FINAL REPORT

ALTERATIONS IN THE HYDROLOGIC CYCLE INDUCED BY URBANIZATION IN NORTHERN NEW CASTLE COUNTY, DELAWARE: MAGNITUDES AND PROJECTIONS

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by

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Project Objectives

The project sought to identify, for three watersheds in northern New Castle County, the magnitude and hydrologic consequences of alterations in surface runoff and streamflow characteristics brought about by urbanization. Inferrably, the impervious and less pervious land surface created by urban development increases the overland or surface runoff to streams and rivers. The increase in surface runoff is necessarily accompanied by a decrease in the amount of water that enters the soil. This decrease in infiltration means that less water is available for the sum of evaporation and percolation to the ground water table. Depending on the seasonal occurrence of precipitation, either or both of ground water flow and evaporation may be decreased, though of course a good deal of the runoff from impervious surfaces may run onto lawns and gardens so that some of it does in fact infiltrate. The objective of the project was to model the effects of urbanization on the components of the hydrologic cycle mentioned.
Specific objectives were to:

1) Determine, for three watersheds, land surface distribution among a) impervious surface, b) surface significantly altered during urban construction, c) agricultural land, and d) land in woods or forest; for 1954, 1962, and 1968, from aerial photographs available for those dates.

2) Measure the precipitation and runoff from selected small urban watersheds, and from less disturbed watersheds, by use of weirs constructed downstream from the watersheds.

3) Model the amount of runoff as a function of the relative amounts of a) land surface as determined in 1), and b) the accompanying surface infiltration and soil moisture storage capacities.

4) Determine by use of water budgeting techniques and long term temperature and precipitation records for land use as in 1954 (assuming no further urbanization) the long term partitioning among a) surface runoff; b) interception, soil storage, and subsequent evaporation; and c) percolation to the ground water table

(ultimately to base flow).

5) Determine, by use of water budgeting techniques for increasingly urbanized watersheds, the long term changes by partitioning of precipitation among the components of the hydrologic cycle as for 4).

6) Determine, by comparing the results of 4) and 5) for three watersheds, the incremental effects of incremental increases in urbanized surfaces on the partitioning of precipitation among the components of the hydrologic cycle as for 4) and 5).

Extent of Achievement of Project Objectives and Summary of Research Procedures Used

Project objectives were achieved as follows:

1) Determination of land surface distribution on three watersheds (Shellpot, Christina, White Clay Creek between the Creek's two gaging stations)for 1954, 1962, and 1968. Land surface analysis was entirely completed for all three years for Shellpot Creek watershed (north of Wilmington), the smallest (7.46 sq. mi.), most urbanized of the three watersheds. Large scale (1 in. = 400 ft.) aerial photographs, and field checks, were used. Images of buildings, roads and parking lots were individually scaled, while areas of given soil types (transferred from the Soil Survey of New Castle County), forest, and field were determined by use of a dot grid overlying the photographs. Separate determinations of a number of the areas by a student worker and the principal investigator varied by no more than three percent for any area.

Land surface analysis was nearly completed for all three years for the Christina River watershed (20.5 sq. mi.). The land surface distribution and soil types were determined quantitatively from small scale (1 in. = 20,000 ft.) aerial photos by scaling road length and determining other land areas by use of a dot grid overlying the photos. Houses and other buildings were individually counted and their individual or average sizes determined by field measurement. It was intended to determine surface distribution in developed areas from large scale photos as was done for Shellpot Creek watershed, but this was never accomplished. Areas developed in 1968 but not developed in 1962 or 1954 were recorded on separate transparent overlays, but this information has not been reduced to numerical form because of insufficient funds and time.

Land surface analysis was completed for 1954 for the watershed of White Clay Creek (21.1 sq. mi., north of Newark) between the creek's two gaging stations, as for the Christina watershed, but cutting of budget requests in the project's second year required abandonment of that analysis for 1962 and 1954.

A land surface analysis like that for Shellpot using large scale (1 in. = 200 ft.) aerial photos was done for the urbanized watershed (Fairfield Crest in north Newark, 55 acres) for which surface runoff was measured with a weir. Additionally, field determination of the impervious surface which fed runoff directly into gutters and storm sewers, as opposed to that which fed runoff into lawns or gardens, was carried out for this watershed.

2) <u>Measurement of precipitation and of runoff for selected small watersheds</u>. This was accomplished for two watersheds, one urbanized and one forested. Weirs (asphalt coated plywood, with trapezoidal, sharp crested openings placed across existing runoff channels and with float gages in stilling wells to measure runoff head) were constructed on channels for each of five small watersheds. Two of these weirs were shortly destroyed by vandalism. A third, placed downstream from a construction site, was buried in sediment after two rain storms. One, placed in a stream draining an urbanized watershed (Fairfield Crest, Newark) of 55 acres, was enclosed with chainlink fence after several instances of vandalism, and provided reliable data. The fifth, draining a forested area of 12 acres, was sufficiently hidden to escape vandalism. It also provided good data. The two usable weirs were calibrated at low and medium flows by use of a box and stopwatch. Volume per cubic second at a number of float

gage heights was determined. These measured values were then statistically fitted to values obtained for rectangular and triangular weir openings taken separately, from formulas in King and Wisler (1922), with constants as determined by King and Hertzler (Reinhart and Pierce, 1964). The correlation coefficient between the predicted and measured values was then .999 with negligible standard error. For high flows from the urbanized watershed (up to 1.0 cu m/sec) three attempts were made to measure flow in a trapezoidal flume constructed downstream from the weir's stilling well, by use of a pygmy current meter. Each of the three times, the flume was washed out and floated during heavy runoff so that measurements could not be obtained. As a consequence, it proved necessary to use the curve fitted to the low and medium flow measurements for estimating large flows as well.

During 47 storm periods (and a number of high precipitation probability periods in which no rain fell); lasting for from several hours up to six consecutive days, manual observations of weir head were taken and recorded at intervals varying from two to thirty minutes, depending on the rapidity of change in head. During some storms clogging of the stilling well with sediment, and on three occasions sticking of the float gage because of snow and ice, prevented reliable head readings, so that data from only 33 storms proved usable. Data were punched on cards and a program was written for calculating total streamflow during and immediately after the storm period--until the stream had returned to pre-storm base flow or until storm sewers feeding into the stream were no longer carrying water.

Five precipitation gaging sites were established around the urbanized watershed, and one near the wooded watershed. It proved impossible to prevent theft except at two sites near the weirs (seven of the ten gages were ultimately stolen) so that precipitation readings were obtained at only these two sites. Readings for the two never varied for whole storm periods by more than .02 inches.

3) <u>Modelling the amount of runoff as a function of the relative</u>

amounts of land surface with specified hydrologic characteristics. A model of surface runoff as a function of the fractions of land possessing varying infiltration characteristics was successfully developed. The correlation coefficient between the runoff predicted by the model and measured runoff from the 55 acre watershed used to develop and test the model was .996, indicating that the model accounted for 99 percent of the variation in runoff, as compared to 93 percent for precipitation alone. The standard error was .06 in. Even omitting the five storms for which runoff was a half inch or more and which, since their relative weighting would be so great as compared to all other observations (most runoff values less than .20 in), would have disproportionate weight in the regression, r and s were .98 and .06 respectively for the model estimate, .96 and .02 for precipitation alone.

Corresponding values for the forested watershed were not determined because runoff greater than .01 inch occurred during only three of the 33 storms. During one of the three (Hurricane Agnes, in June 1972) the weir was leaking (modelled runoff was 1.25 of the 6.24 inches of precipitation). For the other two storms, runoff occurred because of the construction of a parking lot at the top of the watershed (the model predicted no runoff).

The model of runoff from impervious surface was developed from observations made during the course of the project. It was noted during several of the storm observation periods that water began to flow in gutters and storm sewers after precipitation had accumulated to .03 inches during winter (Oct. - March) and in summer during cloudy weather. Runoff began after .08 inches of precipitation during sunny summer weather. These were taken as the amounts of precipitation used in initial wetting of impervious surfaces. Precipitation in excess of these values was modelled as running off from that portion of impervious surface which drained directly into gutters and storm sewers. For impervious surfaces which drained onto lawns and gardens, precipitation in excess of initial wetting requirements was modelled as increasing the effective precipitation on the lawn and garden areas.

For the lawn and garden areas, as well as for fields and woods in the other watersheds studied, surface runoff was estimated by using the Soil Conservation Service (SCS) method for estimating storm runoff for flood control and evaluation purposes (Soil Conservation Service, 1964). The SCS method estimates runoff by

$$R = \frac{(P - .2Z)^2}{P + .8Z} \qquad (1$$

where R is surface runoff and P is daily precipitation. Z is defined by

$$Z = \frac{100 - 10C}{C} \qquad (2$$

where C expresses the combined effects on infiltration of temperature, soil moisture content, soil permeability, and soil infiltration capacity as affected by land use or cover. C may vary from 0 to 100 as the surface of interest varies from perfectly pervious to perfectly impervious. As C increases, therefore, Z decreases, and R increases. After a period of dry weather it takes 1.10 inches of rain in a day before any surface runoff occurs, even from the heavy soils typical of urban areas.

For the Fairfield Crest watershed, a value of C corresponding to the SCS value for meadow in good condition, with heavy soils, was chosen. This value was selected because of the high quality of lawns in the development, and the common observation that soil profiles and structure are severely disrupted during construction.

The runoff from impervious surfaces which drained onto lawns and gardens rather than directly to gutters and storm sewers was assumed to be spread evenly over the lawn and garden area and this amount was added to the measured precipitation value in determining surface runoff by equation (1. The estimated volume of runoff from the two types of surface, impervious and pervious, was divided by the watershed area in order to obtain an average estimated runoff figure. Similarly, the measured runoff volume was divided by watershed area to obtain an average measured runoff figure. The precipitation, and estimated and measured runoff, are tabulated in Table 1 for the urbanized watershed, Fairfield Crest.

4) Determination by use of water budgeting techniques and long term temperature and precipitation records, the long term partitioning of precipitation among the components of the hydrologic cycle, assuming no additional urbanization after 1954. The effects of urbanization on the partitioning of precipitation among the components of the hydrologic cycle - surface runoff, evapotranspiration, and percolation to ground water and base flow - was examined by use of a water budget incorporating the model of surface runoff developed as discussed in 3). In form, the budget used is like that of Thornthwaite and Mather (1955). It incorporates an estimate of moisture demand, or potential for evapotranspiration (defined by the energy available) as the upper limit on evapotranspiration for a given period. Precipitation in excess of the period demand is entered into a soil moisture storage account, or, if that account is full (the soil is at field capacity), into a surplus account, which is percolate to ground water and base flow. If period precipitation is less than potential evapotranspiration, moisture is withdrawn from the soil moisture storage account to the limits of that account.

For this study, a cumulative daily budget was run for 1950 through 1968. Estimated surface runoff was subtracted from precipitation before allocation to evapotranspiration and soil moisture storage. Potential evapotranspiration (PE) was estimated by Thornthwaite's (1948) method from monthly temperature data. An annual curve of estimated daily PE was derived from the mid-month daily values (the average daily value for each month) and the daily PE values used for field and forest areas was taken from that curve. Soil hydrologic type (based

Table 1. Precipitation and estimated and measured runoff from the 55.2 acre urbanized watershed of Fairfield Crest, for 33 storm periods

Starting Time				Ending Time				Inches		
Year	Month	Day	Time	Year	Month	Day	Time	Precip.	Estimated runoff	Measured runoff
71	10	9	2100	71	10	13	1200	3.75	1.53	1.82
71	10	23	2312	71	10	26	2400	1.73	.36	.33
71	11	19	1645	71	11	19	1835	.04	.00	.00
71	11	29	0805	71	12	1	2400	1.30	.48	.44
71	12	6	1325	71	12	9	1200	.94	.14	.15
72	1	4	0855	72	1	4	1900	.12	.02	.02
72	1	4	2035	72	1	5	0805	.36	.05	.05
72	3	22	0300	72	3	22	1800	.63	.09	.07
72	5	2	1610	72	5	5	2400	.66	.10	.09
72	5	8	2020	72	5	11	2400	1.22	.19	.17
72	5	30	2400	72	5	31	1400	.31	.04	.04
72	5	31	0030	72	6	01	1040	.40	.06	.05
72	6	13	0730	72	6	14	1730	.72	.11	.07
72	6	16	1540	72	6	17	2014	.12	.01	.02
72	6	17	2014	72	6	20	1957	.45	.07	.05
72	6	21	0100	72	6	27	2400	6.24	3.09	3.10
72	6	29	0630	72	7	1	2400	.87	.13	.11
72	7	5	0300	72	7	8	1200	.36	.05	.06
72	7	8	1500	72	7	8	1854	.06	.00	.00
72	7	13	0100	72	7	16	0400	1.13	.18	.17
72	7	16	0900	72	7	17	2400	.18	.02	.02
72	8	27	2120	72	8	28	1000	.69	.10	.05
72	9	9	849	72	9	9	1047	.04	.00	.00
72	9	12	1103	72	9	12	1420	.06	.00	.00
72	9	13	0930	72	9	13	1300	.03	.00	.00
72	9	14	1600	72	9	15	2400	.92	.14	.15
72	9	18	1858	72	9	18	2031	.03	.00	.00
72	9	25	1630	72	9	25	2145	.18	.02	.01
72	10	5	1355	72	10	5	2315	.35	.05	.03
72	10	6	1505	72	10	9	1700	1.48	.22	.20
72	10	28	710	72	10	31	847	1.09	.17	.16
72	11	8	307	72	11	13	1745	2.65	.81	.74
72	11	14	100	72	11	16	1910	2.82	.90	1.07

on permeability) for field and forest areas was taken from the National Engineering Handbook listing (Soil Conservation Service, 1964). For urban lots, the least permeable classification was assumed. Soil moisture storage capacity values were taken from the Soil Survey of New Castle County, Delaware (Matthews and Lavoie, 1970) for field and forest areas. A value of two inches was used for urban lots on the basis of the average value (1.93 in.) for ten 20 inch soil cores taken in the Fairfield Crest watershed area.

Soil moisture storage was divided into four accounts corresponding to the wetting fronts of the four most recent rains. PE not satisfied from the surface account was assumed to withdraw moisture from the second account, that still not satisfied to withdraw from the third account, and similarly for the fourth account. For each account, soil moisture extraction (actual evapotranspiration, or AE) as a fraction of PE (demand) was assumed to decline in proportion to the soil moisture available, so that if soil moisture storage were one-fourth the maximum value, for example, AE would be one-fourth the PE.

The budget was applied to Shellpot Creek Watershed using the precipitation records from Porter Reservoir, which lies on the southwest edge of the watershed. Areas in the various land surface classifications in 1954 were used to evaluate long term partitioning as if additional urbanization had not occurred after 1954. Budgets were run separately for the ten different combinations of land surface type, soil hydrologic type, and soil moisture storage capacity. An average value weighted by the fraction of area in each combination was then determined.

5) Determination, by use of water budgeting techniques, the long term changes in partitioning of precipitation among the components of the hydrologic cycle. The water budget of 4) was applied to Shellpot Creek watershed in the same way as for 4) except that areas in the various land surface classifications in 1954, 1962, and 1968 were assumed to change

continuously in the intervening years. The areas in impervious surface and urban lots thus increased continuously during this time, while area in agricultural fields decreased continuously. Forest area increased in some parts of the watershed and decreased where urbanization occurred. The areas of the watershed in each land surface type in the three years are given in Table 2. From 1954 to 1968 impervious surface almost doubled, surfaces disturbed during construction more than doubled--though field and forest still comprised 59 percent of the total area in 1968.

Table 2. Land area in various hydrologic surface types in Shellpot Creek Watershed for 1954, 1962, 1968

Year	Area of Hydrologic Surface Type, Acres			
	Impervious	Building Lots	Fields	Forest
1954	498	380	2116	1485
1962	824	711	1864	1020
1968	983	857	1694	945
Percent Change 1954-1968	+97	+125	-20	-36

In Table 3 are indicated the effects of the changes in surface area shown in Table 2, as determined by application of the model of surface runoff to Shellpot Watershed. Modelled surface runoff, assuming continuously changing surface hydrologic characteristics, is compared with modelled surface runoff assuming 1954 surface hydrologic characteristics. The approximate doubling of urbanized surface area has, expectably, more than doubled the surface runoff in 1968 as compared to 1954 land surface characteristics.* The effect on percolate to ground water was

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*For 1954 land surface characteristics, modelled average surface runoff, percolate to ground water, and actual evapotranspiration were six, twelve, and twenty inches, respectively. Over impervious surfaces, average actual evaporation was limited to three inches so that surface runoff would increase by a factor of five - twelve inches of percolate and seventeen inches of actual

Table 3. Urbanization induced changes in components of the hydrologic cycle, as evaluated by a daily water budget incorporating an estimate of surface runoff, for Shellpot Creek Watershed, North Wilmington, Delaware, 1954-1968+

Year	Surface Runoff		Percolate to Ground Water		Total Runoff		Actual Evapotranspiration	
	1954 Land Use	Changing Land Use	1954 Land Use	Changing Land Use	1954 Land Use	Changing Land Use	1954 Land Use	Changing Land Use
1954	4.63	4.63	9.11	9.11	13.73	13.73	20.86	20.86
1955	7.79	8.07	8.18	8.12	15.98	16.19	23.09	22.83
1956	6.06	6.77	9.74	9.55	15.80	16.31	22.80	22.34
1957	5.26	6.03	13.34	12.98	18.60	19.00	18.24	17.57
1958	8.42	10.41	21.47	20.66	28.89	31.08	22.87	21.90
1959	6.40	8.11	11.06	10.59	17.46	18.70	24.32	22.87
1960	8.60	11.25	15.25	14.39	23.84	25.64	23.82	22.25
1961	5.82	8.59	15.86	14.80	21.68	23.39	24.20	22.37
1962	4.85	7.53	13.88	12.72	18.73	20.25	21.75	19.69
1963	4.35	7.09	8.55	8.22	12.90	15.31	21.53	19.42
1964	5.45	8.46	15.15	13.80	20.61	22.26	18.28	16.04
1965	4.90	8.25	9.58	9.09	14.47	17.33	22.26	19.83
1966	4.98	8.25	9.50	8.36	14.48	17.11	18.07	15.66
1967	10.95	16.57	20.64	17.98	31.59	34.55	22.15	19.50
1968	5.02	8.68	14.59	12.61	19.61	21.30	20.11	17.12
Totals	93.48	128.69	195.90	183.48	289.37	312.15	324.35	300.25
Cumulative Difference	+35.21		-12.42		+22.78*		-24.10*	

+Vegetated surfaces were assumed to have the hydrologic surfaces of meadow in poor condition (for fields and building lots) and woods in fair condition, giving a value of 20 and 28 for C in equation 2, p. 6, as compared to a value of 21 for building lots in the Fairfield Crest, Newark watershed, which had better maintained lawns.

*Differences in numerical values of total runoff and actual evapotranspiration occur because of differences in soil moisture storage on beginning and ending dates.

less marked. Of the 35 inch total increase in average watershed surface runoff for the 15 year period, only 12 inches came from percolate. This means that less than one inch per year was diverted from ground water recharge, while two inches per year were diverted from actual evapotranspiration.

In deriving Table 3 it was assumed that the energy diverted from use in actual evapotranspiration (AE) over impervious surfaces was not used for AE over vegetated surfaces. This assumption is unrealistic--it can be assumed that vegetated surfaces in urbanized areas are subject to the "oasis" effect just as oases in the desert are. Energy for added AE is transferred by air movement into the oasis so that evapotranspiration there exceeds that which would occur if the whole surrounding area were wet. In urbanized areas, the urban heat island is at least in part a result of the diversion of energy from AE to heating the ground and air. There is, however, little if any basis for assuming any given partitioning among the alternative energy sinks--increased evapotranspiration from vegetated areas, and heating of the ground and air. Inferrably (but not certainly, because increased convection would mask the amounts of energy used in heating the air as indicated by increased air temperature) the amount diverted to heating the air is small, since over vegetated, "wet" surfaces, energy used in heating the air is only 15-25 percent of that used in evapotranspiration. The limiting assumption is that essentially all the energy is ultimately diverted to increased <u>potential</u> for evapotranspiration over vegetated surfaces. This assumption is most acceptable in suburban areas such as the watershed of Shellpot Creek, where housing developments are interspersed among fields and wooded areas.

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evapotranspiration over vegetated surfaces would be added to the six inches of surface runoff when impervious surface was created.

Table 4 was prepared under the assumption that energy diverted from use for evapotranspiration over impervious surface, because of lack of available storage capacity, is entirely available as added potential evapotranspiration distributed uniformly over vegetated surfaces. Otherwise Table 4 is like Table 3. The reduction in percolate to ground water is greater, 18 as compared to 12 inches for the other limiting assumption (no increase in PE over vegetated surfaces), as in Table 3, for the fifteen year period. Correspondingly, the reduction in actual evapotranspiration is less, because of the assumed increase in potential evapotranspiration.

Under either of the above assumptions as to the disposition of the energy that cannot be used for evapotranspiration over impervious surfaces, the decrease in percolate to ground water is modest during the 15 year period. Even in 1968, the final year, after impervious surface had doubled, percolate had decreased by only two inches, or 14 percent.

To evaluate the ultimate effects of essentially residential development, it may be assumed that development is carried to its limit, so that ultimately no field or forest area will be left in the watershed. Under this assumption, 54 percent of the land area will be covered with impervious surface and the other 46 percent will be in building lot area, a vegetated surface with low infiltration and storage capacities. Given such a watershed surface, differences in surface runoff, percolate to ground water, and actual evapotranspiration for the 1954 surface and the completely developed surface are shown in Table 5 for 1954, 1962, and 1968, the years for which aerial photos permitted actual determination of surface cover.

From Table 5 it can be seen that complete residential development of Sheilpot Creek Watershed would result in a reduction of about 6.5 inches in percolate to ground water, or half of that which would occur with the 1954 watershed surface. Were the ground water tapped for water supply this would mean a loss of 175,000 gallons per acre per year, or enough to meet residential

Table 4. Urbanization induced changes in components of the hydrologic cycle as evaluated by a daily water budget incorporating an estimate of surface runoff and allocating the PE not used over impervious surfaces to use over vegetated surfaces, for Shellpot Creek Watershed, North Wilmington, Delaware, 1954-1968+

Year	Surface Runoff		Percolate to Ground Water		Total Runoff		Actual Evapotranspiration	
	1954 Land Use	Changing Land Use	1954 Land Use	Changing Land Use	1954 Land Use	Changing Land Use	1954 Land Use	Changing Land Use
1954	4.63	4.63	8.41	8.41	13.03	13.03	22.00	22.00
1955	7.79	8.07	7.19	7.12	14.98	15.18	24.36	24.15
1956	6.06	6.77	8.01	7.78	14.08	14.54	24.52	24.25
1957	5.26	6.03	12.02	11.45	17.28	17.47	19.04	18.49
1958	8.42	10.41	19.17	18.11	27.59	28.53	25.11	24.67
1959	6.40	8.11	10.21	9.31	16.62	17.42	25.85	24.67
1960	8.60	11.25	13.09	11.85	21.69	23.10	25.59	24.55
1961	5.82	8.59	14.60	12.94	20.42	21.53	25.99	24.75
1962	4.85	7.53	12.25	10.65	17.09	18.18	22.69	20.86
1963	4.35	7.09	7.80	7.21	12.14	14.30	22.60	20.92
1964	5.45	8.46	13.93	12.16	19.39	20.62	18.94	16.94
1965	4.90	8.25	8.91	8.21	13.81	16.46	23.65	21.65
1966	4.98	8.25	7.99	6.83	12.97	15.07	19.01	17.07
1967	10.95	16.57	18.42	14.49	29.37	31.06	24.13	22.64
1968	5.02	8.68	13.60	11.16	18.62	19.84	21.32	18.99
Totals	93.48	128.69	175.60	157.65	269.06	286.33	344.80	326.60
Cumulative Difference	+35.21		-17.95		+17.27*		-18.20*	

+Vegetated surfaces were assumed to have the hydrologic surfaces of meadow in poor condition (for fields and building lots) and woods in fair condition, giving a value of 20 and 28 for C in equation 2, p. 6, as compared to a value of 21 for building lots in the Fairfield Crest, Newark watershed, which had better maintained lawns.

*Differences in numerical values of total runoff and actual evapotranspiration occur because of differences in soil moisture storage on beginning and ending dates.

Table 5. Potential urbanization induced changes in components of the hydrologic cycle, as evaluated by a daily water budget incorporating an estimate of surface runoff, for Shellpot Creek Watershed, North Wilmington, Delaware, 1954-1968 [#+]

Year	Surface Runoff		Percolate Ground Water		Total Runoff		Actual Evapotranspiration	
	1954 Land Surface	Complete Urbanization	1954 Land Surface	Complete Urbanization	1954 Land Surface	Complete Urbanization	1954 Land Surface	Complete Urbanization
1954	4.63	18.97	8.41	5.44	13.03	24.42	22.00	11.09
1962	4.85	20.63	12.25	6.46	17.09	27.09	22.69	10.74
1968	5.02	19.31	13.60	5.89	18.62	25.20	21.32	9.67
15 Year Totals	93.48	344.18	195.90	96.99	289.37	441.17	324.35	171.48
15 Year Average	6.23	22.94	13.06	6.47	19.29	29.41	21.62	11.43
Cumulative Difference	+250.70		-98.91		+151.80[*]		-152.87[*]	
Average Difference	16.71		-6.60		10.12		10.19	

[#] Figures are comparable to those in Table 4. Potential evapotranspiration not used over impervious surfaces was allocated to vegetated surface area.

[+] Vegetated surfaces were assumed to have the hydrologic surfaces of meadow in poor condition (for fields and building lots) and woods in fair condition, giving a value of 20 and 28 for C in equation 2, p. 6, as compared to a value of 21 for building lots in the Fairfield Crest, Newark watershed, which had better maintained lawns.

[*] Differences in numerical values of total runoff and actual evapotranspiration occur because of differences in soil moisture storage on beginning and ending dates.

demand for 290 days, assuming three residences per acre (as in 1968) and residential demand of 200 gallons per day. The lowest amount of annual percolate in the 15 year period is less markedly affected--with complete urbanization it would be 4.9 inches in 1956 as compared to 7.2 inches with the 1954 land surface.

Other components of the hydrologic cycle are more markedly affected by urbanization than is percolate to ground water. As demonstrated in table 5, and illustrated in Figure 1 for 1968, surface runoff is more than tripled and actual evapotranspiration is reduced to less than half. Correspondingly, instances of flash flooding in low lying areas become more frequent and troublesome, while the urban heat island becomes more pronounced.

The inferences to be drawn for the center city, which is essentially all impervious surface can be mentioned. For the 1954-1968 period actual evapotranspiration on impervious surfaces averaged 2.5 inches, even assuming a wetting extraction from surface runoff of only .03 inches, as was done here. The remaining 38.3 inches of precipitation all would become surface runoff, with no percolation to ground water

Evaluation of the model against measured runoff from Shellpot Watershed

The model of surface runoff as developed from the measured precipitation, runoff, and land surface characteristics for the 55 acre Fairfield Crest Watershed and used in evaluating the effects of urbanization of Shellpot Creek Watershed on the components of the hudrologic cycle, was tested against the measured runoff data for the watershed, as collected by the Geological Survey (USGS). Correspondence between modelled and measured runoff, whether that from the surface alone or including percolate to ground water as base stream flow, was of course less than perfect. There are, however, some encouraging assurances of the validity of the model as a result of the comparison with USGS data.

As the first test of the model, estimated runoff was compared with measured runoff for 47 single day storms--12 in 1954, 15 in 1962, and 20 in 1968*. These years were chosen because they were the years for which aerial

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*November and December of the preceding year, and January and February

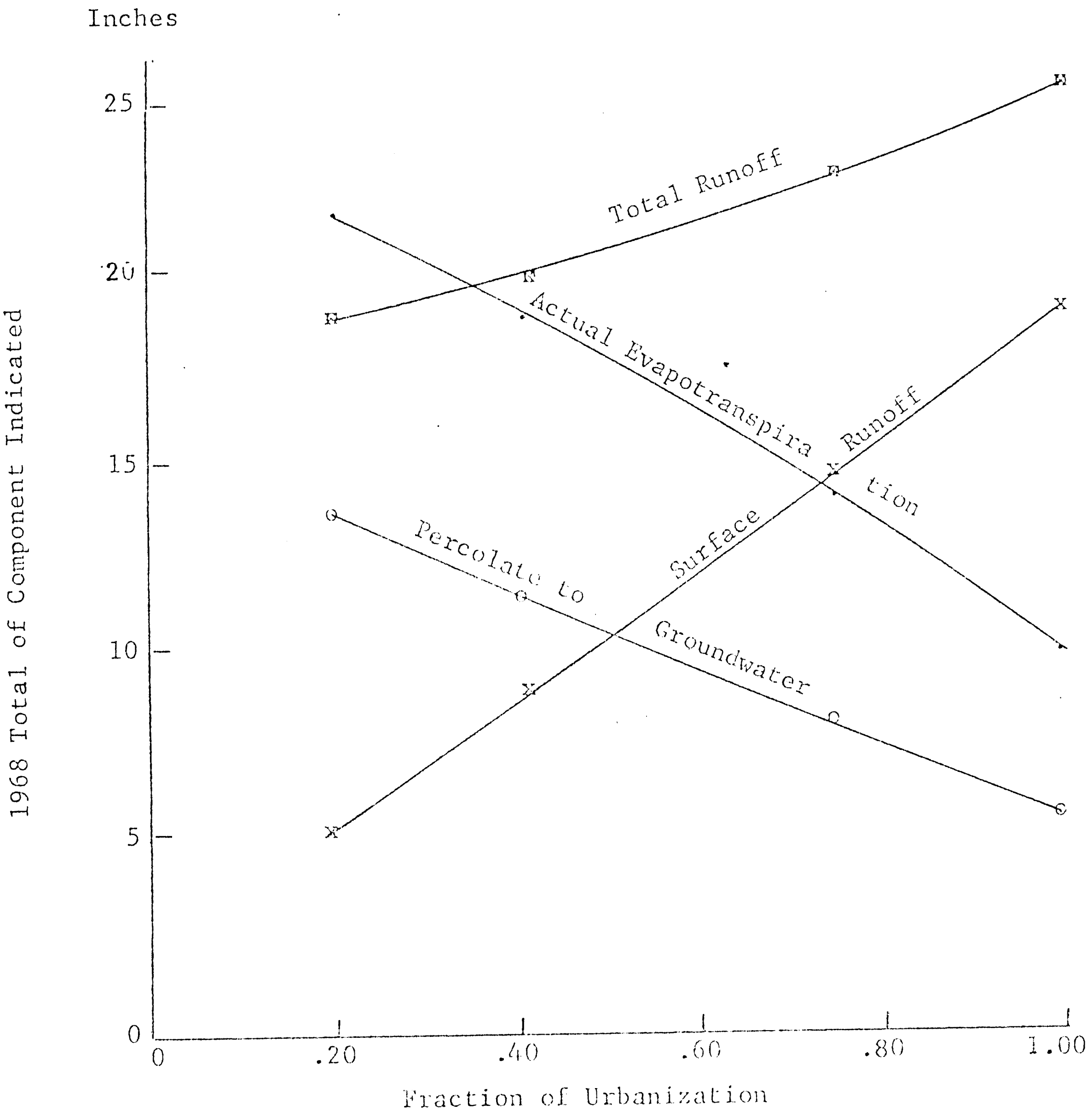

Figure 1. Effect of fraction of residential urbanization on surface runoff, percolate to ground water, total runoff, and actual evapotranspiration for 1968

photos were available and for which watershed surface types could therefore be measured with adequate accuracy. Separation of surface runoff from base flow in the stream flow record was done by assuming that when average daily streamflow increased the increase was initially caused by surface runoff, and that flow before the increase was base flow. It was also assumed that all flow greater than the initial base flow was surface runoff until flow declined to 1.5 times the initial flow--for single day storms this always occurred by the end of the third day. The method may overestimate surface runoff since even with a slope of .00005 water will flow over a concrete surface at the rate of 1.5 miles per day and the watershed is only 4.5 miles in length.

The correlation coefficient r, between model-estimated surface runoff and measured surface runoff for single day storms was .82 as compared to .52 between precipitation and measured surface runoff. The regression coefficients were .04 for the y-intercept and 1.36 for the slope of the regression line (-.22 and .57 respectively, for precipitation as the estimator of surface runoff). For individual years and between model-estimated and measured surface runoff r was .35 for 1954, .98 for 1962, and .81 for 1968. While y-intercepts were satisfactorily near the origin in all years--within .2 inches--the slope of regression always considerably exceeded the desired value of unity. By this test the model significantly underestimates surface runoff.

The test is not conclusive as to the model's validity. As was mentioned earlier, precipitation records used were those from the Porter Reservoir gage, which lies on the southwest edge of the watershed. A single gage is of course not representative of a 7.46 sq. mi. watershed--in fact, on two occasions measured runoff exceeded precipitation and on several others it nearly equalled precipitation. Use of data from the Marcus Hook gage, some three times as far from the center of the watershed as the Porter Reservoir gage, gave a higher r between modelled and measured runoff than the use of the Porter Reservoir data-.84 as compared to .82--and use of the average of the two estimates gave an r of .87. In both cases, however, the slope of

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of the succeeding year were included in each case so that each year represents a 16 month period.

the regression line was nearly three as compared to the desired value of unity.

Other possible reasons for the model's apparent underestimate of surface runoff include the possibility of inaccurate gaging of streamflow, and watershed characteristics that result in rapid delivery to streamflow of a part of the percolate to ground water. Neither of these possiblities could be evaluated within the scope of the project. On-site observation of the stream gaging site in July, 1973 revealed a channel which could circumvent the gaging site during high flows, but this would undergage runoff, rather than overgage it, so it would not explain the discrepancy. Throughout the watershed, on the other hand, unsealed drainage pipe is used to carry runoff under vegetated areas so that considerable amounts of the water entered in the water budget as surplus would find more rapid than normal entry into streamflow. This may serve to explain the greater apparent runoff during and immediately after storms than the model estimates. Some confirmation of this possibility exists in the fact that runoff significantly in excess of model estimates was lacking when no percolate to ground water appeared in the water budget estimates of apportionment of precipitation.

A second test of the model's validity as an estimator of surface runoff involved the comparison of annual amounts of estimated and measured surface and total runoff. By this test the model's validity is better established than by comparing daily runoff values. While r between model-estimated and measured annual surface runoff is only .74, r between the two for total annual runoff is .95. This indicates that 91 percent of the variation in total annual runoff is accounted for by the model. By contrast, variability in precipitation accounts for only 67 percent of the variation in annual runoff. Given the single precipitation gage with which runoff was estimated, this result of the model's application is very encouraging.

The model overestimates total annual runoff by about three inches--the regression coefficients are: a = -2.77 and b = .94. This could be because the estimate of PE is too low, a common criticism of the Thornthwaite estimate (McGuinness and Bordne, 1972). Gaging inaccuracies could also contribute. The data from both Wilmington, to the south, and Marcus Hook to the northeast, show lower precipitation values for the period. Application of the model to Marcus Hook data gives r = .94, a = -1.4784, b = .98. An average of the Marcus Hook and Porter Reservoir precipitation data estimates gives r = .96, a = -2.60, b = .99. Another possible source of error is the difference in watershed area between the USGS value used in determining runoff in inches for their records, and the values obtained in both this study and by the New Castle County Planning Department. The values from both the latter sources are five percent lower than the 7.46 sq. mi. used by the USGS. Use of the smaller figure would reduce the difference between estimated and measured total runoff to 2.0 and .7 inches for the Porter Reservoir and Marcus Hook precipitation data, respectively.

Within the limits of the data available the model is reasonably well validated. Application to more watersheds is desirable in order to adequately verify or modify it as necessary. This, however, proved impossible, though originally contemplated for two additional watersheds, because of lack of funds.

Listing of Significant Results

1) Development of a highly reliable model of surface and total runoff in an urbanized area. The model estimates surface runoff as a function of the relative fractions of surface area possessing various combinations of hydrologic characteristics. The hydrologic characteristics of interest include soil permeability, surface treatment, and storage capacity.

2) Application of the model to Shellpot Creek Watershed in North Wilmington, Delaware under several conditions of measured and assumed combinations of surface hydrologic characteristcs. The application revealed a tripling of surface runoff, a one-half increase in total runoff, and a halving of both percolate to ground water and actual evapotranspiration, as urbanized surface (residential use, 54 percent impervious surface) increased from 20 to 100 percent of the watershed area.

LITERATURE CITED

King, Horace W. and Chester O. Wisler. 1922. Hydraulics. New York, John Wiley and Sons.

McGuinness, J. L. and Erick F. Bordne. 1972. A Comparison of Lysimeter-Derived Potential Evapotranspiration with Computed Values. U. S. Dept. Agr. Tech. Bull. 1452. 71 pp.

Matthews, Earle D. and Oscar L. Lavoie. 1970. Soil Survey of New Castle County, Delaware. U.S. Dept. Agr. Soil Cons. Serv.

Reinhart, Kenneth G., and Robert S. Pierce. 1964. Stream-gaging Stations for Research on Small Watersheds. U.S. Dept. Agr. Handb. 268. 37 pp.

Soil Conservation Service. 1964. National Engineering Handbook. Section 4. Hydrology.

Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. Geogr. Rev. 38:85-94.

Thornthwaite, C. W., and J. R. Mather. The Water Balance. Publications in Climatol. Vol. III. No. 1. Centerton, N. J., Lab. Climatol. Drexel Inst. Technol. 86 pp.

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