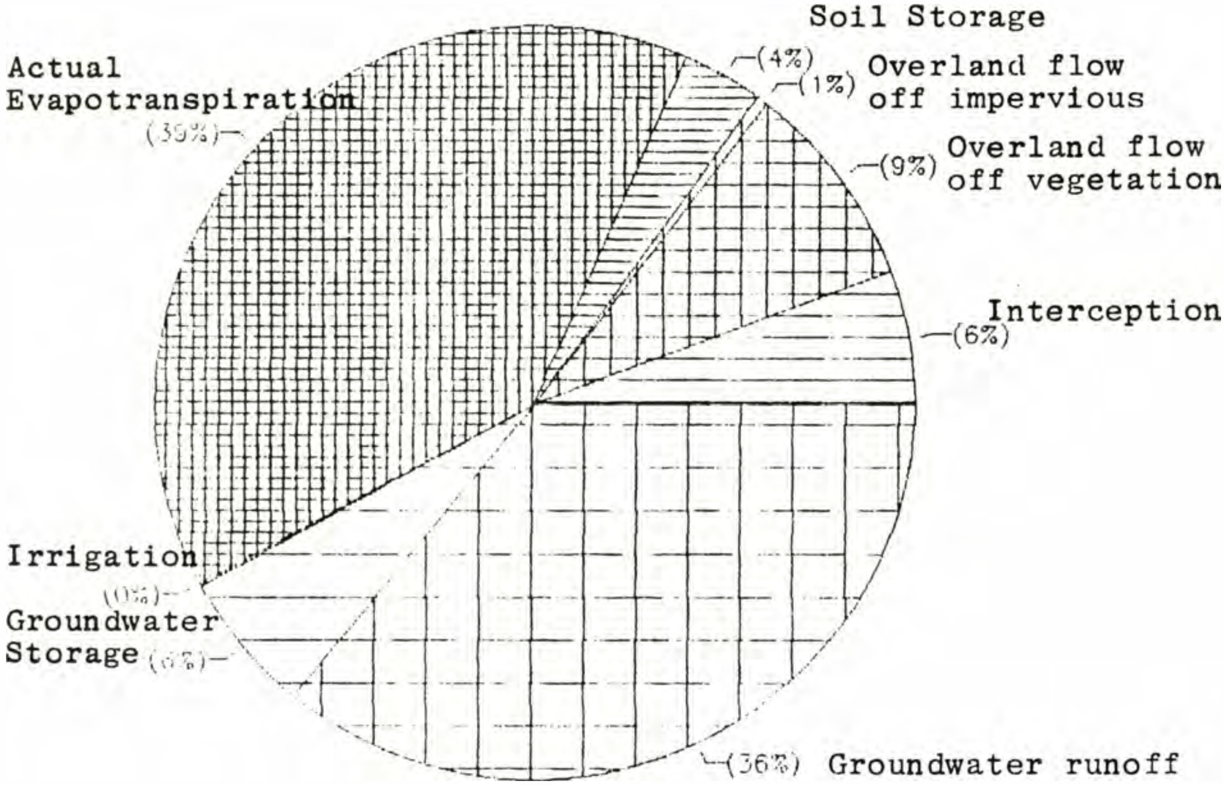


Figure 7. Output components of 1952 - 1953 water balance as percentage of total input.

Water balance for 1987 - 1988

The 1987 - 1988 water balance shows generally good agreement between the monthly measured and calculated values of discharge (Tables 10 and 11), with nine months having a difference of 5 mm or less. In October and November, 1988 the measured and calculated discharge were equal (Table 11). A notable exception to the generally good agreement is the 20 mm difference between calculated and measured discharge values for December, 1987 (Table 11). A possible explanation of this difference is presented in the Discussion and Conclusions section.

The output components of the water balance made up the following percentages of total input: interception, 6.2 percent; overland flow off vegetated surfaces, 3.8 percent; overland flow off impervious surface, 2.0 percent; soil moisture storage, 6.2; actual evapotranspiration, 37.2 percent; irrigation withdrawals, 0.6 percent; groundwater storage, 10.1; and groundwater runoff, 34 percent (Figure 8).

Water balance for 1987 - 1988 using climate from 1952 - 1953

To determine the effects of changing land use on the water balance of Fishtrap Creek basin, I used the climate of 1952 - 1953 and the land-use percentages of 1987 - 1988 (Table 2) to construct a hypothetical water balance for the Fishtrap Creek basin (Table 12). I used this hypothetical water balance to calculate the volume of output components (I, OFV, OFI, AE, GR, and TRO) that would occur if the same weather pattern (precipitation, temperature, sunshine duration, ect.) from the 1952 - 1953 time period occurred in 1987 - 1988. In effect, I maintained the climate constant, while allowing the land use to evolve over a thirty-six year period from the land use of 1952 to the land use of 1987.

The hypothetical water balance predicted the following changes in

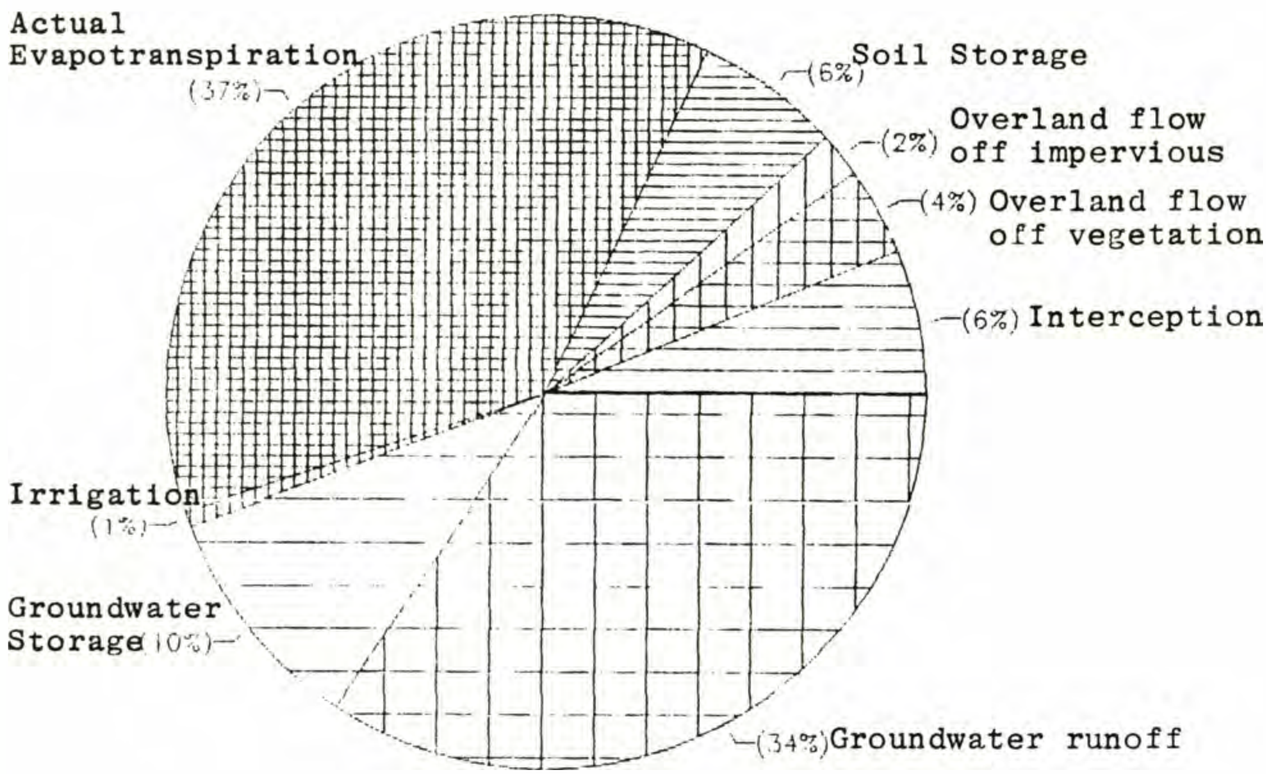


Figure 8. Output components of 1987 - 1988 water balance as percentage of total input.

Table 12. Hypothetical water balance: 1952 - 1953 climate in water balance calculations for 1987 - 1988.

Components *	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
1. P	81	23	27	42	52	27	168	373	106	119	91	56	1166
2. AP	-1	1	0	-1	-8	9	-7	-19	25	-7	6	2	0
3. X	3	1	1	2	2	1	9	21	6	6	4	3	58
4. I	9	3	4	5	3	3	8	18	5	7	10	7	82
5. OFV	1	0	0	0	0	0	9	75	20	4	1	0	110
6. OFI	2	1	1	1	1	1	3	10	3	3	2	1	27
7. EP	72	21	24	38	42	34	149	272	108	105	88	53	1007
8. PE	103	123	97	62	25	0	9	18	21	50	74	109	691
9. EP-PE	-31	-102	-74	-24	18	34	140	254	87	56	14	-56	316
10. Acc Wl	-48	-150	-224	-248	0	0	0	0	0	0	0	-56	-726
11. ST	39	10	4	3	20	55	70	67	67	70	73	34	512
12. DST	-20	-28	-6	-1	18	34	15	-3	0	3	3	-39	-24
13. AE	92	49	30	39	25	0	9	18	21	50	74	92	498
14. S	0	0	0	0	0	0	125	257	87	53	11	0	533
15. IR	1.4	1.4	1.4	1.4	1.4	.0	.0	.0	.0	.0	.0	.0	7.0
16. AR +	54	35	22	13	7	5	129	343	317	265	189	126	1504
17. DET	36	23	15	9	5	3	86	230	212	177	126	85	1008
18. GR	18	11	7	4	2	2	42	113	105	87	62	42	496
19. OF	3	1	1	1	1	1	12	85	23	7	3	1	138
20. TRO	21	12	8	5	3	3	54	198	128	94	65	43	634

* P, precipitation; AP, additional precipitation; X, extra water from impervious surface; I, interception; OFV, overland flow off vegetated surfaces; OFI, overland flow off impervious surfaces; EP, effective precipitation; PE, potential evapotranspiration; Acc Wl, Accumulated water loss; ST, soil moisture; DST, change in soil moisture; AE, actual evapotranspiration; S, surplus; IR, irrigation withdrawals; AR, available for runoff; DET, detained water; GR, groundwater runoff; OF, total overland flow; TRO, total calculated runoff.

\+ 55 mm of water was carried over from May output components of the water balance. Total runoff (TRO) increased in every month except July 1987 through September 1987 (October 1987 showed a 1 mm decrease) (Figure 9a). Groundwater runoff (GR) decreased in the mid-summer to late-fall months (July - October) and increased in all other months except November, 1987 when it remained the same (Figure 9b). Overland flow off impervious surfaces (OFI) increased in every month except October 1987 when there was no change (Figure 9c). Interception (I) increased in eight months (June, July, August, September, November, March, April, and May), decreased in two months (December and January) and remained the same in two months (October and February) (Figure 9d). Actual evapotranspiration decreased slightly in six months (June, July, August, February, April, and May) and remained the same in the other six (Figure 9e). Overland flow off vegetated surfaces (OFV) increased slightly in June, 1987, decreased in January, 1988 and remained the same in the remaining months (Figure 9f).

Total runoff (TRO), groundwater runoff (GR), overland flow off impervious surfaces (OFI) and interception (I) all increased on an annual basis (Figure 10). However, overland flow off vegetated surfaces and actual evapotranspiration decreased in yearly totals (Figure 10).

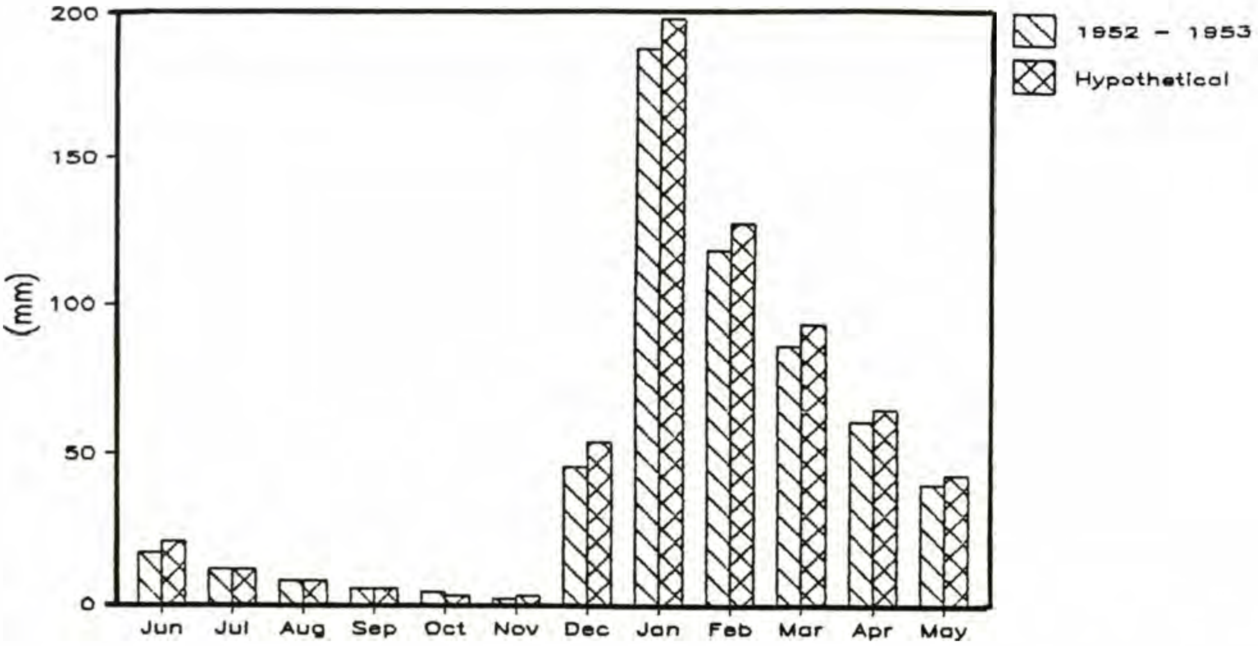


Figure 9a. Comparison of total runoff (TRO), 1952 - 1953 and hypothetical water balance for 1987 - 1988.

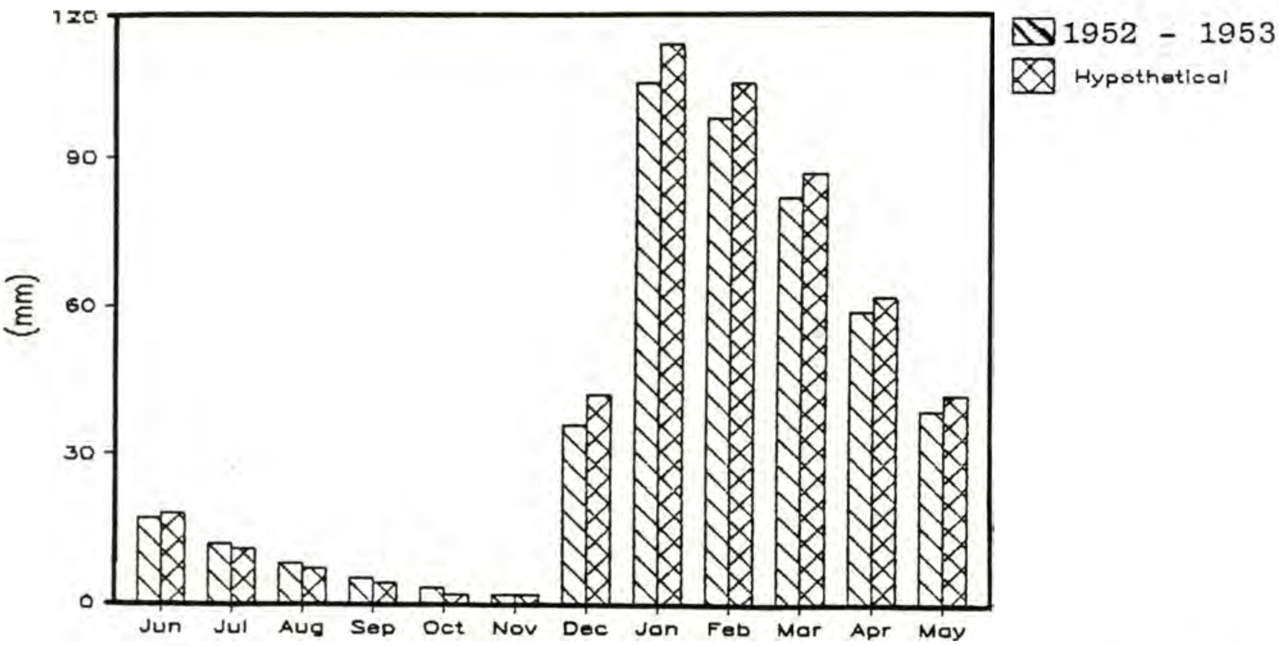


Figure 9b. Comparison of groundwater runoff (GR), 1952 - 1953 and hypothetical water balance for 1987 - 1988.

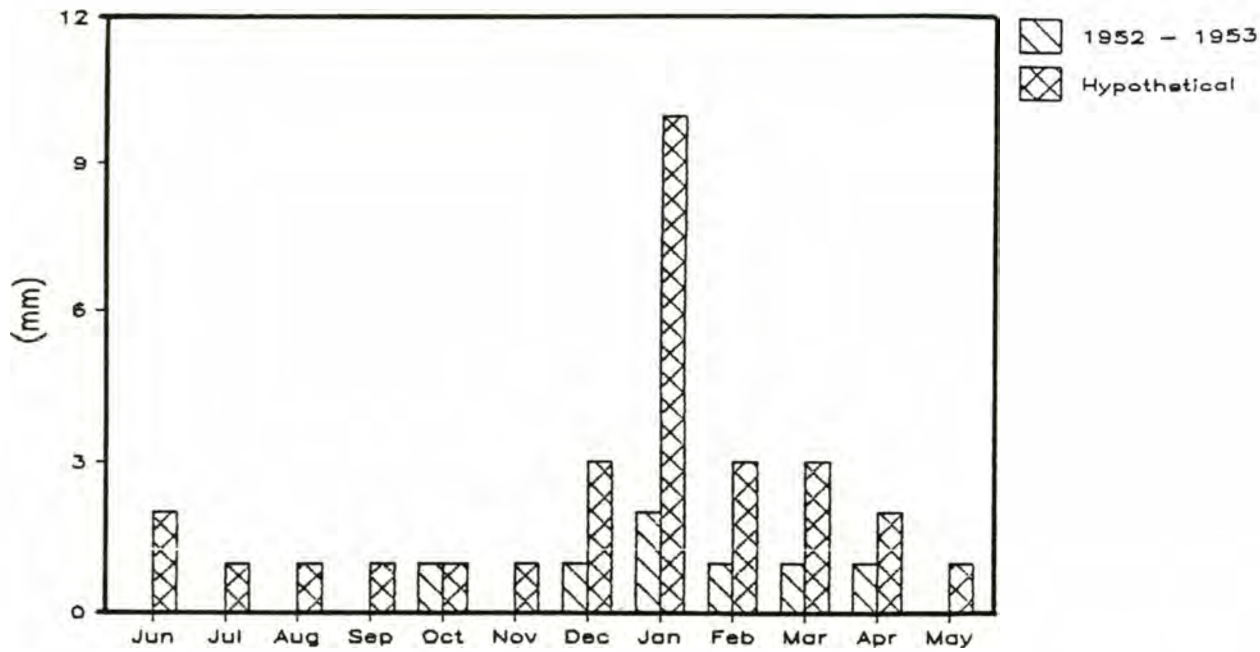


Figure 9c. Comparison of overland flow off impervious surfaces (OFI), 1952 - 1953 and hypothetical water balance for 1987 - 1988.

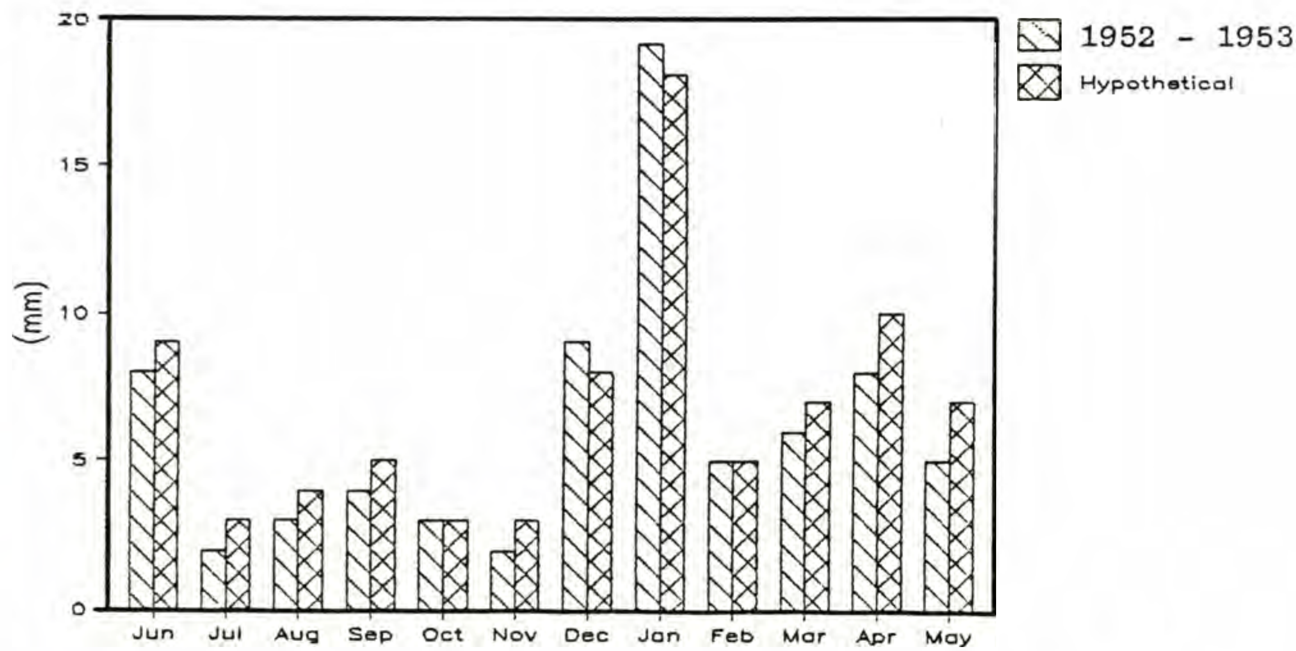


Figure 9d. Comparison of interception (I), 1952 - 1953 and hypothetical water balance for 1987 - 1988.

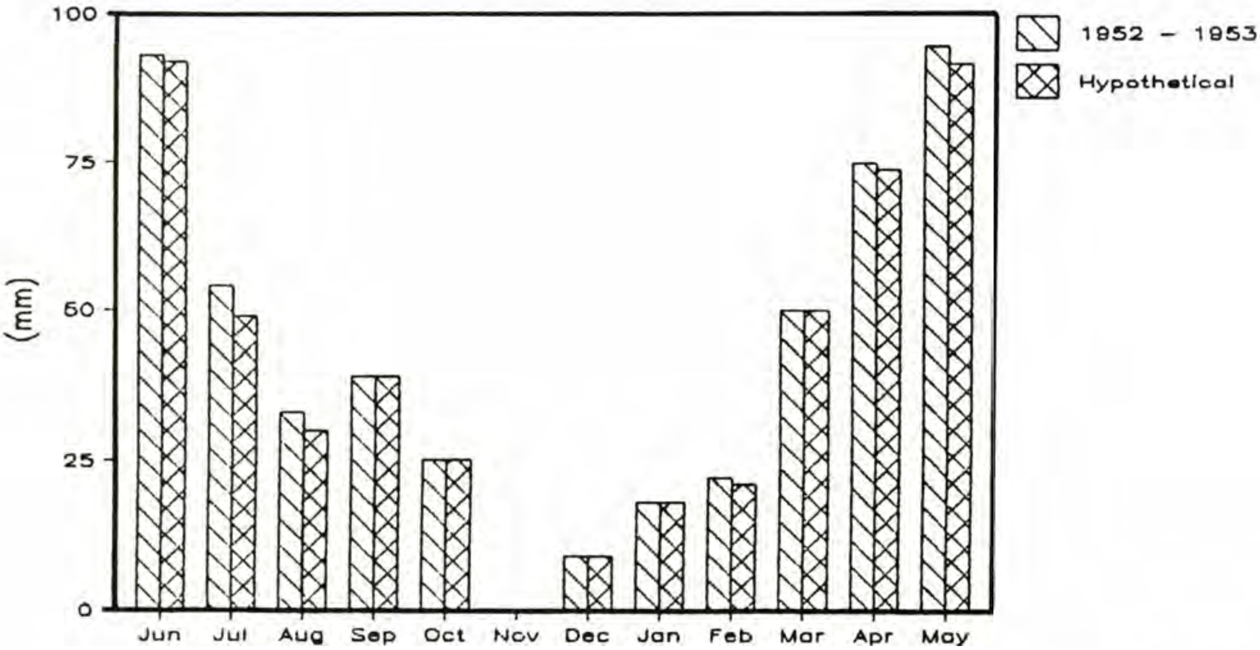


Figure 9e. Comparison of actual evapotranspiration (AE), 1952 - 1953 and hypothetical water balance for 1987 - 1988.

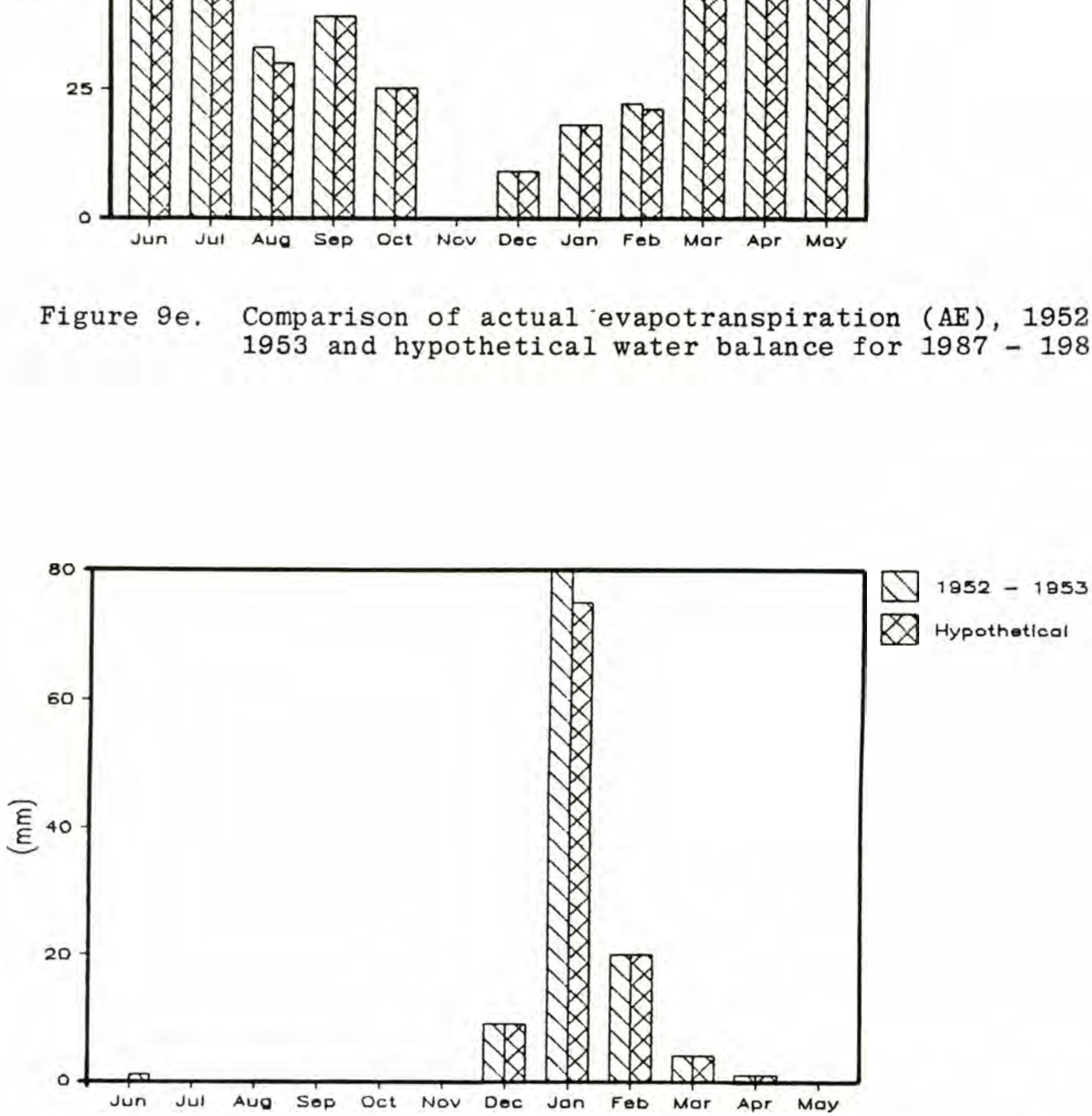


Figure 9f. Comparison of overland flow off vegetated surfaces, 1952 - 1953 and hypothetical water balance for 1987 - 1988.

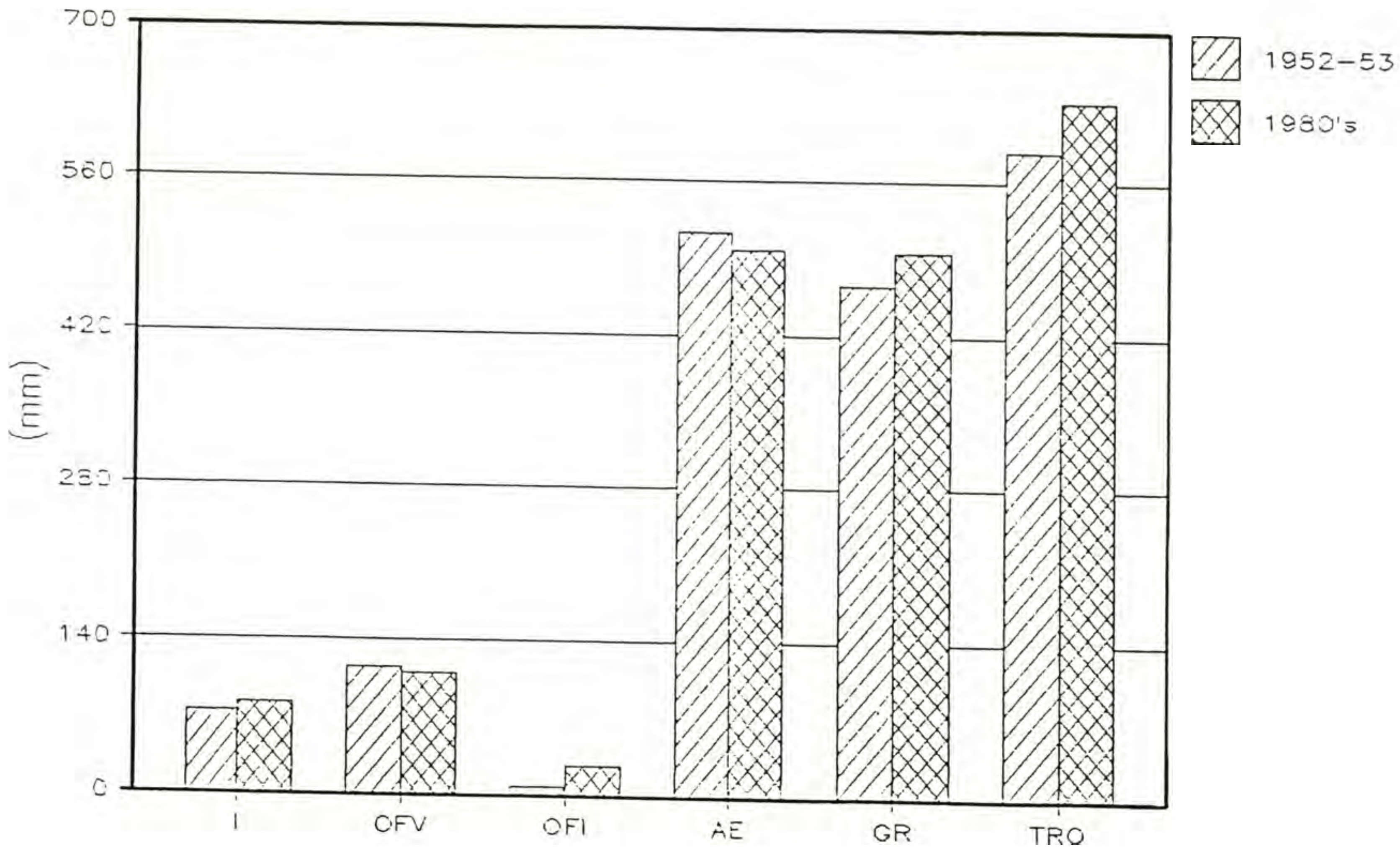


Figure 10. Comparison of water-balance variables, 1952 - 1953 and hypothetical water balance for 1987 - 1988 (Annual values).

DISCUSSION AND CONCLUSIONS

The reliability of stream discharge data acquired from water-balance calculations depends on the accuracy in measuring each of the water-balance variables. Although it is possible to make estimates of errors involved in calculating some of these variables, other errors are impossible to determine; thus a statistical analysis of the overall error is impractical (Appendix B).

As an alternative, the correlation between monthly measured and calculated stream discharge was examined (Table 11 and Figure 6). The close correlation (both annual and monthly) suggests that the estimates used in constructing the water balance were correct. Unfortunately, this method only tests the accuracy of the calculated stream discharge data (TRO) and not the reliablity of the remaining variables such as interception, actual evapotranspiration, irrigation withdrawals, overland flow off vegetated surfaces, overland flow off impervious surfaces, and groundwater runoff (for an estimate of the reliability of these variables see Appendix B). Compensating errors in these variables could make calculated runoff sensitive to temperature, rooting depth, or other parameters, yet cause no net bias.

The procedure for calculating water balances (Appendix A) accurately predicts monthly stream discharge (Tables 9, 10 and 11) for both time periods, except in months that follow prolonged dry spells (December 1952 and December 1987 are examples). In these months, the water-balance calculations predict much larger stream discharges than actually occurred (Tables 9, 10, and 11). The monthly water-balance calculations assume that after interception (I), overland flow from impervious surface (OFI), overland flow from vegetated surface (OFV), actual evapotranspiration

(AE), irrigation withdrawals (IR), and the amount of water needed to replenish the root zone of the soil column are all subtracted from precipitation, the remaining water immediately runs into the groundwater reservoir where it can contribute to groundwater runoff. The above assumption appears to be valid except in December 1952 and December 1987, when some water appears to be delayed or stored before infiltrating into the groundwater reservoir. Possible reasons for this discrepancy are that the water-balance method did not take into account soil moisture storage below the rooting zone and/or the lag time required for the initial precipitation to travel through this zone before entering the groundwater reservoir. Either or both of these reasons could cause some water to be held over from the initial heavy precipitation month into the next few months before it becomes available for groundwater discharge. Neither reason would cause an error in the annual balance.

The five principal land-use areas in the Fishtrap Creek basin have evolved in different ways over the past 36 years (Table 2). Areas used for pasture decreased by 16.5 percent, which was in part balanced by an increase of 11.7 percent in lawn grass. The area used for growing crops increased by 4.8 percent, while the area covered by woodlands decreased by 6.2 percent. Impervious surface area, which has the greatest affect on overland flow, increased from 1.8 to 8.0 percent of the basin.

The hypothetical water balance, calculated using the land use from 1987 - 1988 and the climate from 1952 - 1953 (see Results), predicted a number of changes in the water-balance variables. Increases in impervious surface area caused an increase in interception from late-spring to late-fall followed by a very slight decrease in the winter months (Figure 9c).

The decrease in woodlands (deep rooting depth and high evapotranspiration rate) coupled with increases in impervious surface area (zero rooting depth and low evapotranspiration rate) and in area used for crops (seasonal rooting depth and evapotranspiration rate) caused both soil moisture at field capacity and potential evapotranspiration to decrease on a monthly and annual basis (Table 13 and Figure 9e).

Increases in impervious surface area, which directly controls OFI, caused overland flow off the impervious surface to increase from 7 to 27 mm on an annual basis (Table 9 and 12; Figure 9c). The largest monthly increases occurred in months with high precipitation (Figure 9c).

Land-use changes in the basin did not affect overland flow off the vegetated surfaces (Figures 9f and 10). Decreases in areas of woodlands and pastures, which had low runoff potential, appear to have been compensated by an increase in low runoff potential lawn grass.

Decreases in actual evapotranspiration and soil moisture at field capacity (Table 13) resulted in more water being available to recharge the groundwater reservoir. Thus causing more water to be discharged as groundwater runoff in the winter to early spring months (Figure 9b). Groundwater runoff decreased in the mid-summer to late-fall months because more precipitation was removed from the water balance as interception and overland flow (off the impervious surfaces) before it could recharge the groundwater reservoir (Figure 9b). On an annual basis, the hypothetical water balance predicted that groundwater runoff from the basin increased by 6.4 percent over the groundwater runoff generated from 1952 through 1953 (Tables 9 and 12).

The increases in groundwater runoff and overland flow off the impervious surfaces caused total runoff (TRO = OFI + OFV + GR) to increase in every month except July and November, when it remained constant (Figure 9a). Total runoff increased on an annual basis from 588 to 634 mm (7.8 percent) (Tables 9 and 12) with the largest increases occurring in

Table 13. Weighted monthly averages (mm) of soil moisture at field capacity and potential evapotranspiration.

	Soil moisture at field capacity		Potential evapotranspiration	
	1952 - 53	1987 - 88	1952 - 53	1987 - 88
June	90	76	105	97
July	92	77	125	129
August	92	77	99	84
September	92	77	63	58
October	90	75	25	18
November	87	73	0	23
December	85	70	9	0
January	81	67	18	8
February	81	67	22	23
March	84	70	50	49
April	87	73	75	52
May	89	75	111	84

the winter and spring months (Figure 9a). Of this 7.8 percent increase, 2.7 percent occurred due to increased discharge of overland flow to the stream channel and 5.1 percent occurred due to increased base flow (groundwater discharge) to the stream channel.

The hypothetical water balance demonstrates that increased runoff would occur under the identical climate regime, but with a change in impervious surface area from 1.8 percent (1953) to 8.0 percent (1988). Thus urbanization of the Fishtrap Creek basin appears to have substantially increased the total discharge that the creek must handle as well as the peak discharge during storm events. Therefore, if similar storm events occurred in both periods of time, the storm event occurring in 1987 - 1988 should show increased runoff. I compared storm events from the two periods that met the following criteria: 1) both storms occurred in the month of June (June 1952 and June 1987), 2) the two storms had nearly the same total precipitation (June 1952 = 17.8 mm; June 1987 = 18.0 mm), 3) both storms lasted three days (June 27 - 29, 1952, and June 20 - 22, 1987), 4) both have approximately the same distribution of rainfall for the duration of the storm (largest amount of precipitation occurred on the second day of each storm event), and 5) both have approximately the same amount of five day antecedent precipitation (June 1952 = 0.51 mm; June 1987 = 0.25 mm). The June 27 - 29, 1952 storm event produced no change in the stream discharge, but the storm event which occurred from June 20 - 22, 1987 produced an increase in stream discharge of 18.8 percent. Other storm events, which satisfied most but not all the criteria stated above, also show increased discharge during the 1987 - 1988 period. The larger hydrologic response due to storms in 1987 is consistent with the hypothesis that land-use changes in the basin have increased the stream discharge immediately after storm events as compared to pre-urbanization (1950's) levels. Without detailed information on the intensity and distribution of rainfall during these events for both time periods, a more thorough analysis is not feasible.

Calculation of a water balance for small basins such as Fishtrap Creek may be beneficial in three ways. First a balance allows estimates of available water, both in the stream channel and the groundwater reservoir. These estimates are needed to legislate domestic and commercial water rights. Secondly, through a balance the contribution to the stream discharge from the groundwater reservoir can be monitored during the late-summer and fall low-flow periods. These periods are most critical to anadromous fish. Third, through the use of water balances, regional planners should be able to zone or otherwise require mixed land use that would compensate for undesirable effects of urbanization on surface and groundwater discharge in order to maintain desired hydrologic characteristics of a basin.

GLOSSARY AND LIST OF ABBREVIATIONS

Precipitation (P) is the water that naturally falls on the basin.

Interception (I) is the precipitation that is trapped on impervious surfaces and evaporated.

Interception storage (Is) is the maximum amount of water that vegetation or impervious surfaces can store on their surfaces.

Actual evapotranspiration (AE) is the actual portion of precipitation returned to the air by direct evaporation and by transpiration of vegetation.

Soil Moisture (ST) is the amount of water stored in the root zone of the soil.

Change in soil moisture (DST) is the monthly change in soil moisture.

Overland flow from vegetated surfaces (OFV) is the overland flow that is derived from vegetated surfaces in the basin.

Overland flow from impervious surfaces (OFI) is the overland flow that is derived from the impervious surfaces in the basin.

Overland flow (OF) is the amount of precipitation that runs off the ground directly into the stream channels with no chance to infiltrate.

Groundwater storage (GWS) is the amount of water in the groundwater reservoir.

Change in groundwater storage (DGS) is the month to month change in groundwater storage.

Groundwater runoff (GR) is the amount of groundwater that leaves the basin and sustains stream flow.

Irrigation withdrawals (IR) is the amount of water removed from the stream or unconfined surface aquifer and used to water crops.

Additional precipitation (AP) is water that runs off the impervious surfaces and onto vegetated surfaces where it infiltrates.

Effective precipitation (EP) is the amount of precipitation that has been able to infiltrate into the ground.

Potential Evapotranspiration (PE) is the amount of evapotranspiration that can occur if there is no shortage of precipitation.

Accumulated water loss (Acc Wl) is the monthly soil moisture loss that is totaled from month to month.

Surplus (S) is the excess water that leaves the soil by gravitational drainage when the soil is at field capacity.

Detained water (DET) is the amount of water that is held over from one month to the next.

Irrigation (IR) is the amount of water used to irrigate, computed from actual water rights in the basin.

Available for runoff (AR) is the amount of water that can leave the basin in any one month.

Total runoff (TRO) is the total amount of water that leaves the basin as overland flow and groundwater runoff.

REFERENCES

Alley, W.M., On the treatment of evapotranspiration, soil moisture accounting, and aquifer recharge in monthly water balance models, Water Resour. Res., 20(8), 1137-1149, 1984.

Anderson, E.R., Energy budget studies, U.S. Geol. Surv. Prof. Pap., 269, 1954.

Armstrong, J.E., Post-Vashon Wisconsin glaciation, Fraser lowland, British Columbia, Canadian Geol. Surv., Bull., 322, 1981.

Creahan, K., Water table elevation and groundwater flow in an unconfined aquifer in northern Whatcom county, Washington, Masters thesis, 55 pp., Western Wash. Univ., Bellingham, 1988.

Dagg, M. and Blackie, J.R., Estimates of evaporation in east Africa in relation to climatological classification, Geogr. J., 136, 227-234, 1970.

Dunne, T., and L.B. Leopold, Water in Environmental Planning, W.H. Freeman and Co., New York, 1978.

Easterbrook, D.J., Geologic Map of Western Whatcom County, Washington, U.S. Geol. Surv. Map, LI-854-B, 1:62500, 1976.

Freund, J.E., Modern Elementary Statistics, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1981.

Helvey, J.D., and J.H. Patric, Canopy and litter interception of rainfall by hardwoods of eastern United States, Water Resour. Res., 1, 193-206, 1965.

Lull, H.W., Handbook of Applied Hydrology, McGraw-Hill, New York, 1964.

Mather, J.R., Estimation of areal average precipitation using different network densities and averaging techniques, Publications in Climatology, 28(2) 1-99, 1975.

Mather, J.R., Use of the climatic water budget, Publications in Climatology, 32(1), 1-60, 1979.

Mather, J.R., Using computed stream flow in watershed analysis, Water Resour. Bull., 17(3), 474-482, 1981.

McKay, D.C., and R.J. Morris, Publications Canadian Climate Program, Canadian Government Publishing Center, Ottawa, 1985.

Mockus, V., National Engineering Handbook, Hydrology Branch, U.S. Dept. of Agricul., Washington, D.C., 1972.

Muller, R.A., A water balance evaluation of the effects of urbanization on water yield in metropolitan northeast New Jersey, U.S. Dept. of the Interior, Washington, D.C., 1969.

Penman, H.L., Natural evaporation from open water, soils, and grass, Proceedings of the Royal Society of London, 193, 120-145, 1948.

Penman, H.L., 1961, Weather, plant and soil factors in hydrology, Weather, 16, 207-219, 1961.

Soroshian, S., U.K. Gupta, and J.L. Fulton, Evaluation of maximum likelihood parameter estimation techniques for conceptual rainfall runoff models: influence of calibration data variability and length on model credibility, Water Resour. Res., 19(1), 251-259, 1983.

Thomas, H.A., Improved methods for national water assessment, U.S. Water Resour. Council, Contract WR15249270, Washington, D.C., 1981.

Thornthwaite, C.W., An approach toward a rational classification of climate, Geogr. Rev., 38(1), 55-94, 1948.

Thornthwaite, C.W., and J.R. Mather, The water balance, Publications in Climatology, 8(1), 1-104, 1955.

Thornthwaite, C.W., and J.R. Mather, Instructions and tables for computing potential evapotranspiration and the water balance, Publications in Climatology, 10(3), 181-311, 1957.

Troutman, B.M., Errors and parameter estimation in precipitation-runoff modeling, Water Resour. Res., 21(8), 1195-1213, 1985.

Walker, M.G., Water resources of the Nooksack River basin and certain adjacent streams, Water Supply Bull., 12, 1-187, 1960.

APPENDIX A

Step-by-step computation of water balance

APPENDIX A

Worksheets for computation of water balances for 1952 through 1953 and 1987 through 1988 (Tables 9 and 10) contain monthly averages (weighted by land-use category) of precipitation (P), additional precipitation (AP), extra water from impervious surfaces (X), interception (I), potential evapotranspiration (PE), soil moisture (ST), overland flow off vegetated surfaces (OFV), and overland flow off impervious surfaces (OFI). The purpose of this appendix is to describe the step-by-step computational procedure for the water balance.

Total field-measured precipitation (P) is entered in the first row. In this study, I assumed that 50 percent of the precipitation that falls in the last three days of each month will be able to recharge the soil and groundwater in the next month. Row two contains these values of additional precipitation. For example, 20 mm of rain are recorded for the last three days of October 1952 (Table 9),and 10 mm of this amount is carried over to November. However, 2 mm of precipitation was carried over from the last three days of September, 1952, causing a net change in the precipitation (P) of [AP = 2 mm - 10 mm] = -8 mm (row 2, Table 9).

Of the precipitation that falls on the impervious surfaces, 70 percent runs off onto nearby vegetated surfaces and subsequently infiltrates. This extra water (X) is entered into row three. Row four contains the monthly interception values. Amounts of overland flow off the vegetated surfaces (OFV) and overland flow off the impervious surfaces (OFI) are entered in rows five and six, respectivly. Effective precipitation (EP) is the total amount of precipitation that infiltrates. EP (row seven) is calculated by the following equation.

$$EP = P + AP + X - I - OFV - OFI \qquad (3)$$

Potential evapotranspiration (PE) in row eight was calculated by the Penman (1948) method. Penman (1948) used an energy-balance approach to calculate potential evapotranspiration (PE). In general the energy-balance for a vegetated surface (Dunne and Leopold, 1978) can be written as:

$$Qn = Qs - Qrs - Qlw + Qv - Qet - Qh - Qc \qquad (4)$$

Where:

Qn = net all-wave radiation input to vegetated surface.

Qs = incoming solar radiation.

Qrs = aQs = reflected solar radiation.

a = albedo (reflectivity of the vegetative cover).

Qlw = net longwave radiation from the vegetative surface to the atmosphere.

Qv = net energy advected to vegetation.

Qet = energy used for evapotranspiration.

Qh = energy transferred from vegetation to air as sensible heat.

Qc = changes of energy stored in heating soil and vegetation.

(All the above energy units are expressed in calories per square centimeter of ground surface).

Advected energy (Qv) is small in areas of uniform vegetation and can be eliminated (Dunne and Leopold, 1978). Changes of energy stored in the plants and soil (Qc) are very small for periods of a day or longer (Penman, 1961) and can be ignored. With these modifications, the equation simplifies to:

$$Qn = Qs - Qrs - Qlw - Qet - Qh \qquad (5)$$

Net longwave radiation (Qlw) is calculated using the Brunt Equation (Equation 6) (Anderson, 1954).

$$Qlw = z \times T^4 \times [0.56 - (0.08 \times e^{0.5})] \times (1 - ac) \qquad (6)$$

Where:

z = the Stefan-Boltzmann constant (1.17×10^{-7} cal/cm^2/$^oK^4$/day).

T = air temperature at the 2-meter level (^oK).

e = vapor pressure of the air at the 2-meter level (mb).

a = a constant depending on the cloud type: 0.25, 0.60, and 0.90 for high, medium, and low clouds, respectively.

c = cloudiness (decimal fraction of the sky covered).

Average monthly values of incoming solar radiation (Qs), for the weather station located at Abbotsford Airport (Figure 2), were calculated by McKay and Morris (1985). Using these values, net all-wave radiation (Qn) was calculated as shown below (Dunne and Leopold, 1978):

$$Qn = Qs \times (1 - a) - Qlw \qquad (7)$$

Dividing Qn by the weight density of water (p = 1 gram / cm^3) multiplied by the latent heat of vaporization of water (L = 590 cal / gram), the energy components are expressed as equivalent depths of evaporation (H) (Equation 8):

$$H = Qn / (p \times L) \qquad (8)$$

The contribution of mass-transfer to evapotranspiration (Ea) (Penman, 1961) was determined using Equation 9 below.

$$Ea = [0.013 + (0.00016 \times u_2)] \times (V_s - V_a) \qquad (9)$$

Where Ea is expressed in units of cm/day.

u_2 = windspeed (km/day).

V_s = saturation vapor pressure (mb) of a water surface at air temperature.

V_a = Atmospheric vapor pressure (mb).

Daily potential evapotranspiration (PE) is then calculated using Equation 10 (Dunne and Leopold, 1978).

$$PE = [(D/Y \times H) + Ea] / (D/Y + 1) \qquad (10)$$

Where:

D = is the slope of the curve relating saturation vapor pressure to temperature (mb / $^{\circ}C$) (Dunne and Leopold, 1978).

Y = psychometric constant (0.66 mb / $^{\circ}C$) (Dunne and Leopold, 1978).

The difference between effective precipitation (EP) and potential evapotranspiration (PE) is calculated in row nine. When PE is greater than EP there is not enough water for evapotranspiration to proceed at the potential rate and the plants are forced to use water that is stored in the soil. This monthly loss from soil storage due to plant transpiration is accumulated (row ten) until EP is greater than PE.

Soil moisture (ST) and the change in ST over time (DST) are both functions of precipitation, actual evapotranspiration, soil properties and surface vegetation. Thornthwaite and Mather (1955; 1957) discuss mechanisms of soil moisture variation and provide tables and graphs to determine actual soil moisture content based on the field capacity of the soil and the amount of water the soil has lost. The analytical solution (Alley, 1984) for soil moisture, on which the tables and graphs are formulated, is employed here:

When P_i is less than PE_i for the i^{th} month

$$ST_i = ST_{i-1} \exp[- (PE_i - P_i) / FC] \qquad (11)$$

Where:

P_i = precipitation

PE_i = potential evapotranspiration

ST_i = soil moisture

FC_i = soil moisture field capacity

Using Equation 11 and data from Table 16, soil moisture for July 1952 (for example) was calculated as follows:

$$ST_{July = 16\ (mm)} = 47 \times \exp[- (125 - 23) / 92] \qquad (12)$$

Using the appropriate accumulated water loss and field capacities, the same procedure was applied to August and September to calculate moisture contents of 7 and 5 mm (row eleven). In October, effective precipitation was greater than potential evapotranspiration by 16 mm (row nine). This water is assumed to have been stored in the soil and raised the soil moisture content from 5 mm in September to 21 mm in October (row eleven). Again in November EP was greater than PE, and 34 mm of additional water was added to the soil storage, raising it to 55 mm. In December, 135 mm of moisture was available to recharge the soil which, brought it up to field capacity at 85 mm. The soil moisture remained at field capacity (soil moisture at field capacity (FC) varies from month to month due to rooting depth changes) until May 1953 when EP was less than PE by 58 mm causing soil moisture to reduce to 46 mm.

Change in soil moisture (DST) was the actual change in storage from one month to the next, either positive or negative (row twelve).

When EP exceeds PE, the actual evapotranspiration (AE) in row thirteen equals the potential rate because rainwater was considered to be easily available to the plant. This was the case even if the soil moisture of the whole root zone was not raised to the available water capacity (Dunne and Leopold, 1978). When the evapotranspiration demand must be partially satisfied from the stored soil water, however, AE was the sum of EP and the amount of soil moisture withdrawn from storage, e.g. 54 mm (22 + 32) in the case of July (row thirteen).

When the soil reaches field capacity and there is excess effective precipitation, the excess that leaves the soil by gravitational drainage is called moisture surplus (S). Moisture surplus (row fourteen) can only occur in months where EP is greater than AE. When this occurred:

$$S_i = (P_i - PE_i) + ST_{i-1} - FC_i \qquad (13)$$

otherwise S = 0

The moisture surplus drains to the groundwater and eventually to streams. Row fifteen contains values of water withdrawn from the water table for irrigation.

The sum of the moisture surplus from each month plus the amount that was detained (DET) from the previous month (row seventeen) minus the water used for irrigation (row fifteen) equals the water that was available for runoff (AR) in any one month (row sixteen).

A major problem in computing a water balance for a small basin is determining what fraction (L) of the AR remains as groundwater storage (Alley, 1984; Mather, 1979, 1981). Thus groundwater runoff for each month (indicated by subindex "i") is (row eighteen):

$$GR_i = (1 - L)(DET_{i-1} + S_i) \qquad (14)$$

The portion that remains (L) varies with the depth and texture of the soil and the physiography of the basin (Dunne and Leopold, 1978).

Thornthwaite and Mather (1955) originally suggested L = 0.50. For small basins in New Jersey, Mather (1975, 1981) suggests L values ranging from 0.80 to 0.70. Alley (1984) showed a strong negative correlation between the DUR (ratio of the stream flow equaled or exceeded 10% of the time to the stream flow equaled or exceeded 90% of the time) of a stream and the L parameter. For this study, an L value of 0.67 was determined by comparing the DUR of Fishtrap Creek to the DUR and L values obtained by Alley (1984).

Row nineteen contains the monthly values of total overland flow calculated by adding rows five (OFV) and six (OFI). Total runoff (TRO) in row twenty was the sum of groundwater runoff (row eighteen and overland flow (row nineteen). Measured runoff (MRO; row twenty) is the measured value of runoff from independently-collected stream gaging station data (see text).

APPENDIX B

Assessment of error in water-balance components

APPENDIX B

Quantitative information on the input and output variables of a basin's water balance are needed to construct a water-balance model. Unfortunately, independent measurements for many of these variables commonly are not available, and one has to resort to using empirical estimates, which can be subject to large errors. The degree to which errors affect the accuracy of a water balance depends on the variable involved. For instance, a 20 percent error in the monthly estimate of interception would have little affect on water-balance results, while the same error in precipitation estimates could make a major difference. For a more complete explanation of different methods for statistically evaluating the errors involved in parameter estimations for water-balance models see Troutman (1985) and Sorooshian, Gupta, and Fulton (1983). Ideally, the error for each variable should be estimated independently. The dependent variable is then calculated using the water-balance equation. Thus, the certainty of the monthly discharge could be obtained from a propagation of these errors. For this study, the certainty of monthly discharge values was not determined, using the propagation of errors method, because no sound basis for estimating errors of many of the variables could be determined. However, I could estimate error for some of the variables.

Where possible, I calculated standard error (SE) for the variables (Freund, 1981).

$$SE = S / n^{0.5} \qquad (13)$$

Where S is the standard deviation of the sample and n is the sample size.

Precipitation

The accuracy of estimating precipitation for a defined area from measurements at gages in a network depends on both the position of the gages relative to each other and the number of the gages used (Mockus, 1972). In mountainous areas, the vertical distance to the gage is also important but for the low-relief Fishtrap basin only the horizontal distance is significant.

I estimated standard error for each storm event in the Fishtrap basin for the time periods 1952 - 1953 and 1987 - 1988 by the nomogram method of Mockus (1972), which utilizes basin size, number of gaging stations, storm precipitation amount, and annual precipitation (Figure 11). The method assumes that the precipitation stations are evenly distributed in or near the basin. In the Fishtrap basin this assumption is valid because the two stations are located near the north end of the basin (Abbotsford Airport, B.C.) and near the south end of the basin (Clearbrook, WA)(Figure 1).

I calculated average monthly standard error in precipitation estimations for 1952 - 1953 and 1987 - 1988 by compiling the standard error for the individual storm events in each month (Table 14).

Interception

Interception errors are difficult to evaluate because interception estimates were not determined from large data sets amenable to statistical analysis. The only exception is corn which has a calculated standard error of ten percent (Lull, 1964).

Potential evapotranspiration

The Penman (1948) method of calculating potential evapotranspiration was chosen for this study because the method gives the best results when compared to other available climatic methods (Dagg and Blackie, 1970;

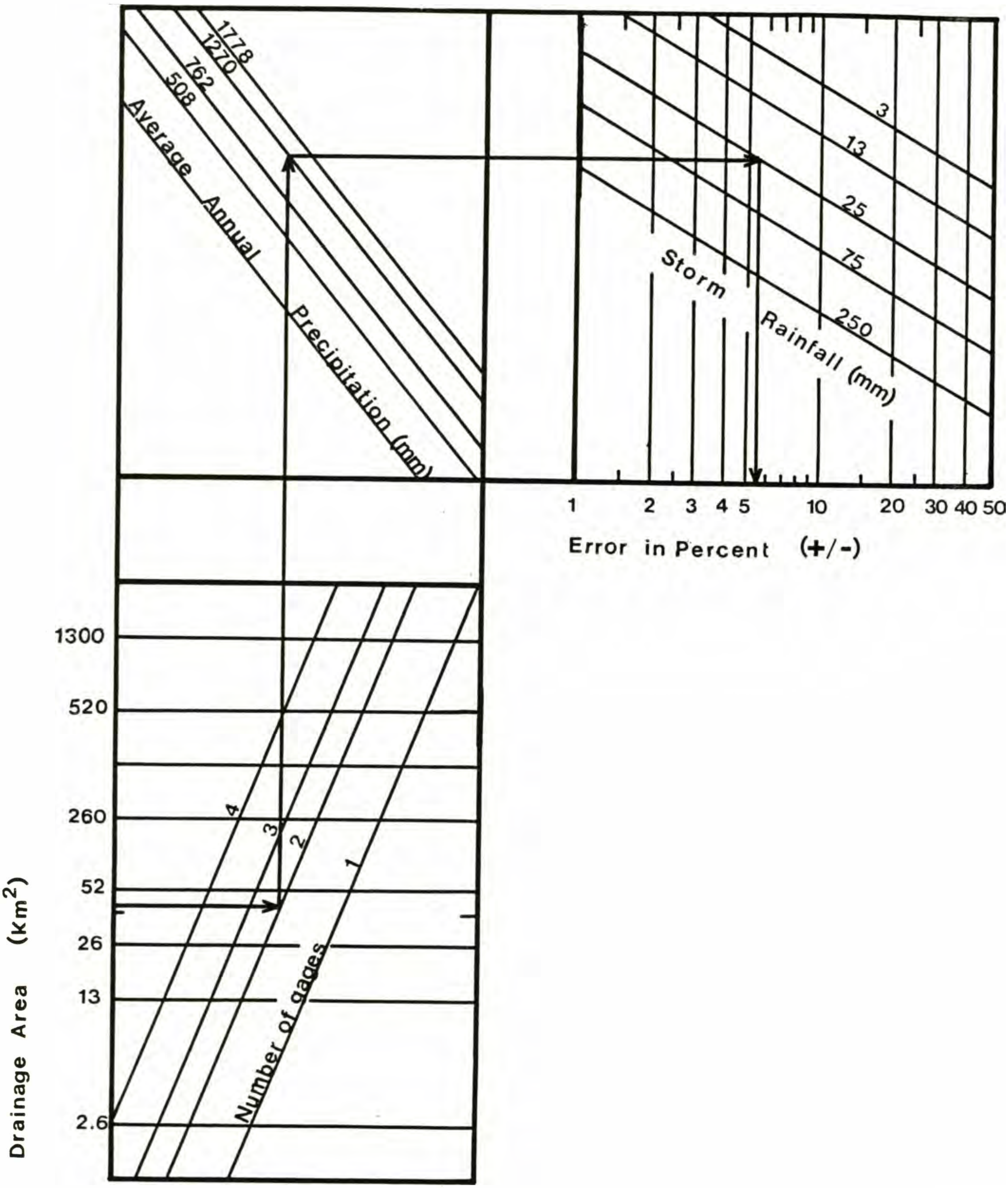


Figure 11. An abbreviated nomogram for estimating the error in watershed average rainfall amounts. The example is for a 25 mm storm event falling in the 42 sq. km Fishtrap Creek basin (average annual precipitation = 1270 mm), in which there are two precipitation gages. For complete nomogram, see Mockus, 1972.

Table 14. Monthly precipitation errors and average monthly error for the Fishtrap Creek basin.

	Precip *	Error +	Precip *	Error +
	1952 - 1953		1987 - 1988	
June	81	23	24	25
July	23	8	49	10
August	27	6	15	10
September	42	15	29	17
October	52	9	17	16
November	27	16	86	6
December	168	9	168	13
January	373	5	94	15
February	106	17	93	4
March	119	14	133	5
April	91	25	140	16
May	56	7	150	9
Avg. Monthly error		13		12

* Precipitation (mm).
\+ Average error in percent.

Dunne and Leopold, 1978). Using the Penman method, errors in calculated evapotranspiration generally range from 10 to 20 percent of monthly values (Dunne and Leopold, 1978).

Soil moisture at field capacity

Soil moisture at field capacity (ST) is the product of average rooting depth and average available water capacity (Equation 2). Standard error about the mean (Equation 13) for average rooting depths was 2.7 percent for lawn grass, 5.7 percent for pasture, and 2.5 percent for crops.

Overland flow from vegetated surfaces

Overland flow estimates, based on the Soil Conservation Service method (Mockus, 1972), are derived from precipitation estimates and the appropriate runoff curve number. Because the technique for selecting a curve number is empirical, the inherent error in the overland flow calculations cannot be calculated.

Irrigation withdrawals

Monthly withdrawals of water for irrigation from the unconfined surface aquifer were estimated from the water rights allocated by the Washington State Department of Ecology. An evaluation of the error involved in this variable is not possible.

Miscellaneous variables

Not estimated for this study because of insufficient data were illegal stream and surface aquifer withdrawals and tiling of fields to improve drainage. If either or both of these processes were going on in the basin, they could have affected the correlation between measured and calculated stream discharge values.

Measured stream discharge

Stream gaging is subject to certain errors of measurement especially when sediment or other objects change the shape of the calibrated discharge area (Mather, 1981). United States Geological Survey (USGS) records are usually considered accurate within 10 to 15 percent (Mather, 1981). My stream gaging technique is similar to that of the USGS (Appendix C) and is subject to the same errors.

Overall error

The difficulty in determining confidence intervals for many of the water-balance variables makes it impossible to determine statistically the overall reliability of the water-balance calculations. An alternative method of examining the accuracy of the calculations is discussed in Discussion and Conclusion.

APPENDIX C

1987 - 1988 stream discharge data

APPENDIX C

The monthly stream discharge values used to check the calculated water-balance values for June 1987 - May 1988 were calculated from a rating curve (gage height versus stream discharge) (Figure 12) that was constructed for Fishtrap Creek by the following procedure.

A staff gage was established near the previous USGS stream gage on Fishtrap Creek (Figure 2) in May 1987. The stream discharge was measured at various water heights on the staff gage until a reliable stream discharge versus gage height curve could be constructed (Figure 12). A Stevens type F water-level recorder was installed in June 1987 to record a complete gage height versus time spectrum. Average daily gage heights were used to calculate daily stream discharges, which were then compiled for monthly and yearly totals (Table 15). The stream channel was gaged approximately every two weeks from July 1987 through May 1988 to check the accuracy of the rating curve.

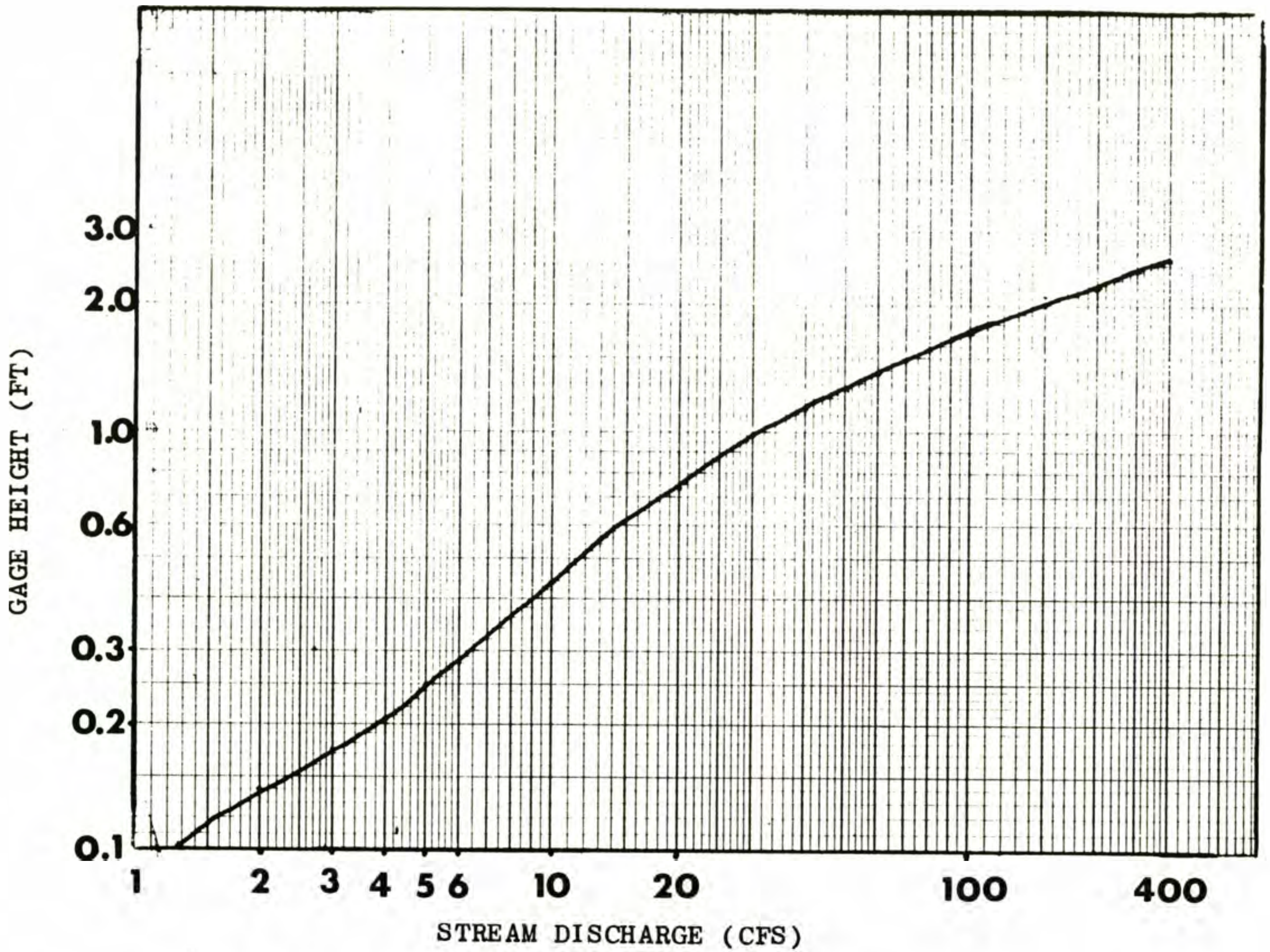


Figure 12. Rating curve for Fishtrap Creek, 1987 - 1988.

Table 15. Stream discharge data, 1987 - 1988.

	cfs *	mm +
June	520	34
July	233	15
August	88	6
Sepember	54	4
October	55	4
November	172	11
December	748	49
January	915	59
February	1005	65
March	1069	69
April	1361	88
May	1095	71

* Cubic feet per second.
+ Millimeters of water over the basin.